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Advanced Design and Manufacturing of Composite High-Powered Rockets

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Advanced Design and Manufacturing of Composite High-Powered Rockets

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Abstract

Matt Whitfield: Advanced Design and Manufacturing of Composite High-Powered Rockets
(Under the direction of Dr. Jack McClurg)

This thesis covers aspects related to the design and manufacturing of high-powered composite competition rockets. Research related to the project was performed over the course of three years of participation on the University of Mississippi Rocket Rebels competition team. Areas of the project covered include project definition, rocket design, and rocket manufacturing. Project definition covers how to build a team, select a competition, and establish communication, among others. The rocket design portion discusses the work that goes into meeting competition performance requirements, and includes simulations from the 2018-19 Rocket Rebels rocket. The rocket manufacturing portion includes a summary of manufacturing performed by the Rocket Rebels, as well as discussion of the methods used. Finally, a proposal to restructure the rocket is presented in chapter 5.

While there were many successful operations and achievements for the 2018-19 project, it ultimately did not lead to being able to compete in the selected competition. This is explained in the rocket proposal. Along with discussion of this throughout the thesis, successful test launches are also described, along with the various successes of the present year's team.

Preface

Why Rocketry?

The evolution of technology has brought about many challenges, as well as new and exciting possibilities. New technologies have served to improve the quality of human life by improving the areas of medicine, transportation, and communication, among others. However, few of these new technologies have led to such collaborative efforts and the advent of new ideas like the desire for the exploration of space and its wonders. The United States has a rich history of space exploration and rocketry. The space program's accomplishments have inspired countless young Americans to pursue a career in engineering. The future holds many exciting possibilities in the space industry, and it will certainly attract many new engineers. In sponsoring the Rocket Rebels, the University of Mississippi has provided students the opportunity to get hands on experience in the area of rocketry, using many advanced techniques that are common in industry. Experience is invaluable to the new engineer, so the ability to be a part of such a project at an undergraduate level is certainly a blessing.

Notice

Due to unforeseen difficulties in manufacturing, the construction of the rocket was not completed in due time for the selected competition. As this was a late development, much of the thesis was written as if the competition launch was still taking place. Chapter 5 has been written regarding a proposal to restructure the project, as well as the difficulties encountered and future work to be completed.

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List of Abbreviations

AI: Artificial Intelligence
CAD: Computer-Aided Design
CDR: Critical Design Review
CME: Center for Manufacturing Excellence
FDM: Fused Deposition Modeling
FRR: Flight Readiness Review
NAR: National Association of Rocketry
NASA: National Aeronautics and Space Administration
PDR: Preliminary Design Review
USLI: University Student Launch Initiative

Chapter 1: Project Introduction

The 2018-19 edition of the University of Mississippi Rocket Rebels is the third iteration of the university's rocket competition team. Each year, the Rocket Rebels are formed from a group of students that are engineers of various fields including mechanical, chemical, and electrical engineering; as well as other interested students. There are no technical qualifications to join the Rocket Rebels, but prospective members are required to fill out an application of interest. These applications are reviewed by team leadership and new members will be accepted upon review. The Center for Manufacturing Excellence (CME) at the University of Mississippi provides a space for the Rocket Rebels to work. The CME possesses a 12,000 sq. ft. factory floor that contains many pieces of machinery ranging from hand tools to heavy machinery. Additionally, the CME contains most of the equipment required to perform rocket construction using carbon fiber; including an automated cutting table to cut plies from stock material, a freezer to ensure the material stays in ready condition, and a vacuum system to debulk the layups. GE Aviation in nearby Batesville, Mississippi allows the Rocket Rebels to utilize their autoclave to cure the carbon fiber layups when completed. The CME also allows the Rocket Rebels to utilize advanced 3D printing machines for various rocket parts, such as nose cones. Factory floor technicians are also able to assist in the usage of various machines and in advisory roles when required. Funding for the project comes from a cost sharing grant between the CME and the National Aeronautics and Space Administration (NASA) Space Grant. The NASA Space Grant is a program that seeks to give opportunities to Americans to participate in NASA-related projects by supporting related educational opportunities. [1]

This thesis seeks to study the best methods for student design and manufacturing of composite high-powered rockets. This goal will be accomplished by studying the performance and methods of the current year's team, as well as recounting successes and failures of the past year's team. A little information about each of the three iterations of the Rocket Rebels follows in **Table 1**.

Table 1: Rocket Rebels Competition Overview

Year	Rocket Name	Rocket Design Characteristics	Competition	Status
2018-19		Carbon fiber body consisting of 4" body tube section over the whole length. 3D printed nosecone.	Argonia Cup	Competition not made
2017-18	Airshark	Carbon fiber body consisting of 4" diameter lower body section, and a 6" diameter payload bay. 3D printed nosecone and body tube connector.	Spaceport America Cup	Failed in Test
2016-17	Presidium	Carbon fiber body with 6" diameter body tube. 3D printed nosecone.	NASA USLI Competition	Failed in Test

As **Table 1** shows, each of the two previous rockets constructed by the Rocket Rebels have failed before reaching the competition. However, there have been successful test flights during those years. Airshark flew a test flight in the spring of 2018 that, while encountering errors, greatly helped the team to identify areas of high performance in manufacturing as well as areas for improvement. It was recovered in good condition and was able to be launched again later in the spring. Presidium underwent several test flights with successes. For example, in its first flight, Presidium flew to over 6000 ft before landing. Each successful flight has been a motivator and encourager as the team has continued.

Areas of discussion in this thesis include:

1. Project Definition and Organization
2. Rocket Design
3. Rocket Manufacturing

The final product of this thesis will be an exploration of methods used in the construction of the 2018-19 rocket, as well as a summary of lessons learned from previous years. The end product could also serve as a guide for future teams as they go to work on building rockets.

Before continuing to the discussion of each point, **Figure 1** is provided below for reference throughout the length of the thesis.

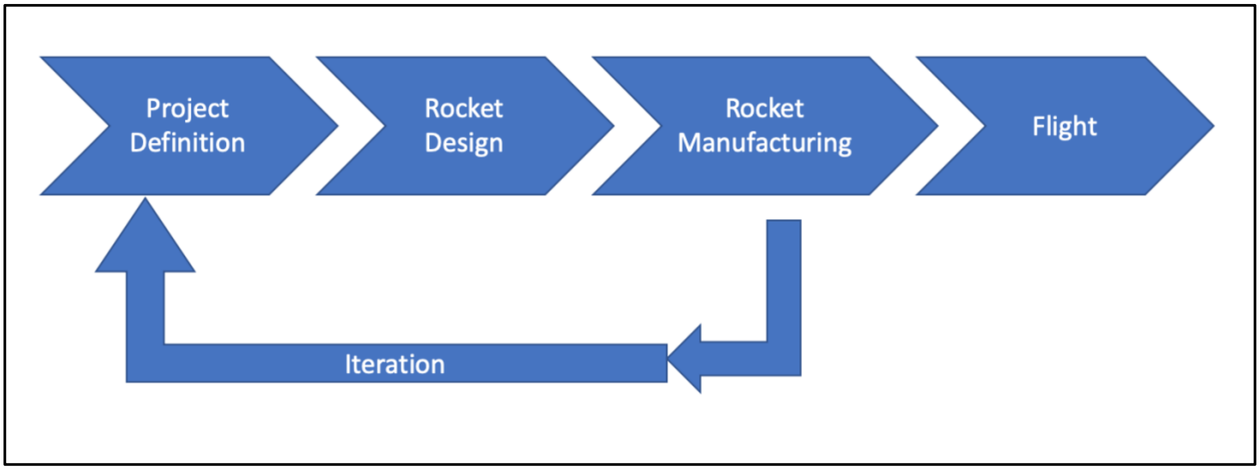

Figure 1: Project Flow

This figure shows the process by which the project flows. Before design or manufacturing can begin, the project and its variables must be defined. Then, a highly detailed design process will be undertaken to ensure that the rocket meets all performance and competition requirements. The rocket will then go into manufacturing. The manufacturing and design stages are both highly iterative in nature, and feed back into the project definition stage. In the context of the Rocket Rebels, each year has affected the next years design and helped to improve the process. It is important to stay in a mindset of continuous improvement as a team when building rockets.

