N-Class Two-Stage Supersonic Sounding Rocket for Research and Development

Final Report

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DISCLAIMER

EXECUTIVE SUMMARY

Our senior capstone design project requires us to design, fabricate, test, and launch a two-stage high-powered rocket to an altitude up to 48k ft AGL max and reach and maximize time at the velocity at Mach 2 and above. The main goal of this project is to utilize our engineering knowledge to conceptualize, design, and manufacture a product that meets our client's needs. Our main stakeholder is Northrop Grumman Space Systems, Launch Vehicles Division. They are experts in space launch and military launch vehicles. NG mentors will help us with our design process and technical aspects of our design project.

The vehicle is required to carry a payload of up to 10 pounds inside of a 6-inch internal diameter bay, this is a main requirement of the client, but the full requirements are listed later in the report. With our baseline requirements from the course and the clients, we have set to come up with a full concept vehicle. Throughout the report is our process from benchmark comparisons, mathematical modeling, concept generation, and then concept selection. Once concept selection was completed, we started 3D modeling of the launch vehicle within Solidworks. Final design was accepted by our mentors and clients and manufacturing began. The process helps us expand our design and compare it to similar launch vehicles that have many different capabilities.

The current progress of the design is at the final manufactured stage. The final concept is currently meeting our hard requirements from the client. We have a two-stage launch vehicle with an internal diameter of 6”. The vehicle is refined into component layout, recovery system functionality, avionics bay flight computers, separation system mechanism, and nose cone geometry.

Progression made with this concept can now move into final testing of the manufactured prototype. The vehicle will be launched on December 14th, 2024. The launch will take place at the Phoenix Tripoli Eagle Eye Launch site.

Analysis was used to create a prototype system of the main launch vehicle. Our analysis will utilize commercial programs. In addition to CAD, we will be using simulation systems like FEA, CFD, and flight simulation software to visualize our calculations into the 3d model world. The tools help us complete complex calculations and solutions to the design progress. Initial prototyping will be based on reducing risk on the full-scale launch vehicle. The final prototype is full physical functional model of the design processes and will be tested in a flight to prove the design. Testing will provide valuable data to the design, and we will gain confidence within our design and improve where deemed necessary by calculations and the results of our flight test to further the use of the vehicle for future capstones.

The project is completed through the manufacturing and final testing. Moving forward with the project, we look forward to a successful flight and learning about any improvements that can be implemented to make this design useable for the future.

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1 BACKGROUND

The Northrop Grumman Supersonic Rocket Team is undertaking an ambitious capstone project to develop a two-stage supersonic rocket made from advanced composite materials. Partnering with Northrop Grumman, the team aims to meet stringent technical specifications while enhancing Northern Arizona University's (NAU) rocketry capabilities. This project seeks not only to meet but to exceed client expectations, all within a budget of $7,000.

The rocket is designed to serve as a launch platform for capstone payloads and as a testbed for future space shot rockets. Key objectives of the project include maximizing payload capacity, ensuring full recoverability, and accounting for potential environmental conditions. Success will be measured by adherence to client requirements, the proper functioning of all components, and improved performance achieved through extensive testing and simulation.

The vehicle is projected to reach a peak altitude of 31,000 feet above ground level (AGL), attain a speed of Mach 2.0, and successfully complete a separation event, followed by safe recovery without damage. Flight simulation software has confirmed that all mission goals, including the safe recovery of the vehicle, are attainable. Progress throughout the project will be documented through presentations, reports, and analysis memos, marking this endeavor as a significant advancement for NAU's rocketry development program.

1.1 Project Description

The primary objective of this mission is to develop a cost-effective test platform capable of reaching a peak altitude of at least 30,000 feet, maintaining a supersonic speed of Mach 2, and enduring accelerations exceeding 12g, all while carrying a scientific payload that adheres to Northrop Grumman's (NG) exact specifications. Although the initial altitude requirement was set at 40,000 feet, it has been adjusted to 30,000 feet due to launch site restrictions, while all other performance criteria remain unchanged.

The launch vehicle is constructed from composite materials selected during the analysis phase of the critical design review, ensuring optimal strength-to-weight characteristics. To enhance performance and reliability, the team will utilize tools such as RASAero and other simulation software to predict flight trajectories, conduct structural analyses, and model aerodynamic flows. These simulations will ensure the vehicle is fully equipped to meet the requirements established by the course, client, and project sponsors.

The final launch vehicle will be fabricated and fully tested by the team, completing a flight at the Arizona Eagle Eye Tripoli launch site in Wickenburg, AZ, during the fall of 2024. This mission represents a vital step in advancing the team's technical capabilities and achieving the project's ambitious goals.

The full list of requirements set by the course and the clients is stated in section 2.

1.2 Deliverables

During the project timeline, the team will use a series of deliverables to stay up to date on progress. These deliverables include presentations, a Preliminary Design Report (PDR), and Analysis Memos that summarize the technical requirements. Consistently tracking progress throughout the project will help the team ensure that they are meeting their goals and delivering a high-quality product.

First Semester:

- Presentation 1 – Tailored towards research for the project and minor engineering calculations for the prototype envisioned.
- Presentation 2 – The team created several designs and critiqued them to narrow down to the final design.
- Report 1 – Breaks down of the past two presentations and their challenges. In addition, it provides a fluent synopsis of the progress the team made.
- Analysis Memo – An individual task requiring selection and mathematical justification of a key engineering characteristic, design component, or decision crucial to the project's viability.
- Preliminary Design Review
- Presentation 3 – A final presentation that should detail the prototype's functionality and include pros and cons, detailed drawings, and financial analysis.

Second Semester

- Build Presentations – include Bill of Materials, Manufacturing Plans, and Purchase Plans for each version.
- Testing Plans – Detailed instructions of our experiments to verify our rocket meets the engineering requirements.
- Final CAD Package – All assembly files, SolidWorks parts, and additional hardware files are included in a compressed ZIP file to be delivered to the client.
- Initial Testing Results – Ground testing of all avionics and ejection charges.
- Final Testing Results – Full flight of the vehicle.
- Poster – Brief summary of the project to be shown at the EFest.
- Efest Presentation – Presentation to industry, school, and everyday people.

1.3 Success Metrics

The success of our project hinges on meeting the comprehensive requirements outlined by our client for a two-stage supersonic rocket. A detailed list of these requirements can be found in **Section 2.1**. Additionally, the flawless operation of each component during flight is paramount to achieving our objectives.

Beginning with the nose cone selection, we have opted for the Von Karman design, for its exceptional stability and minimal drag at supersonic speeds. However, the challenge of temperature flux poses a potential threat to the integrity of the epoxy layers, jeopardizing its aerodynamic properties. To address this concern, our team will analyze temperature fluctuations during flight to ensure the nose cone’s structural integrity remains intact.

Moving on to the body of the rocket, we anticipate significant pressure drag during supersonic flight, potentially leading to undesirable bending or buckling. Thus, our strategy entails conducting rigorous strength tests on various carbon fiber layer orientations. Adhering to ASME methodologies, we will determine the optimal number of layers and orientations to achieve maximum strength. Success will be gauged by minimal body deformations and a Factor of Safety exceeding 3.

A critical challenge lies in the development of an effective separation system for the rocket.

Given the Rocket Club's previous focus on single-stage rockets, we lacked guidance on suitable separation mechanisms. The success criteria entail an as expected separation at the designated time and the system's ability to maintain structural integrity during flight.

Lastly, the performance of our motors is pivotal to the rocket's overall success. Without proper ignition and propulsion timing the maximum performance can suffer. Thus, extensive simulations utilizing RockSim will be conducted to optimize motor performance and ensure the attainment of Mach 2 speeds. Given budget constraints, real-world testing of motor configurations will be limited to final flight plans. However, onboard GPS tracking will provide real-time velocity feedback, enabling us to validate our success margin.

Below is **Table 1** defines what our definition of success is dependent on. This can be a quick guide to gauge our success out in the field when final launch time arrives.

Mission Success Criteria

Table 1: Mission Success Criteria

Success Levels	Goals
Complete Mission Success	- Separation system works as expected, successful separation and second stage motor ignition. (CR1, CR2, ER2) - Payload safely delivered and landed. Data captured. (CR4, CR7, CR6, CR10, ER1, ER3, ER6) - Launch vehicle performance meets altitude goal. (CR5, CR6, CR9, ER2, ER3, ER4, CR3) - Launch vehicle recovered in reusable condition, no damage to vehicle at all. (CR3, CR5, CR8, CR10, ER6, ER5) - Recovery system performs as expected and designed. (CR1, CR2, CR10, ER2, ER6) - No anomalies (drastic angle change, bird strike, etc.) during full flight and payload mission until completed flight and recovery (All CRs and ERs)
Partial Mission Success	- Flight success (All CRs and ERs) - Velocity and altitude requirements met (CR4, CR6, CR7, CR9, ER1, ER3) - Payload flown but no data recorded. (CR5, ER4) - All components are recovered and reusable with minor damage. (CR1, CR3, CR10, ER4, ER6)
Partial Mission Failure	- Failure of payload or launch vehicle performance (All CRs and ERs) - Successful flight with failure of payload data recording or delivery (CR5, ER4) - Velocity or altitude requirement missed. (CR5, CR6, CR9, ER2, ER3, ER4, CR3) - Vehicle or payload systems damaged during flight or landing (CR1, CR3, CR10, ER4, ER6)

Complete Mission Failure	- Failure of both launch vehicle and payload systems (CRs and ERs) - Failure of recovery system deployment and beyond reasonable repair state (CRs and ERs) - Failure of vehicle before, during, or after flight (All CRs and ERs)

2 REQUIREMENTS

The requirements section of the report contains the requirements set forth in the project proposal by the customer, and the engineering requirements derived by the team from customer requirements. Each customer and engineering requirement has a definition of how it pertains to the project and what is being designed through the requirement. The first set of requirements, there were still questions that the team needed answered, along with knowing needing to know which requirements the client wanted the team to focus on. There have been edits and changes to the customer and engineering requirements throughout the project and reviews and meetings with the client. The team started understanding what the client wants/needs as the project continued. Some of the engineering requirements just have a successful or unsuccessful goal due to that aspect of the design needing to function with no anomalies. The requirements listed below are the current set of customer and engineering requirements developed by the team and the client, with the updated QFD at this current stage.

2.1 Customer Requirements (CRs)

The client's initial customer requirements were outlined in the proposal. Following several meetings, the client clarified certain aspects of these requirements and introduced a few additional ones. These changes were influenced by the nature of the class, as the client seeks specific analyses. Below is the complete list of customer requirements.

- CR1- Develop a two-stage launch vehicle.
    - The vehicle needs to be a two-stage rocket. Two stages mean the rocket needs an initial booster that will eject off the vehicle after being used to maximize the flight time and velocity. The second stage will continue the flight after the first stage ejects off the vehicle.

- CR2- Use of a stage separation device.
    - The client wants the team to use the prototype separation method discussed. The specific information on the separation system is proprietary Northorp Gruman information and cannot be shared in the report.

- CR3- The vehicle will be constructed of composite materials.
    - The client would like the vehicle to be constructed out of a composite material for strength and lightweight capability. The client would also like composite material to be replaceable for reuse.

- CR4- Vehicle will reach an altitude of at least 30,000 ft AGL (Above Ground Level).

  - The client would like the vehicle to reach the height of 30,000ft. This is a hard number that is not subject to change. The launch site we chose to launch the vehicle at has an altitude ceiling of 48,000ft ASL and we lowered the altitude as a safety to not pass the FAA Wavier.

- CR5- Final launch vehicle will be required to carry a maximum 10 Lb payload that will fit within a 6” diameter bay
  - One of the major requirements set by the clients is the vehicle should have a payload bay that should have a 6” diameter. The vehicle should have the ability to carry at least a 10 lbs payload. As stated by the client, this requirement is important as the vehicle is for research uses.

- CR6- Vehicle required to reach a maintain over Mach 2 or roughly 1500 mph and maximize time spent at that speed or greater.
  - This is a major requirement set by the client. The client would not just like the vehicle to reach Mach 2, but also maximize the time spent at Mach 2 or greater. Mach 2 is equivalent to about 1500 mph. The rocket being at this speed will result in the application of compressible flows and non-linear representations.

- CR7- Acceleration of the vehicle needs to meet a minimum of 12g’s.
  - The force acting on the vehicle during flight should result in at least 12g acceleration.

- CR8- Vehicle trajectory will be simulated in Rocksim and RASAero.
  - The trajectory of the vehicle should be modeled in both Rocksim and RASAero. Both programs are a modeling application for rockets, you can set the parameters you need to predict flight characteristics on the vehicle.

- CR9- Vehicle required to use commercial rocket motors.
  - The team must use solid fuel commercial rocket motors to easily replace and reuse the vehicle. Future use may be experimental motors for capstones.

- CR10- Recovery of entire launch vehicle for reuse.
  - The client would like the team to design the entire vehicle to be reused after each launch. Other than the motors, the entire vehicle needs to be reuseable or in a reparable state.

2.2 Engineering Requirements (ERs)

Engineering requirements are developed based on the customer requirements outlined above. There are fewer engineering requirements than customer requirements, as some of the latter have been consolidated. In the initial customer requirements, specific goals for the vehicle and the team were established. Throughout the process of collaborating with the client, the engineering requirements evolved from the team's original proposals to reflect the current specifications.

- ER1- Max Velocity – Mach 2 or 1500 mph
  - The velocity is the speed of the vehicle as it flies. This requirement is one of the

major engineering requirements. The goal is to reach and maximize the time at Mach 2 /1500mph. The goal time duration at Mach 2 the team is aiming for is at least 30 seconds.
    - The requirement is a two-sided constraint as this can be engineered by the body size, but the other requirements will affect the velocity of the vehicle. Every part of the rocket will affect the velocity of the vehicle as the more weight we add the or take off it will affect the velocity.

- ER2- Separation Event – Successful or unsuccessful separation
    - This requirement as it pertains to the project is just a yes or no if it works. The project is not specifically designing a separation system, but rather the vehicle needs to have two stages. The team just needs to know if the separation works with the device that will be chosen.
    - This requirement is a one-sided constraint as the only constraint that would affect the separation event is the separation device and method. Nothing else affects the separation event.

- ER3- Altitude – At least 30,000 ft AGL (Above Ground Level)
    - Altitude is one of our major engineering requirements, as the altitude can be measured and engineered by the team. The client also stated they want the vehicle to reach this height. The capstone instructor initially set the altitude goal as 50,000ft but the FAA Wavier holder wanted to lower the altitude due to concern of breaking the wavier.
    - This requirement is a two-sided constraint, like the velocity requirement every aspect of weight and speed will affect the altitude the vehicle is able to reach. For example, if you change weight this will affect the altitude, same with fins of the vehicle.

- ER4- Payload Weight – 10lbs
    - As this is a research vehicle, the client is adamant that the vehicle has the capability to sustain supersonic flight with a 10 lbs payload. The team does not know exactly what the payload is, but the vehicle needs to be able to safely return to the ground. The measurement of the payload will be how many pounds max the vehicle can carry to while maintaining supersonic flight.
    - This requirement is a one-sided constraint since it cannot change due to the client. This goal is set and will only affect other requirements, rather than being able to engineer this requirement.

- ER5- Cost of production - $7000 USD
    - This is the requirement is relatively important as the client would like this not to be a expensive vehicle and something that could be used multiple times, but they could build more without excessive cost. For this purpose, we would say this requirement could be related to the project budget. We have a budget of roughly $7000, if the team does not exceed that price, then this engineering requirement will be fulfilled. If the team can build the vehicle with less of the budget, then that would result in a better result of the engineering requirement being fulfilled.
    - This requirement is a one-sided constraint as we cannot really design for a low

cost of production. We can only design our rocket and with the lowest price possible by low material, not super expensive parts, but the cost of production does not really affect this specific project.

- ER6- Reusable – more than 1 use
    - The requirement will be measured by the number of uses the vehicle will have before needing major maintenance or needing to be replaced. For our purposes, the team cannot launch the final product more than 1 or 2 times. Therefore, if the vehicle has minimal damage after our launches, the team will predict the number of uses the vehicle has, before needing major maintenance or being replaced.

- ER7- Payload Volume – 282.7 in^3
    - This requirement was the least regarded as important as the client did not have any specific volume requirement and the payload weight is more important than the payload volume. The team has assumed that most 10 lbs payloads would approximately be less than 10 in tall. The volume measurement will be measured in cubic inches. If the team can reach the goal of 282.7 in^3 this engineering requirement would be considered successful.
    - This is a two-sided constraint due to the team being able to engineer this, and this would for example affect the lightweight constraint. This both has an effect and can be affected by other requirements. This could be seen as a one-sided constraint, but it is really a two-sided constraint.

2.3 House of Quality (HoQ)

Below is the QFD, also known as the HoQ. The team updated the HoQ/QFD from the initial HoQ/QFD due to the client and team discussing the ranking and changing of the initial customer and engineering requirements. The first version of the QFD had the customer and engineering requirements derived from the proposal and from the first few discussions with the client and what the client was talking about most. After the first draft of the QFD, the team reviewed the QFD with the client and the client decided that the weights and some of the customer and engineering requirements needed to be changed. The CR and ER from sections 2.1 and 2.2 were edited in the QFD to show what needs to be focused on in the overall project. The current QFD is shown below:

System QFD

Project: Two Stage Supersonic Rocket

Date: 3/18/2024

#	Technical Requirement	1	2	3	4	5	6	7	8	9
1	Altitude	(++)								
2	Body Diameter		(++)							
3	Vehicle Speed	(++)		(++)						
4	Vehicle Acceleration	(++)		(++)	(++)					
5	Payload Weight	(+)	(+)	(+)	(+)	(++)				
6	Seperation Event		(+)	(+)			(++)			
7	Reusable		(+)	(+)	(+)	(+)	(+)	(++)		
8	Payload Volume		(++)			(+)			(++)	
9	Body Material		(+)	(+)		(+)	(+)	(++)		(++)

#	Customer Needs	Customer Weights	Altitude	Body Diameter	Vehicle Speed	Vehicle Acceleration	Payload Weight	Seperation Event	Reusable	Payload Volume	Body Material	1 Poor	2	3 Acceptable	4	5 Excellent
			Technical Requirements									Customer Opinion Surv				
1	Lightweight	4	9	3	9	9	9	1	3	1	9					
2	Altitude	7	9	1	9	9	9	9		1	3					
3	Max Velocity	8		1	9	9	9	9		1	3					
4	Payload Weight	5	3	9	9	9	9				1					
5	Cost of Production	3		3				1	9	1	9					
6	Separation Event	6	1	1	3	1		9	1		1					
7	Payload Volume	1		9	1		3			9						
8	Reusable	2		1	1	3		1	9	1	9					

	Altitude	Body Diameter	Vehicle Speed	Vehicle Acceleration	Payload Weight	Seperation Event	Reusable	Payload Volume	Body Material
Technical Requirement Units	ft	in	mach	g's	Lbs	N/A	# of uses	in^3	lbs
Technical Requirement Targets	40000	6.25	2	12	10	Successful or not	5	282.7	45
Absolute Technical Importance	120	98	237	228	219	198	63	33	137
Relative Technical Importance	12.0	9.81	23.7	22.8	21.9	19.8	6.3	3.3	13.7
	6	7	1	2	3	4	8	9	5

Figure 1: Quality Function Deployment/ House of Quality

3 Research Within Your Design Space

3.1 Benchmarking

For our benchmarking we have three low to high end launch vehicles as our benchmarking of our vehicle. We want to compare our vehicle somewhere in between these three options.

Figure 2: Wildman Jr Two-stage Rocket

The first benchmark is the Wildman Jr two stage rocket kit. This is a hobby kit that does not carry a payload but still has the functionality and performance of a two-stage rocket. This compares lower than where our launch vehicle is ranked between this.

