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High Powered Rocketry Emphasizing Dual-Deployment Recovery Systems

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HONORS THESIS

Certificate of Approval

High Powered Rocketry Emphasizing Dual-Deployment Recovery Systems

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Approved to fulfill the requirements of HON 437

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High Powered Rocketry Emphasizing Dual-Deployment Recovery Systems

Submitted in partial fulfillment

of the requirements

for the Murray State University Honors Diploma

McKayla Jo Hoskin

05/2020

Abstract

This paper outlines the overall project completed by MACH during the 2019-2020 school year to fulfill the requirements for EGR 498 and EGR 499 as well as the honors thesis requirements. The scope of the paper covers the design and construction of a high powered rocket as per the requirements set by the NASA Student Launch Competition, with a focus on components of dual-deployment recovery systems. Brainstorming, design, optimization, testing, re-design, and components of a high powered rocket are all discussed, though final testing remains incomplete due to complications from COVID-19. Simulation results and launch predictions are included to compensate for the lack of actual test data. The project was done under the mentorship of Dr. Terry McCreary (Ph.D. in Analytical Chemistry).

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Introduction

The Murray Aeronautical Charter (MACH) was developed to construct a rocket that would compete in the 2020 NASA Student Launch competition. Right away, the team realized that the deadline to apply for the competition was immediate and, unfortunately, determined that it was impossible to complete the application before it closed. Thankfully, MACH compromised and decided to continue with the project without the competition to finalize it. The project neared completion with the help of Dr. Terry McCreary, who has significant experience in the construction of model rockets, but was not finished due to COVID-19. It is necessary for comprehension of the project to include information about the entirety of the project but the focus of this paper will be on the fundamentals of dual deployment. The project requirements obtained from the NASA Student Launch regulations are included in Appendices A-E.[1]

Background

Dual deployment is utilized to ensure a safe recovery of rockets flown to high altitudes, especially if weather conditions are windy.[2] During assembly, two parachutes are attached to each side of the coupler of the rocket using shock cords. The first deployed parachute will be smaller in size than the second and will release at apogee using a black powder ejection charge once the motor has completed its burn. This smaller parachute allows the rocket to descend at a quick, but controlled pace.[3] If the main parachute was released at apogee, the rocket's fall would be slow, allowing wind to cause significant drift and chances of a safe and timely recovery become slim. Once the rocket reaches an appropriate height, the second parachute can be deployed by again using a black powder ejection charge. It is important that the rocket has not

[1] (NASA, 2020)
[2] (USA Patent No. 807,014, 2007)
[3] (Milligan, 2014)

accelerated to too great of a speed otherwise the parachute could be torn and the rocket would increase in speed until impact, likely destroying the rocket. The black powder ejection charges used to release both parachutes cause pressure to build inside of the rocket until the adjacent body tube is separated from the rest of the rocket. The second ignition charge utilizes a delay to ensure the rocket is at the appropriate height for release of the parachute. In our case, this height could not be below 500 ft due to project constraints.

Design

Objective

The overall objective of the project was to design a rocket that could reach a target altitude of 3893 feet, safely return to earth using dual-deployment methods, be recovered, and relaunched within the span of 45 minutes. Further requirements developed for the project follow the NASA regulations for the Student Launch competition (Appendices A-E).

Prototype

The project began with the development of three miniature model rockets. Brainstorming exercises (Appendix F) and initial drawings (Appendix G) were executed. The first design was a tall, thin rocket with rectangular fins. The second was a short, thick rocket with inverted fins. The third drawing resembled the first but was shorter, had a greater diameter and more angular fins. The fourth design shows an incredibly short, wide rocket with large fins. These four designs were analyzed using the Pugh Selection Method.

Pugh Selection Method

Using information from the Pugh Selection Method[4], the initial drawings were analyzed. The team agreed upon design three as the datum and created a Pugh chart, Figure , to compare performance in several criteria of each concept to design three. Plus signs indicate better performance, “S” indicates no appreciable difference (Same), minus signs indicate worse performance.

Pugh Selection Chart for MACH Rocket				
	Concepts			
Selection Criteria	**1**	**2**	**3**	**4**
Low Weight	S	+		-
Thrust target	+	S		-
Sectional Area	+	S		-
Launch Safety	S	-		S
Recovery Safety	S	-		S
Speed	+	S		-
Reusability	S	S	Datum	S
Durabiltiy	-	-		-
Landing Accuracy	S	S		S
Relaunch Time	S	S		S
Manufacturability	-	-		+
Payload Capacity	-	-		+
# of Pluses	3	1		2
# of Minuses	3	5		4

Figure 1: Pugh Selection Chart

[4] (Dieter & Schmidt, 2013)

Concept one was chosen and the focus became to make the rocket as thin as possible, having identified this trait as positively affecting criteria such as thrust target, sectional area, and speed. After analysis, three computer modeled drawings were built (Figures 2, 3 & 4). These computer models were tested and optimized using a software called OpenRocket.

<u>Model V2C1</u>

The prototype rocket V2C1, Figure 2, implements a single body diameter moving directly from the lower body to the upper body and leading into the nosecone. Initial thoughts were that this would increase aerodynamic stability since mass would increase and the design is more uniform throughout.

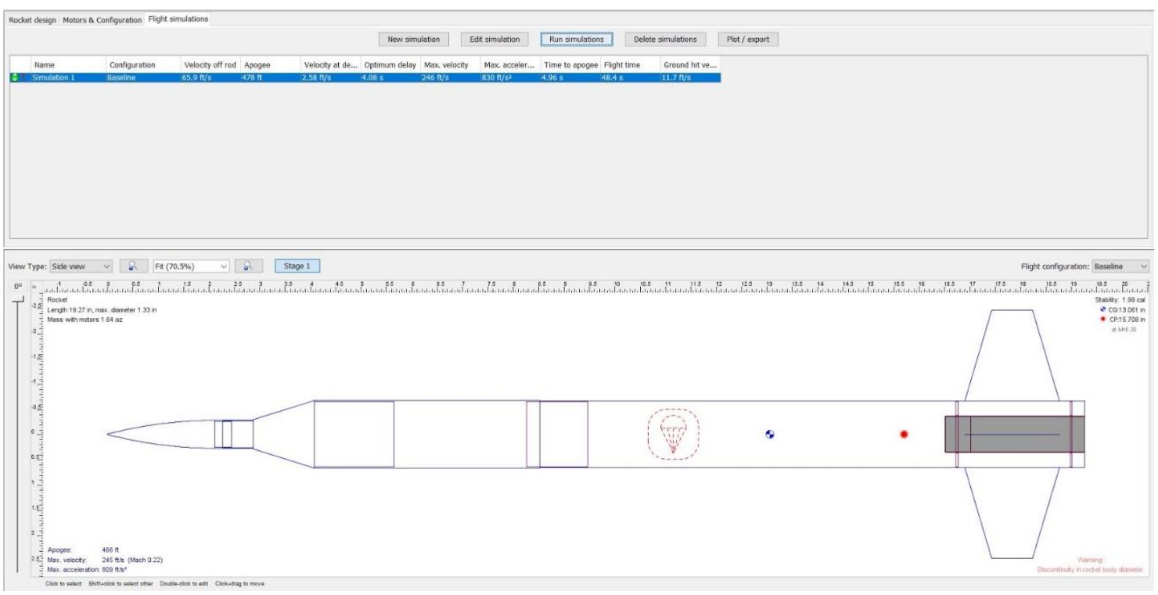


Figure 2: Model V2C1

<u>Model V2C2</u>

Model V2C2, Figure 3, resembles model V2C3, differing only in the length of the upper body. The upper body was cut in half to mitigate drag effects and high mass values. This rocket is what the team predicted to achieve the highest altitude; therefore, this was predicted to be the “best” performing prototype rocket.

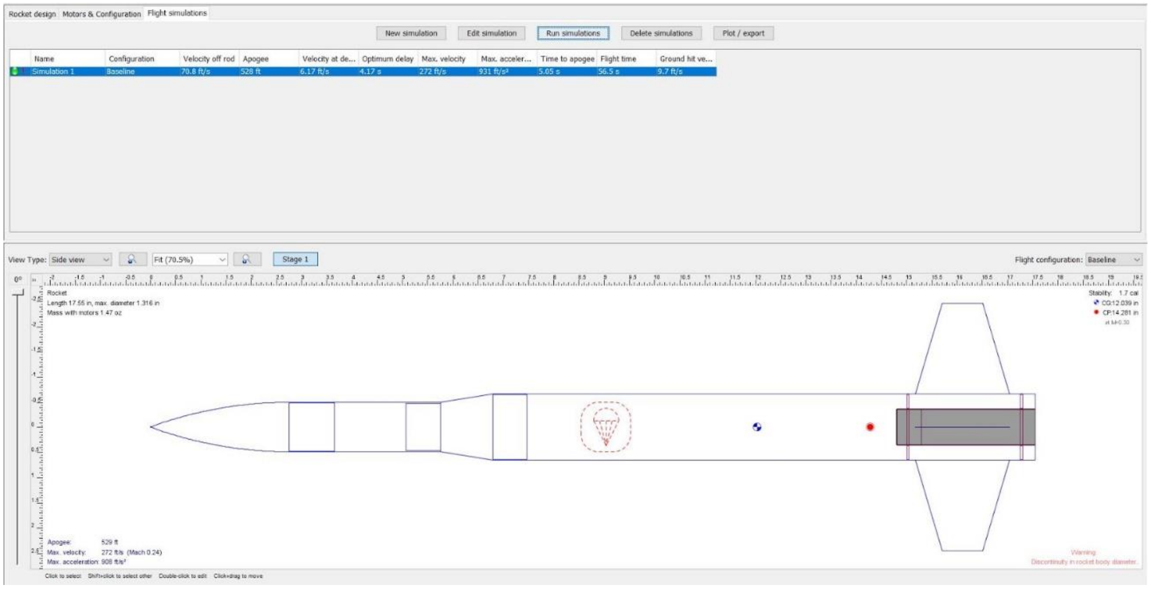


Figure 3: Model V2C2

<u>Model V2C3</u>

Model v2c3, Figure 4, implements two body diameters: a larger lower body diameter and smaller upper body diameter. The longer upper body compared to V2C2 increased drag but provided more static stability.