Chapter 2: Project Definition and Organization

As with any project, before any real work can begin, the team will need to develop a detailed idea for the requirements of the project, as well as how the team will be assembled and organized. There are many steps to the process of defining the project and organizing the team, so each step will be discussed separately. Each step will consist of a section discussing methods for its completion, as well as the process followed by the Rocket Rebels during the present and past years. This will provide readers with theoretical and practical ideas about how best to organize their team.

Project Leadership

The first thing that needs to be determined is project leadership. The requirements for project leadership should include willingness to take responsibility for not just the team's successes, but also their failures; the ability to dedicate a significant amount of time to the project; the technical knowledge to lead the team well; great communication skills; and an honest enthusiasm about rocketry. The process of building a rocket is a long-term project and will often lead to unforeseen challenges that will need to be addressed. The leader must be able to meet these challenges and lead the team through them, utilizing both their own knowledge, as well as knowledge gained by communication with mentors. Ideally, the team will have a faculty mentor as well as a mentor working in industry. The mentors exist to provide guidance to the team in the realm of technical knowledge as well as project management. The faculty mentor will be able to communicate with administration to assist with project funding, and can function as an everyday advisor to the team when assistance is needed.

The Rocket Rebels were begun in 2016 by Dillon Hall. Hall was able to secure manufacturing professor Jack McClurg as a faculty advisor in the CME; as well as Cody Hardin, a manufacturing engineer at Orbital ATK in Iuka, MS, now Northrop Grumman. Hardin has since gone to work for Aurora Flight Sciences in Columbus, MS. Hardin had also been a major part of the rocket team at Mississippi State University during his time in college and was still certified to build high powered rockets. Additionally, due to his connections with Orbital ATK, Hardin was able to provide the Rocket Rebels with carbon fiber and other materials to be used in the construction of the rocket. The materials in question will be discussed much more in depth during the Rocket Manufacturing portion of the thesis.

Before becoming a professor, Dr. McClurg also worked at Orbital ATK, and was very familiar with the processes being used to construct composite rocket parts. This knowledge and experience, as well as his standing with the administration of the CME, was very useful in planning and securing funding for the project. Hall maintained leadership throughout the first and second years of the Rocket Rebels. During the second year, Garrett Reed functioned as a co-leader in order to gain experience for leading during the present year, and I am currently a co-leader under Reed.

Competition Selection

There are a great variety of competitions available to students to participate in. Competitions have varying requirements in the areas of size, engine power, payload capability, maximum altitude, flight speed, required writing, certification, etc. The leadership team and mentors must examine multiple different competitions to determine which is best for them. Some important factors to consider include location, time requirements, appropriateness of challenge to skill of team, payload requirements, and certification requirements. **Table 2** below shows the reasoning behind each of these criteria.

Table 1 shows the past competitions that the Rocket Rebels have been a part of, the University Student Launch Initiative (USLI) competition is a very thorough competition sponsored by NASA. The competition takes place in Huntsville, AL, and while the competition is just one day, there are events taking place for multiple days around the actual launch. NASA USLI requires multiple long reports throughout the year including a project proposal document, preliminary design review (PDR), critical design review (CDR), and flight readiness review (FRR). The first report, the proposal, was due September 8, and the launch date was April 8. USLI is a very long project that will require the team to get to work promptly at the beginning of the fall semester. Because the reports tend to be very long, it requires a significant time commitment from team members. NASA provides some measure of guidance for the project, but it is still a very challenging project, especially for a new team. NASA also requires a large community student engagement program run by the team to engage high school or middle school students. In addition, the team mentor has

Table 2: Competition Selection Criteria

Criterium	Reasoning
Location	Students will likely have to travel either on a weekend during school, or during the summer. The longer it takes to get to the competition the longer they will be away from other responsibilities and the more funding will be needed for lodging and travel. Additionally, travel to and from test ranges has to be considered.
Time Requirements	The following questions are useful for evaluating time requirements: Is there enough time to complete the build? When does the competition take place and will students be able to take time away to travel? Also, each student will have unique time needs due to their current class load, which gets heavier as students progress.
Appropriateness of Challenge	Building a rocket is a very challenging project. Can the team manage the challenge required by the competition? The Rocket Rebels, with plenty of qualified and experienced mentoring and help still have managed to fail both years the project has been attempted thus far.
Payload Requirements	What is the competition requiring the rocket to do in regards to payload? Some merely want participants to protect a fragile object, while others want to deploy and recover a payload. Some competitions also enforce an altitude goal as the requirement.
Certification	Competitions generally require either the National Association of Rocketry (NAR) or Tripoli certification for at least one member of the team. Is someone on the team certified or can they get certified in time?

to be certified through either NAR or Tripoli. The NAR and Tripoli are both nonprofit organizations seeking to support amateur rocketry. They each provide certifications that, while separate, are seen as equivalent in many competitions.

The Spaceport America Cup is a large competition taking place in Las Cruces, New Mexico, concluding in June. This competition does not require the same amount of time and work as the USLI competition does, as it lacks the need for many detailed reports. The Rocket Rebels were able to begin work in January 2018 and would have had the rocket ready with an abundance of time left before launch day had the rocket not failed. Travel would also have been a greater expense due to being farther away than USLI.

The Argonia Cup was chosen for the present year's competition because of its unique challenge; as well as its timeframe, which would allow more students to make the trip. The main objective is to fly a rocket to 8000 feet above ground level and return it safely, including its golf ball payload. No extensive reporting is required, however, a video documenting construction of the rocket as well as flight simulations was necessary. More detailed requirements of the Argonia Cup will be discussed in the Rocket Design portion of the thesis.

Team Formation

Depending on the university, the requirements for admitting students to the rocket team may vary. In some cases, with low interest from the student population, all interested students may be accepted in order to fill out the team. In other cases, with very high interest, an application system may be applied in order to ensure that the team is filled with those students who are most able to dedicate significant time to the project or have some experience with some aspect that will go into the project. Each system has merits and drawbacks. In a system where all interested students are accepted, it is more likely that the team will have attendance issues than if team members are more closely vetted. However, allowing any interested students to take part increases interest and visibility of the project as a whole, and prepares more people to work on the project in the future. For the past two years, the Rocket Rebels have used an application system. The application consisted of questions regarding why the applicant wants to be a part of the team, what their experience is, and their work availability. Team leaders review the applications, and select the candidates who are best suited to the goals of the project. Both systems have seen positives and negatives, and this will be practically expanded on in Chapter 5.

Team Organization

The construction of a composite high powered rocket is a complex project, thus it is crucial that the team be organized in the best way to take advantage of each members skills and interests. Over the course of the Rocket Rebels history, the team has used a sub-team system, as well as a lumped-team system. A sub-team system splits the team members up into sub-teams including Propulsion, Structures, Avionics, Recovery, and Payload. Team members can be divided into each sub-team based on interest and need. Team members in each sub-team will assist with any portion of the project, but are mainly responsible for their sub-team. A lumped-team system does not have individual sub-teams, but involves all team members working on all parts of the project. The sub-team system helps to focus each team member on their responsibilities, while the lumped-team system helps to educate each team member on all aspects of the project, and offers an advantage when work attendance is an issue. Both systems have advantages and disadvantages, so it must be decided by project leadership which is better for their team and project. Sub-teams encourage accountability and focused work, while limiting access to working on everything; conversely, in a lumped-team system, each member can experience each part of the project, but don’t focus in as much on any one thing.

Communication

Perhaps the most important administrative aspect of the project is setting up a regular and clear channel of communication. This includes regular meeting times as well as a digital means of quick communication. To determine meeting times, the team leaders should poll the individual schedules of each team member, and select a time slot that works for the most team members. With regards to a digital means of communication, there are many options available, but just two will be discussed here:

Slack™ is a great system that allows users to set up a workspace for their team, and then create subchannels within the workspace for more detailed discussions. For example: if the rocket team elected to form subsystem teams, each team could have a separate channel (i.e. structures, propulsion, avionics, etc). Slack™ also allows users to upload and send files to each other through the normal chat system, which is a more direct tool than email.

GroupMe™ is also a very good system that has some key differences from Slack™. GroupMe™ is not a focused teamwork application like Slack™, but it is widely used and every team member probably uses it already. It does not allow sub-chats like Slack™, but it is easy to create multiple chats for each sub-team if desired.

Each of these areas of project definition are very important in the initial stages of a rocket design project, and their importance carries throughout the entire project. Without a strong bedrock, no team can function at its maximum potential. Therefore, it should be a primary concern of project leadership to make sure each of the aforementioned sections, as well as others determined by the team, are secured.