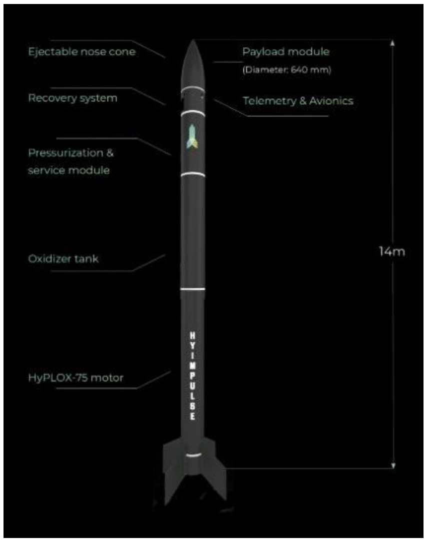


Figure 3: Hyimpulse Sounding Rocket

The second benchmark is the Hyimpulse sounding rocket. This is a medium sized sub-orbital vehicle. This is used for reaching beyond the Karmen line and into zero gravity weightlessness. This is a much bigger vehicle than ours and is used for the same purpose. The vehicle is a single stage rocket but still functions as a high altitude launch vehicle for running experiments. Our vehicle will be placed below this as our requirements are not designing a space launch rocket.

Figure 4: Northrop Grumman/ Firefly Medium Launch Vehicle

The final benchmark is the Northrop Grumman MLV, as seen above. This is an orbital class launch vehicle. This vehicle is capable of delivering a payload into orbit around earth. We wanted to add this comparison to create the benchmark of where we are at. The comparison to an orbital launch vehicle ground the design aspects of our vehicle and where the complexity of all the benchmarks compare to each other.

3.2 Literature Review

3.2.1 Lindsey Dineyazhe

[1] "A - C F D - Applied Computational Fluid Dynamic Analysis of Thermal and Fluid Flow Over Space Shuttle Or Rocket Nose Cone"

A-CFD is a research project-based book that analyzes the thermal and fluid flow over the nose cone of hypersonic space shuttles. The book investigates the effect of shock waves on pressure, temperature, and other parameters. The optimization process is conducted to identify the best-suited shape of nose cones for best-suited hypersonic flight. This reference supports this project by conducting an analysis on thermal and fluid flow over a rocket nose cone to assess what kind of nose cone would be better able to withstand high temperatures that are generated from aerodynamic heating.

[2] "Rocket Flight Engineering"

This book discusses all components of rocketry, including many studies done to determine flight characteristics of rockets in differing conditions. Several sections of the book focus on rockets in supersonic flight. This reference benefits this project as it also goes into depth of nose cone design best for supersonic flight.

[3] “A review on computational drag analysis of rocket nose cone”

This article analyzes various shapes and characteristics of a rocket nose cone to minimize aerodynamic drag and heat generation during ascent. Different software programs, including Catia and Solid work, are used to design and analyze the nosecone's shape.

Flow simulations are conducted to identify the most efficient nose profile with the least amount of drag at different Mach numbers.

[4] "NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS INVESTIGATION OF THE DRAG OF VARIOUS AXIALLY SYMMETRIC NOSE SHAPES OF FINENESS RATIO 3 FOR MACH NUMBERS FROM 1.24 TO 7.4"

This report does an in-depth study of determining the nose cone drag for Mach numbers ranging from 1.24 to 7.4 with a fineness ratio of 3. Pressure-distribution measurements are also observed for the nose cone models. This report benefits the project as the rocket is expected to reach Mach 2 or higher and the best nose cone for this should be assessed.

[5] "Optimization Design of Rocket Nosecone for Achieving Desired Apogee by Empirical Research and Simulation-Based Comparison"

This paper focuses on using research and simulations to determine what aerodynamic rocket nose cone design allows for higher apogee results. An analysis of the effects of the nose cone material, size, and shape are done using OpenRocket software and Solidworks. This research benefits this project's design of the nose cone to allow the rocket to reach the desired altitude by minimizing drag.

[6] "Richard Nakka's Experimental Rocketry Site"

This website consists of tons of information and resources for amateur experimental rocketry. It covers many terms and aspects of the design of almost every part of a rocket. This website is helpful for this project, especially for members with little to no rocketry experience, in the design process as most components will be made from scratch.

[7] "Nose Cone Tip Thermal Analysis - MIT Rocket Team - MIT Wiki Service"

This website performs a thermal analysis of a rocket nose cone tip. As the nose cone is the part of the rocket subjected to the most heat, it has potential for burning and damage when in flight. This analysis is important for the design of the nose cone in this project to avoid these damages.

3.2.2 Avery Charley

[8] "Fundamentals of Aerodynamics"

The book presented a basic analysis of the drag equation for an object in flight. However, our rocket will face supersonic conditions where analytical analysis is limited. Therefore, we have no choice but to rely on theories supported by experimental data gathered in supersonic conditions. The Drag Equation we used helped us to determine the amount of force needed to detach the first stage of the rocket through drag separation.

[9] "Hybrid Rocket Propulsion Design Handbook"

This chapter provides essential equations that are fundamental for rocket design and can be applied to various chemical propulsion systems. These equations cover important parameters such as thrust, characteristic velocity, specific and total impulse, and are accompanied by a summary table that clarifies their relationships. The chapter also explains the rocket equation and discusses aspects of staging.

[10] "Fundamentals of Rocket Propulsion"

I found this book to be very informative regarding the analytical aspect of multistage rockets. It provided an overview of the purpose of multistage, followed by the "Rocket Equation" which emphasizes the significance of achieving higher velocity during flight. However, the references mentioned in the book are specifically intended for large space rockets, whereas our application is much smaller and lighter. Despite this, the mathematical calculations and breakdown of the Rocket Equation provided in the book are still useful for our purposes.

[11] "Numerical Investigation on the Interaction between Rocket Jet and Supersonic Inflow"

This paper studies the interaction between a rocket jet and supersonic inflow through numerical simulation using the Navier-Stokes equations with a k-ω SST turbulence model. The results show that the nozzle inlet mass flow rate significantly affects the interaction, with low rates causing flow separation and shock train. In contrast, higher rates result in continuous gas expansion and more complex shocks downstream.

[12] "Effect of Silane Coupling Treatments on Mechanical Properties of Epoxy Based High-Strength Carbon Fiber Regular (2 x 2) Braided Fabric Composites."

The study focused on enhancing the adhesion of carbon fiber-reinforced composites by modifying epoxy resin with 3-aminopropyltriethoxysilane (APTES) and 3-aminopropylmethyldimethoxysilane (APMDMS). Various concentrations of silane treatment were applied to the epoxy resin. Results indicated that APTES/APMDMS-treated epoxy/carbon braided composites at 0.5 wt% exhibited improvements in tensile and flexural strength, as well as tensile and flexural modulus. Impact testing revealed enhancements of 6.87% and 4.31% for 0.5 wt% APTES and APMDMS composites, respectively, compared to untreated ones.

[13] "Fins for Rocket Stability"

I've been looking for information on separation systems, but then I decided to broaden my search to rocket fin design. I found a website that was easy to navigate and provided a lot of helpful information. It explained the ideal lengths and number of fins to use, as well as the importance of having a low center of gravity for the rocket.

[14] "Exploring the different types of rocket staging – a comprehensive GUIDE,"

I chose this article as an overview of the staging process. It involves separating a rocket into stages, each with its own engine and fuel supply. Single-stage rockets are suitable for small payloads. Two-stage rockets are the most common and lift the rocket with better efficiency. Multistage rockets offer improved efficiency, payload capacity, and speeds, making them ideal for deep-space missions. Each type shapes space exploration as technology evolves.

[15] "Low Shock Payload Separation System"

This report was created for a previous capstone project, and it provides a detailed overview of the magnetic separation system that was designed for a significantly larger fuselage. Since the client had worked with the former team, I was able to outline the concept of the separation system based on the previously tested product. However, the main challenge is to streamline the parameters to align with our current project.

3.2.3 Austin Paothatat

[16] “Rocket Propulsion.”

Basic rocket design textbook goes into the fundamentals of rocket science and how they work. We will utilize this to cover our basis on the theory of rocket propulsion and motion. The main topics that we would use are staging and the rocket equation.

[17] “The flight of uncontrolled rockets.”

The book covers the uncontrolled flight events of rockets. It describes the aerodynamics affects, rotational motion, and what calculations are needed to predict the trajectory which will further help us in creating our Matlab simulation code.

[18] “Aerodynamics and flow characterization of multistage rockets,”

Aerodynamics of our two-stage flight is going to be important to maximize the boost stage to get us to our requirements. The 2nd stage fin flow will affect our booster stage fins aerodynamics and will need to account and model to see the effects this will have depending on our fin design and locations.

[19] “Multidisciplinary optimization of single-stage sounding rockets using solid propulsion”

The second stage will require optimization to reach our flight requirements of the second stage. Although this paper is directed toward a space shot rocket, we can use this to optimize our design within the same Mach speed regime and design for even higher altitudes for future flights.

[20] “Multistage 2-DOF Rocket Trajectory Simulation Program for Freshmen Level Engineering Students,”

The paper covers a Matlab code that students use to predict flight trajectories within a certain accuracy. We will be required to create our own version of this to predict the trajectory of our rocket. This will be a great reference into the coding and what analysis is used to create methods like Eulers and Runge-Kutta. We will use this code to also plot our flight in a google map and find the possible landing locations of the vehicle.

[21] “Glenn Research Center,”

Glenn Reasearch Center is a website that covers design aspects of rockets and other related physics problems. This will be a good resource to use as baseline calculations are made. Overall source for fundamental rocketry and physics.

[22] “Preliminary design and test of high altitude two-stage rockets in New Zealand,”

This document describes the development of a high-altitude rocket design by students at the University of Canterbury. The document covers the entire vehicle design from propulsion, staging, and recovery of their system and the floatation device used to recover in a body of water. This is a similar project in terms of physical vehicle design but ours is at a much lower altitude.

3.2.4 Koi Quiver

[23] “Viscous hypersonic flow: theory of reacting and hypersonic boundary layers.”

This book relates to the project overall by providing information of effects of the air at turbulent flows. The book supplies specific information specifically for calculating the coefficient of skin friction, boundary layer, etc. as the air is turbulent. The book also provides all the same information for the flow of air being laminar. The rocket will really have a main effect of skin friction drag and a little pressure difference drag with the design we have chosen.

[24] “Rocket Propulsion Elements"

This book provides information on the basics of rocketry and rocket propulsion. This provides a good sense of base knowledge pertaining to the project and how to go about

calculating forces on the rocket. If the team needs to do any calculations on nozzles, this book has information on how to calculate it for certain nozzles.
[25] "A REVIEW ON NOSE CONE DESIGNS FOR DIFFERENT FLIGHT REGIMES"
This paper provides knowledge on how different nose cones designs react to supersonic flight. The main calculation the paper provides is the total nose cone drag. Which is an aspect of drag that needs to be calculated for our vehicle. The paper provides information on the nose cone design we decided to use for the overall design. This paper helps greatly with what is happening with understanding how supersonic air flows around our nose cone.
[26] "CONCEPTUAL DESIGN AND ANALYSIS OF TWO STAGE SOUNDING ROCKET,"
This paper provides information on two staging rockets and how air flows around different designs of the body. The paper graphs the effects of temperature vs the altitude, along with drag coefficient and drag force vs the Mach number. This provides a representation of what our rocket's drag forces and coefficient if the bodies are similar. The paper also provides the basic formulas the authors used to help guide the team's thinking.
[27] "Engineering Toolbox"
This site is a resource used to sometimes find values of certain variables or research information on certain methods. Used for research and reminders of general engineering knowledge. I have used this to find the value of the drag coefficient for a certain situation. Can also use it to find different drag coefficients.

[28] "Multi-objective optimization of a fin shape for a passive supersonic rocket stage"
This document provides information and a baseline of how to calculate the drag of rocket fins at supersonic flight. It provides the research of the IEEE organization. The document provides multiple coefficients of drag for geometries that have already been determined but are like the fin geometry the team has chosen.
[29] "Skin-Friction and Forced Convection from Rough and Smooth Plates"
This paper provides information on how to potentially calculate the skin friction of a surface, in this case the body of our rocket is going to be constructed completely out of carbon fiber and most likely surfaced with epoxy. If we cannot find a general skin friction coefficient for the surface, then we would have to calculate our own. This paper would help and provide information on how to do that. If we need to change the material, then we could recalculate the skin friction of the surface.
[30] "What is the best Fin shape for a model rocket"
This is a newsletter article from the company Apogee components. The contents of the article are talking about the best designs for rockets. They have elliptical, rectangular, trapezoidal, etc. Designs and provide some general drag force calculations for each design and at a certain angle of attack.
[31] "Laminar Composites"
This is a textbook that has to do with working with composites in aerospace applications. The specific airflow applications in this textbook are all laminar flow cases. The book does not have to do with turbulent flow, which is the type of airflow the vehicle will be in, but the layup of the carbon fiber is the information that most pertain to the project.
[32] "Mechanics of Composite Structures"
This is a textbook that has to do with how composites in certain structure forms will react to forces. This will help make most of the vehicle's parts. The book will also help when the team decides to do testing on layers of carbon fiber to see how much stress can be put

on the vehicle.

3.3 Mathematical Modeling

3.1.1 Nose Cone – Lindsey Dineyazhe

An important aspect of the nose cone is its ability to withstand extremely high stagnation point temperatures of a high altitude, supersonic flight. To ensure that the nose cone does not take any damage from the heat, an analysis of the stagnation temperature on it must be done. The stagnation temperature should not exceed the nose cone's material melting point. The following **Equation (1)** will be used to calculate the stagnation temperature in K, Kelvin:

$$T_{stag} = T_s\left(1 + \frac{\lambda-1}{2} \cdot Ma^2\right) \qquad \textbf{[1]}$$

where T_s is the static temperature at a given altitude in K, λ is the specific heat ratio for air valued as a constant of 1.4, and Ma is the Mach number to be reached. For this analysis, a worst-case scenario will be examined to determine precautions needed avoid failure if these scenarios are encountered. Therefore, values above the minimum required altitude and Mach number will be used in the stagnation temperature calculation. The static temperature at an altitude of 55,000 ft (about 16.76 km) would approximately be 218 K. Additionally, the maximum Mach number for supersonic speed to be use is 5. Inserting these values into **Equation (1)** gives us a stagnation point temperature of 1308 K. To accommodate this potential scenario, the team decided to incorporate a metal tip to the nose cone that will be able to withstand the stagnation temperature for a majority of the nose cone. A steel material will be used for the nose cone tip as the melting point for steel is approximately 1623 K, well above the calculated stagnation temperature.

Another crucial aspect of the nose cone is the fineness ratio. The fineness ratio is the ratio of the length of the nose cone body to its maximum diameter as seen in **Equation (2)**. An increase in this ratio would help reduce the wave drag coefficient affecting the nose cone but can also increase the skin friction drag due to more exposed surface area. Generally, a high fineness ratio is desired for supersonic speeds, at approximately 5:1. Anything above this would hardly reduce wave drag and only increase friction drag.

$$Fineness\ ratio = \frac{L}{D} = L{:}D \qquad \textbf{[2]}$$

In **Equation (2)**, L is the length of the nose cone in inches and D is the maximum diameter at the base of the nose cone also in inches. Using the currently set diameter of the rocket body, 6.25 inches, would also be the base diameter of the nose cone, the equation above is adjusted to find an acceptable nose cone length to achieve a fineness ratio of 5:1. The nose cone would need to be 31.25 inches in length for the desired fineness ratio.

3.1.2 Rocksim and RASAero Simulations – Austin Paothatat

Simulations provide vital information for our flight performance and recovery system. Utilizing two software programs called Rocksim and RASAero, these two programs will assist us in the simulations of our flight profile. These will be used as the basis for our vehicle performance and to pull data from and compare our calculations and Matlab code. Current models of the launch vehicle can be found below.

__**Modeling**__

- **RockSim**
  Below is the modeling in RockSim. This is the current design and with estimated mass based on design. The results showed that we will reach the speed and acceleration performance requirement. The main concern is Rocksim is built for subsonic vehicles but still useful for recovery information. Final simulations will be completed in RASAero which is designed for supersonic and hypersonic flight.

Full Scale Capstone Rocket
Length: 178.0000 In. , Diameter: 6.1700 In. , Span diameter: 14.1700 In.
Mass 37358.109 g , Selected stage mass 37358.109 g
CG: 112.0634 In., CP: 123.1594 In., Margin: 1.82
Engines: [N3300R-Plugged-1][N1000W-0]

Figure 5: RockSim Meta Data

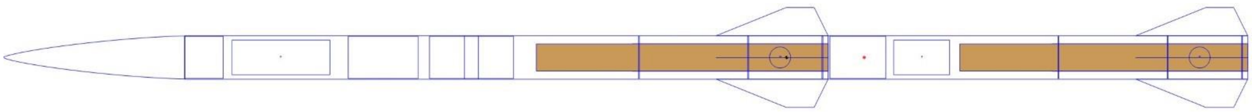


Figure 6: RockSim Model

Simulation	Results	Engines loaded	Max. altitude Feet	Max. velocity Miles / Hour	Max. acceleration Gees	Velocity at deployment Miles / Hour	Velocity at launch guide departure Miles / Hour	Time to apogee	Total flight time
32		[N4800T-0] [N1000W-P]	35160.11	1031.52	15.17	67.11	83.41	43.98	167.26
33		[N1000W-0] [N4800T-P]	37464.90	1736.92	24.68	37.46	45.75	51.42	126.51
34		[N1000W-0] [N4800T-P]	37074.15	1726.73	24.67	39.13	45.75	51.14	126.23
35		[N1000W-0] [N3300R-P]	33637.47	1453.03	16.54	35.58	48.00	49.17	120.88
36		[N1000W-0] [N3300R-P]	34243.44	1461.02	16.54	24.77	48.00	49.65	121.95
37		[N1000W-0] [N3300R-P-1]	34496.06	1456.19	16.62	34.18	48.00	50.50	122.87
38		[N1000W-0] [N4000-0]	35465.22	1566.36	16.94	49.42	43.40	51.70	121.52

Figure 7: RockSim Flight Data

- **RASAero**
  RASAero is a program designed to be used with supersonic rocket flight and will better suit our needs as a program and flight profile verification. This is new software to the team and the results will need to be verified before trusting the program RASAero gave us similar speeds but says we will reach our altitude goal of 31k ftt AGL. RASAero can import Rocksim files and compare mass, CG, CP locations, along with vehicle performance values. The results are below but look promising to reach our performance goals. The two pieces of software will need to be compared more and verified by hand calculations to complete further analysis to get our flight conditions correct. Simulations will be updated until and on launch day. Final RASAero simulations were reviewed by Tripoli mentors and verified for correctness and safe flight parameters.

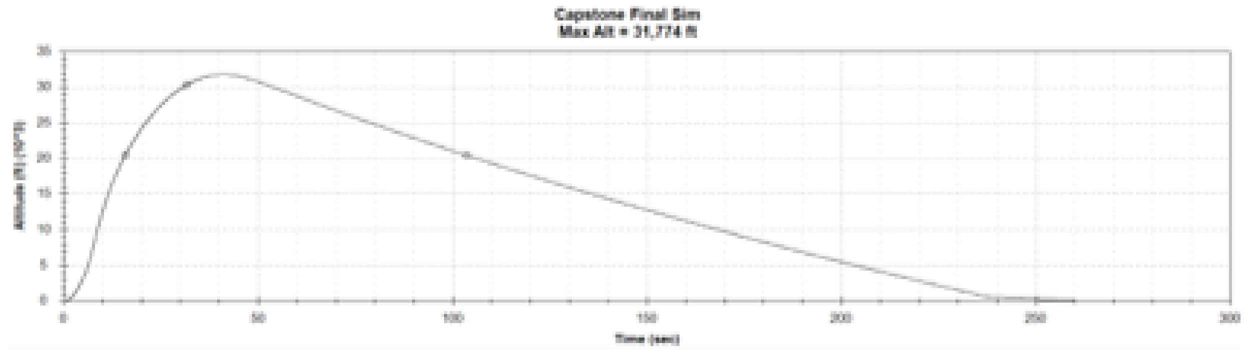


Figure 8: RASAero Flight Data

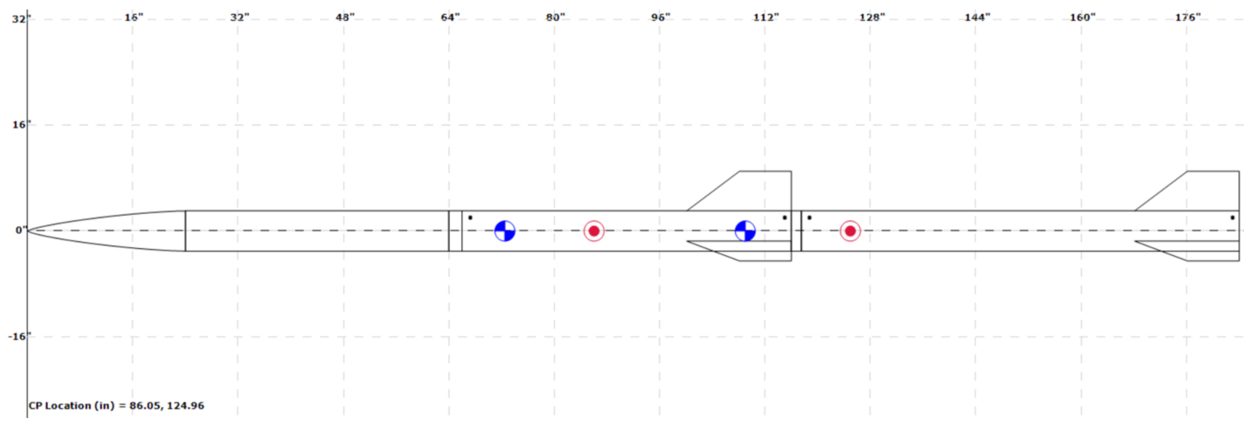


Figure 9: RASAero Model

The RASAero simulation is the most up-to-date model of the vehicle. We will run another simulation on the day of launch with weather conditions and final vehicle weight and CG to ensure the flight will be successful.