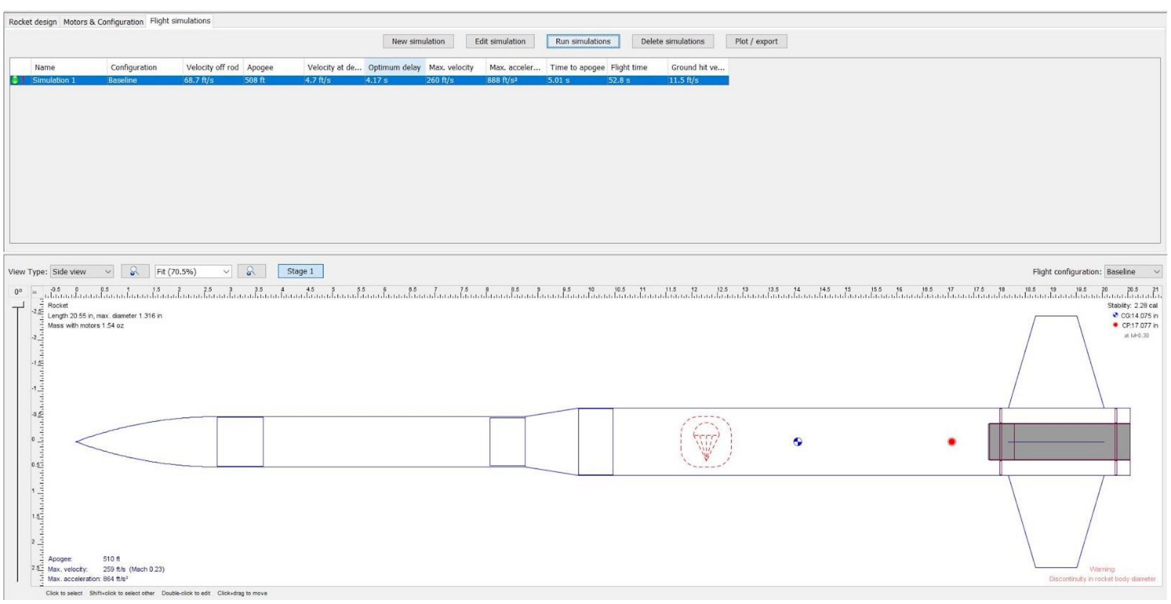


Figure 4: Model V2C3

After reviewing the results from each test flight in OpenRocket, the team predicted that the model V2C2 (Figure 3) would perform better than the other models. The prototypes were then built using three Estes Nike Apache rocket kits, supplemented by nosecones, body tubes, transitions, an altimeter, and other basic tools provided by Dr. McCreary to aid in construction. The completed prototypes are shown in Figure 5. It is important to note that the prototype rockets utilized a single-deployment system whereas the main rocket utilized the aforementioned dual-deployment system.

Figure 5: Completed mini-rockets (from left; V2C1, V2C3, V2C2)

<u>Testing</u>

The three prototype rockets were launched on December 14, 2019 in Hopkinsville, KY. Three launches were performed for each design, except for V2C2 due to a malfunction at the launch pad, using Estes B6-4 motors. The rockets each held an altimeter that measured the altitude reached. Results from this launch can be found in Appendix H. The results clearly showed that model V2C3 performed the best, disproving our hypothesis.

Main Rocket

The main rocket design is divided into five subsystems: Aerodynamic, Engine, Body, Altimeter, and Dual-Deployment. Each subsystem will be discussed in short but, as stated previously, emphasis will lie with the dual-deployment recovery system.

<u>Dual-Deployment</u>

As per the project requirements, the rocket was to be launched, recovered, and relaunched within a 45 minute time frame. In order for the rocket to be relaunched, it had to land and be recovered safely. To do this the team decided to utilize a dual-deployment recovery system.

Alternatives

The alternative to a dual-deployment recovery system is a single-deployment recovery system. This entails only a single parachute deployed at a desired altitude. The drawbacks from a single-deployment are the higher likelihood of drift due to wind and/or dangerously high speed upon impact that damages the rocket beyond immediate repair. One of the project requirements stated that the rocket must land within a 2,500 ft radius from the launch pad. Factoring in wind, a single-deployment rocket would likely drift outside of the allowable radius. The rocket also must be relaunched within 45 minutes of the first launch, making it paramount that it is not irreparably damaged upon landing.

The prototype rockets utilized a single deployment recovery system because they were not launched as high as the main rocket would have been, thereby lessening the chance of drift and acceleration due to gravity.

A simulation was ran in OpenRocket using a 12 inch diameter drogue parachute, Figure 6, and a 36 inch diameter main parachute, Figure 7, both with drag coefficients of 0.80. These data values were suggested by Dr. McCreary. The drogue parachute was to be deployed one second after apogee. The one second delay was put into place in case the altimeter malfunctioned and released the parachute before apogee, which would likely cause the parachute to tear. The main parachute was released at 500 feet to satisfy our general requirements. Results from this simulation are shown in Figure 8.

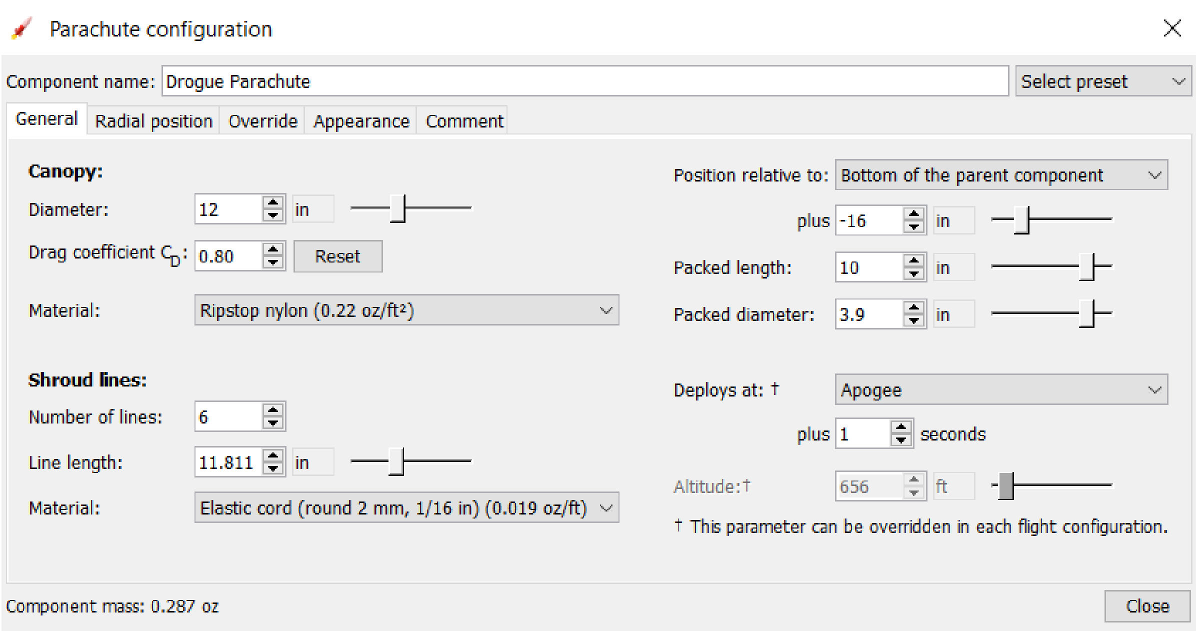


Figure 6: Drogue Parachute Data

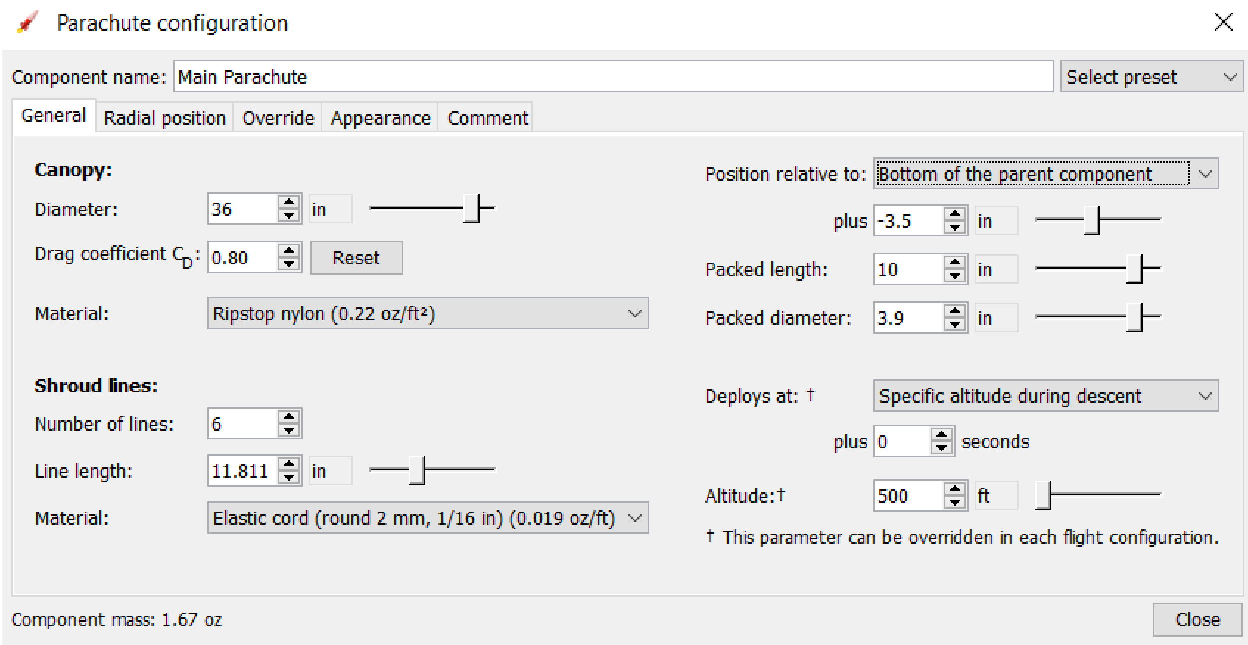


Figure 7: Main Parachute Data

Name	Configuration	Velocity off rod	Apogee	Velocity at de...	Optimum delay	Max. velocity	Max. acceler...	Time to apogee	Flight time	Ground hit ve...
Simulation 1	[J450DM-14]	46.6 ft/s	4572 ft	101 ft/s	13.2 s	771 ft/s	424 ft/s²	15.5 s	71 s	31.7 ft/s