Material Acquisition

The list of materials that each rocket team will need varies heavily on individual rocket design. Thus, this section will not discuss any specific materials that need to be acquired, nor suggest specific suppliers. However, selection of, and communication with, suppliers is very important. The 2018-19 Rocket Rebels started the year with an already established list of suppliers who had been able to meet the team's needs in the past. While many of these suppliers were able to again meet the needs of the team, some were not able to supply what was needed. For example, the supplier of blue tube (the rocket's interior structural frame) for the past years rockets was not able to supply their product in a reasonable amount of time, so new suppliers had to be sourced. Before purchasing any materials for the project, it is important to have a conversation with the supplier regarding the needs of the team in the areas of timeline, quantity, and quality. In some cases, the supplier may have the product in stock, but will be unable to ship it to the team in enough time for it to be integrated into the rocket. To avert situations like this, it is key to produce a materials requirement early on, so the team has sufficient time to contact suppliers and receive the materials. It is also best to have multiple allowable material options for each key need, just in case what is originally called for is not available.

Chapter 3: Rocket Design

The design of a high-powered rocket is an extremely complicated process that has many steps and many considerations. This chapter will discuss many of these steps, ranging from design conception through design simulation. This section will also include operations such as material selection and procurement. Rocket design is an activity that can be done in conjunction with the entire team, or can be a more focused responsibility of the team leadership.

The most important thing to consider when beginning rocket design is the competition's set of requirements. As previously discussed, all competitions have varying requirements, sometimes with regards to payload, and others to rocket capability. Some competitions may require the rocket to fly to a certain height, while others may just require it to safely return a payload. Before beginning any kind of design, it is best to collect all requirements for the rocket and have them on hand during design. This ensures that the design work will be focused from the start on fulfilling all requirements, and is better than having to modify the design later to better fit the requirements. The design requirements for the 2019 Argonia Cup are as follows:

- The maximum installed impulse for this competition will be one (1) commercially available 5,120 Newton-Second motor (L Motor). Motor clusters, air starts, and multi-stage motor configurations are prohibited. Spark emitting motors (Skidmark type motors) are prohibited.

- Any deployable payload should limit the descent velocity to less than 30 ft/s.
- Any propulsion/steering system designed to recover the payload cannot be used to boost the payload to the target apogee.
- A commercially available, altitude recording altimeter with onboard data storage shall be used for altitude determination and may be used for payload deployment and/or rocket recovery. If two or more altimeters are used, the averaged apogee height of each altimeter will be used for determination of rocket apogee.
- Launch vehicles shall be launched at an elevation angle between 83 and 85 degrees (5 to 7 degrees off vertical). All flights will be angled away from the flight line regardless of wind direction.
- All flights must have a minimum of a 5:1 thrust to weight ratio at liftoff.
- Launch configuration flight stability shall be achieved by maintaining a minimum center of pressure/center of gravity static margin of no less than 1 body caliber during flight.
- Apogee must occur at or above 8000’ above ground level (field elevation is approximately 1249’ mean sea level (MSL)). Any flight not reaching this altitude will be disqualified. Each team may make up to three flight attempts with the closest qualified landing score being their official flight.

- All launch vehicle components must be recovered in a “re-flyable condition” after flight. [2]

The last condition is perhaps the most challenging. Recovering a rocket in a condition that can be re-flown starts with the very beginning stages of rocket design. Each of the individual subsystems of the rocket have to work in conjunction with one another reliably in order for the rocket to return safely. While these rules are specific to the 2019 Rocket Rebels competition, they will be considered the governing rules as both the Rocket Rebels and general rocket design is discussed.

Design Overview

The design of the 2019 rocket is simple, and is familiar to the team members who were part of the 2018 Airshark team. The rocket consists of a uniformly 4” diameter body tube that makes up the entire body of the rocket, four fins on the base of the rocket, and a 3D-printed nose cone. A diagram of the rocket is shown below in **Figure 2.**

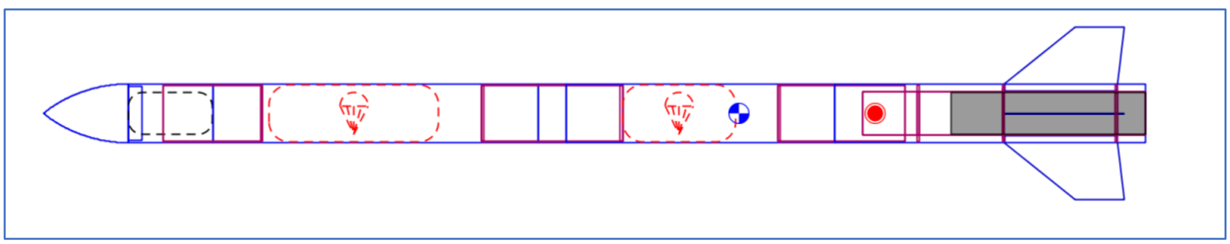

Figure 2: Basic Side Sketch of Rocket

Figure 2 was created using the OpenRocket software, which was the main design software chosen for this project. OpenRocket is a “free, fully featured model rocket simulator that allows you to design and simulate your rockets before you build and fly them." OpenRocket allows users to construct a rocket by selecting components and adding them to any existing components. A stage list is maintained on the left side of the screen to allow the user to easily ensure correct placement. **Figure 3** below will show the user interface of OpenRocket. The program can simulate over 50 variables that may affect the performance of the rocket in flight, and can perform in six degrees of freedom. OpenRocket also boasts features such as artificial intelligence (AI) help in design, easy exporting to computer aided design (CAD) files, and a motor database that helps the user choose the correct motor for their design. OpenRocket has been the design choice for the Rocket Rebels each year of performance. While many of the design features were chosen in conjunction, before discussing design simulations, each of the subsystems will be discussed in depth.

Additional OpenRocket simulations will be discussed later in the Rocket Design portion of this thesis.