Rocket Motor Selections

In **Table 2** are the specifications in our critical design motor choice for this point in the design. Below are shown the basic specifications of the motor like total impulse, total mass, burn time, and propellant mass. With these motors simulated we receive the performance values in **Table 2**.

Table 2: Critical Design Motor Choice Specifications

Motor	Total Impulse (N-s)	Total Mass (Grams)	Burn Time (Seconds)	Propellant Mass (Grams)

N2200DM (Booster)	10,657	11,997	5.4	7,183
N3300R (Sustainer)	14,041	12,054	4.4	7,512

3.1.3 Separation System- Avery Charley

Multistage is essential in achieving higher velocities without requiring a large motor. However, to achieve this objective, it's important to establish an efficient connection between the stages and ensure impeccable timing during the disconnection process. This synchronization is crucial to optimize propulsion efficiency and maintain trajectory integrity. As a result, the primary focus shifts towards engineering the necessary structural robustness to withstand the intense forces acting upon the vehicle during both the unity and separation phases.

As the rocket accelerates and transitions into supersonic speeds, traditional analytical methods encounter limitations in accurately predicting the diverse levels of drag it will encounter. To address this challenge and estimate the drag forces necessary for stage separation, we turn to the Drag Equation tailored for incompressible speeds.

$$D_i = \frac{1}{2}\rho V^2 C_d A_{cyl} \qquad \textbf{[3]}$$

In addition, the Parasitic Drag Equation and weight of the stages will help in finding the total drag force.

$$D_f = \frac{1}{2}\rho V^2 C_f A_{SA} \qquad \textbf{[4]}$$

$$W = m \cdot g \qquad \textbf{[5]}$$

The team expected to achieve a velocity under Mach 1 (which is equivalent to 630.67 ft/s) at an altitude of around 9,500—10,000 feet. For my analysis, I will set the altitude at 10,000 feet (~3000 meters). The next step was understanding the value for our Coefficient of Drag (Cd), which was different from various sources that rockets usually have a Coefficient of Drag (Cd) ranging from 0.75 to 0.89. Since the supersonic rocket is technically a rocket, I chose the "model rocket" Coefficient of Drag at 0.75. Obtaining accurate values for parasitic drag on carbon fiber proved to be challenging due to conflicting information from various sources and different versions of the material. However, after thorough research, I managed to find a reliable source that provided the value of 0.3. Using the dimensions and weight obtained from Austin's RockSim simulations, I calculated the total drag force on the Upper Stage to be 7389.58 N (1661.24 lbf) and the Booster Stage to be 4136.01N (929.81 lbf). These values account for the parasitic drag induced by both stages. While these are large forces to overcome for the separation system, I will be assuming the rockets thrust will carry the separation system without straining it during flight until separation.

- Booster Stage Aerodynamics Calculations (10,000 feet/ ~3000 m):

$$D_f = \frac{1}{2}\rho V^2 C_f A_{SA}$$

$$D_{fB} = \frac{1}{2}\left(0.9093\frac{kg}{m^3}\right)\left(192.227\frac{m}{s}\right)^2 (0.3)(0.752m^2) = 3790.05\ N$$

$$W_B = m \cdot g = 10.35kg \cdot 9.81\frac{m}{s^2} = 101.53\ N$$

$$F_{total} = D_{fB} + W_B = 3790.05\ N + 101.53\ N = 3891.58\ N \rightarrow\ 874.86\ lbf$$

- Upper Stage (2nd Stage) Aerodynamic Calculations (10,000 feet/ ~3000 m):

$$D_f = \frac{1}{2}\rho V^2 C_f A_{SA}$$

$$D_{iU} = \frac{1}{2}\left(0.9093\frac{kg}{m^3}\right)\left(192.227\frac{m}{s}\right)^2 (0.75)\left(\frac{\pi}{4}(0.157m)^2\right) = 244.43\ N$$

$$W_b = m \cdot g = 14.23\ kg \cdot 9.81\frac{m}{s^2} = 139.60\ N$$

$$D_{fU} = \frac{1}{2}\left(0.9093\frac{kg}{m^3}\right)\left(192.227\frac{m}{s}\right)^2 (0.3)(1.39m^2) = 7{,}005.55\ N$$

$$F_{total} = D_{iU} + W_b + D_{fU} = 244.43\ N + 139.60\ N + 7{,}005.55\ N = 7389.58\ N \rightarrow 1661.24\ lbf$$

It's worth noting that the Upper Stage of a rocket experiences a significantly greater drag force than the lower stage, primarily due to the size difference between the two. This means that when calculating the total drag on the rocket, it's safe to assume that the Upper Stage will bear the brunt of the Induced Drag, while the Booster Stage will experience more of the Parasitic Drag. Considering these factors is crucial for accurate calculations and successful rocket design.

3.1.4 Fin drag – Koi Quiver

At supersonic flights the drag from the fin would have a larger affect than the vehicle fins being at subsonic flight. For the first part of analysis, I calculated the rocket fin drag. I calculated for a single fin and then multiplied that force by the number of fins to get the total drag force from the fins. There were some assumptions made to get certain numbers to get an accurate calculation.

The assumptions made were Coefficient of a flat plate at turbulent flow, density of air at 20,000ft elevation, and a little bit of error due to air compressibility at Mach 2. The variables are:

- v = 686 $\frac{m}{s}$
- C_d = 0.005
- A = 0.01677 m^2
- P = *0.0880349* $\frac{kg}{m^3}$

The formula used to calculate the drag for is:

$$D = \frac{1}{2}\rho v^2 C_d A \qquad \textbf{[6]}$$

The calculated drag of one fin of the vehicle is 1.74 N or 0.390 lbf. To account for the total drag force was calculated to be 13.9 N or 3.12 lbf.

3.1.5 Flow Simulation – Koi Quiver

Below are baseline flow simulations run through the SolidWorks flow simulator. The sections of the vehicle that were analyzed were the full vehicle just before separation and second stage at the max velocity of Mach 2.0.

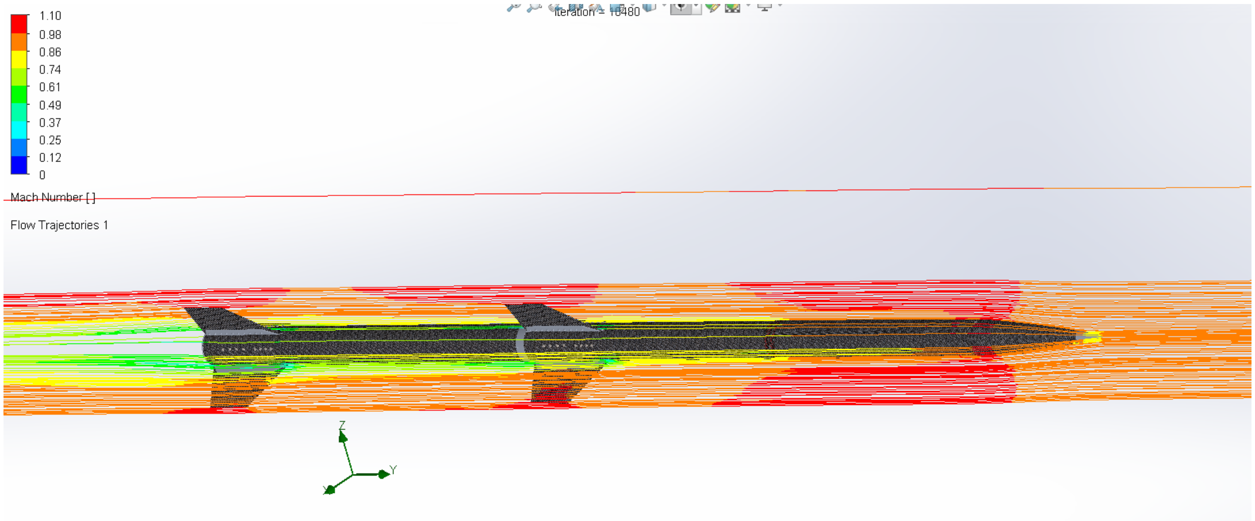


Figure 10: Velocity Flow Simulation of Entire Vehicle

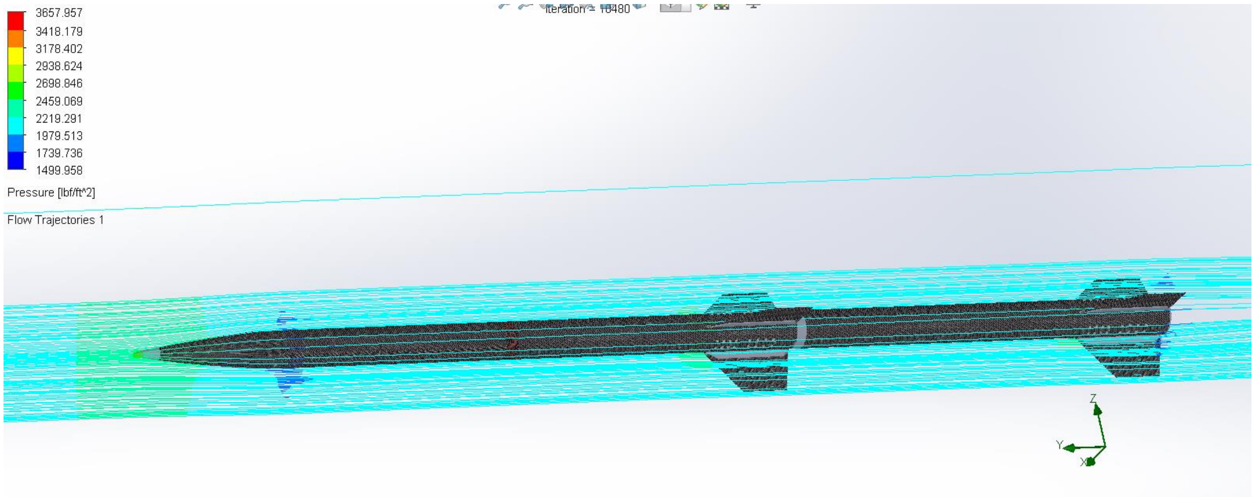


Figure 11: Pressure Flow Simulation of Entire Vehicle

Figures 10 and **11** show the velocity and pressure flow around the full rocket body. **Figure 10** shows the velocity of air in Mach number. Red shows regions of flow at the fastest velocity. Green shows the area of slowest velocity. The air flows at about Mach 0.5 in the green region and about Mach 1.10 in the red region. This shows that Mach 1.0 is not uniform over the entire vehicle body and the further down the rocket body the fluid is, the slower the fluid is. This follows the laws of subsonic flow.

Velocity changes for the full rocket are related to the change in pressure. After regions of higher pressure, the velocity increases. At regions of the highest velocity are regions of low pressure abiding by the laws of fluid dynamics. This changes when it comes to supersonic flow shown below.

Figure 12: Velocity Flow Simulation of Second Stage

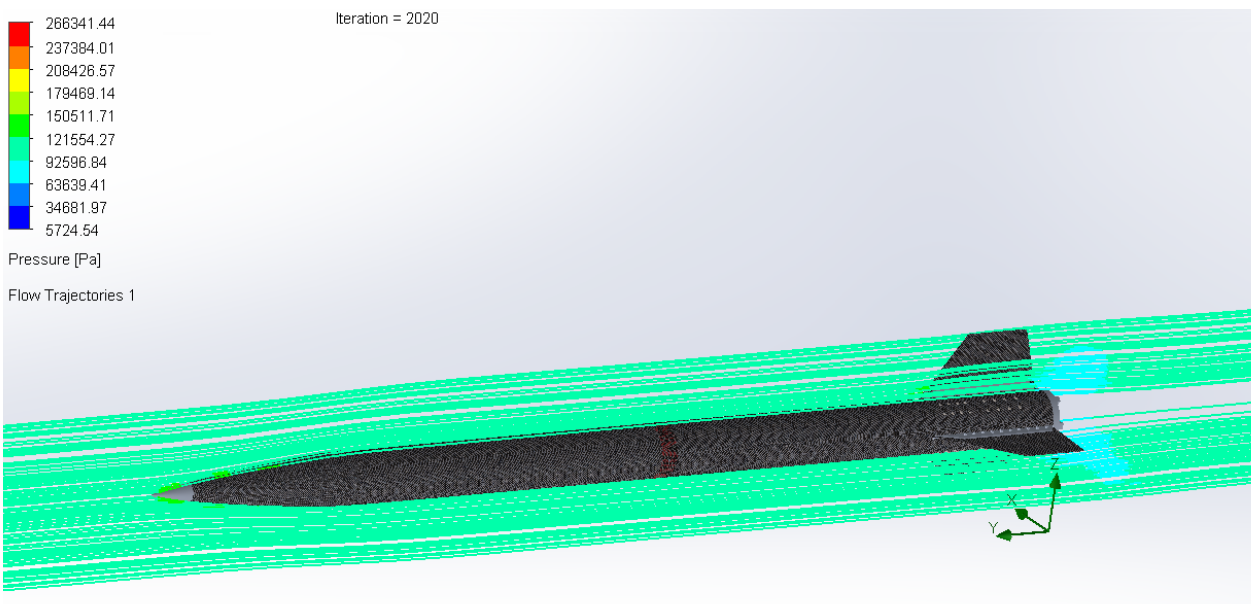


Figure 13: Pressure Flow Simulation of Second Stage

The SolidWorks flow simulator shows that the rocket has more uniform velocity flow around the second stage body. The flow directly surrounding the body is slower than Mach 2.0, but the air passes the boundary layer flowing around Mach 2.0. The same is similar for pressure around the vehicle body, it is uniform over most of the outer surface. However, at the end of the vehicle body, the region of lower pressure is way bigger than that of subsonic flow. Meaning drag force is more in supersonic flow than subsonic flow. At higher pressure for both subsonic and supersonic flow have an increase of temperature. The areas of higher pressure where most heating will occur are at the tip of the nose cone and fins. These are the regions in most danger of heating. In subsonic flow major heating does not occur, but in supersonic flow major heating at these regions of higher pressure does occur.

The SolidWorks models work for subsonic flow; however, it is not accurate for supersonic flow. For future analysis the team will do ANSYS fluid flow Simulation to receive more accurate numbers in supersonic flow. Along with turbulence and heating calculations.

4 Design Concepts

4.1 Functional Decomposition

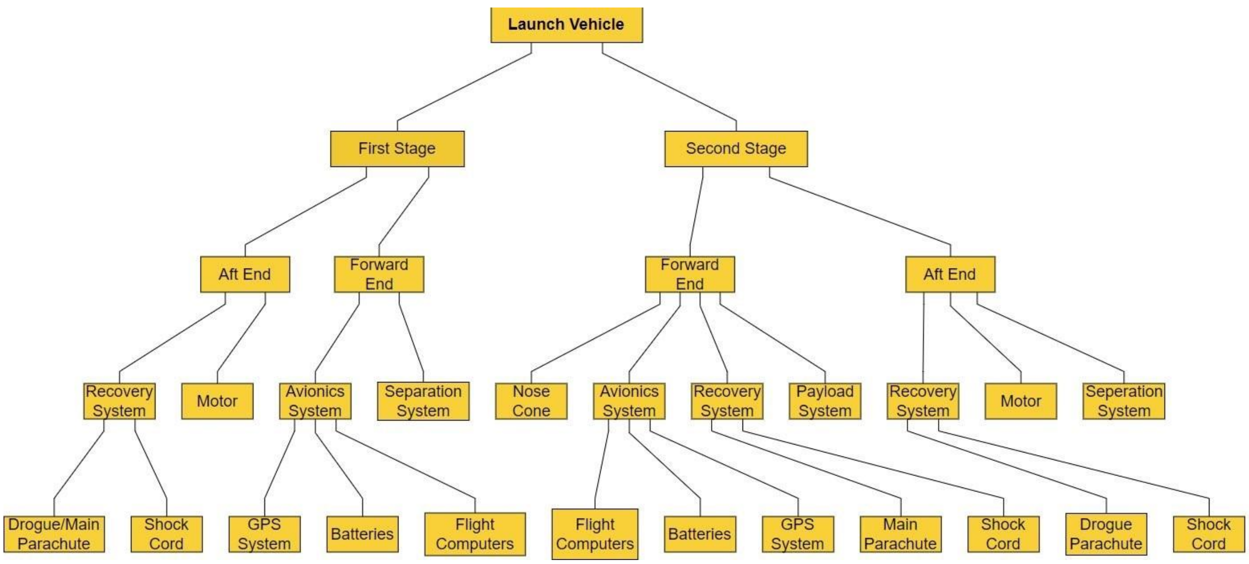


Figure 14: Functional Decomposition Chart

Above in **Figure 14** is our functional decomposition chart that visually displays our flow of components into subsystems and into the final launch vehicle configuration. We will utilize this in our design process as we come to create drawings for all subsystems and components.

We can use the chart to organize our drawings from a top-level assembly of the launch vehicle and flow from the single components to create subassembly drawings including systems like avionics, recovery, and separation systems. We will build on this chart to include drawing names, part numbers and where they will flow into. Keeping the CAD and drawings organized will allow us to easily find them and see what we have completed so far.

The chart will also be utilized to create our testing, and mechanical assembly procedures. This will allow us to compare where the flow will need to stem from and how our assembly will be step by step of components, subsystems, and final launch vehicle. Procedures and testing will benefit us when we are preparing to assemble and launch the vehicle.

4.2 Concept Generation

<u>All photos of concepts are in **Appendix A**</u>

4.2.1 Avionics

The avionics system will house all flight computers that record our data and control recovery energetics. These are planned to be the raven blue Feather Weight altimeters. These systems will be redundant on both the booster stage and 2nd stage. The concepts below cover the type of recovery system the avionics will be used with.

Concept 1: Single deployment both stages no drogue/Streamer [A1]

Single Deployment- Both stages will house one main parachute that will be deployed at a predetermined low altitude (around 500ft AGL). The vehicle will have one separation event deploying the drogue/streamer at apogee and there will be a system to deploy the main parachute from the deployment bag.

Concept 2: Dual deployment both stages [A2]

Dual deployment- The vehicle will have two events; The first event will be the drogue parachute deployment. This event will happen at or near the apogee of the stages. The vehicle will fall under the drogue parachute until the next event that will deploy the main parachute at a predetermined altitude.

Concept 3: Single deployment 2nd stage and Dual deployment booster stage [A3]

Single/dual deployment- This style will utilize the A1 and A2 recovery systems. The single will be on the 2nd stage and the dual on the booster stage.

Concept 4: Dual deployment 2nd stage and Single deployment booster stage [A4]

Single/dual deployment- This style will utilize the A1 and A2 recovery systems. The dual will be on the 2nd stage and the single on the booster stage. Single on the booster makes a much less complex system and allows for lighter weight boost stage to maximize performance.

Concept 5: Single deployment both stages drogue/Streamer [A5]

Single deployment- This style will utilize the A1 and A2 recovery systems. The single deployment will be in both stages. This is the same concept as A1 but will use a drogue or streamer during the descent until the main parachute is deployed.