Figure 8: Simulation Results (1)

The results of this simulation show a ground hit velocity of 31.7 ft/s. This likely would not destroy the rocket but would cause some damage. After further calculations, it was determined that the rocket would actually need a 48 inch diameter parachute to properly slow the descent rate.

Optimization

Appendix I shows information about the J450DM motor. The weight of the motor was the vital component here, enabling the weight of the rocket before launch (4280.78g) and at apogee to be determined (3058.916g).

Appendix J shows mass ratios of the rocket utilized in calculating the descent rate of the rocket including empty mass and full mass.[5] Also pictured is a rough sketch of the internal components of the rocket.

Appendix K shows the calculations used to arrive at the necessary diameter of 46 inches for the main parachute and the final descent speed of less than 16.4 ft/s of the falling rocket.[6] [7] These calculations utilized the free fall equation,

$$F_d = \frac{1}{2}\rho C_d A v^2$$

where F_d is the drag force, ρ is air density, C_d is drag coefficient, A is area of the parachute ($\frac{\pi D^2}{4}$, D is diameter), and v is the velocity through air. This velocity is a rough measurement because the drogue parachute will also continue to slow the rocket once the main parachute is deployed. The drogue parachute's descent velocity was calculated to be 63.75 ft/s.

The diagram in Appendix L shows the general flight path of the rocket including each parachute deployment. After calculating the falling rate of the rocket using the equation $d = vt$ where d is distance, v is velocity and t is time; it was determined that the main parachute would need to deploy at approximately 62.745 seconds after apogee. This would mean the altimeter would need to induce the second black powder ignition charge 78.245 seconds into the flight in order for the main parachute to be released 500 feet above ground.

Validation Testing

Shown in Figure 9 are results from the simulation in OpenRocket using the 12 inch diameter drogue parachute with drag coefficient of 0.8 (modeling the 12" Printed Nylon

[5] (Benson, 2014)
[6] (Culp, 2008)
[7] (Carasco, 2016)

Parachute from Apogee Rockets[8]) and the 48 inch diameter main parachute with drag coefficients of 2.2 (modeling the “48" Fruity Chutes: Classic Elliptical” parachute from Apogee Rockets[9]). The drogue parachute was to be deployed one second after apogee. The main parachute was released at 500 feet to satisfy our general requirements. Figure 10 shows a graph of the flight path and Figure 11 shows results of the simulation.

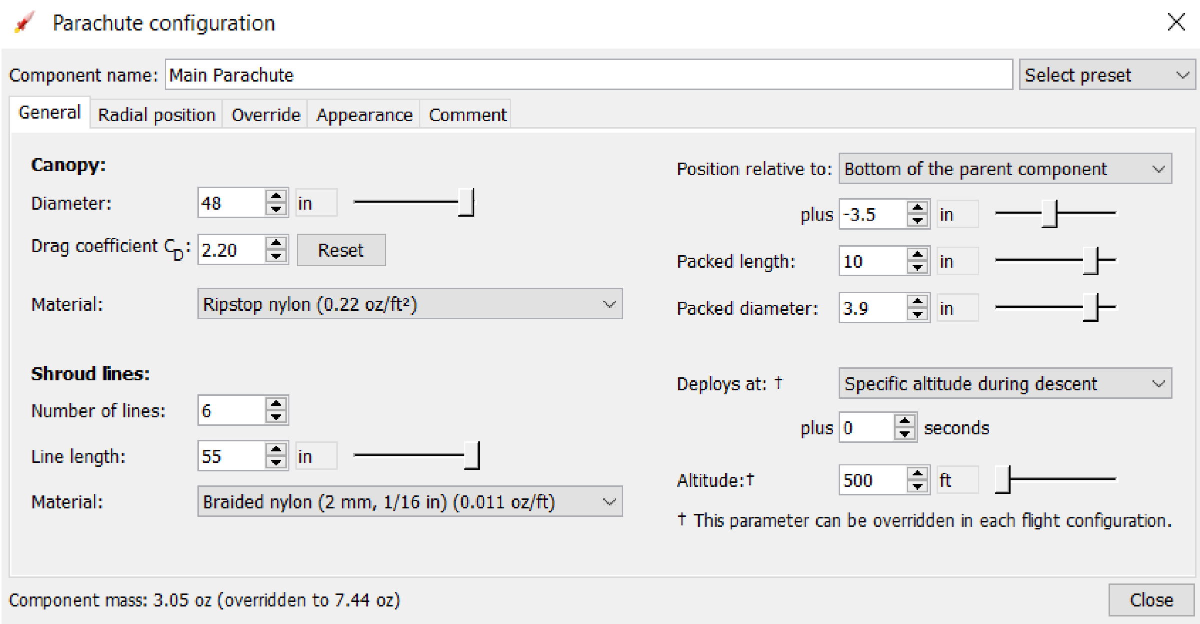


Figure 9: 48” Main Parachute Data

[8] (Rockets, Apogee Components, 2019)
[9] (Rockets, Apogee Components, 2019)

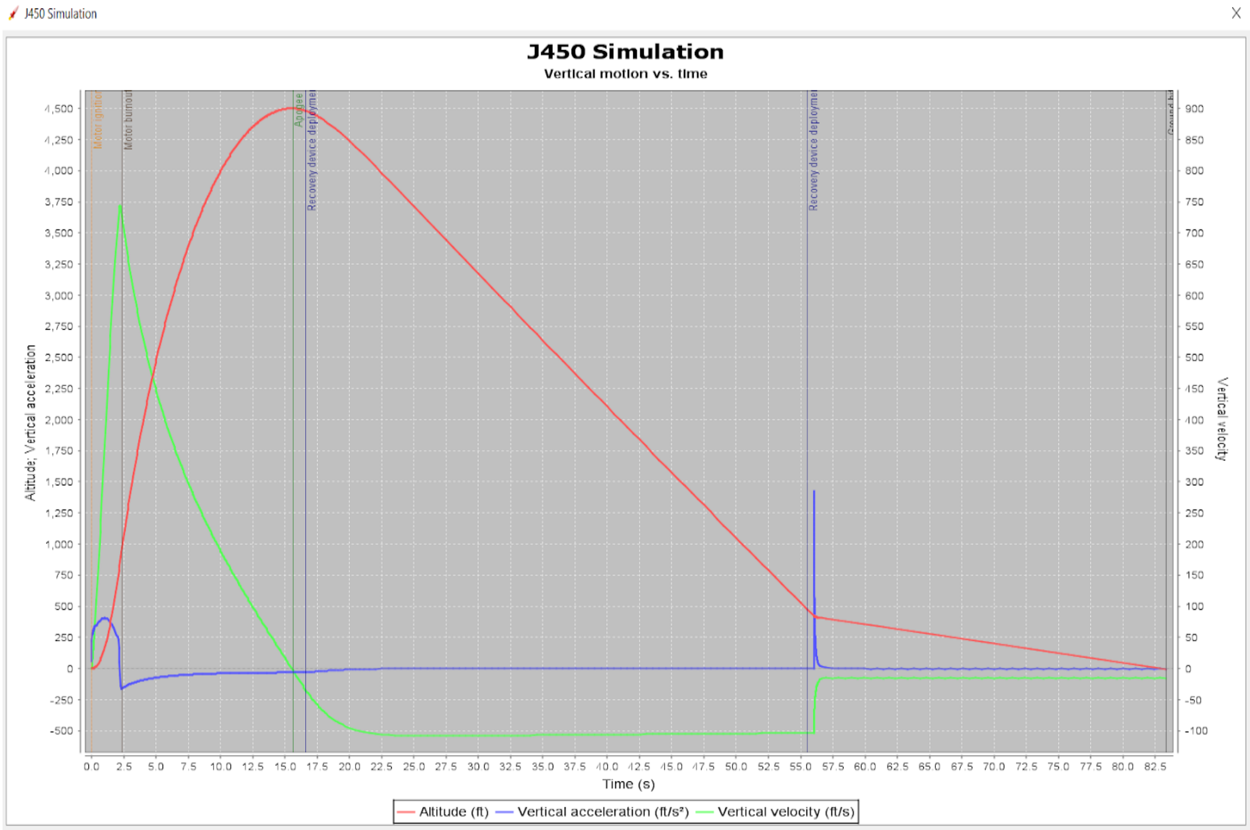


Figure 10: Graph of Flight Plan

Name	Configuration	Velocity off rod	Apogee	Velocity at de...	Optimum delay	Max. velocity	Max. acceler...	Time to apogee	Flight time	Ground hit ve...
J450 Simulation	[J450DM-14]	44.9 ft/s	4500 ft	104 ft/s	13.3 s	744 ft/s	407 ft/s²	15.5 s	83.4 s	14.5 ft/s
J99 Simulation	[J99-P]	25.2 ft/s	4276 ft	98.1 ft/s	9.15 s	404 ft/s	96.2 ft/s²	19.1 s	89.8 s	13.7 ft/s

Figure 11: Simulation Results (2)

According to the simulation data, the ground hit velocity now would be 14.5 ft/s which is a reasonable speed. This lines up with the calculations made by hand.