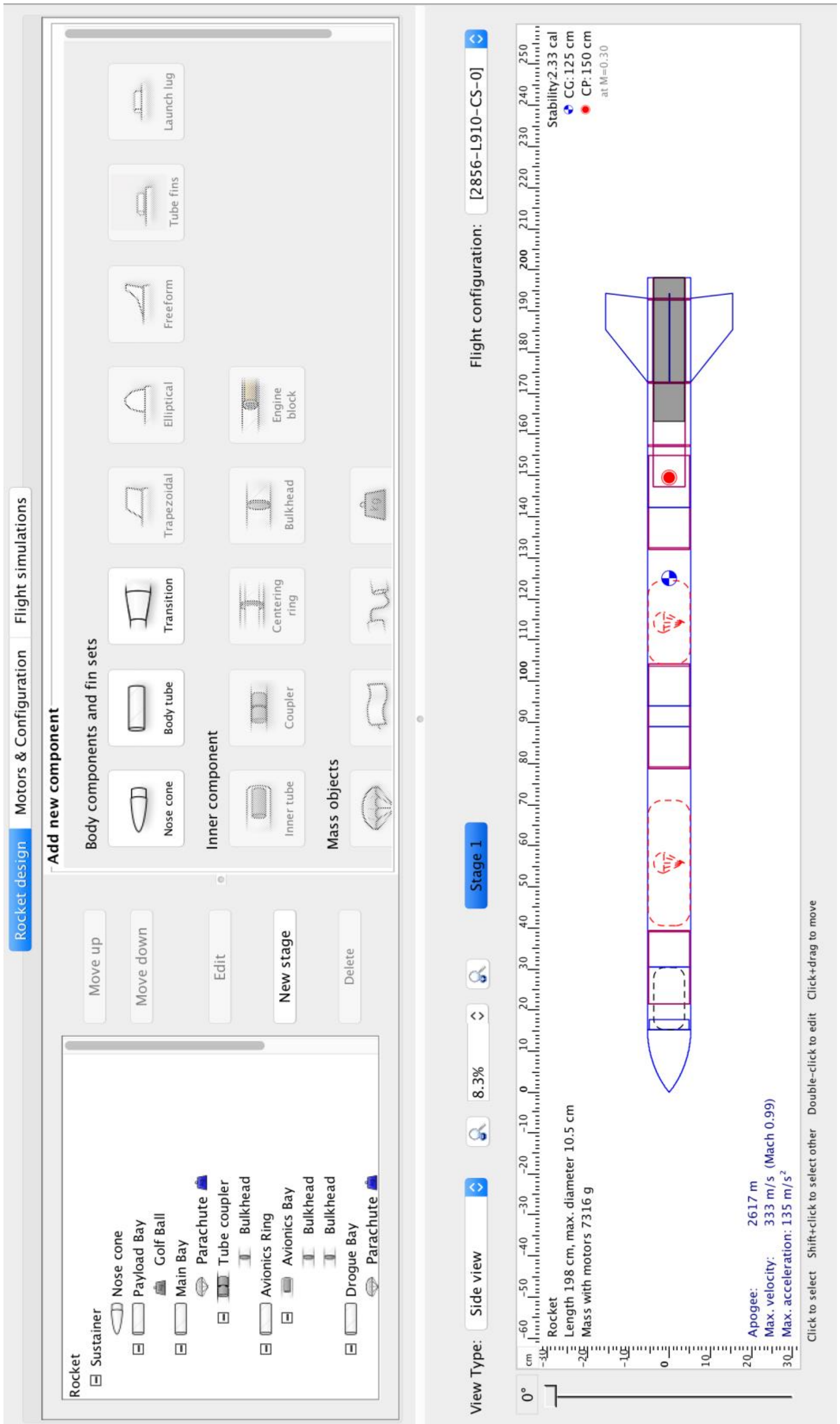

Figure 3: OpenRocket User Interface

Rocket Body

As previously mentioned the main body of the rocket consists of a 4” diameter tube topped by a nosecone, with four fins on the bottom. Inside, the body tube consists of a payload bay, the main parachute bay, the drogue parachute bay, the avionics bay and an engine bay (or fin can). The diameter of the rocket was chosen to be 4” out of convenience and proven capability. Additionally, because the diameter of the rocket is the same as the lower portion of Airshark, the motor mount tube may be re-used.

The body tube itself is comprised of layers of 14 mil (0.014”) carbon fiber. An advanced hand layup process was used to construct the body tube. Carbon fiber as a material is very lightweight and very strong, making it an ideal material for the rocket construction. Additionally, composite hand layup is an advanced industry-standard technique in which team members are gaining experience. The carbon fiber utilized for the construction of this rocket was provided by Orbital ATK (now Northrop Grumman) in Iuka, MS. The CME provides the team usage of its freezer to store the material so that it does not cure prematurely.

In order to ensure that the rocket body would have good strength in each force application direction, a layup process was created with five layers. With carbon fiber, the best way to ensure directionally uniform strength is to layer sheets in different directions. For this layup, the process is shown below in **Table 3.** The angles shown refer to the angle of the ribbon direction respective to the length of the mandrel tube the layup is occurring on.

Table 3: Ply Table

Ply	Direction
1	0°
2	45°
3	90°
4	45°
5	0°

The rocket body was designed to be split up into smaller segments, which will be discussed more in depth during the Rocket Manufacturing section of this thesis. Each of these smaller segments are designed to contain internal systems such as the parachutes and the payload bay.

Nose Cone

In the past year, the nose cone of the rocket was 3D printed from Ultem 1010 Resin. Ultem 1010 is a high performance thermoplastic with high strength, great thermal stability, and the ability to withstand steam autoclaving. The resin is available in multiple grades including general purpose and Certified Grade (CG) for special applications such as food and medical industries. Ultem 1010 is a fused deposition modeling (FDM) thermoplastic. It has the highest heat resistance, chemical resistance, and tensile strength of any FDM thermoplastic, and is primarily used in the aerospace and automotive industries. FDM is a process that builds strong, long lasting, and dimensionally stable parts with the greatest accuracy and repeatability of any 3D printing technology. However, Ultem is expensive, and the past years nosecone cost close to $1000, the initial plan for the current year’s rocket was to print a new Acrylonitrite Butadiene Styrene (ABS) nosecone in order to cut costs incurred using when Ultem. However, this eventually changed and will be discussed in the Rocket Manufacturing section. [3]

Fins & Internal Carbon Fiber Parts

Additionally, stock sheets of carbon fiber/epoxy were made using a hand layup process to be utilized in the cutting of fins, centering rings, and bulkheads. The sheets were designed to be laid up using a combination of 14 mil (0.014”) and 28 mil (0.028”) carbon fiber/epoxy prepeg in an alternating pattern. Prepreg material is carbon fiber material already impregnated with epoxy prior to usage. Epoxy holds together the carbon fibers in a matrix. Ribbon direction was alternated between 0 and 90 degrees due to a lack of material to make 45 degree sheets. Since the sheets were small, it was possible for the sheets to be cured by the CME’s oven rather than needing to be cured in a full-sized autoclave.

One reason that the Airshark failed in test was the misalignment of one of the fins. This misalignment caused the rocket to spin out of control, ultimately leading a dummy weight being used to simulate the payload to smash through the payload bay wall. To correct this issue, the 2018-19 Rocket Rebels used a 3D printing process to create a fin placement guide. The fin placement guide slid down onto the fin can, and was a good tool for ensuring that the fins were correctly aligned. The fin guide was designed to be printed from polylactide (PLA) material.

The fins and internal carbon fiber parts were designed using the Creo Parametric™ 3D modeling software. Creo Parametric™ allows the easy conversion of 3D models into 2D drawing files, which were used for these parts. The design decision was that the CME’s water jet cutter would be used in the removal of these parts from the carbon fiber stock sheet. A total of four fins, five bulkheads, and three motor mount centering rings were required for the manufacture of the rocket. Drawing files (.dwg) can be seen below for the fins, bulkheads and centering rings in **Figures 4, 5, and 6.**