4.2.2 Separation Systems

Concept 1: Flanged Drag Separation [B1]

I came up with an idea while studying the various ways to separate a two-stage rocket. The concept is based on a technique called "Drag Separation," where the pressure drag from the vehicle pulls off the empty first stage. The drawing illustrates a wider flange with a slightly larger diameter at the top of the rocket. This should help the separation forces remove the first stage more effectively. The con of this design is the possibility the separation will not happen due to a snug fit between the two bodies.

Concept 2: Cupped Separation with Boat Tail [B2]

This variation of the concept involves drag separation technique, but with a different approach. Unlike the traditional method where the upper body cups the lower body, this approach has the lower body cupping the upper body with little to no resistance when separating. To ensure the upper body doesn't fall off easily, the lower half will require a secure mechanism. Adding a boat tail to the end of the rocket has been mentioned by multiple sources as an advantage of this design. This addition increases the overall speed during flight and provides additional performance values. However, the disadvantage of this design is the lack of structural support between the upper and lower body.

Concept 3: Universal Separation [B3]

This concept is the standard for drag separation in all model rockets large and small. The inner tube has a small decrease in diameter to fit the upper body securely. The pros of this design are the universal acceptance of this method, and the con is the lack of performance improvements.

Concept 4: Twist Lock Separation [B4]

The idea behind this concept comes from a twist-off jar. The indentations on the inner design will securely lock the two bodies together while the 3 springs on the inside are strained to the unlock position. The pro of this design is the locking connection between the two bodies. However, the con of the design is the same as the pro, the twist motion could send the rocket flying in the opposite direction. IN addition, the springs could not have enough force to separate the two bodies.

Concept 5: N/A

4.2.3 Body Design

The concept generation of the body design parameters were two-stages, payload bay, basic aerodynamic understanding, and a few extra parameters. All these rocket bodies would be constructed with carbon fiber, so the construction method would be laying layers of material.

Concept 1: Different Diameter Two-Stage Body [C1]

This concept was designed with the idea that the two stages have different diameters. The first stage, the bottom stage, having a larger diameter than the second stage, the upper stage. The reason the first stage was larger was for drag when it is time for the first stage to separate from the second stage, which was also to house the motor and have space for extra devices in the future for the first stage. This concept was also inspired by the large rockets built by NASA in the past. The first stage being larger was also to house a larger motor if needed.

Concept 2: Uniform Diameter Two-Stage Body [C2]

This concept was designed to have a uniform diameter all the way down the rocket for simplicity of construction, ease of aerodynamic capability, and strength of the body. There is uniform force at every point on the walls of the vehicle and no complexity of stress calculations. This is the simplest design for both the first and second stage of the vehicle. Least amount of drag over the body of the rocket.

Concept 3: Payload Bay Mid-Body Bulge Two-Stage Body [C3]

This concept was designed with the intention to minimize nose cone drag, less material need in construction, and still achieve the wanted payload bay inner diameter. The downside of this concept is the construction of the bulge would be difficult as the bulge has a nonlinear diameter change due to trying to decrease the drag around the payload bay. The bulge would create more drag as the air would have to go around creating a higher presser change. The rest of the body diameter would also be minimal, wide enough to fit the motors.

Concept 4: Front Payload Bay Bulge Two-Stage Body [C4]

This concept was designed like concept C3 but to achieve the payload bay diameter with the least amount of drag, the payload bay would be moved to right behind the nose cone. This is so there is only one diameter change over the body, still creating drag but not as much as concept C3. This would also complicate the construction of the overall body as the diameter change is nonlinear. The rest of the body would be minimal diameter to try and eliminate some of the drag around the body.

Concept 5: Atom Bomb style Two-Stage Body [C5]

This concept was designed with the idea of 1940's era bombs. The second stage, the upper stage, of the vehicle was designed to reduce drag around the payload bay's bulge. The first stage of the vehicle had a minimum diameter to fit the rocket motor and attempt to reduce drag. The concept will still result in more drag than concept C2.

4.2.4 Fin Design

Concept 1: Trapezoidal Rocket Fin [D1]

This concept was designed to maximize area but attempt to reduce drag the further out from the body the fin gets. The trapezoidal design is a common fin used by many similar designs. The straight lines of the fin are there to minimize the development heat on the rocket fin.

Concept 2: Arrow Fin Style Rocket Fin [D2]

This concept was designed to allow for better air flow around the fin. The area of the fin would result in the vehicle being less stable as it travels through the air.

Concept 3: Body bonded Rocket Fin [D3]

The concept was designed to have a method to bond a rocket fin to the outside of the body if a minimal diameter rocket body is used. This would require a type of adhesive and the base of the fin to have the same curvature as the rocket body.

Concept 4: Boat Fin Style Rocket Fin [D4]

The concept was designed to ease the airflow around the rocket fin and increase the area more than concept D2. Like a boat fin.

Concept 5: Classic Style Rocket Fin [D5]

This concept was designed to have a large area and not create as much heat as the rounded rocket fins at supersonic flight. This rocket fin was modeled after the rocket fins of the 50's and 60's.

4.2.5 Nose Cone

Concept 1: Tangent Ogive [E1]

The Tangent Ogive concept is the formation of a part of a circle where the base lies on the radius of the circle and is tangent to the rocket's body. This profile shape is also can be easily constructed as the circle's segment can just be drawn using a compass. The radius of the circle that forms this profile is related to the wanted length and base radius of the nose cone.

Concept 2: ½ Power [E2]

The ½ Power concept is part of a power series of parabolic nose cone shapes, characterized by a blunt tip. The ½ is the 'n' factor that controls the bluntness of the nose. The base of this shape is also not tangent to the rocket's body, which can affect its aerodynamic, but can be modified to smooth the discontinuity.

Concept 3: Conical [E3]

The conical concept is a common and simple nose cone shape. The sides of the cone are straight lines coming to a point, making it the easiest cone to manufacturer. Its ease of manufacturing allows for accurate measurements and a faster build. However, the hard transition from the base of this type of nose cone to the rocket's body can increase drag.

Concept 4: Ellipsoid [E4]

The Ellipsoid concept consists of a half of an ellipsoid profile shape rotated about its major axis. Its blunt tip and tangent base are ideal for subsonic flight; however, it may not be ideal for supersonic flight.

Concept 5: Von Karman [E5]

The Von Karman concept is a nose cone shape mathematically derived to achieve minimum drag, rather than use of geometric shapes. It originates from the Haack series shapes where the shape of the cone is determined by C in the following equation:

$$y = \frac{R\sqrt{\theta - \frac{\sin(2\theta)}{2} + C\sin^3\theta}}{\sqrt{\pi}}$$

[7]

$$\theta = \cos^{-1}\left(1 - \frac{2x}{L}\right)$$

For the Von Karman C=0, R is the nose cone base radius, and L is the length of the nose cone. Although the base for this shape is also not tangent to the body, the discontinuity is minimal, and has almost no effect on the drag.

4.2.6 Internal Rocket Layout

The rocket's interior will consist of a main parachute, a drogue parachute, avionics/electronics, two motors, and the payload. While there will be parachutes, avionics, and a motor for each stage in the rocket, the payload bay should be within the second stage only, so as to remain within the rocket after separation. The layout of these components in each stage is considered.

Concept 1: Payload Bay in the Nose Cone [F1]

This concept places the payload bay within the nose cone and where the avionics bay in each stage is placed between the parachute bays.

Concept 2: Payload Bay with Drogue Bay [F2]

This concept places the payload bay with the drogue bay in the second stage.

Concept 3: Payload Bay After Nose Cone [F3]

This concept places the payload bay right after the nose cone.

Concept 4: Payload Bay with Avionics Bay [F4]

This concept places the payload bay with the avionics bay after the nose cone rather than in between the parachute bays.

Concept 5: Payload Bay Between Parachute Bays [F5]

This concept places the payload bay between the parachute bays while the avionics bay is placed with the drogue bay.

4.3 Selection Criteria

The selection criteria for the concept selection were:

1. Vehicle Speed
2. Vehicle Acceleration
3. Payload Weight
4. Separation Event
5. Body Material
6. Altitude
7. Body Diameter
8. Reusable
9. Payload volume

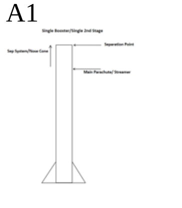
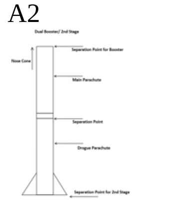
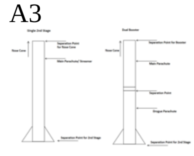
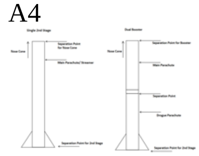
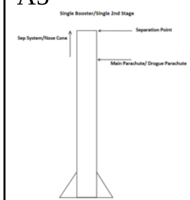
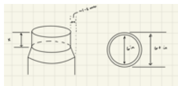
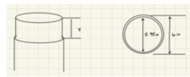
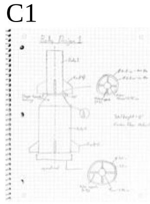
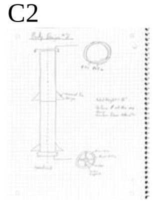
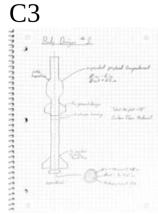
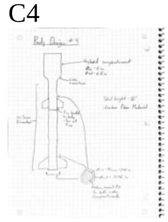
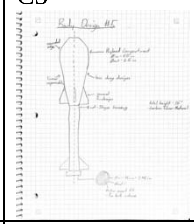
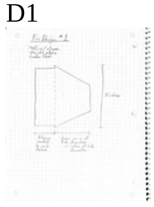
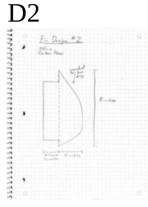
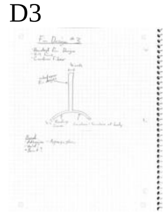
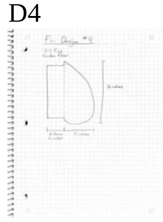
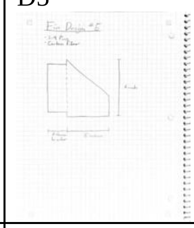
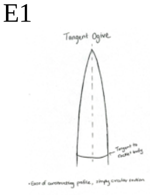
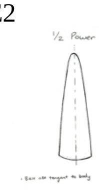
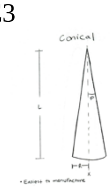
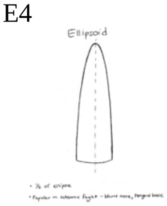
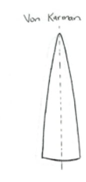
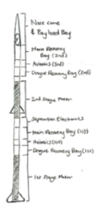
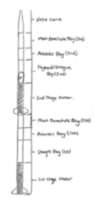
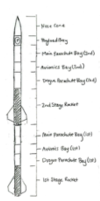
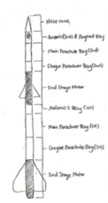
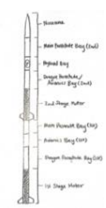
The selection criteria when the team did the selection process were rated as seen above. Any concept that leads to the vehicle speed being the overall best determiner if the concept was best for the design. All the selection criteria were taken from QFD since the importance of the selection criteria and the reasoning we were looking for certain design decisions were already sorted. All the selection criteria have the ability to have calculations and mathematical reasoning behind why the concept was chosen. Choices were also made on what the client found most important to the flight of the vehicle and were implemented in the QFD. These parameters can change for future project requirements with different motor selections and additional design implementations.

4.4 Concept Selection

4.4.1 Morphological Matrix and Designs

The concepts for each of the subsystems are placed in a morphological matrix seen in **Table 3.** From this matrix six differing full body designs are made using various concepts. Each design is pitted against each other in the following chart and matrix to narrow down to the best final design.

Table 3: Morphological Matrix

Subsystem	**1**	**2**	**3**	**4**	**5**
Avionics	A1 	A2 	A3 	A4 	A5 
Separation System	B1 	B2 	B3 	B4 	B5
Body Design	C1 	C2 	C3 	C4 	C5 
Fin Design	D1 	D2 	D3 	D4 	D5 
Nose cone	E1 	E2 	E3 	E4 	E5 
Rocket Layout	F1 	F2 	F3 	F4 	F5 

<u>Design 1</u>

Components: A3, B1, C1, D4, E2, F4

Description: Single deployment 2nd stage and Dual deployment booster stage, Flanged Drag Separation, Different Diameter Two-Stage Body, Boat Fin Style Rocket Fin, ½ Power Nose Cone, Payload Bay with Avionics Bay

Design 2

Components: A1, C2, D1, E5, F5

Description: Single deployment both stages no drogue/Streamer, Uniform Diameter Two-Stage Body, Trapezoidal Rocket Fin, Von Karman Nose Cone, Payload Bay Between Parachute Bays

Design 3

Components: A5, B4, C5, D3, E4, F1

Description: Single deployment both stages drogue/Streamer, Twist Lock Separation, Atom Bomb Two-Stage Body, Body bonded Rocket Fin, Ellipsoid Nose Cone, Payload Bay in the Nose Cone

Design 4

Components: A4, B3, C4, D2, E1, F3

Description: Dual deployment 2nd stage and Single deployment booster stage, Universal Separation, Front Payload Bay Bulge Two-Stage Body, Arrow Fin Style Rocket Fin, Tangent Ogive Nose Cone, Payload Bay After Nose Cone

Design 5

Components: A1, C1, D5, E5, F5

Description: Single deployment both stages no drogue/Streamer, Different Diameter Two-Stage Body, Classic Style Rocket Fin, Von Karman Nose Cone, Payload Bay Between Parachute Bays

Design 6 (Datum)

Components: A2, B2, C3, D5, E3, F2

Description: Dual deployment both stages, Cupped Separation with Boat Tail, Payload Bay Mid-Body Bulge Two-Stage Body, Classic Style Rocket Fin, Conical Nose Cone, Payload Bay with Drogue Bay. This design was designated as the datum, meaning its abilities to meet the listed concept criteria were neither exceptionally nor poorly executed.

4.4.2 Pugh Chart

After creating the six designs, they were evaluated in a Pugh Chart. Based on the design criteria, the other five concepts were assessed in relation to the datum. The Pugh Chart is shown in **Table 4** below.

Table 4: Pugh Chart

Concept	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
		X		X	X	

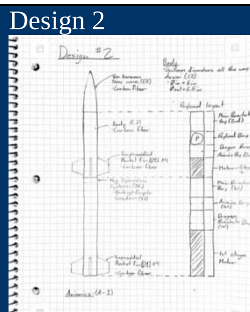
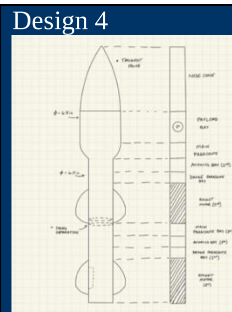
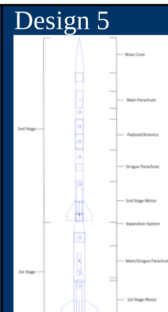
Criteria						
Max Velocity	- (wide body, more drag)	+ (aerodynamic)	- (high drag force)	S	S	datum
Separation Event	S	+	S	+	+	datum
Payload Capacity	-(unstable)	+(stable)	S	S	-	datum
Altitude	-	+(max velocity	-	S	S	datum
Lightweight	-(wide body)	+(less material)	-	S	-	datum
Cost of Production	-(more material)	+(less material)	-	S	-	datum
Reusable	S	S	S	S	S	datum
Payload Volume	-	-	+	S	-	datum
∑+	0	6	1	1	1	N/A
∑-	6	1	4	0	4	N/A
∑s	2	2	3	7	3	N/A

All five designs were scored relative to the datum where + is meets the criteria more than the datum, - is meets the criteria less than the datum, and S is the same or equivalent as the datum. All the symbols were then tallied and the three designs that consisted of the least -'s were Designs 2,4 and 5.

4.4.3 Decision Matrix

The three concepts chosen from above are then quantitatively compared against the design criteria. This comparison was conducted using a Decision Matrix seen in **Table 5** below. Scaled-up versions of the three designs evaluated can be seen in **Appendix B**.

Table 5: Decision Matrix

Criterion	Weight	Design 2 		Design 4 		Design 5 	
		Un-weighted score	Weighted score	Un-weighted score	Weighted score	Un-weighted score	Weighted score
Max Velocity	30%	100	30	90	27	95	28.5

Separation Event	0%						
Altitude	25%	100	25	90	22.5	95	23.75
Payload Weight							
Lightweight	15%	85	12.75	70	10.5	80	12
Cost of Production	15%	95	14.25	75	11.25	90	13.5
Reusable	10%	95	9.5	95	9.5	95	9.5
Payload Volume	5%						
Total	100%	Sum:	91.5	Sum:	80.75	Sum:	87.25

Each criterion was weighted based on importance to the customer and engineering requirements. The designs were scored unweighted and weighted then summed up. The design that scored the highest in most criteria and overall was Design 2.

4.4.4 Final Design

Design 2 from above became the team's current final design. A final depiction of this design was created in SolidWorks and shown in **Figure 15** below. The benefits of this design include a balanced weight distribution, a simple aerodynamic body, simplified avionics and recovery systems, ease of manufacturability, and best performance.

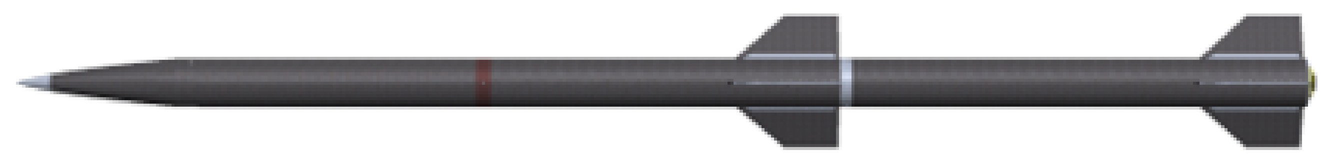


Figure 15: Final CAD Design

5 Schedule and Budget

5.1 Schedule

The entire Gantt Chart for both semesters is viewable in the Appendix. **Figures 16** and **17** below is a snippet of our Gantt Chart, highlighting the final stages of the project. Due to technical issues, the chart displays only the left-side details without the corresponding visual elements on the right. Unexpected circumstances prevented the team from accessing the launch site in mid-November, necessitating a rescheduled emergency launch for mid-December. Consequently, the team is unable to present any results or flight data at this time.

TASK	ASSIGNED TO	PROGRESS	START	END
Stage 3				
Team Staff Meeting 7	Team	100%	10/10/24	10/10/24
Assembly hardware Procurement Checkup	Lindsey, Avery	100%	10/21/24	10/23/24
Parachute 1 Procurement Checkup	Lindsey, Avery	100%	10/21/24	10/23/24
Parachute 2 Procurement Checkup	Lindsey, Avery	100%	10/21/24	10/23/24
UGRADS Registration	Team	100%	10/18/24	10/24/24
Peer Eval 2	Individual	100%	10/21/24	10/25/24
Team Staff Meeting 8	Team	100%	10/17/24	10/17/24
Booster Assembly	Team	100%	10/14/24	11/12/24
Main Rocket Assembly	Team	100%	10/14/24	11/12/24
Draft of Poster	Team	100%	10/18/24	10/31/24
Finalized Testing Plan	Team	100%	10/21/24	11/1/24
Hardware Status Update - 100% Build	Team	100%	11/1/24	11/12/24

Figure 16: Stage 3 of 2nd Semester Project deliverables.

Stage 4				
Team Staff Meeting 9	Team	100%	10/24/24	10/24/24
Peer Eval 3	Individual	100%	11/11/24	11/15/24
Final Poster and PPT	Team	100%	11/11/24	11/17/24
Initial Testing Results Video	Team	0%	11/11/24	11/21/24
Final CAD Packet	Team	100%	11/4/24	11/22/24
Product Demo and Testing Results in class	Team	50%	9/27/24	11/27/24
Final Report	Team	70%	11/18/24	12/3/24
Final Website Check	Team	80%	11/18/24	12/4/24
Final Product Demo	Team	0%	11/18/24	12/5/24
Operation/Assembly Manual	Team	0%	11/25/24	12/5/24
Expo PPT and Poster Presentation Delivery I	Team	0%	12/6/24	12/6/24
Practice Presentations	Team	0%	12/2/24	12/5/24
Peer Eval 4	Individual	0%	12/9/24	12/12/24
Client handoff	Team	0%	12/9/24	12/11/24
Secondary Launch Date (Emergency)	Team	0%	12/14/24	12/15/24

Figure 17: Final Stage of the project in the Last Semester

As of the completion of this report, a few final deliverables, such as the Website Check and the Operation/Assembly Manual, are still in progress. The Gantt chart has been instrumental in keeping us organized and on track, providing clear visibility of tasks and upcoming deadlines. This tool has allowed us to efficiently balance our academic responsibilities while maintaining focus on the project, ensuring steady progress and confidence in completing all deliverables on time.