Unfortunately, we were unable to see the dual-deployment recovery system used or tested in the field due to COVID-19.

<u>Altimeter</u>

The team decided to use two altimeters to measure altitude as well as velocity. Later, it became clear that two altimeters were needed specifically for the dual-deployment system due to need for two black powder ejection charges. One altimeter would ignite black powder to release the drogue parachute and the other would trigger the release of the main parachute.

The altimeter calibration subsystem was completed by Emma Workman. The altimeters utilize pressure through a static port outside of the rocket to measure altitude. The more modern altimeter utilizes an integrated measurement system, Air Data Computer (ADC), which allows it to measure all the attributes listed above. This system provides more precise data, however the use of multiple altimeters together creates a reference system which helps provide more comprehensive information about the rocket's position and angles.[10] While altimeter calibration isn't necessary for flight (most altimeters are pre-calibrated), it does ensure more accurate results and provide more precise data; however, we were never able to calibrate them due to COVID-19.

Fins

Fins are used to provide stability for the rocket. The fins subsystem was focused on by Kyle Britton. In order to determine the effect of different parameters (cant angle, height, position, root chord, sweep, and tip chord) on the stability of the rocket, we used optimization software to vary each parameter and note the change in stability. After noting the general trends, we established feasibility limits and optimized parameters accordingly.

Specifications for the fins relative to the rocket body tube can be seen in the screenshot in Figure 12. The SolidWorks capture, Figure 13, shows the final cutting specifications accounting for the part of the fins within the rocket, attaching to the inner tube.

[10] (Hoke, 2019)

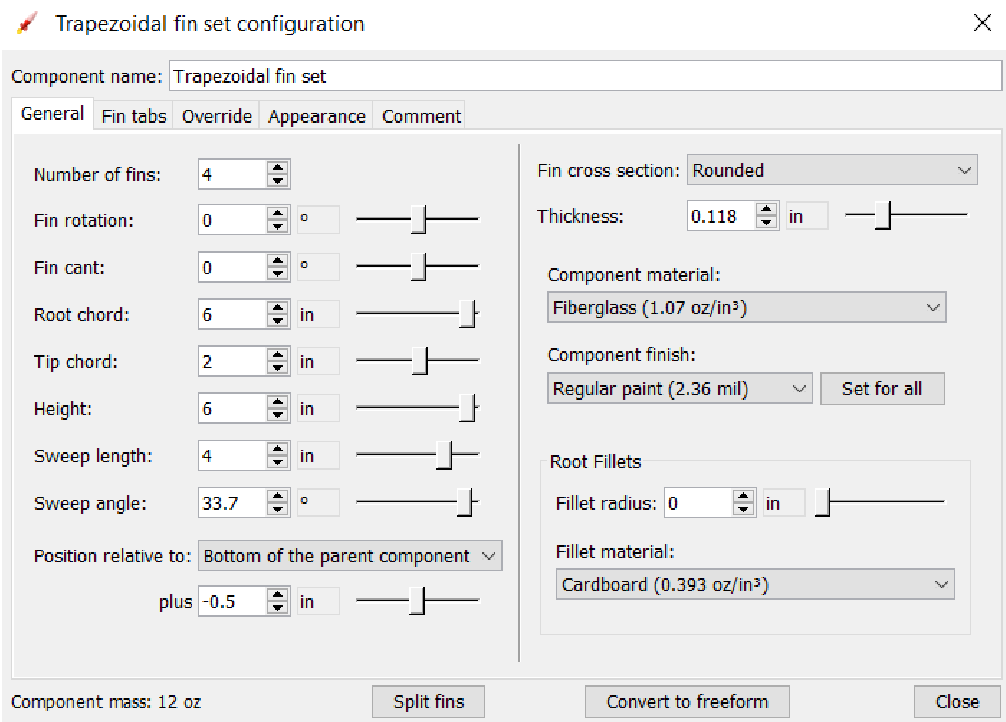


Figure 12: Fin Specifications

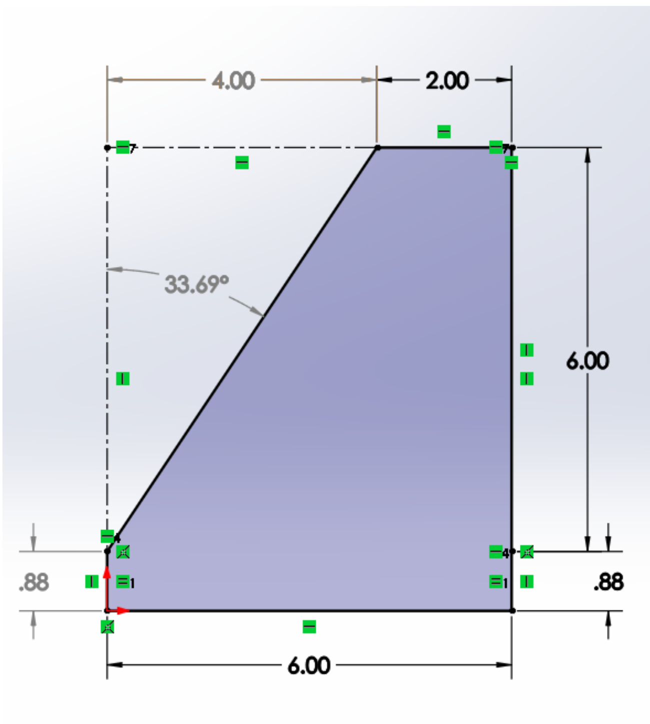


Figure 13: SolidWorks Fin Drawing

Engine

There are three types of motors: single use, reloadable, and hybrid. Single use motors are burned, and then the entire motor is removed and discarded. Reloadable motors use casings which can be permanently mounted in the rocket. Fuel is then prepared - allowing for more customization of delay times - and placed into the casing. Hybrid motors use a more complicated system of both liquid and solid propellants/fuel.[11] The team chose to use a single-use motor since there is less preparation time and we wanted to minimize the time between launches.

There are also different power levels or classes of motors. According to Apogee Components, “Each letter classification's maximum total impulse is twice that of the prior.”[12] Requirement 2.10 means that we have a maximum class of L. The minimum power is determined by that which is needed to get the rocket with no ballast to the chosen height of 3,893 feet. In theory any motor between these two boundary conditions could be chosen, but more powerful motors mean more ballast is needed to reduce the apogee to our target value. While ballast is adjustable and there are dense options that would not exceed our planned ballast payload volume, it was important to overshoot our goal so that we would have room for unexpected resistance, but not to the point of needing excessive ballast in the case of the accurate simulations. The main determining variables were availability, preparation time, and power. The Aerotech J450 motor was chosen and simulation results using this motor are shown in Figure 14 and Figure 15.

[11] (Components, 2019)
[12] (Components, 2019)

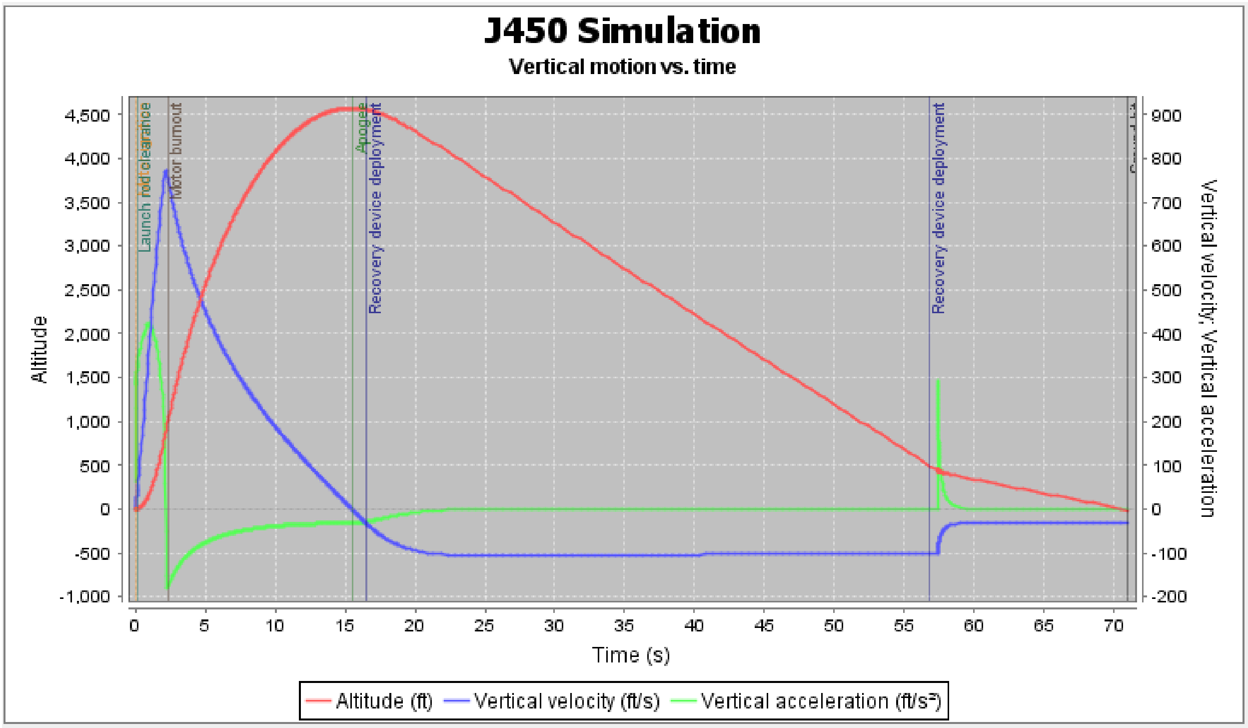


Figure 14: J450 Motor Simulation

	Name	Configuration	Velocity off rod	Apogee	Velocity at de...	Optimum delay	Max. velocity	Max. acceler...	Time to apogee	Flight time	Ground hit ve...
!	J450 Simulation	[J450DM-14]	46.6 ft/s	4572 ft	101 ft/s	13.2 s	771 ft/s	424 ft/s²	15.5 s	71 s	31.7 ft/s
!	J99 Simulation	[J99-P]	25.7 ft/s	4470 ft	95.4 ft/s	9.3 s	420 ft/s	102 ft/s²	19.2 s	75.9 s	29.9 ft/s