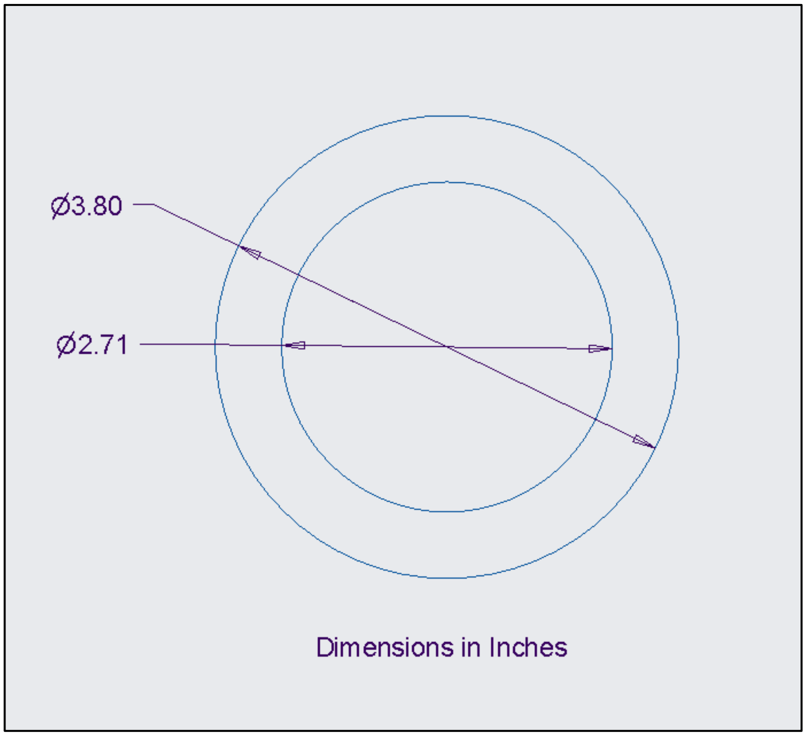

Figure 4: Centering Ring Dimensional Drawing

Figure 5: Bulkhead Dimensional Drawing

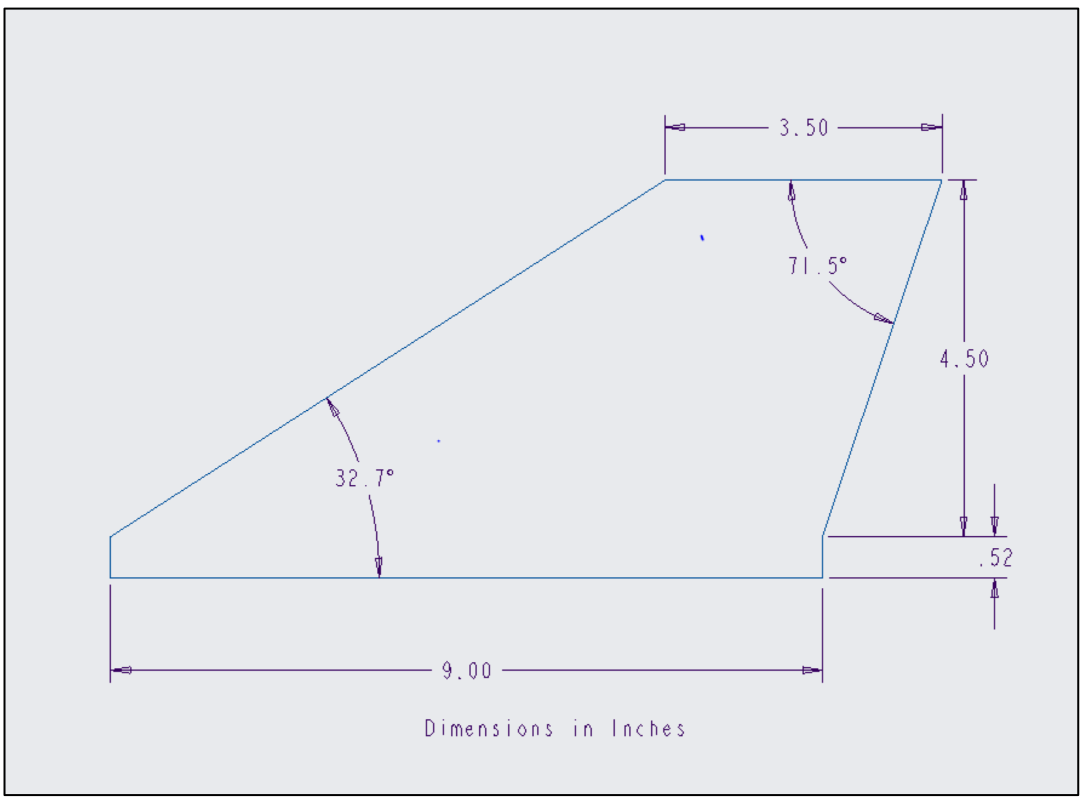

Figure 6: Fin Dimensional Drawing

Propulsion System

The propulsion system for the rocket consists of the engine, as well as its retaining assembly. The motor chosen for the rocket was the Cesaroni L910 C-Star Rocket Motor. Cesaroni Technology manufactures a variety of products including hobby rocket motors, commercial rocket motors, and ammunition. The L910 C-Star was chosen because it best fits the design requirements after iterative simulations. **Table 4** below shows the technical specifications for the L910 C-Star motor.

Table 4: Cesaroni L910 C-Star Technical Specifications

Brandname	Pro75 2856L910-P	**Manufacturer**	Cesaroni Technology
Man. Designation	2856L910-P	**CAR Designation**	CTI 2856-L910-CS-P
Test Date	4/13/2012		
Single-Use/Reload/Hybrid	Reloadable	**Motor Dimensions mm**	75.00 x 350.00 mm (2.95 x 13.78 in)
Loaded Weight	2615.8 g	**Total Impulse**	2856.1 N-s (642.1 lb.s)
Propellant Weight	1270.0 g	**Maximum Thrust**	1086.1 N (244.2 lb)
Burnout Weight	1251.5 g	**Avg Thrust**	907.1 N (203.9 lb)
Delays Tested	plugged	**ISP**	229.3 s
Samples per second	1000	**Burntime**	3.15 s
Notes	11.6% L		

The L910 C-Star is a solid propellant rocket motor. An engine using solid propellant is loaded with grains of propellant material, and is ignited by a spark near the nozzle of the motor. The spark ignites the fuel inside the bottom of the motor, and burns through the propellant until none remains inside the motor. The alternative to a solid propellant motor is a liquid propellant motor, however, for safety and complexity, that option was not pursued by the Rocket Rebels.

Along with the motor, the propulsion system also includes components such as the motor mount tube, motor retaining assembly, and centering rings. The motor mount tube houses the motor and is mounted inside the fin can of the rocket. In order to ensure that the motor mount tube is properly positioned, centering rings are placed around it. The centering rings are donut-shaped rings of carbon fiber that have an interior diameter equal to the outer diameter of the motor mount tube; and an outer diameter equal to the interior diameter of the fin can. The centering rings are attached with epoxy to the motor mount tube and the fin can for stability. Finally, at the base of the rocket, the motor retaining assembly is attached. This assembly allows the motor mount tube to be removed or restrained in the rocket. It features a threaded ring that sits inside the fin can, with screw-on cap that retains the motor mount tube when engaged, as seen in **Figure 7.**

Figure 7: Motor Retaining Assembly

Design Simulations

Before progressing from design to manufacturing, it is very important to run iterative design simulations to ensure that the rocket meets all criteria and will successfully accomplish its mission. Based on results of the simulations, each of the above design areas may need to be altered. The design simulations are performed inside the OpenRocket software, and are based on the following geographical data for Argonia, Kansas listed in **Table 5.**

Table 5: Geographical Criteria for Argonia, Kansas

Geographical Criteria	
Latitude	37.3 °N
Longitude	97.8 °E
Elevation	1249 ft

Competition requirements state that the launch angle of the rocket must be between five and seven degrees from vertical; for the simulations, six was used. All other settings in OpenRocket such as wind speed and wind direction were left at their default values. The various simulations done for the rocket are displayed and analyzed below.

Figure 8 shows the vertical motion of the rocket against time. The total flight time is estimated to last about 210 seconds, and the apogee of the rocket was reached in 21.02 seconds. Because the competition requirement states that apogee must be reached at least 8,000 feet above ground level, it is permissible for the simulation to start altitude at ground level rather than sea level. Tabulated data reveals that the apogee of the rocket occurs at 8565.3 feet above ground level. This is well above the required altitude, and is satisfactory for the performance of the rocket. Vertical velocity and acceleration are also plotted on this graph. The only competition enforced regulation dealing with either velocity or acceleration is that any ejected payload must descend at some velocity less than 30 ft/s. Since there is no ejected payload planned for the rocket, this requirement was disregarded.