5.2 Budget

Our budget consisted of initial funding, fundraising, and deduction of expenses related to the project. Our initial funding was provided by our client in the amount of $7,000. As a requirement during the first semester of capstone, we needed to fundraise an additional 10% of the client funding. Utilizing the fundraising platform, GoFundMe, and direct donations from family and friends, we were able to surpass our goal, raising approximately $940 toward our project. First semester expenses mainly consisted of parts needed for our separation system prototype. Second semester expenses included hardware, material, personnel protection equipment (PPE), tools, and motors. All of which were crucial to the manufacturing process of the rocket. Future expenses anticipated are travel expenses to the launch site and reimbursements to team members who paid out-of-pocket expenses relating to the project. **Table 6** below describes the funding/expense and amount for each where green cells indicate added funds, red indicates deducted expenses, and yellow indicates pending or anticipated expenses to be deducted from the remaining budget.

Table 6: Summary of Overall Project Budget

Funding/Expense	*Description*	*Amount*
Client Funding	*Northrop Grumman*	*+$7,000*
Fundraising	*Donations, GoFundMe*	*+$938.78*
First Semester Expenses	*Prototype*	*-$191.05*
Second Semester Expenses	*Hardware, material, PPE, tools, motors*	*-$3,312.25*
Future Expenses	*Travel, +reimbursements*	*~$1,500*
Total Remaining:		*$1,864.52*

5.3 Bill of Materials (BoM) & Manufacturing Plan

To bring this project to life, we've meticulously cataloged all the necessary parts and resources in a Bill of Materials (BOM). This serves as our blueprint for sourcing, organizing, and assembling the components. For ease of presentation, the table has been formatted to fit the width of this document. A full-scale version with complete details is included in the appendix, along with the Manufacturing Plan for further reference.

Table 7: Simplified Bill of Materials

SUBSYSTEM	ITEM NO.	PART NUMBER	DESCRIPTION	QTY.	TOTAL PRICE ($)	ACQUISITION METHOD	PRIMARY VENDOR
NOSECONE	1	NC_cone	Nose Cone Shell	1	N/A	Manufacture	NovaKinetics
	2	NC_coupler	Nose Cone Coupler	1	N/A	Manufacture	NovaKinetics
	3	NC_bulkhead	Nose Cone Bulkhead	1	N/A	Manufacture	IMS
	4	eyebolt-type2_ai	Bulkhead Eyebolt	1	N/A	Donated	NAU Rocket Club

	5	NC_met altip	Metal Nose Cone Tip	1	N/A	Donated	NAU Rocket Club
	6	flat washer type a narrow_ ai	Bulkhead Flat Washer	1	N/A	Donated	NAU Rocket Club
	7	NC_mtw asher	Metal Tip Washer	1	N/A	Donated	NAU Rocket Club
	8	92095A1 96	M6 Button Head Hex Drive Screw	1	$12.50	Order	McMaster Carr
	9	92095A2 84	M8 Button Head Hex Drive Screw	2	$12.72	Order	McMaster Carr
	10	94645A2 10	M8 Nylon Lock Nut	2	$11.16	Order	McMaster Carr
BODY	11		2nd Stage Body Tube (50in. X 6.17in.)	1	N/A	Manufacture	NovaKineti cs
	12		Payload Body Tube	1	N/A	Manufacture	NovaKineti cs
	13		Lower Body Tube	1	N/A	Manufacture	NovaKineti cs
FIN CANIST ERS	14		Aft End Centering Ring with Sep Brace	2	N/A	Manufacture	IMS
	15		Centering Ring	4	$88.65	Manufacture	IMS
	16		Fin Bracket Left	6	$25	Manufacture	IMS
	17		Fin Bracket Right	6	$25	Manufacture	IMS
	18		Long Bracket 1	12	25	Manufacture	
	19		Long Bracket 2	12	25	Manufacture	
	20		Long Bracket 3	6	25	Manufacture	
	21		Long Bracket 4	6	25	Manufacture	
	22		Corner Bracket	24	N/A	Manufacture	IMS
	23	92095A2 14	M5 Button Head Hex Drive Screw	72	$25.00	Order	McMaster Carr
	24	91294A1 93	M4 Hex Drive Flat Head Screw	12 0	$25.00	Order	McMaster Carr
	25	94645A1 01	M4 Nylon Lock Nut	12 0	$28.10	Order	McMaster Carr

	26	94645A102	M5 Nylon Lock Nut	72	$33.24	Order	McMaster Carr
	27	94645A210	M8 Nylon Lock Nut	12	$11.16	Order	McMaster Carr
	28	91292A214	M8 18-8 Stainless Steel	12	$23.82	Order	McMaster Carr
	29	97483A095	Aluminum Flush Mount Rivets	60	$15.62	Order	McMaster Carr
	30		Fin	6	$340.21	Order	Composite Envisions
	31		2nd Stage End Cap	1	N/A	Manufacture	IMS
AVIONICS	32		Avionics Coupler 2nd Stage	1	N/A	Manufacture	NAU Rocket Club
	33		Avionics Bulkhead	4	N/A	Manufacture	NAU Rocket Club
	34		flat washer type a narrow_ai	12	N/A	Donated	NAU Rocket Club
	35		eyebolt-type2_ai	2	N/A	Donated	NAU Rocket Club
	36		Avionics Sled (3D Printed)	2	N/A	Manufacture	
	37		Raven 4 v9	4	N/A	Donated	NAU Rocket Club
	38		GPS Tracker v15	2	N/A	Donated	NAU Rocket Club
	39	92001A321	18-8 Stainless Steel Wing Nut	8	N/A	Donated	NAU Rocket Club
	40	90322A657	High-Strength Steel Threaded Rod	8	N/A	Donated	NAU Rocket Club
	41		Switch Band	1	N/A	Donated	NAU Rocket Club
	42		hex thick nut_ai	2	N/A	Donated	NAU Rocket Club

RECOVERY	43		Main Parachute	1	N/A	Donated	NAU Rocket Club
	44		Drogue, Booster	1	N/A	Donated	NAU Rocket Club
	45		Drogue, SS	1	N/A	Donated	NAU Rocket Club
	46		Main parachute, Booster	1	N/A	Donated	NAU Rocket Club
	47		Aerotech 98/15360 Motor casing	2	N/A	Donated	NAU Rocket Club
	48		Aerotech N1000W	1	$1,257.99	Order	Aerotech
	49		Aerotech N3300R	1	$1,302.69	Order	Aerotech
	50		Shock Cord 8800lbs	2	N/A	Donated	NAU Rocket Club
	51		Tender Decender	2	N/A	Donated	NAU Rocket Club

Below is a summary of the Bill of Materials, highlighting the total number of parts required for the project and the overall cost. The discrepancy between the total parts needed and those received is due to the pending delivery of two motors and the main parachute. The parachute is currently in transit and expected to arrive within the next few days, while the motors will be delivered directly to the launch site for safety reasons. Apart from these items, the entire vehicle is fully assembled and ready for launch.

Table 8: Summary of Funding spent and Parts Collecting

Total Parts Needed	653	Total Parts Received	653
Total Cost ($):	$ 3,631.32	Parts On Hand (%)	100%
Total Spent	$ 3,703.30	Assembled (%)	100%

6 Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

The FMEA table provided the team with an effective way to visual flight risks within the design. When creating the table, the team collaborated with NG to cover the anomalies that can occur and how to mitigate them properly. There are many variables that have to perform perfectly, or it can affect flight performance or result in total failure of the vehicle. With the FMEA created, we based our analysis on the highest risk items to ensure that when they are subjected to flight conditions, we have confidence that they will survive and perform nominally.

Table 9: FMEA

Item #	Item	Failure	Root Cause	Likelihood 1 = least 5 = most	Severity 1 = least 5 = most	Precaution	Performance 1 = least 5 = most	Schedule 1 = least 5 = most	Cost 1 = least 5 = most
1.1	Separation System (Staging)	Fails to Separate, buckling, thermal,	Electrical Failure, Mechanical failure	3	5	Ground Testing before launch to certify system	1	3	3
1.2	Separation System (Structural)	Failure in flight of sep. system, impact, thermal	System detaches mid-flight/ aero forces exceed limits	2	4	Ensure system is secured before flight.	1	3	3
1.4	Body (Structural)	Body bending, cracks, deformities	Forces during flight/temperature	2	5	Visual/NDT inspections	2	2	3

1.5	Fins (Structural)	Bending, cracks, deformities	Material deformation, adhesive epoxy failure	2	5	Visual/ NDT inspections	2	2	3
1.6	Avionics	Flight computers do not set off energetics	Battery failure, electrical short, match failure	2	5	Ground testing with energetics	4	2	3

6.2 Initial Prototyping

6.2.1 Separation System

6.2.1.1 Question

During the initial phase of the project, the team recognized that the most significant challenge lay in the effective operation of the Separation System. This component was crucial for the project's success, as its reliability would directly influence the overall performance of the system. Consequently, we concentrated our efforts on tackling this challenge with our first prototype. The central question guiding our development was: *Can the Separation System operate consistently and reliably under anticipated conditions?* This inquiry informed our design, testing strategies, and objectives, ensuring a comprehensive evaluation of the system's functionality and the identification of potential areas for enhancement.

6.2.1.2 Answer

In compliance with the NDA clause, the team identified several critical flaws in both the design and performance of the system. Acknowledging the significance of these issues, the team dedicated the second semester to revisiting and refining the design. Despite our best efforts, the challenges posed by manufacturing costs exceeding budget constraints were substantial. As a result, the development of the advanced Separation System had to be discontinued. Instead, the team implemented a more streamlined and cost-effective approach to separation, ensuring continued progress within the project's limitations.

6.3 *Other Engineering Calculations*

6.3.1 FEA of Bottom Plate of Separation System

A based FEA was performed on the lower section of the separation system. The main concern with the lower section is the bending moment of the launch vehicle. During analysis, we could not determine an exact force the system would experience during flight. We applied a 300 lb force with the bottom plate fixed to see the deflection and stress of the material with a cantilevered load where it will experience with the upper ring section. This analysis could be further defined with the full launch vehicle and see how the full interaction between parts would perform. There was a focused stress from the uprights of the lower ring section on the inner ring. This location is the most unsupported area of the separation system, and it is clear where the weak point is. Once flown, we will inspect and measure to see if any deformation occurred during flight and if there is evidence, we can strengthen the area and wall to ensure no future failures can occur in this area.

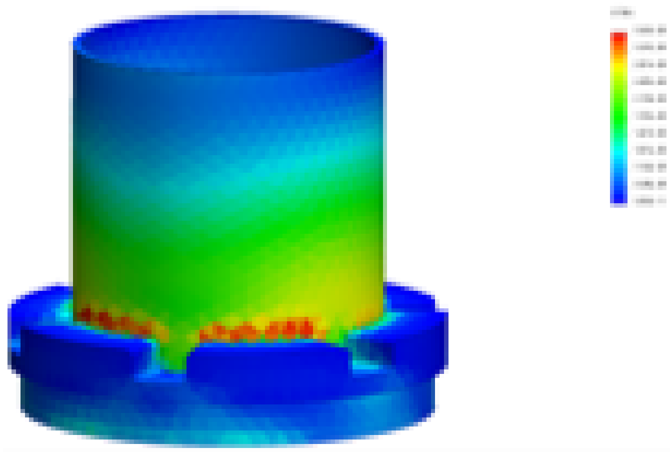


Figure 18: FEA Separation System

6.4 *Future Testing Potential*

Majority of the design and research for the Separation System has been successfully completed. However, due to high manufacturing costs, the team has been unable to advance to the production and testing phase of the project. Moving forward, the team plans to utilize flight data and the forces observed during operation to create a comprehensive simulation and demonstration of the Separation System. This approach will yield valuable insights into the system's performance and identify areas for potential optimization.

Although direct real-world testing would be ideal for validating the design, current budget constraints render this impractical. Instead, the team will depend on Finite Element Analysis (FEA) and advanced simulations to assess the system's capabilities under realistic conditions. These tools will allow the team to refine the design, pinpoint potential issues, and establish a foundation for future testing opportunities when additional resources become available.

7 Final Hardware

7.1 Final Physical Design

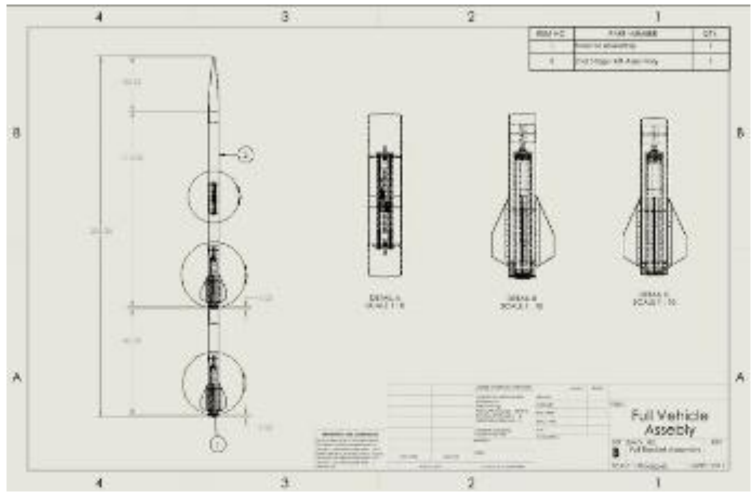


Figure 19: Full Assembly of Vehicle **Figure 20:** SolidWorks Drawing

The Full Vehicle Assembly is displayed alongside team member Koi Quiver to provide a sense of scale. The vehicle's overall length measures approximately 178 inches (14.82 feet). This length reflects updates made since the first semester to accommodate modifications in the motor and subassemblies.

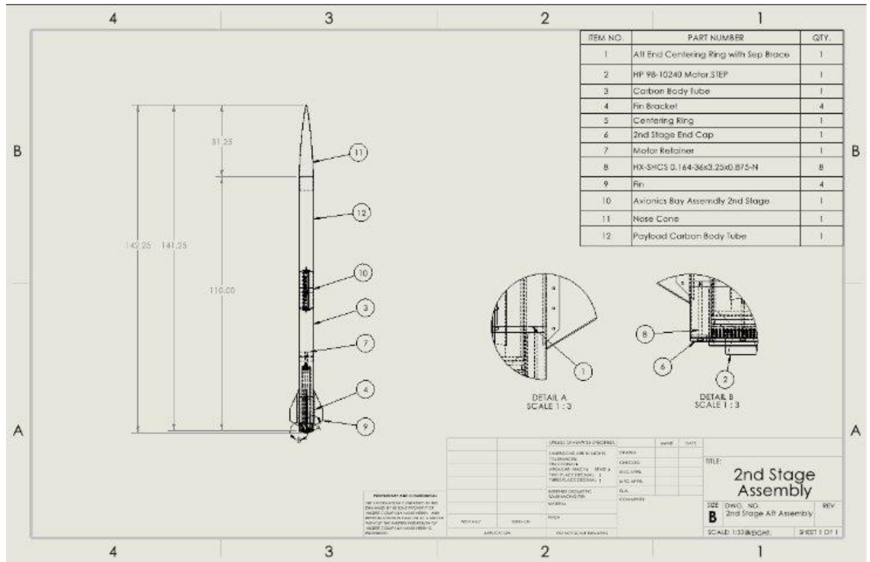


Figure 21: 2nd Stage Assembly Old Fins

Figure 22: 2nd Stage Assembly Old Fins Drawing

Figure 21 illustrates the second-stage assembly, which serves as the primary vehicle traveling at Mach 2 for several seconds while carrying a 10-pound payload. This stage also incorporates the upper section of the separation plates, ensuring seamless integration with the system.

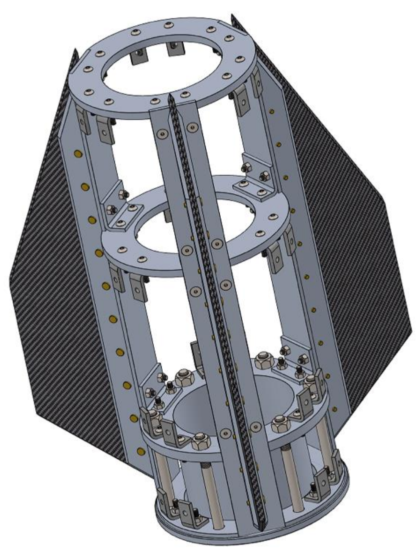


Figure 23: Fin Canister Completed **Figure 24:** 3D Model of Fin Canister

The design of the fin canisters, shown above, was developed to enhance both reusability and durability during flight. Initially, the team selected a four-fin configuration for optimal stability. However, after further analysis, a three-fin design was adopted to reduce weight while still maintaining the required stability. In **Figure 24,** it shows the initial fin design which was changed to **Figure 23** fin design to increase the stability margin.

To address reusability, the team engineered an interchangeable fin canister system. During recovery, fins often sustain damage upon impact, potentially compromising the structural integrity of the vehicle's body. To mitigate this issue, the fins are mounted to the canister rather than directly to the body. This allows damaged fins to be easily replaced during maintenance without affecting the structural integrity of the main vehicle body.

Figure 25: Avionics Bay Assembled

Figure 26: Internal Design of Avionics Bay

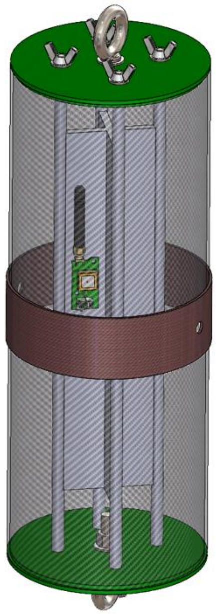


Figure 27: 3D of Avionics Bay

Displayed above are the avionics bay configurations for the second-stage assembly, presented in both covered and uncovered views. The booster stage's avionics bay is more compact compared to the second stage, as it does not include the switch band. Each avionics bay is equipped with a Raven 4 and Raven Blue flight computers to monitor and record data during flight, along with a GPS tracker to facilitate efficient recovery.

Figure 28: Booster Stage with Main Vehicle Fin Can

Figure 29: 3D Model of Booster with old Fins

The booster assembly measures 62 inches in length, designed to accommodate the powerful Aerotech N3300R motor and essential recovery components. Simulations indicate that the booster stage will achieve an altitude of approximately 9,300 feet before the separation event. Like the second stage, the booster stage features a similar fin canister design, with the key distinction being the absence of an attachment plate at its base.

8 Final Testing

8.1 Top level testing summary table

Table 10: Testing Summary Table

Success Levels	Goals

Complete Mission Success	- Separation system works as expected, successful separation and second stage motor ignition. (CR1, CR2, ER2) - Payload safely delivered and landed. Data captured. (CR4, CR7, CR6, CR10, ER1, ER3, ER6) - Launch vehicle performance meets altitude goal. (CR5, CR6, CR9, ER2, ER3, ER4, CR3) - Launch vehicle recovered in reusable condition, no damage to vehicle at all. (CR3, CR5, CR8, CR10, ER6, ER5) - Recovery system performs as expected and designed. (CR1, CR2, CR10, ER2, ER6) - No anomalies (drastic angle change, bird strike, etc.) during full flight and payload mission until completed flight and recovery (All CRs and ERs)
Partial Mission Success	- Flight success (All CRs and ERs) - Velocity and altitude requirements met (CR4, CR6, CR7, CR9, ER1, ER3) - Payload flown but no data recorded. (CR5, ER4) - All components are recovered and reusable with minor damage. (CR1, CR3, CR10, ER4, ER6)
Partial Mission Failure	- Failure of payload or launch vehicle performance (All CRs and ERs) - Successful flight with failure of payload data recording or delivery (CR5, ER4) - Velocity or altitude requirement missed. (CR5, CR6, CR9, ER2, ER3, ER4, CR3) - Vehicle or payload systems damaged during flight or landing (CR1, CR3, CR10, ER4, ER6)
Complete Mission Failure	- Failure of both launch vehicle and payload systems (CRs and ERs) - Failure of recovery system deployment and beyond reasonable repair state (CRs and ERs) - Failure of vehicle before, during, or after flight (All CRs and ERs)

8.2 Detailed Testing Plan

8.2.1 Test 1

8.2.1.1 Summary

The main question that will be answered is will the vehicle survive being launched and reach all the flight goals. The flights goals are reaching Mach 2, 12 g's, 30,000ft AGL, have a successful separation event, and not damage to the vehicle after recovery. The isolated variables are speed and acceleration. There are parts that may be damaged, but the vehicle is already designed for this purpose. The body of the launch vehicle is not to be damaged, along with the payload.