Figure 15: J450 Motor Simulation Results

Body

The body of the rocket housed all of the internal components of the rocket. We considered making the lower body tube a smaller diameter than the upper, thereby reducing drag surface area. This would also provide more stability by moving the center of gravity up the body of the rocket. Dr. McCreary noted that the increased manufacturing complexity of a custom, two-size coupler to transition between the body tubes would likely outweigh any benefits such a design would provide, so we decided to use a constant diameter throughout. The upper body tube was also limited by the size of the payload and commercially available nose cones. A set outer diameter of 4 inches for the upper tube was chosen. The lower body tube could virtually be any size due to the variable motors available and ability to roll parachutes to fit but, for aforementioned reasons, we chose to keep the diameters the same.

The first body tube was going to be pure fiberglass shaped using a mold and hardened with epoxy. After rolling the fiberglass and allowing it to dry/harden, we were unable to remove the mold from the inside of the fiberglass tube, leading us to scrap the attempt and start over. This led to the alternative approach of purchasing components commercially and modifying them as needed.

The main requirement of the body tubes was to provide safe, sturdy compartments to hold the internal components of the rocket including payload, parachutes, altimeters, and motor. The final body of the rocket consisted of two cardboard tubes soaked in phenolic and wrapped in fiberglass cloth that was bonded with epoxy. Once the fiberglass and epoxy had hardened, the tubes were covered in Bondo and sanded to create a smooth finish. One body tube was 30 inches and the other was 32 inches long, both had an outer diameter of 4 inches and an inner diameter of 3.9 inches. Centering rings, bulkheads, the coupler and the motor mount tube (MMT) were also used to create stability and hold the internal components in place. The centering rings and bulkheads were cut out of carbon fiber sheets using a CNC laser to achieve the most accurate cuts possible. The SolidWorks file for these components is shown in Figure 16. The coupler attached the two body tubes and housed the recovery system and altimeters. This section of the rocket was the most laborious for the team. Having accurate dimensions was key since it was paramount that the different components fit snugly together. Sanding also proved highly important since some components needed a smooth finish to decrease drag and others needed a rough finish to ensure a tight fit.

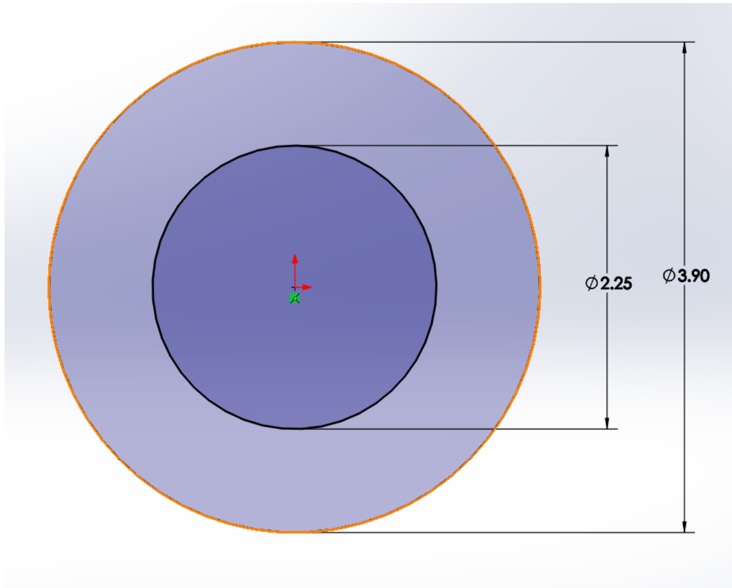


Figure 16: Centering Rings and Bulkheads

A comprehensive list of body components and their measurements is shown in Appendix M. The full Bill of Materials can be found in Appendix N.

Testing/Analysis

We were unable to test the rocket due to COVID-19. The furthest analysis we got was hand calculations and simulations ran on OpenRocket, all of which were included and discussed previously.

Conclusions

After immense trial and error, it was determined that we would use a 48" main parachute and 12" drogue parachute to safely return the rocket to the ground. The dual-deployment system was interesting and complex and, while the end of the project did not turn out as we hoped and it was extremely disappointing to not see this to completion, the amount we learned throughout this process was unmatched. Brainstorming ideas, developing prototypes, designing a rocket, and constructing the rocket was an amazing process. Figuring out calculations that I had never done before to analyze a complex system will undoubtedly prove fruitful in the future. Working as a MACH team member was incredible and fulfilling. Perhaps one day we will launch a rocket on a larger scale.

Bibliography

Benson, T. (2014, June 12). *Mass Ratios*. Retrieved from NASA: https://www.grc.nasa.gov/WWW/K-12/rocket/rktwtp.html

Carasco, J. (2016). *Free Fall Equations*. Retrieved from Introduction to Physics: https://www.introduction-to-physics.com/free-fall-equations.html

Components, A. (2019). *Rocket Motor Basics*. Retrieved from Apogee Rockets: https://www.apogeerockets.com/Rocket-Motor-Basics-Quick-Start-Guide#type

Culp, R. (2008, August 24). *Parachute Descent Calculations*. Retrieved from Rocket Mime: http://www.rocketmime.com/rockets/descent.html

Dieter, G. E., & Schmidt, L. C. (2013). *Engineering Design* (5th ed.). New York, New York.

Hoke, K. (2019, September 11). *Aviation's Crazy, Mixed Up Units of Measure*. Retrieved from AeroSavvy: aerosavvy.com/metric-imperial/

Milligan, T. V. (2014, March 25). *Apogee Components: Peak of Flight*. Retrieved from Selecting the Proper Size Drogue Parachute: https://www.apogeerockets.com/education/downloads/Newsletter361.pdf

NASA. (2020). *NASA*. Retrieved from NASA Student Launch Handbook: https://www.nasa.gov/sites/default/files/atoms/files/2020-sl-handbook.pdf

Rockets, A. (2019). *Apogee Components*. Retrieved from Model Rocket Kits, Resources, and Components: https://www.apogeerockets.com/Building-Supplies/Parachutes/Up-to-24in/12in-Printed-Nylon-Parachute?cPath=42_309_336&

Rockets, A. (2019). *Apogee Components*. Retrieved from Model Rocket Kits, Resources, and Components:

https://www.apogeerockets.com/Building_Supplies/Parachutes_Recovery_Equipment/Parachutes/High_Power/48in_Iris_Ultra_Parachute

Warren W. Farr, I. (2007). *USA Patent No. 807,014.*

Appendices

A. General Requirements

1.1. Students on the team will do 100% of the project, including design, construction, written reports, presentations, and flight preparation with the exception of assembling the motors and handling black powder or any variant of ejection charges, or preparing and installing electric matches (to be done by or under the direct supervision of the team's mentor). Teams will submit new work.

1.2. The team will provide and maintain a project plan to include, but not be limited to, the following items: project milestones, budget, checklists, and personnel assignments.

1.3. Team members will include:

1.3.1. Upperclassmen students actively engaged in the project throughout the year.

1.3.2. Underclassmen students engaged in support/learning roles.

1.3.3. One mentor (see requirement 1.13).

1.4. Teams will upload necessary documents and requirements in PDF format.

1.5. The team must identify a "mentor." A mentor is defined as an adult who is included as a team member, who will be supporting the team (or multiple teams) throughout the project year, and may or may not be affiliated with the school, institution, or organization. The mentor must maintain a current certification, and be in good standing, through the National Association of Rocketry (NAR) or Tripoli Rocketry Association (TRA) for the motor impulse of the launch vehicle and must have flown and successfully recovered (using electronic, staged recovery) a minimum of 2 flights in this or a higher impulse class, prior to PDR. The mentor is designated as the individual owner of the rocket for liability purposes and must travel with the team to launch week.

B. Vehicle Requirements

2.1. The vehicle will deliver the payload to an apogee altitude between 3,500 and 5,500 feet above ground level (AGL).

2.2. Teams shall identify their target altitude goal at the PDR milestone. The declared target altitude will be used to determine the team's success.

2.3. The vehicle will carry one commercially available, barometric altimeter for recording the official altitude to compare with the declared target altitude.

2.4. The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.

2.5. The launch vehicle will have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.

2.5.1. Coupler/airframe shoulders which are located at in-flight separation points will be at least 1 body diameter in length.

2.5.2. Nosecone shoulders which are located at in-flight separation points will be at least 0.5 body diameter in length.

2.6. The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system.

2.7. The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other than what is provided by the launch services provider).

2.8. The launch vehicle will use a commercially available solid motor propulsion system which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).

2.9. The launch vehicle will be limited to a single stage.

2.10. The total impulse will not exceed 5,120 Newton-seconds (L-class).

2.11. Pressure vessels on the vehicle will be approved by the RSO and will meet the following criteria:

2.11.1. The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) will be 4:1 with supporting design documentation included in all milestone reviews.