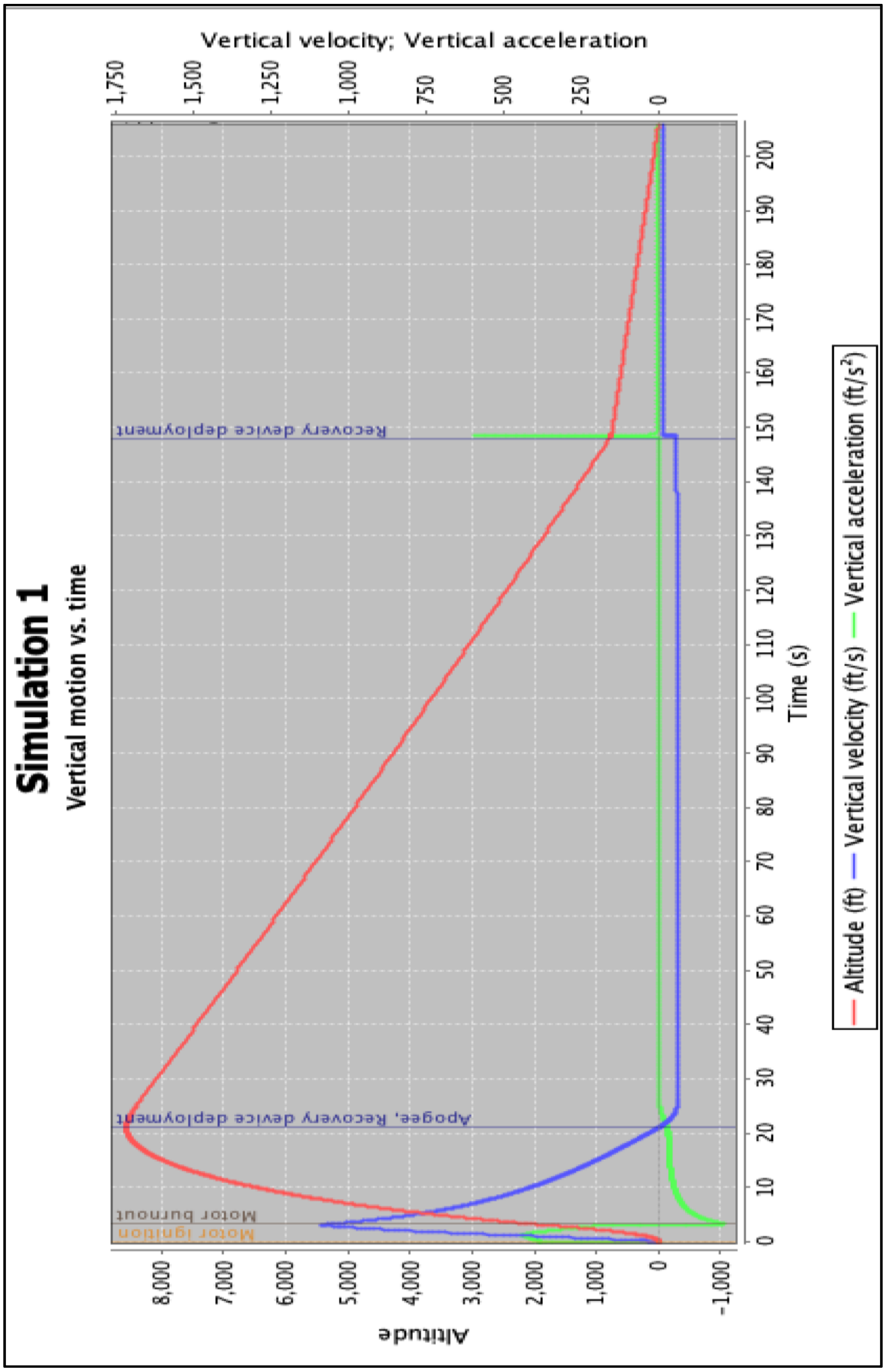

Figure 8: Vertical Motion vs Time Simulation

As expected, maximum velocity increased sharply until engine burnout, then decreased quickly before reaching apogee. At apogee, the drogue parachute is deployed, and velocity holds steady at approximately -19 ft/s until the main parachute deploys. At this stage, the velocity decreases to approximately -4 ft/s until it reaches ground level. Acceleration sharply increases before decreasing to reach maximum negative acceleration at engine burnout (approximately -64 ft/s^2). Acceleration slowly increases back to approximately zero, where it remains while the rocket falls at constant velocity back to ground. There is a jump as expected at the time where the main parachute deploys, but it quickly corrects back to zero when the new constant velocity is reached.

Figure 9 shows the flight side profile simulation of the rocket's flight. This means that if viewed from the side, the rocket would roughly follow the above trajectory. According to the simulation, the rocket should land 961 feet from the launch site. Ideally this would be closer to the actual launch site, however, without knowing the wind speed or humidity on the day of launch, it is not possible to predict perfectly. Because the rocket will be launched into the wind, upon parachute deployment, the wind pushes it back towards the launch site, which can be seen in the figure. In the flight side profile simulation plot, the milestones can be identified as motor burnout, then drogue parachute deployment, and finally main parachute deployment before touchdown. OpenRocket would not label **Figure 9's** milestones like those on **Figure 8.**

While other simulations are available with other variables such as tracking the angle of attack, drag coefficient, and the location of the center of gravity; the above simulations are the only ones that are directly important to the design and manufacturing of this rocket.

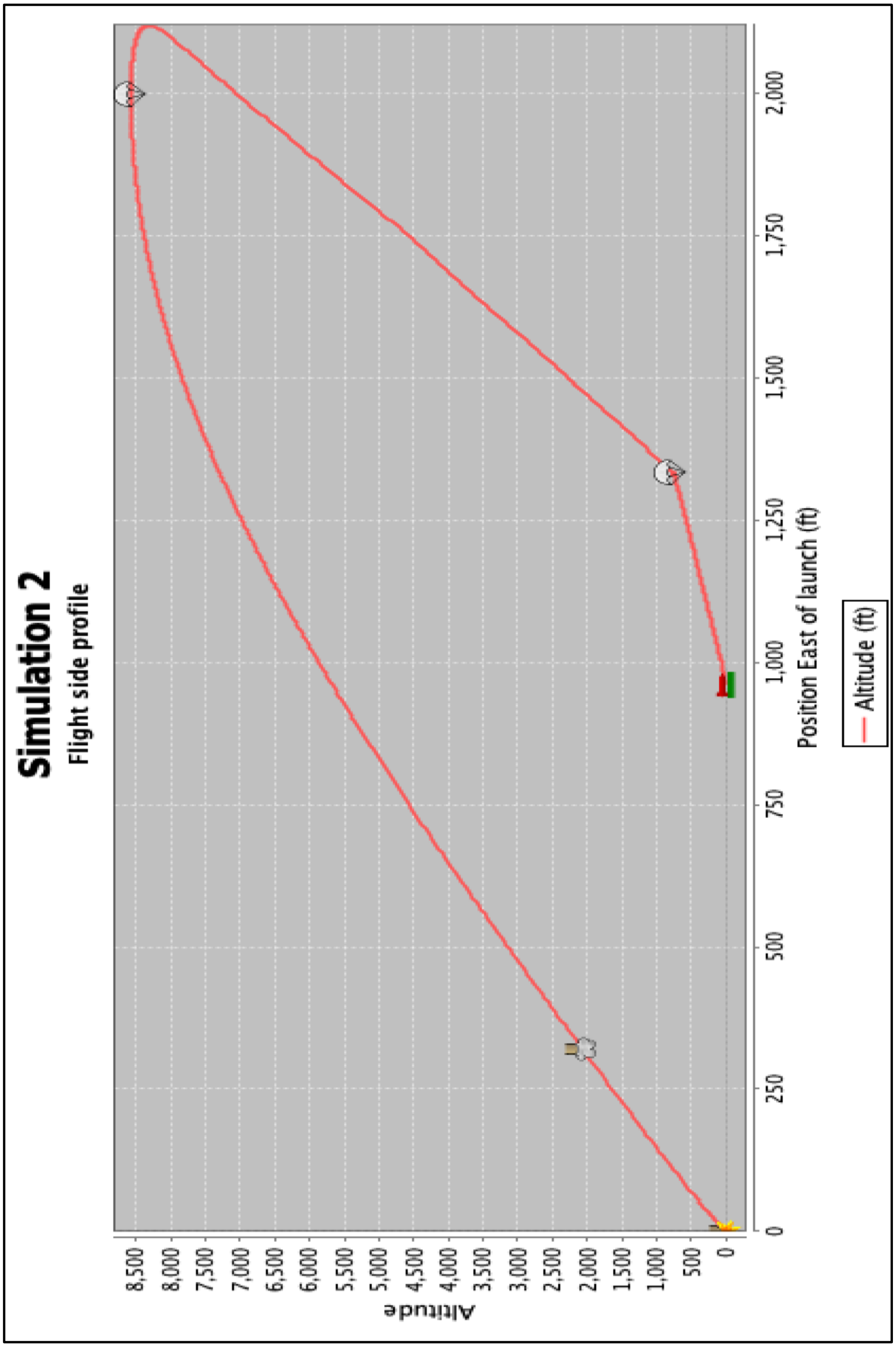

Figure 9: Flight Side Profile Simulation

Design Summary

To summarize the design phase of the process, it can easily be seen how much goes into the design of a rocket. The rockets built by the Rocket Rebels are fairly simple and do not have to deal with many important factors that real rocket do. Thus, the design thought and planning for the rocket was less strenuous than for a full sized rocket. Nonetheless, it can be seen from the above discussion the amount of work that goes into material selection, process planning, and simulation. Without proper material selection, even the best design can easily fail, and without an efficient planning process, streamlined manufacturing is impossible. Design is also a continually iterative process. While the simulations shown in this thesis just reflect the final design choice, it should be noted that in a design process, many different options must be considered and tested to determine which is best.

Before the team even begins to prepare for manufacturing, the design process must be discussed and considered for a significant amount of time. In many cases, issues in manufacturing can be traced back to design, so it is important to fully consider all potential problems, as well as how best to handle these if they occur. Design records should be accessible for reference in the event that they are needed to correct some manufacturing error.

With discussion of the design process completed, it is time to move onto the discussion of rocket manufacturing.

Chapter 4: Rocket Manufacturing

The process of rocket manufacturing is the most time consuming part of the project as a whole, and time must be efficiently budgeted as such. The Rocket Rebels' access to the CME has been a huge benefit to the manufacturing efforts, as well as easily accessible knowledge and assistance. The main manufacturing methods utilized in rocket production by the Rocket Rebels will be discussed below, including decision making and lessons learned.