The equipment that will be needed to test launch the vehicle will be a launch tower, GPS, and flight computers. GPS and flight computers are already incorporated into the design of the vehicle. The software needed to run the GPS and flight computer are going to be used to record the flight path, speed/velocity, and altitude. From this data, the team will be able to derive speed, altitude, and make other calculations requested by the client. This test has a set goal of altitude, separation, and speed/velocity with a 10 lb payload meaning we are not determining how efficient the vehicle is.

8.2.1.2 Procedure

Assembly prep at Launch site:

1. Set the Altimeter and GPS parameters prior assembling the avionics systems.
2. Assemble avionics bays with batteries installed and electronics off.
3. Install and check all hardware connecting body tube and couplers together.
4. Verify all hardware for recovery system is installed and torqued.
5. Visually check to make sure the launch vehicle has no anomalies on the rocket body. All fins are connected securely.
6. Prepare all energetic charges and verify e-match continuity.
7. Fold parachutes and ensure proper coverage with chute protection.
8. Prep the propellant to be inserted into the motor casing.

Pre-flight setup

1. Assemble and secure the launch tower.
2. Ensure rail is secured to the launch tower.
3. Ensure rail connectors are secured tightly to the launch vehicle.
4. Connect the launch vehicle by the rail connectors to the launch tower.
5. The launch vehicle should be angled 90 degrees from the ground, aligning with azimuth.
6. The launch vehicle should be resting on the blast plate of the tower.
7. Install booster section on launch rail in a horizontal position.
8. Install parachute system and attach shock cord to forward motor closure.
9. Place separation system assembly into the forward end of the booster.
10. Verify electronics are off and personal are clear from ends of the vehicle.
11. Install second stage ignitor, primary and backup charges.
12. Insert booster motor casing into the vehicle without ignitor and verify retention system is installed properly.

13. Install second stage avionics bay and verify electronics are off.
14. Secure parachutes and shock cord into protection systems and verify connection to avionics bay eyelet and nose cone eyelet.
15. Install primary and secondary charges.
16. Fully assemble second stage with shear pins once recovery system is installed and verified.
17. Insert loaded motor into second stage.
18. Slide second stage onto rail and slide toward booster.
19. Ensure sustainer ignitor is connected to booster bulkhead connection.
20. While sliding the second stage back, ensure ignitor is installed correctly into second stage motor.
21. Complete stage mating.

Launch

1. Verify all connections and shear pins are installed.
2. Raise vehicle into flight position with a slight tilt into a safe direction 1-5 degrees.
3. Turn on and connect tracking to flight computers and GPS.
4. Last visual inspection of the launch vehicle.
5. Retreat to a minimum safe distance of 1,000 ft or 300m.
6. Before launch, check to see if vehicle is connected to device running the flight computers.
7. Last visual inspection of minimum safe distance red zone. Radius of 1,000 ft or 300m.
8. Last visual inspection of near by air space. If there is a visible entity within the air space wait to launch.
9. After all last check and visual inspection, launch vehicle is ready.

8.2.1.3 Results

The vehicle is expecting to reach 30,000ft AGL, reach Mach 2.0, and have a separation event. Along with return to the ground safely with not damage. The result should be successfully reached, both flight simulation software used show all flight goals being achieved and vehicle being recovered safely with no damage.

Simulation	Results	Engines loaded	Max. altitude Feet	Max. velocity Miles / Hour	Max. acceleration Gees	Velocity at deployment Miles / Hour	Velocity at launch guide departure Miles / Hour	Time to apogee	Total flight time
32		[N4800T-0] [N1000W-P]	35160.11	1031.52	15.17	67.11	83.41	43.98	167.26
33		[N1000W-0] [N4800T-P]	37464.90	1736.92	24.68	37.46	45.75	51.42	126.51
34		[N1000W-0] [N4800T-P]	37074.15	1726.73	24.67	39.13	45.75	51.14	126.23
35		[N1000W-0] [N3300R-P]	33637.47	1453.03	16.54	35.58	48.00	49.17	120.88
36		[N1000W-0] [N3300R-P]	34243.44	1461.02	16.54	24.77	48.00	49.65	121.95
37		[N1000W-0] [N3300R-P-1]	34496.06	1456.19	16.62	34.18	48.00	50.50	122.87
38		[N1000W-0] [N4000-0]	35465.22	1566.36	16.94	49.42	43.40	51.70	121.52

Figure 30: Rocksim flights Simulation

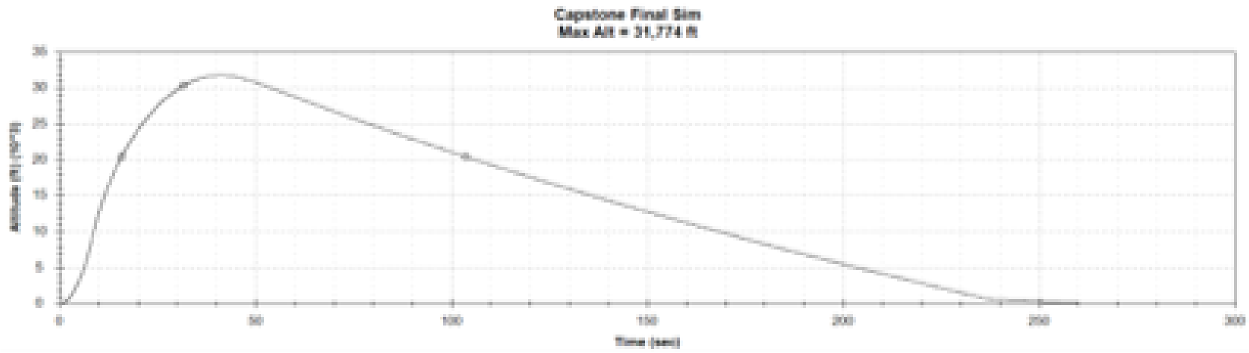


Figure 31: RASAero Flight Profile

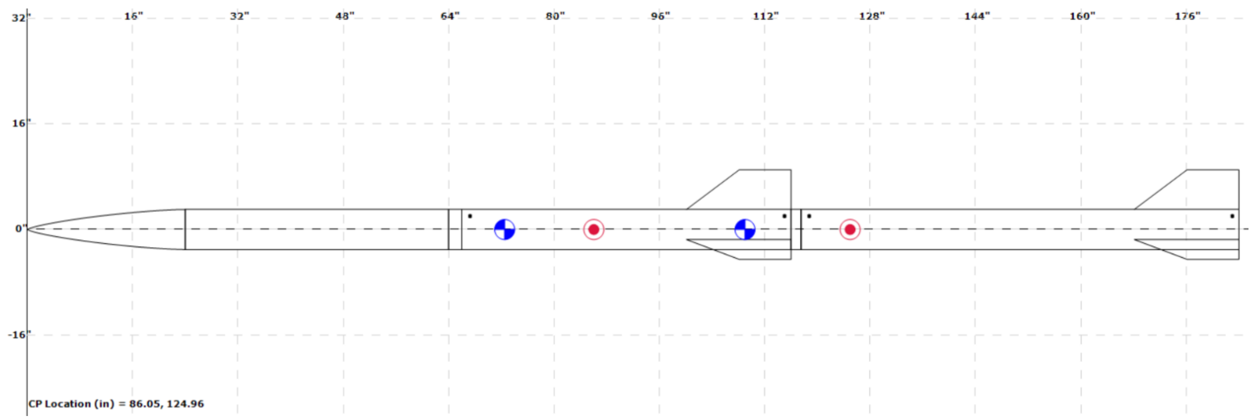


Figure 32: RasAero Flight Simulation

Table 11: Specification Sheet ERs

Engineering Requirements	Target	Tolerance	Measured/Calculated Value	ER Met?	Client Acceptable?
ER1 – Max Velocity	Mach 2 or 1500 mph	±100 mph or ± 0.1 Ma	Measured	Yes	Yes
ER2 – Separation Event	Successful or unsuccessful separation	N/A	Measured	Yes	Yes
ER3 – Altitude	40,000 ft AGL	±500 ft	Measured	Yes	Yes
ER4 – Payload Weight	10 lbs	± 0.5 lbs.	Measured	Yes	Yes
ER5 – Cost of production	$7,000 USD	N/A	Measured	Yes	Yes

ER6 – Reuseable	>1	N/A	Measured/Calculated	Yes	Yes
ER7 – Payload Volume	282.7 in^3	±50 in^2	Measured	Yes	Yes

Table 12: Specification Sheet CRs

Customer Requirement	CR Met?	Client Acceptable
CR1 – Develop Launch Vehicle	Yes	Yes
CR2 – Separation System	No	Yes
CR3 – Composite Materials	Yes	Yes
CR4 – Altitude (40,000 ft.)	Yes	Yes
CR5 – Payload (10 lb.)	Yes	Yes
CR6 – Speed (Mach 2)	Yes	Yes
CR7 – Acceleration (12+ g's)	Yes	Yes
CR8 – Trajectory Simulation	Yes	Yes
CR9 -- Com. Motors	Yes	Yes
CR10 -- Recovery	Yes	Yes

9 Future Work

Looking ahead, several advancements and improvements are planned to further enhance the project's capabilities and versatility.

Future launches will feature updated payload designs to broaden mission objectives and enhance data collection capabilities. As this project serves as a starting point, it will provide valuable insights through both its successes and shortcomings, paving the way for future advancements. Since our client did not specify the size or shape of the payload, our primary objective was to maximize the payload area to ensure versatility. Moving forward, it is anticipated that future projects will benefit from more specific payload requirements, enabling more refined and optimized design concepts.

Exploring the use of higher impulse motors will allow for a wider range of flight profiles, pushing the boundaries of both performance and altitude. One of our Customer Requirements (CRs) was to utilize commercial motors for ease of application. With the vehicle's structure set at a 6-inch diameter and a substantial weight, and a budget of $7,000, larger motors would have been the optimal choice for our needs. However, due to budget constraints, these motors were not feasible for this project. In future projects, with potentially larger budgets, the use of higher impulse motors could greatly enhance performance and capabilities.

Additionally, implementing alternative separation systems would improve both the reliability and adaptability of the vehicle during flight stages. The team invested a significant amount of time refining the design and application of the concept-based separation system. However, due to approaching deadlines and high manufacturing costs, we ultimately chose to discontinue this approach in favor of a more reliable and practical separation method. While these challenges influenced the decision, a dependable separation system is essential for ensuring safety. For example, if the booster were to experience mechanical failure before the separation event, detaching the main vehicle could help prevent further damage and maintain control over the flight.

To streamline production, a composite filament winder will be developed to ensure efficient, high-quality tube construction. During the current project, the body tubes exhibited noticeable wrinkles and imperfections, requiring significant time and effort to sand and smooth the surfaces for optimal aerodynamic performance. By incorporating a composite filament winder in future projects, the next team can reduce these imperfections from the outset, allowing them to focus more on the overall design and performance rather than time-consuming refinements.

Finally, efforts will be directed at simplifying the fin canister hardware to reduce complexity and enhance assembly efficiency. While the fin canister was a promising concept, prioritizing durability and interchangeability, its weight exceeded the team's expectations. To address this, future teams should focus on redesigning and optimizing the canister to reduce its weight. During assembly, the smallest team member had to install the canister onto the body, as the 4-inch diameter opening was too tight for our hands to fit inside.

10 Conclusion

We pursued the primary objectives of this mission to develop a cost-effective test platform capable of reaching a peak altitude of at least 30,000 feet, maintaining a supersonic speed of Mach 2, and enduring accelerations exceeding 12g, all while carrying a scientific payload that adheres to Northrop Grumman's (NG) specifications. To ensure performance and reliability, the team utilized tools such as RASAero and other simulation software to predict flight trajectories, conduct structural analyses, and model aerodynamic flows. The team has completed full manufacturing and initial testing of the vehicle, leaving the remaining tasks of launching the vehicle and obtaining final results. We hope to meet Although the vehicle has not flown, the preparations and analysis performed on the vehicle leaves the team and NG confident that the vehicle will be able to meet all requirements set forth on the team. The vehicle is projected to reach a peak altitude of 31,000 feet above ground level (AGL), attain a speed of Mach 2.0, and successfully complete a separation event, followed by safe recovery without damage. Flight simulation software has confirmed that all mission goals, including the safe recovery of the vehicle, are attainable. The final prototype is completed, and the vehicle is near launch. We believe this will propel NAU’s rocket development program into bigger and better projects involving this launch vehicle and payload capability.

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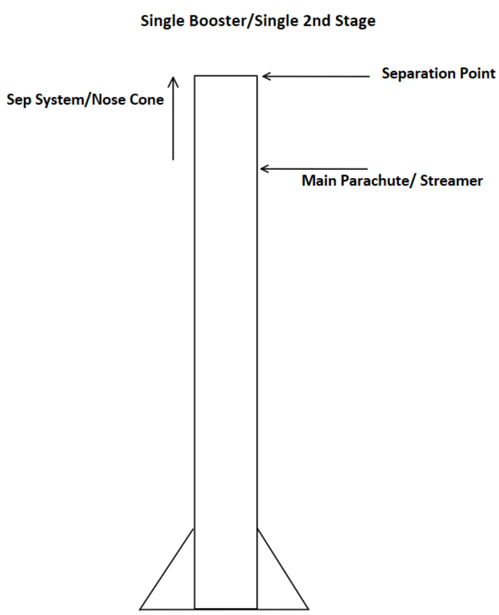
12 APPENDICES

12.1 Appendix A: Concept Generation Pictures

9.1.1 Avionics

[A1]



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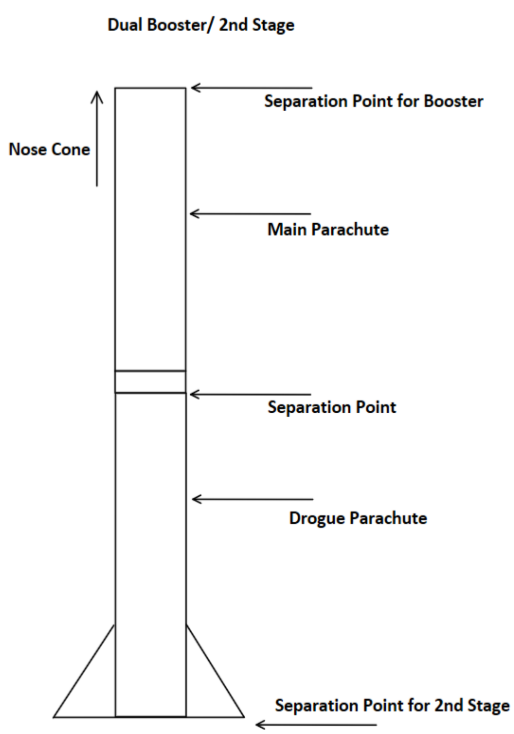
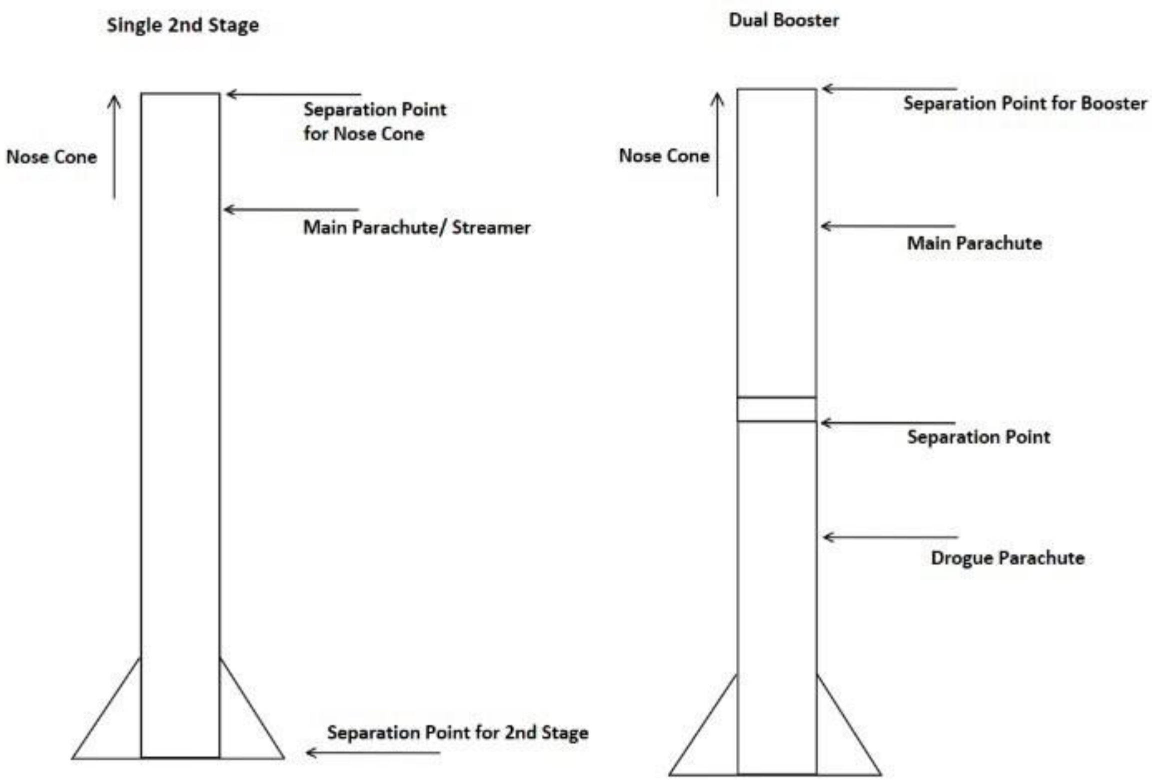
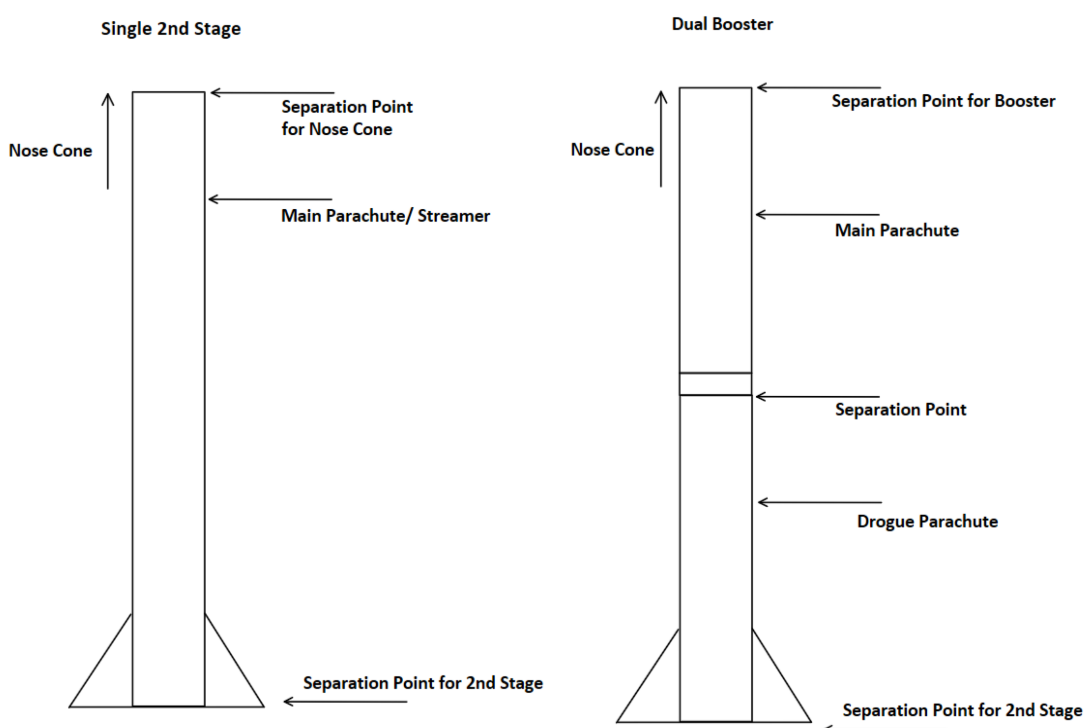