2.11.2. Each pressure vessel will include a pressure relief valve that sees the full pressure of the tank and is capable of withstanding the maximum pressure and flow rate of the tank.

2.11.3. The full pedigree of the tank will be described, including the application for which the tank was designed and the history of the tank. This will include the number of pressure cycles put on the tank, the dates of pressurization/depressurization, and the name of the person or entity administering each pressure event.

2.12. The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.

2.13. Any structural protuberance on the rocket will be located aft of the burnout center of gravity.

2.14. The launch vehicle will accelerate to a minimum velocity of 52 ft/s at rail exit.

2.15. All teams will successfully launch and recover a subscale model of their rocket. Subscales are not required to be high power rockets.

2.15.1. The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale will not be used as the subscale model.

2.15.2. The subscale model will carry an altimeter capable of recording the model's apogee altitude.

2.15.3. The subscale rocket must be a newly constructed rocket, designed and built specifically for this year's project.

2.16. All Lithium Polymer batteries will be sufficiently protected from impact with the ground and will be brightly colored, clearly marked as a fire hazard, and easily distinguishable from other payload hardware.

C. Recovery System Requirements

3.1. The launch vehicle will stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee, and a main parachute is deployed at a lower altitude. Tumble or streamer recovery from apogee to main parachute deployment is also permissible, provided that kinetic energy during drogue stage descent is reasonable, as deemed by the RSO.

3.1.1. The main parachute shall be deployed no lower than 500 feet.

3.1.2. The apogee event may contain a delay of no more than 2 seconds.

3.1.3. Motor ejection is not a permissible form of primary or secondary deployment

3.2. The team must perform a successful ground ejection test for both the drogue and main parachutes. This must be done prior to the initial subscale and full-scale launches.

3.3. Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing.

3.4. The recovery system will contain redundant, commercially available altimeters. The term “altimeters” includes both simple altimeters and more sophisticated flight computers.

3.5. Each altimeter will have a dedicated power supply, and all recovery electronics will be powered by commercially available batteries.

3.6. Each altimeter will be armed by a dedicated mechanical arming switch that is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad.

3.7. Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces).

3.8. The recovery system electrical circuits will be completely independent of any payload electrical circuits.

3.9. Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.

3.10. The recovery area will be limited to a 2,500 ft radius from the launch pad.

3.11. Descent time will be limited to 90 seconds (apogee to touch down).

3.12. An electronic tracking device will be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent section to a ground receiver.

3.12.1. Any rocket section or payload component, which lands untethered to the launch vehicle, will contain an active electronic tracking device.

3.12.2. The electronic tracking device(s) will be fully functional during the official flight on launch day.

3.13. The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).

3.13.1. The recovery system altimeters will be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device.

3.13.2. The recovery system electronics will be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery system electronics.

3.13.3. The recovery system electronics will be shielded from all onboard devices which may generate magnetic waves (such as generators, solenoid valves, and Tesla coils) to avoid inadvertent excitation of the recovery system.

3.13.4. The recovery system electronics will be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics.

D. Safety Requirements

4.1. The team will use a launch and safety checklist during any launch.

4.2. The team must identify a student safety officer who will be responsible for all items in Section 4.3.

4.3. The role and responsibilities of the safety officer will include, but are not limited to:

4.3.1. Monitor team activities with an emphasis on safety during:

4.3.1.1. Design of vehicle and payload

4.3.1.2. Construction of vehicle and payload components

4.3.1.3. Assembly of vehicle and payload

4.3.1.4. Ground testing of vehicle and payload

4.3.1.5. Subscale launch test(s)

4.3.1.6. Full-scale launch test(s)

4.3.1.7. Launch day

4.3.1.8. Recovery activities

4.3.1.9. STEM Engagement Activities

4.3.2. Implement procedures developed by the team for construction, assembly, launch, and recovery activities.

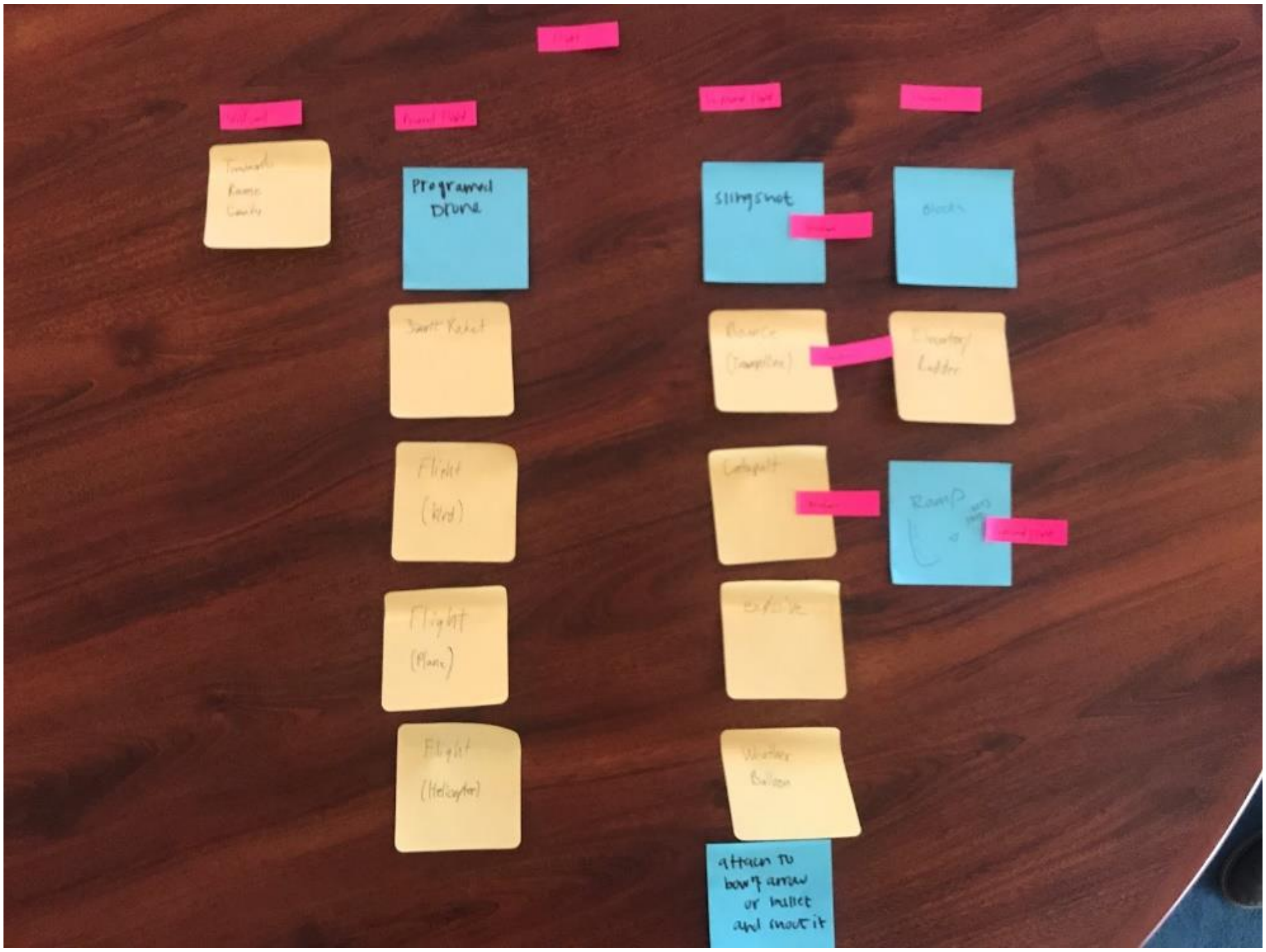
4.4. During test flights, teams will abide by the rules and guidance of the local rocketry club's RSO. Teams should communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.

4.5. Teams will abide by all rules set forth by the FAA.

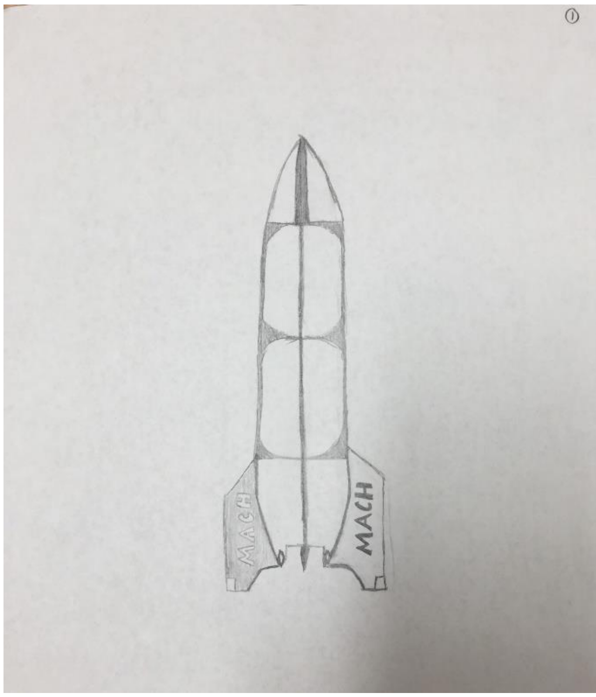
E. Safety

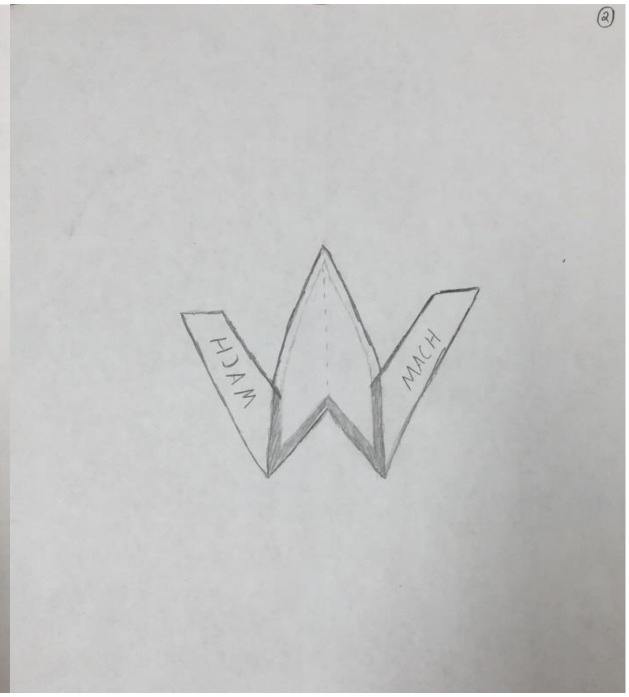
The Federal Aviation Administration (FAA) [www.faa.gov] has specific laws governing the use of airspace. A demonstration of the understanding and intent to abide by the applicable federal laws (especially as related to the use of airspace at the launch sites and the use of combustible/flammable material), safety codes, guidelines, and procedures for building, testing, and flying large model rockets is crucial. The procedures and safety regulations of the NAR [www.nar.org/safety-information/] shall be used for flight design and operations. The NAR/TRA mentor and Safety Officer shall oversee launch operations and motor handling.