Manufacturing as a production phase is heavily dependent on the design phase. Without a workable and detailed design, the rocket cannot be successfully built to meet capability requirements. It should be ensured during the project planning phase that adequate time for manufacturing is allotted before the competition. This allotted time needs to include time to fix manufacturing defects and account for delays in manufacturing. Often, especially in the case of the Rocket Rebels, a new team, unforeseen obstacles occur during manufacturing that slow down the process.

Rocket manufacturing occurs in a number of stages, starting relatively linearly, and then allowing more of a spread out approach. Discussion of rocket manufacturing will largely be based on experience gained by working on the Rocket Rebels' rockets.

Body Tube

The body tube of the rocket forms the main structure of the rocket itself, and contains within itself many of the main components. As previously mentioned, the body tube is made of 14 mil carbon fiber/epoxy prepreg with a hand layup process. The hand layup process is an industry standard process used by many aerospace manufacturers. Theoretically, the hand layup process is relatively simple, but can be more difficult in practical use. Due to the simple cylindrical geometry of the body tube, the process is not overly difficult.

To begin, a tool must be obtained that allows the team to shape the carbon fiber into the shape required. A tool in this sense is simply a mold that the carbon fiber will be laid upon. The tool used for body tube construction is a male configuration tool, meaning that the carbon goes on the outside; a female tool consists of a cavity that the carbon fiber is laid up inside. The cylindrical tool being used for the production of the body tube is referred to as a mandrel tube. The outer diameter of the mandrel tube should be equal to the designed inner diameter of the body tube. The mandrel tube can be seen in **Figure 10.**

Before hand layup can begin, the mandrel tube must undergo a preparatory process. If the tube has been used before, it should be sanded to ensure that no resin or foreign objects exist on the tube. If left un-sanded, any resin bumps or foreign objects may cause defects in the carbon fiber later in the production. It should be noted that because mandrels are often made of metal, sanding will produce metal dust that should not be inhaled. When the surface of the mandrel is satisfactorily smooth, it must be cleaned and sealed before carbon fiber can be applied. Post sanding preparation of the mandrel tube is a three step process, including the application of acetone, mold sealant and release agent.

Figure 10: Mandrel Tube

Acetone is a chemical agent that is used for general cleaning purposes on the mandrel tube. Application of acetone serves to remove any residual dust from the surface of the mandrel, as well as any oils that may have been transmitted to the mandrel during handling. Acetone should be applied to paper towels, and wiped down the surface of the mandrel until no dust shows on a towel after wiping. As a safety precaution, gloves and a respirator should always be worn during the handling of acetone. This may take many iterations, but it is important to ensure the mandrel is clean so that no dust or foreign objects get into the carbon fiber layup.

Mold sealant is applied to the mandrel tube in order to seal any cavities or cracks in the mandrel tube that may cause manufacturing defects in the carbon fiber. The Rocket Rebels have had success using Zyvax SealProof Water-Based Mold Sealer manufactured by Chem-Trend. Zyvax SealProof is an easy applicable mold sealer that is able to effectively overcome porosity in material such as metal, wood, and composites. It is not recommended for parts with a high gloss finish, but is highly satisfactory for its usage. A full description of the application can be found in the referenced work instructions, but a brief description follows. To apply the mold sealant, apply directly or indirectly to the mandrel, and using a paper towel to wipe the liquid into the tube. Ensure that the sealant is always wiped in the same direction, and that no residual liquid can be seen on the mandrel after completion. Allow an hour between each coat for drying, and apply between 4 and 8 coats. Four coats should be sufficient for most applications, and was enough for the Rocket Rebels. [4]

After completion of mold sealant application, the next step is the application of release agent. Release agent is used to ensure that the cured carbon fiber will not stick to the mandrel tube, but will be more easily removable. It is absolutely crucial to ensure that release agent is properly applied to the mandrel tube, as a stuck body tube could be damaged in the efforts to remove it from the mandrel. The Rocket Rebels have used Zyvax 1034W Water Based Release Agent for this purpose. Zyvax 1034W has been specifically created for use in the advanced composited industry, and thus is ideal for usage in this project. Specifically, thermosets, thermoplastics, and pre-preg materials work very well with Zyvax 1034W. As with the above mold sealant, detailed application instructions can be found in the referenced material data sheet. The application process is the same as used for mold sealant, however, it only requires 2-4 coats.

The final preparatory stage of the body tube is the cutting of layup plies. The requirements for each ply were referenced above in the Rocket Design portion of the thesis (including **Table 3**). The Rocket Rebels have used an Eastman cutting table for cutting processes over each of the past three years. Eastman cutting tables are industry standard equipment that provide automatic dimensioned cutting from a provided cutting model. When dimensioning the layup plies, the expanding circumference of the layup surface must be considered. For the first ply, the width of the ply can be roughly equal to the circumference of the mandrel tube, but for each additional ply, the additional diameter that each ply adds to the mandrel needs to be added to the next ply's width. When laid upon the mandrel, it is best to ensure that the length of the mandrel is greater than the required length. It is always better to remove extra material than to need more material. Normally during composite layup processes, a cure cycle would have to be created specifically for the part being cured. While this would normally be the responsibility of the design and manufacturing team, for the Rocket Rebels it has been handled by GE Aviation.

Below is an image of the body tube in its post cure configuration. **Figure 11** shows the main body tube in the center of the image, as well as the carbon fiber plates used for fin/internal part cutouts on the left.

Figure 11: Post-Cured Body Tube and Stock Plates

The body tube as shown is approximately 2 m long. The total required length for the rocket is 1.83 m. The excess material served as insurance against any mistakes in cutting.

Upon completion, the body tube was cut into five sections as follows:

1. Main Parachute Bay
2. Drogue Parachute Bay
3. Fin Can
4. Payload Bay
5. Avionics Bay

Each section is of various length, and the dimensions for each portion can be seen below in **Table 6.**

Table 6: Body Tube Section Length

Component	Length (cm)
Main Parachute Bay	58.4
Drogue Parachute Bay	48.3
Fin Can	55.9
Payload Bay	15.2
Avionics Bay	5.08

Blue tube is a strong cardboard like material that forms the basis of the internal airframe of the rocket. It is a strengthening frame inside the carbon fiber that improves the impact resistance of the rocket body as a whole. According to the 2018-19 Rocket Rebels' blue tube supplier, Always Ready Rocketry, blue tube provides high abrasion resistance, zero cracking, and zero brittleness as an airframe [5]. In addition to providing stability as an airframe, blue tube also functions as a coupling device for the multiple body section parts. Different lengths of blue tube can be found in the different sections based on size and functional requirements. For example, the fin can has blue tube reinforcement from the bottom through the top. Extending out of the fin can, the blue tube also functions as a connection to the drogue parachute bay, which can slide onto the fin can blue tube. The avionics bay features blue tube extending from both sides in order to easily attach to both the drogue parachute bay as well as the main parachute bay.

Considering the design lengths of the body tube sections, it is worth noting that with blue tube extending from each side, the avionics bay can be a minimal size but still hold the entire bay. This is made possible by having the blue tube coupler create a much larger payload bay than can be seen on the exterior of the rocket. Before beginning discussion on the final body tube preparation processes and assembly, some of the other necessary components such as the nose cone and internal components will be discussed below.

Nose Cone

As stated in the Rocket Design portion, the nosecone was designed to be 3D printed with ABS material. The nosecone was 3D printed and upon inspection, it was determined that the printing operation was not satisfactory for the needs of the project. Rather than having a sleek curved surface, it was printed with faceted surfaces. Additionally, the nose cone was too short and not as aerodynamic as hoped. This was a design issue that led to two possible options. First, the design could be corrected. This was a simple option that would not have caused any significant delay, but just the time to reprint. However, this was not pursued because a second option occurred. The second option was to reuse an Ultem nosecone that was used in 2016-17 on a 4” diameter subscale rocket. The used nosecone was removed from the old subscale rocket and reused for the current year’s rocket.

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Figure 12: ABS and Ultem nosecones

Figure 12 shows the new ABS nosecone on the left that was not used, and the older subscale Ultem nosecone that was used in the rocket on the right. It was decided that the nosecone would be spray painted black to match the color of the rest of the rocket.