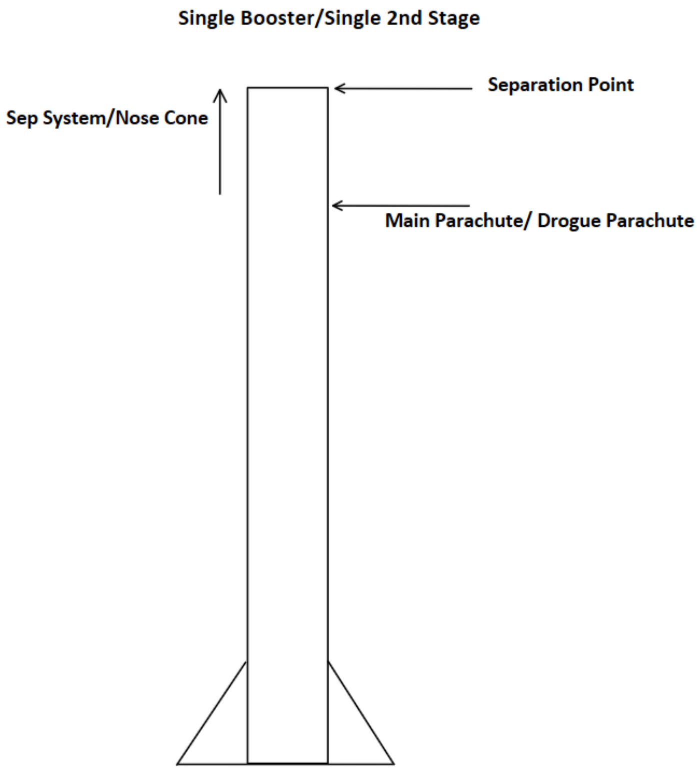
[A3]


Single 2nd Stage
Separation Point
for Nose Cone
Nose Cone
Main Parachute/ Streamer
Separation Point for 2nd Stage
Dual Booster
Separation Point for Booster
Nose Cone
Main Parachute
Separation Point
Drogue Parachute

[A4]

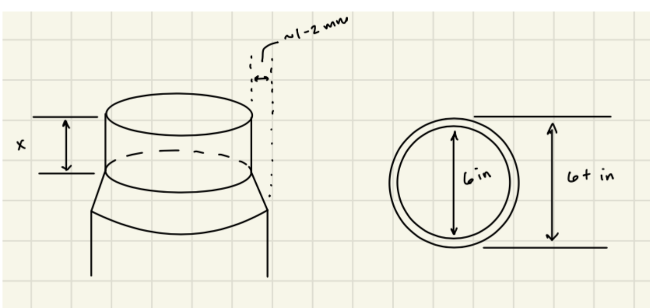

Single 2nd Stage
Separation Point
for Nose Cone
Nose Cone
Main Parachute/ Streamer
Separation Point for 2nd Stage
Dual Booster
Separation Point for Booster
Nose Cone
Main Parachute
Separation Point
Drogue Parachute
Separation Point for 2nd Stage

[A5]

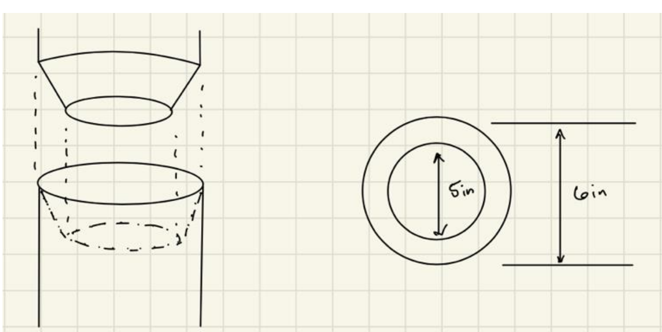


9.1.2 Separation System

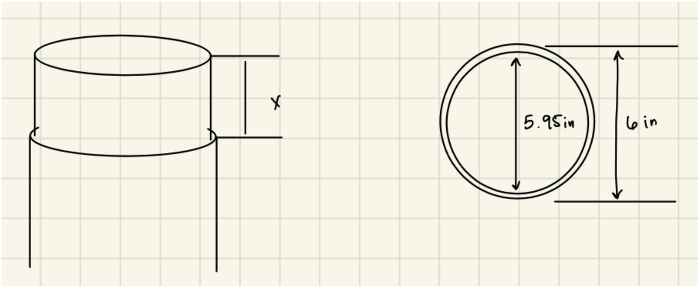
[B1]



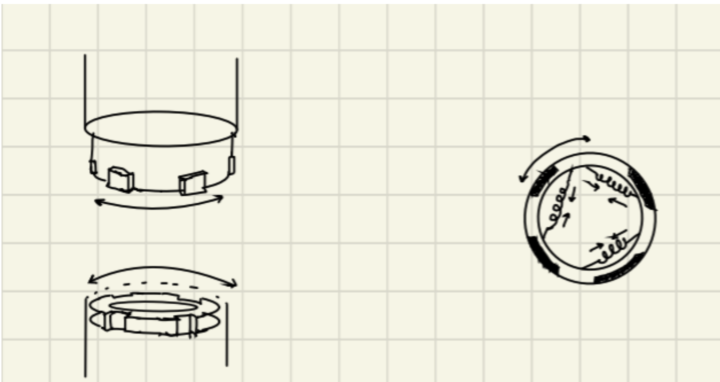
[B2]



[B3]



[B4]

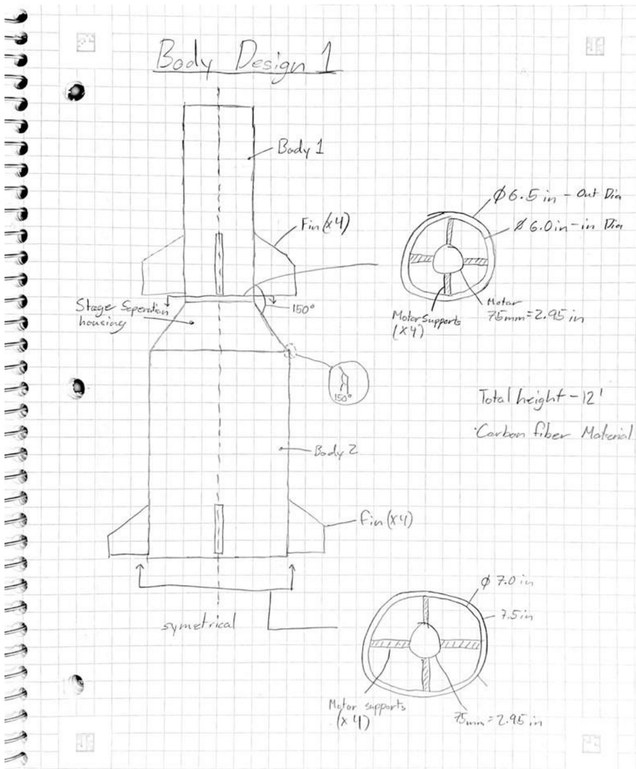


[B5]

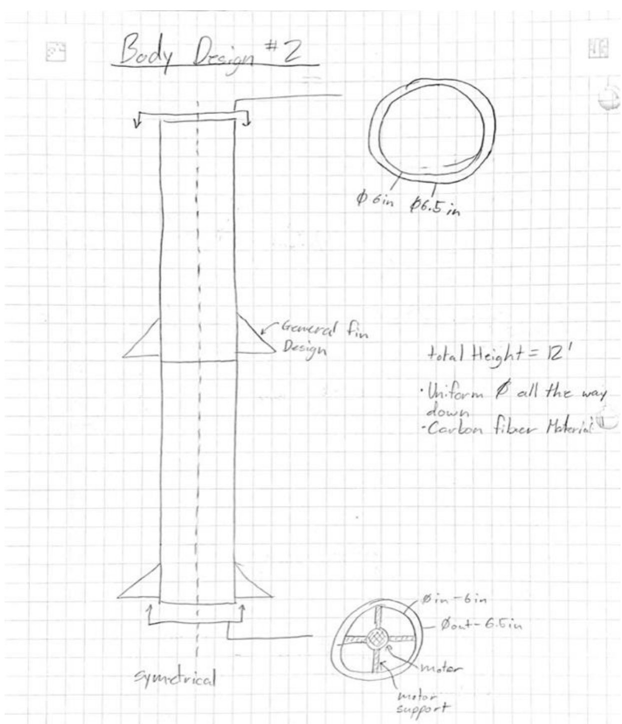
N/A

9.1.3 Body Design

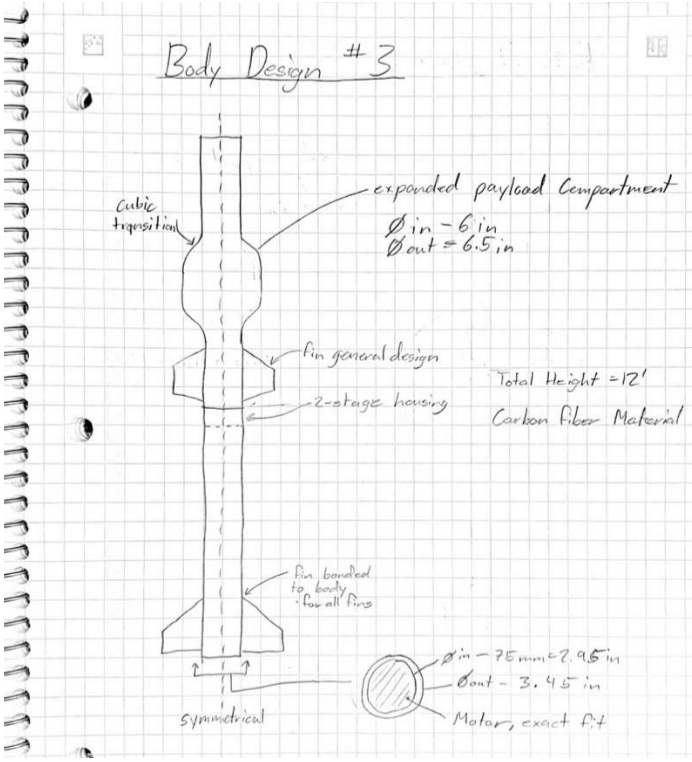
[C1]


Body Design 1
Body 1
Fin (x4)
Stage Separation housing
150°
Body 2
Fin (x4)
symetrical
Ø 6.5 in - Out Dia
Ø 6.0 in - in Dia
Motor Supports (x4)
Motor 75mm = 2.95 in
Total height - 12'
·Carbon fiber Material
Ø 7.0 in
7.5 in
Motor supports (x4)
75mm = 2.95 in

[C2]

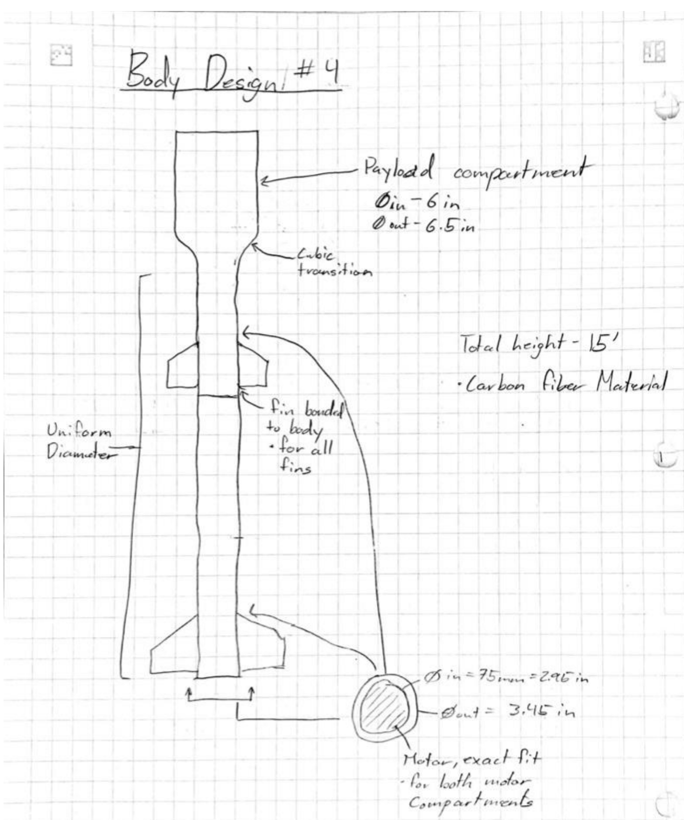

Body Design #2
Ø 6in
Ø6.5 in
General fin Design
total Height = 12'
·Uniform Ø all the way down
·Carbon fiber Material
Ø in - 6in
Ø out - 6.5in
motor
motor support
Symetrical

[C3]



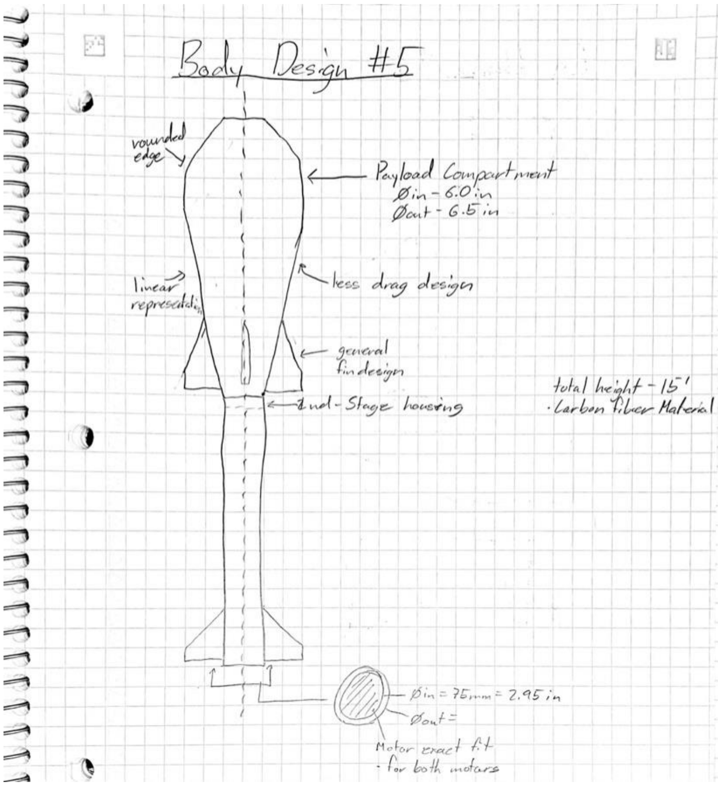
Body Design #3
expanded payload Compartment
Ø in - 6 in
Ø out = 6.5 in
cubic transition
fin general design
2-stage housing
Total Height = 12'
Carbon fiber Material
fin bonded to body
· for all fins
Ø in - 75 mm = 2.95 in
Ø out - 3.45 in
Motor, exact fit
symmetrical

[C4]



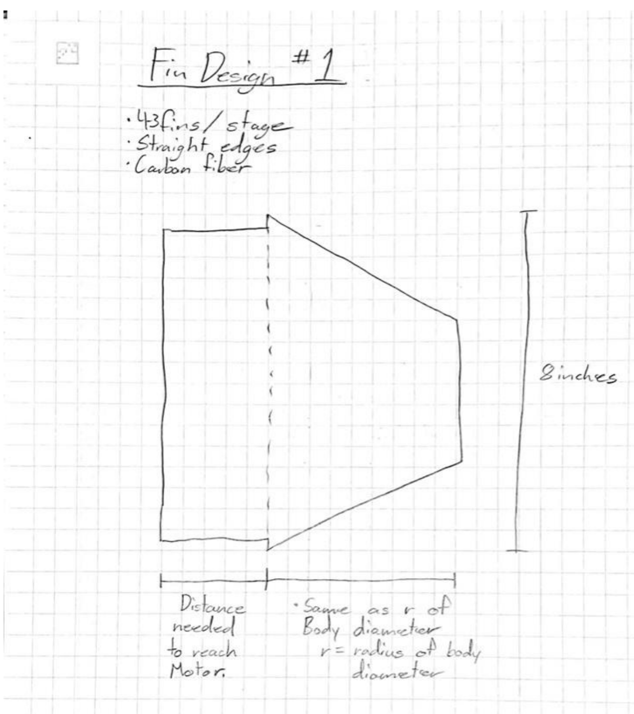
Body Design #4
Payload compartment
Ø in - 6 in
Ø out - 6.5 in
Cubic transition
Total height - 15'
· Carbon fiber Material
fin bonded to body
· for all fins
Uniform Diameter
Ø in = 75 mm = 2.95 in
Ø out = 3.45 in
Motor, exact fit
· for both motor Compartments

[C5]

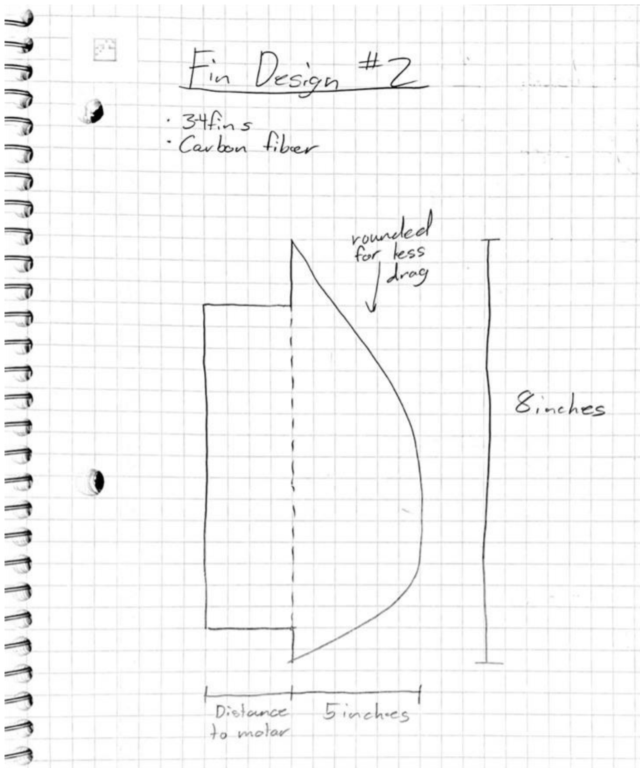


9.1.4 Fin Design

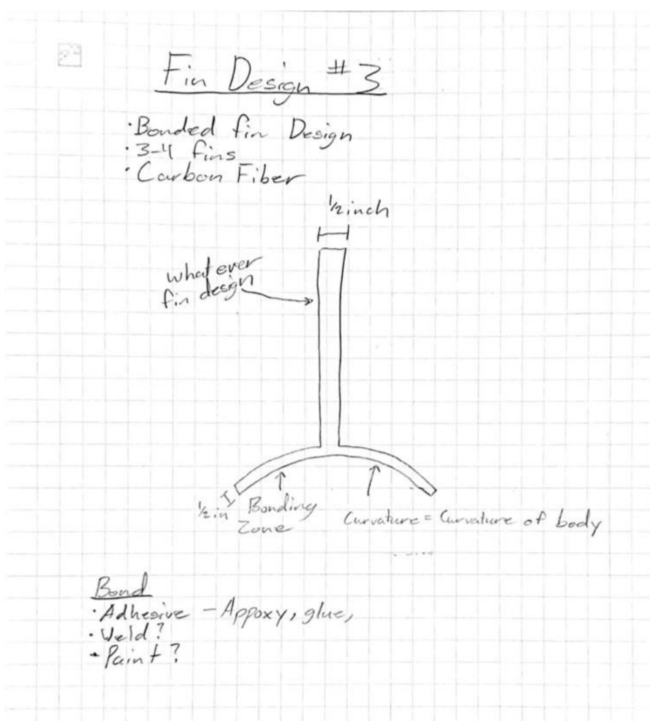
[D1]



[D2]


Fin Design #2
· 34fins
· Carbon fiber
rounded for less drag
8 inches
Distance to motor
5 inches

[D3]

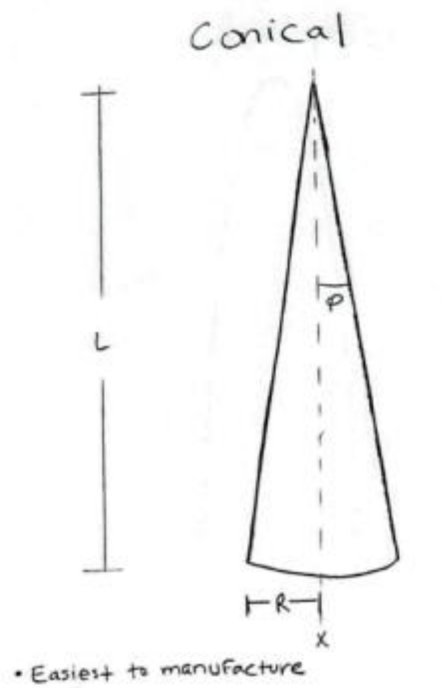

Fin Design #3
· Bonded fin Design
· 3-4 fins
· Carbon Fiber
½ inch
whatever fin design
½ in
Bonding Zone
Curvature = Curvature of body
Bond
· Adhesive - Appoxy, glue,
· Weld?
· Paint?