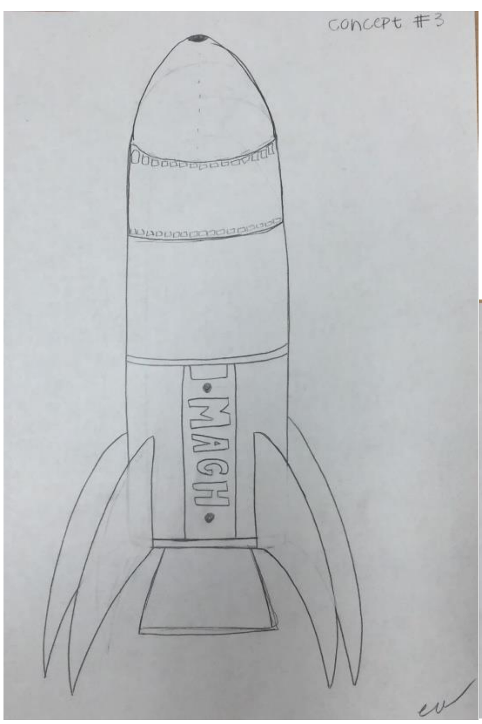
F. Brainstorming

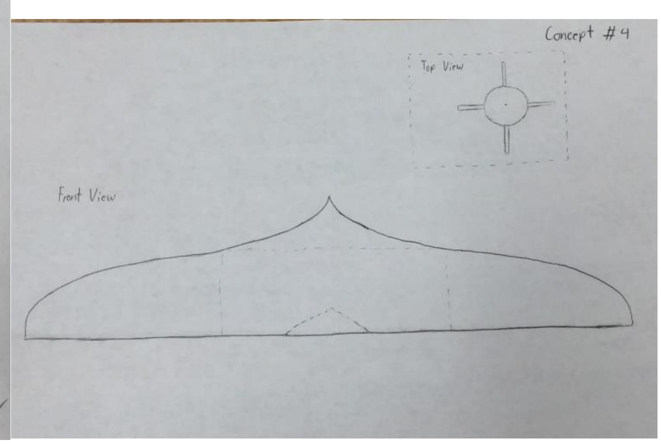


G. Initial Drawings





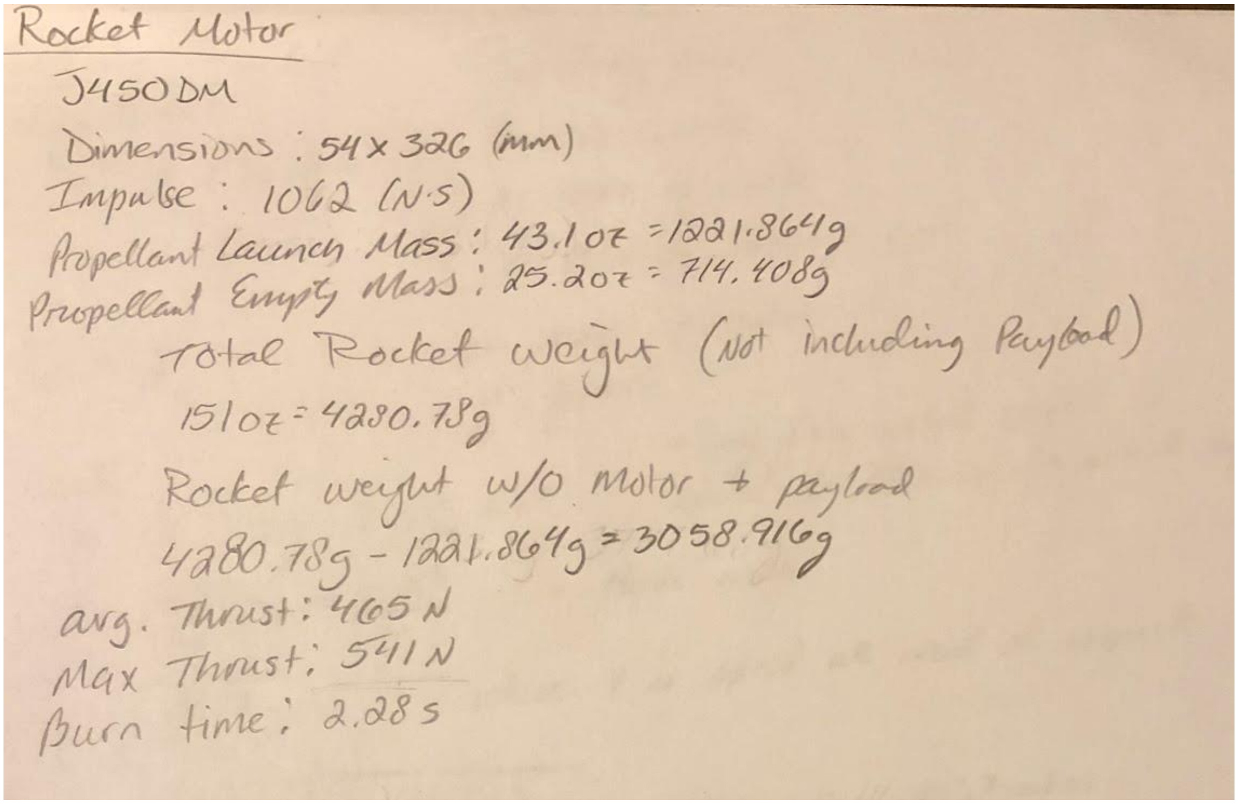




H. Prototype Results

	Trial	Apogee (ft)	Max Velocity (mph)
V2C1	1	319	112
	2	293	80
	3	309	82
V2C2	1	-	-
	2	585	84
	3	325	96
V2C3	1	490	420?
	2	510	491?
	3	570	453?

I. Motor Data



Rocket Motor

J450DM

Dimensions : 54 x 326 (mm)

Impulse : 1062 (N·s)

Propellant Launch Mass : 43.1 oz = 1221.864 g

Propellant Empty Mass : 25.2 oz = 714.408 g

Total Rocket weight (Not including Payload)

151 oz = 4280.78 g

Rocket weight w/o Motor + payload

4280.78 g − 1221.864 g = 3058.916 g

avg. Thrust : 465 N

Max Thrust : 541 N

Burn time : 2.28 s

J.Mass Ratios

Mass Ratios

$16.5oz + 91.4oz = 107.9oz$

Empty mass: $m_e = m_d + m_s = 467.7671g + 2591.146g = 3058.9131g$

Full Mass: $m_f = m_d + m_s + m_p = m_e + m_p = 3058.913g + 1221.864g = 4280.771$

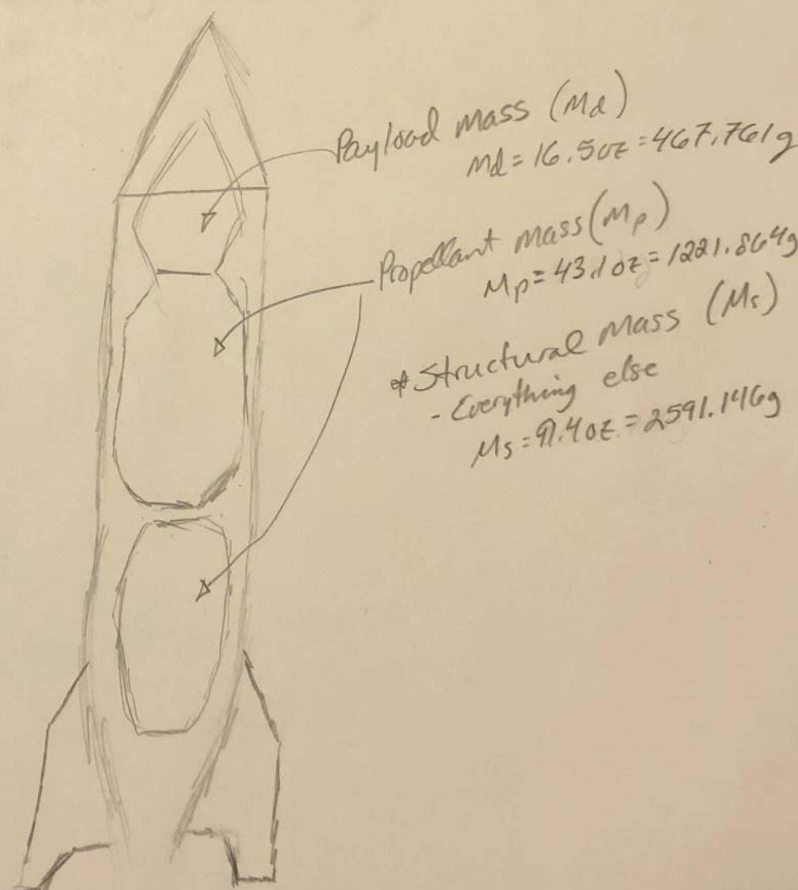
$107.9oz + 43.1oz = 151oz$

Propellant mass ratio: $M_R = \frac{M_f}{M_e} = \frac{151oz}{107.9oz} = 1.399$ ✓

Payload ratio $= \lambda = \frac{M_d}{M_f - M_d} = \frac{16.5oz}{(151oz - 16.5oz)} = .1227$