[D4]

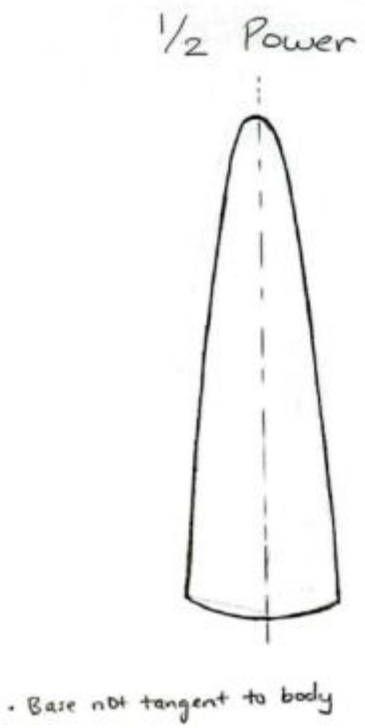
[D5]

9.1.5 Nose Cone

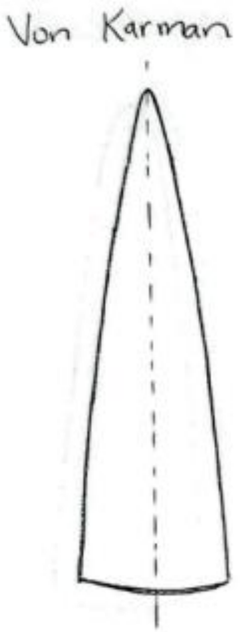
[E1]



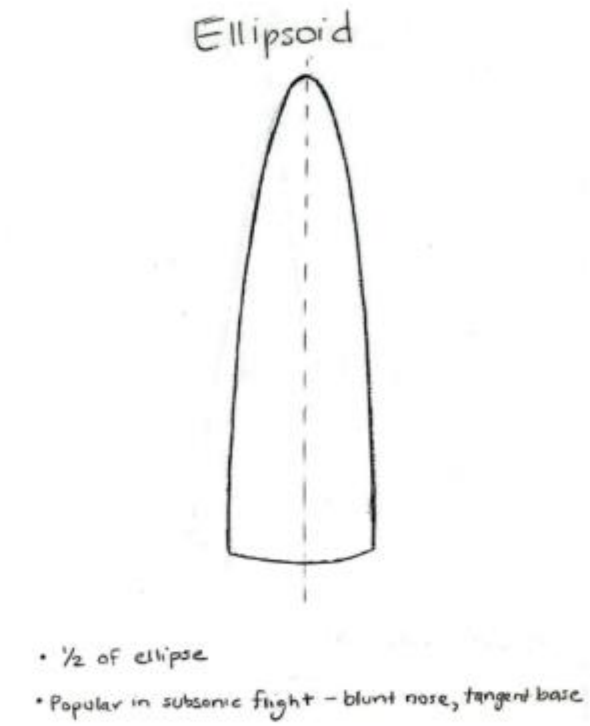
[E2]



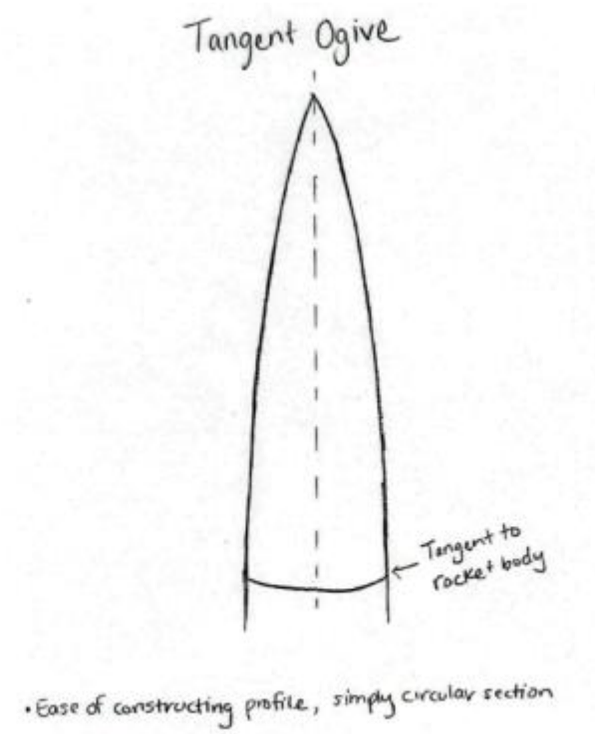
[E3]



[E4]

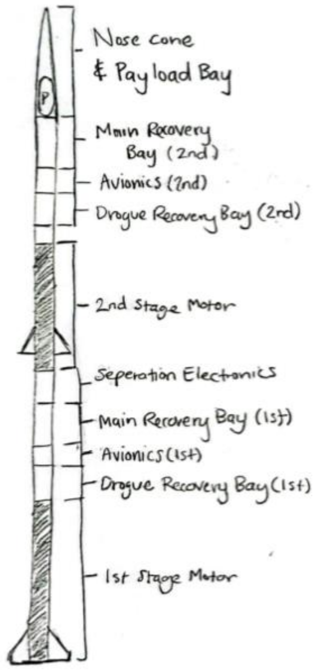


[E5]

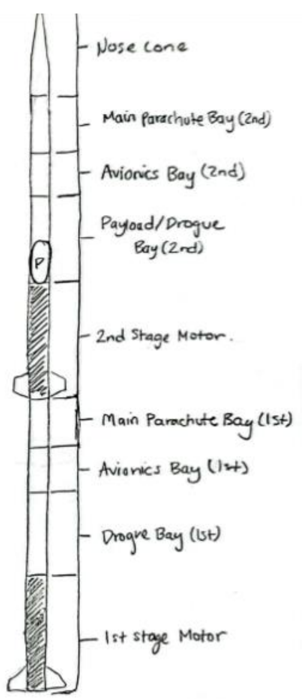


9.1.6 Internal Rocket Layout

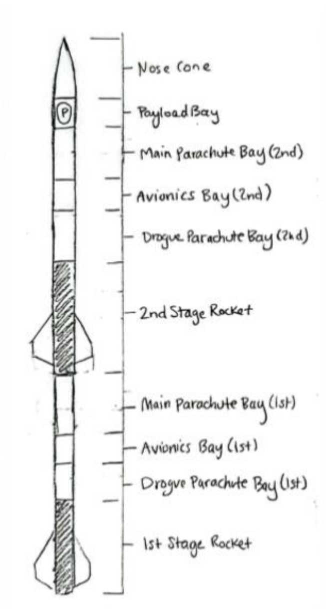
[F1]


Nose cone
& Payload Bay
P
Main Recovery
Bay (2nd)
Avionics (2nd)
Drogue Recovery Bay (2nd)
2nd Stage Motor
Seperation Electronics
Main Recovery Bay (1st)
Avionics (1st)
Drogue Recovery Bay (1st)
1st Stage Motor

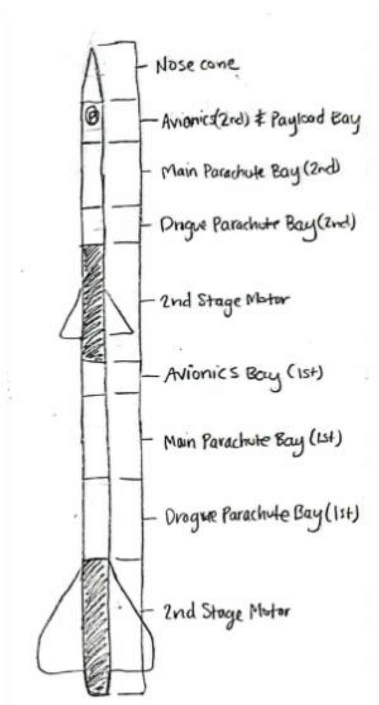
[F2]


Nose cone
Main Parachute Bay (2nd)
Avionics Bay (2nd)
Payload/Drogue
Bay (2nd)
P
2nd Stage Motor.
Main Parachute Bay (1st)
Avionics Bay (1st)
Drogue Bay (1st)
1st stage Motor

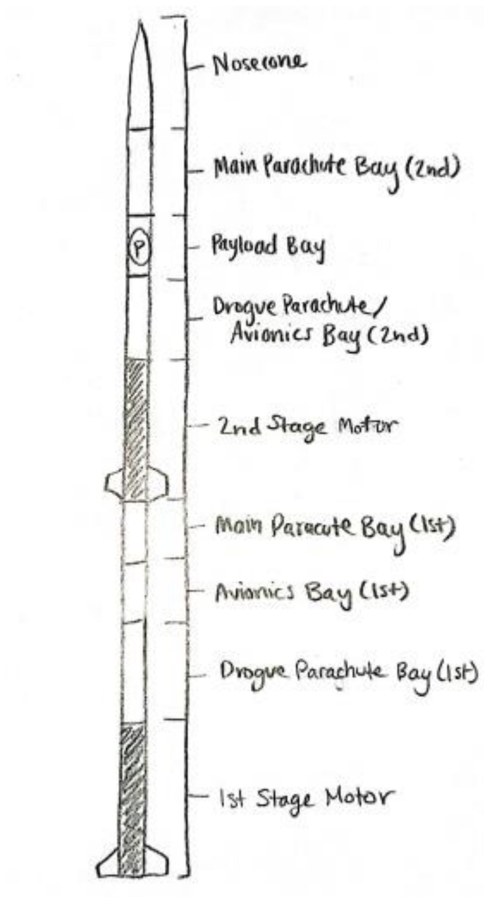
[F3]


Nose Cone
Payload Bay
Main Parachute Bay (2nd)
Avionics Bay (2nd)
Drogue Parachute Bay (2nd)
2nd Stage Rocket
Main Parachute Bay (1st)
Avionics Bay (1st)
Drogue Parachute Bay (1st)
1st Stage Rocket

[F4]

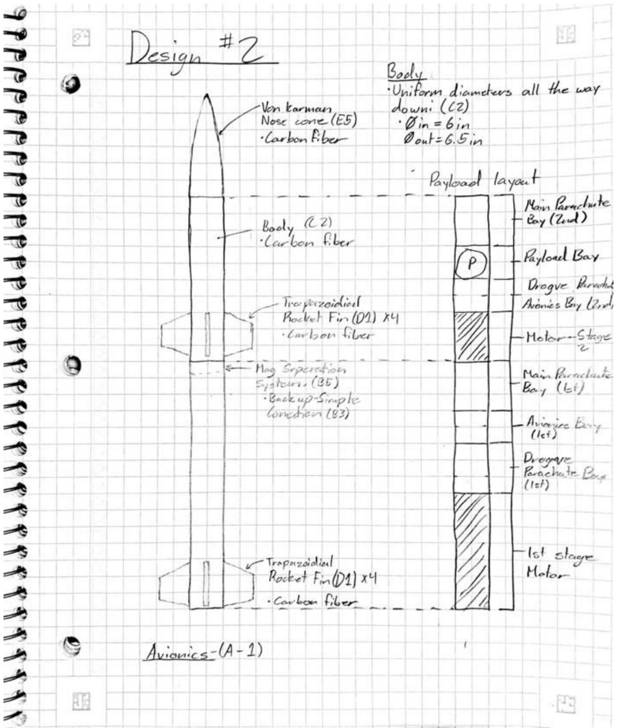

Nose cone
Avionics (2nd) & Payload Bay
Main Parachute Bay (2nd)
Drogue Parachute Bay (2nd)
2nd Stage Motor
Avionics Bay (1st)
Main Parachute Bay (1st)
Drogue Parachute Bay (1st)
2nd Stage Motor

[F5]

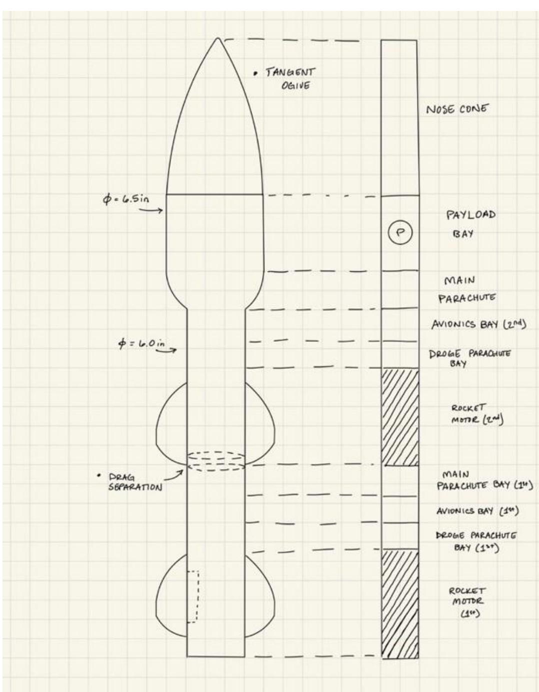


Appendix B: Decision Matrix Designs

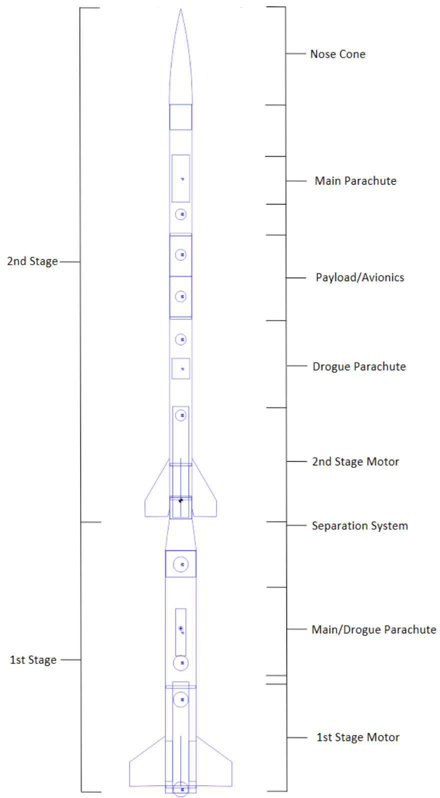
Design 2



Design 4



Design 5



Nose Cone
Main Parachute
2nd Stage
Payload/Avionics
Drogue Parachute
2nd Stage Motor
Separation System
Main/Drogue Parachute
1st Stage
1st Stage Motor

Appendix C: Bill of Materials

SUBSYSTEM	ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.	PRICE ($)	TOTAL PRICE ($)	ACQUISITION METHOD	PRIMARY VENDOR
NOSECONE	1	1	Nose Cone Shell	Carbon Fiber	1	N/A	N/A	Manufacture	NovaKinetics
	2		Nose Cone Coupler	Carbon Fiber	1	N/A	N/A	Manufacture	NovaKinetics
	3		Nose Cone Bulkhead	6061 Aluminum	1	N/A	N/A	Manufacture	IMS
	4		eyebolt-type2_al	Steel	1	N/A	N/A	Donated	NAU Rocket Club
	5		Metal Nose Cone Tip	Steel	1	N/A	N/A	Donated	NAU Rocket Club
	6	92949A347	Button Head Hex Drive Screw	18-8 SS	2	$3.79	$3.79	Order	McMaster Carr
BODY	7		2nd Stage Body Tube (50in. X 6.17in.)	Carbon Fiber	1	N/A	N/A	Manufacture	NovaKinetics
	8		Payload Body Tube	Carbon Fiber	1	N/A	N/A	Manufacture	NovaKinetics
	9		Lower Body Tube	Carbon Fiber	1	N/A	N/A	Manufacture	NovaKinetics
FIN CANISTERS	10		Aft End Centering Ring with Sep Brace	6061 Aluminum	2	N/A	N/A	Manufacture	IMS
	11		Centering Ring	6061 Aluminum	4	N/A	$88.65	Manufacture	IMS
	12		Fin Bracket	6062 Aluminum	6	N/A	N/A	Manufacture	IMS
	13		Corner Bracket	6063 Aluminum	24	N/A	N/A	Manufacture	IMS
	14	92095A196	M4 Button Head Hex Drive Screw	Passivated 18-8 Stainless Steel	36	$8.69	$17.38	Order	McMaster Carr
	15	91263A516	Hex Drive Flat Head Screw	Zinc-Plated Alloy Steel	26	$8.82	$17.64	Order	McMaster Carr
	16	94645A101	M4 Nylon Lock Nut	Zinc-Plated Steel	60	$14.05	$28.10	Order	McMaster Carr
	17	94645A210	M8 Nylon Lock Nut	Zinc-Plated Steel	6	$11.16	$11.16	Order	McMaster Carr
	18	91292A213	18-8 Stainless Steel	Stainless Steel	12	$7.94	$23.82	Order	McMaster Carr
	19	1556A65	Stainless Steel Bracket	Stainless Steel	18	$2.59	$2.59	Order	McMaster Carr
	20	97483A095	Aluminum Flush Mount Rivets	6061 Aluminum	32	$15.35	$15.35	Order	McMaster Carr
	21		Fin	Carbon Fiber	6	$340.21	$340.21	Order	Composite Envisions
	22		2nd Stage End Cap	6061 Aluminum	1	N/A	N/A	Manufacture	IMS
AVIONICS	23		Avionics Coupler 2nd Stage	Steel	1	N/A	N/A	Manufacture	NAU Rocket Club
	24		Avionics Bulkhead	6061 Aluminum	2	N/A	N/A	Manufacture	NAU Rocket Club
	25		flat washer type a narrow_al	6062 Aluminum	12	N/A	N/A	Donated	NAU Rocket Club
	26		eyebolt-type2_al	Steel	2	N/A	N/A	Donated	NAU Rocket Club
	27		Avionics Sled (3D Printed)	3D Polymer	2	N/A	N/A	Manufacture	
	28		Raven 4 v9		4	N/A	N/A	Donated	NAU Rocket Club
	29		GPS Tracker v15		2	N/A	N/A	Donated	NAU Rocket Club
	30	92001A321	18-8 Stainless Steel Wing Nut	18-8 SS	8	N/A	N/A	Donated	NAU Rocket Club
	31	90322A657	High-Strength Steel Threaded Rod	Steel	4	N/A	N/A	Donated	NAU Rocket Club
	32		Switch Band	Carbon Fiber	1	N/A	N/A	Donated	NAU Rocket Club
	33		hex thick nut_al	Steel	2	N/A	N/A	Donated	NAU Rocket Club
RECOVERY	34		Main Parachute	Nylon	1	N/A	N/A	Donated	NAU Rocket Club
	35		Drogue, Booster	Nylon	1	N/A	N/A	Donated	NAU Rocket Club
	36		Drogue, SS	Nylon	1	N/A	N/A	Donated	NAU Rocket Club
	37		Main parachute, Booster	Nylon	1	N/A	N/A	Donated	NAU Rocket Club
	38		Aerotech 98/15360 Motor casing	6061 Aluminum	2	N/A	N/A	Donated	NAU Rocket Club
	39		Aerotech N1000W	Propellant	1	$1,257.99	$1,257.99	Order	Aerotech
	40		Aerotech N3300R	Propellant	1	$1,153.99	$1,302.69	Order	Aerotech
	41		Shock Cord 8800lbs	Kevlar	2	N/A	N/A	Donated	NAU Rocket Club
	42		Tender Decender	6061 Aluminum	2	N/A	N/A	Donated	NAU Rocket Club
				Total Parts Needed	352			Total Parts Received	349
SEPERATION SYSTEM OMITTED DUE TO NDA BUT INCLUDED IN FINAL CALCULATIONS				Total Cost ($):		$3,314.18		Parts On Hand (%)	99.15%
				Total Spent			$3,503.30	Assembled (%)	95.00%