Structural Coefficient: $\varepsilon = \frac{M_s}{M_p + M_s} = \frac{91.4oz}{43.1oz + 91.4oz} = .67955$

$MR = \frac{1+\lambda}{\varepsilon + \lambda} = \frac{1 + .1227}{.67955 + .1227} = 1.3994$ ✓



K. Free Fall Calculations

Falling Rocket

Drag force:
$F_D = \frac{1}{2} \rho C_d A V^2$

F_D: drag force
ρ = air density
A: area of chute
V = velocity through air

$F_R = mg$

m = mass of rocket =
g = gravity

Need:
$F_D = F_R \Rightarrow mg = \frac{1}{2} \rho C_d A V^2$

* drag force equals weight of rocket to determine parachute size

$A = \frac{2mg}{\rho C_d V^2} = \frac{\pi D^2}{4}$ ← chute area

$D = \sqrt{\frac{8mg}{\pi \rho C_d V^2}}$ where V is speed we want at impact

$D = \sqrt{\frac{8(3.773\,kg)(9.8\,m/s)}{\pi(1.22)(2.2)(5\,m/s)^2}} = 1.185\,m \approx 46.4567$ inches

We would need at least a 46" diameter chute to provide a safe landing.

* Choosing a 48" diameter parachute we get:

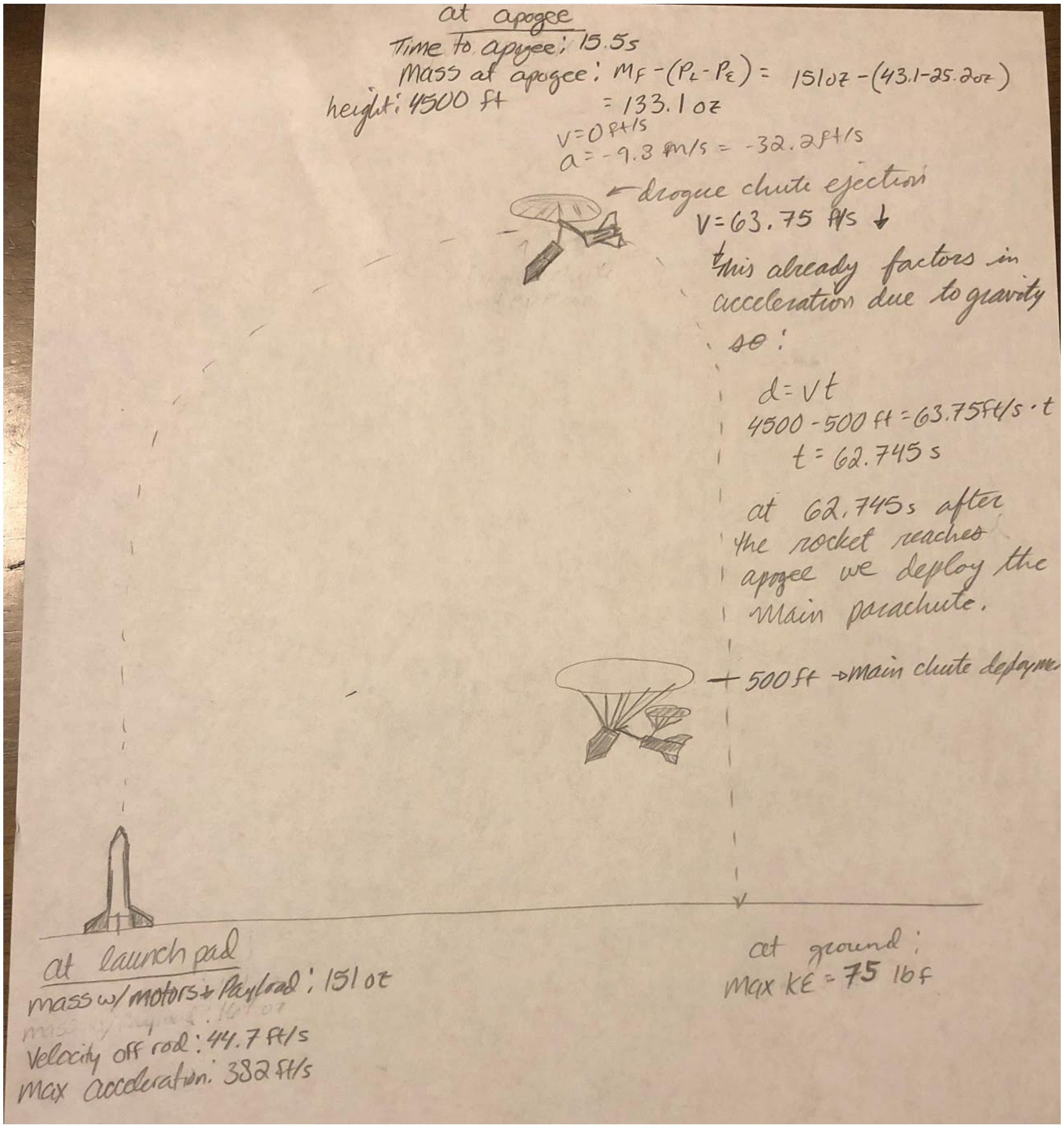
$V = \sqrt{\frac{8mg}{\pi \rho C_D D^2}} = \sqrt{\frac{8(3.773)(9.8)}{\pi(1.22)(2.2)(1.185^2)}} = 5\,m/s = 16.4042\,ft/s$

for the 12" diameter drogue parachute:

$V = \sqrt{\frac{8(3.773)(9.8)}{\pi(1.22)(2.2)(.3048)^2}} = 19.432\,m/s = 63.75\,ft/s$

* This is a little fast but should be okay since we upped the diameter of the main chute.

L. General Rocket Flight Path



M. Table of Body Components and Dimensions

Component		Measurement 1	Measurement 2	Measurement 3	Measurement 4	Average or Calculated Final Value
Body Tube 1	Outer Diameter	4.0380	4.0113	4.0420	-	**4.0304**
	Inner Diameter	3.8990	3.8950	3.8960	-	**3.8967**
	Thickness	0.0780	0.0815	0.0750	0.0730	**0.0769**
Body Tube 2	Outer Diameter	4.0265	4.0310	4.0500	-	**4.0358**
	Inner Diameter	3.9010	3.8885	3.8935	-	**3.8943**
	Thickness	0.0785	0.0765	0.0875	0.0940	**0.0841**
MMT	Outer Diameter	2.2530	2.2570	2.2530	-	**2.2543**
	Inner Diameter	2.1455	2.1435	2.1415	-	**2.1435**
	Thickness	0.0635	0.0620	0.0615	0.0620	**0.0623**
Transition Tube	Outer Diameter	3.8670	3.8725	3.8835	3.8625	**3.8714**
	Inner Diameter	3.7490	3.7730	3.7565	3.7605	**3.7598**
	Thickness	0.0650	0.0630	0.0645	0.0655	**0.0645**
Large Bulkhead	Outer Diameter	-	-	-	-	**3.8975**
	Dowel Hole	-	-	-	-	**0.3125**
Small Bulkhead	Outer Diameter	-	-	-	-	**3.7618**
	Dowel Hole	-	-	-	-	**0.3125**
Centering Ring	Outer Diameter	-	-	-	-	**3.8975**
	Inner Diameter	-	-	-	-	**2.2523**

N. Bill of Materials

Bill of Materials				
Item	**Cost**	**Quantity**	**Total**	**Function**
Jolly Logic Altimeter Three	$ 99.95	1	$ 99.95	Measure rocket altitude, velocity, acceleration, etc.
Aerotech J450-14A Metalstorm Dark Matter 54mm - DMS motors	$116.99	3	$ 350.97	Power the rocket
Fiberglass Cloth	Provided by Dr. McCreary		$ -	Wrap phenoilc tubing to create body tubes
Fiberglass Fins	Provided by Dr. McCreary	4	$ -	Provide aerodynamic stability
Tubing, Phenolic Airframe, 3.9	$ 41.98	2	$ 83.96	Frame for the body of the rocket
4" Nose Cone 16" long	$ 15.00	1	$ 15.00	
4" Heavy Duty Short Nose Cone 9.5" long	$ 19.95	1	$ 19.95	
54mm Motor Mount tube 24" long	$ 6.45	1	$ 6.45	
4.0 Phenolic Tube Coupler	$ 9.98	2	$ 19.96	
15 Min Mid-Cure Epoxy 9 oz	$ 19.50	1	$ 19.50	Bond fiberglass cloth together on the phenolic tubes
4" Heavy Duty Nose Cone 17" long	$ 21.95	1	$ 21.95	
NC-20 NOSE CONES	$ 4.60	1	$ 4.60	
Estes Nike Apache Model Rocket Kits	Provided by Dr. McCreary	3	$ -	Prototype Rockets
Carbon Fiber Sheet	Provided by Dr. Rogers	1	$ -	Used to create centering rings and bulkheads
BONDO/Hardener	Provided by Dr. McCreary	1	$ -	Smooth and strengthen body tubes
Moonpies (16.5 oz)	Provided by Kyle	1	$ -	Payload
Total			$ 642.29	