Interior Components

The sheets of cured carbon fiber/epoxy previously mentioned as being used for the creation of bulkheads, fins, and centering rings were cut using the CME's water jet cutter. To begin the cutting process, drawing files had to be created for each part that could be uploaded into the water jet cutter for use. All performance of the water jet cutter was done with the assistance of the CME technicians. Upon cutting of the stock sheet, it was found that during the cure, an error occurred with pressurization of the plies. The resulting layup cross-section was highly porous and had poor resin consolidation. Cavities were easily seen in between the layers of prepreg. Though some centering rings had been installed, it was determined that a new layup be made for the cutting of fins and bulkheads. Though not exposed to forces from the rapidly moving air, an additional centering ring will be installed for further internal security.

Below are images of the internal components including the centering ring and the fins. **Figures 13, 14, and 15** show the centering ring, fin, and bulkheads. The precision of the cuts and lack of variation in the curve shows the quality of the water jet cutter.

Figure 13: Centering Ring

Figure 14: Fin

Figure 15: Bulkhead

Parachute Repair

Upon the beginning of work on the 2018-19 rocket, it was quickly noticed that either parachute repairs would be required, or new parachutes would need to be purchased. Both the existing main and drogue parachutes had sustained damage during the last year's launch and could not be reused in their current state. The team explored both options before coming to a decision. The parachute supplier claimed that it was possible to repair them, and also offered to make new parachutes. However, while discussing specifications, the supplier quit communicating, and this option was ruled out. Simultaneously, the option of out-sourcing the repair to a local repair shop was pursued. One repair shop was interested in the project and offered that they may be able to perform the repair, but another solution became apparent before this was finalized. Hardin, the team mentor, offered a contact who repaired his parachutes in the past, and was local. While no cost was incurred, the Rocket Rebels did offer to pay for the repair. This option was deemed better because the contact had previous experience repairing parachutes, and was a local, reliable contact. The Rocket Rebels supplied ripstop nylon material to be used in the repair. Images of the parachutes can be seen below in **Figures 16 and 17.** It is unclear whether the damage was a result of a tear or burn. The holes do not exhibit any sort of edge as would be expected with a tear, but does not show any burn signs.

Figure 16: Damaged Main Parachute

Figure 17: Damaged Drogue Parachute

Post-Cure Body Tube Preparation

Returning now to the body tube of the rocket, there was still work to be done regarding the preparation of the body tube. After being cut into subsections, each body tube piece underwent a sanding process. The sanding process was performed using a die grinder, and performed on the surface of the CME's water jet cutter. This is because carbon fiber dust is highly dangerous to breathe, and water could be sprayed on the tubes to help collect the dust. Additionally, as a safety feature, operators of the sanding process wore breathing masks to protect themselves from the harmful dust. The purpose of the sanding was to remove any ridges or bumps that may have appeared during the curing process of the carbon fiber. Additionally, the ends of the body tubes were sanded to be level, so that when connected, the tubes would fit together seamlessly. A die grinder is essentially a small circular sander powered by compressed air rather than electricity; this made it an ideal tool to use near water because there was no electric accident potential.

After the sanding process was completed for each body tube section, they were coated in a clear epoxy resin for a smoother outer surface, as well as better aesthetics. The epoxy resin was a two part mixture consisting West System 105 Epoxy Resin and 206 Hardener. Upon mixing, the material had a pot life of approximately 25 minutes The mixed resin was applied to the rocket body using wooden craft sticks, and applied in a smooth coat. The coating was allowed to harden overnight, and any bumps or runs were sanded off. The resulting coat added a sleek and shiny exterior to the carbon fiber body. [6]

Another sanding operation was performed on the blue tube prior to installation in order to help it fit snugly inside the body tube sections. After sanding, Loctite EA 9394

Aero Epoxy was used to secure the blue tube inside the body tube. 9394 Epoxy is a very high strength aerospace-grade binding material obtained by the Rocket Rebels from Orbital ATK. 9394 epoxy is a two part mixture that cures at room temperature. According to its data sheet, shear strength at ambient temperature reaches approximately 4000 psi, and tensile strength is around 6,675 psi. The referenced material document provides more specifics on mixing instructions, as well as other strength data. [7]

Fin Can and Motor Mount Assembly

The fin can of the rocket is the bottom segment where the fins are attached and the motor is mounted. As previously mentioned, the fin can has blue tube reinforcement extending from the bottom to just outside of the top. The first step in the assembly of the motor mount segment was to install a smaller 3" blue tube inside the main 4" structural blue tube. The small tube exists to form a sheath for the main motor tube to reside in. In order to ensure the smaller tube is perfectly centered in the fin can, the centering rings previously manufactured were attached by the application of 9394 Epoxy. The fin can may be seen below in **Figure 18.**

Centering rings were attached at the base and midpoint of the tube. After these rings were secured to the smaller blue tube, more epoxy was applied to the outside of the centering rings and they were inserted into the fin can and allowed to harden. The result was a smaller tube inside the fin can that would later hold the engine.

The next step was to install a motor retaining assembly onto the base of the fin can. The motor retaining assembly is a two part assembly consisting of a base with external threads, as well a ring-shaped cylindrical internally threaded cap. The cap allows the motor tube to be installed or removed at any time. The base was attached to the bottom of the fin can also using 9394 Epoxy. After the retainer assembly was installed, the motor mount tube was inserted. With the installation of the motor, the rocket propulsion assembly will be complete.

The final step for the preparation of this segment of the rocket was the installation of the fins. As was previously mentioned, a 3D printed fin placement guide was used in this application. The process of obtaining the guide was not as smooth as desired, requiring multiple attempts to get a correctly fitting guide. This issue is discussed more in detail in Chapter 5.

At the time of this writing, this is the current state of the rocket. Future work required for final completion can be seen below in Chapter 5, which discusses each of the remaining items that need to be completed in order to launch the rocket.

Figure 18: Fin Can

Chapter 5: Project Restructure

Early in March 2019, the Rocket Rebels proposed a restructured plan for the 2019 rocket project. The deadline for the Argonia Cup had come, and the rocket was not done, and still needed a significant amount of work. As such, team leadership met together and devised a proposal to take to the team mentors regarding what should be done regarding the future of the rocket project. This chapter will discuss issues that the team encountered during the process, as well as work that still needs to be accomplished (with a brief discussion of methodology), as well as the proposal for what shall be done with the rocket.

Proposal

The Rocket Rebels will continue constructing the rocket and complete it by the end of the spring 2019 semester. At this time, a test launch will be performed to assess the state of the rocket. The rocket will then be passed along to the next year's team to conduct maintenance and improvement techniques. This will be beneficial for Reed, who will be returning as the project leader without a majority of the team, who will be graduating and no longer a part of the team. New members will have to be educated and instructed in many areas regarding rocket building and having a pre-built rocket will be highly beneficial for their use. This will also decrease the required budget for the next year's team. The proposal was accepted by team mentors McClurg and Hardin.

Issues Encountered

Over the course of the project, mainly in the spring, there were many difficulties that the team encountered that drastically slowed down the progress of the project as a whole. These range from process and material issues to workforce issues. The following as some of the issues faced, as well as some background into those.

1. During the process of printing the fin placement guide, the 3D printing process led to three incorrect or incomplete parts. The first iteration of the placement guide had an interior diameter that was not big enough to correctly fit on the rocket, and thus was not able to be moved into position for cutting the fin slots. This was an easily avoidable human measurement error, and should never have happened. The second iteration corrected this problem, however, during the printing process, the filament being used to print the part broke. This caused the 3D printer to stop making the part, and instead complete its programming without any material. The third iteration encountered a similar problem, starting to print the part, but only finishing about one third of the design. It was determined in the interest of time that because it technically located the fin slots, it was workable. This will be revisited with the new restructuring plan.
2. As previously mentioned in Chapter 3, sheets of carbon fiber/epoxy were made to serve as material for fins, centering rings, and bulkheads. The centering rings and

bulkheads were cut with no problems, and the material was satisfactory. However, when the fins were cut, it was discovered that the majority of the material experienced a pressure issue during its cure, which resulted in a highly porous layup with partial delamination. As a result, new sheets of carbon fiber/epoxy had to be constructed. Because the new material available at this time was exclusively 14 mil, the team decided to use seven sheets instead of five. The result was a very well compacted sheet that had a good surface, however it was not thick enough. Another sheet then had to be made, using 15 sheets. This final process produced a sheet with enough satisfactory material for the cutting of the fins. To account for possible defects in the already installed centering rings, an additional centering ring cut from this new material will be installed for additional support.

3. It was mentioned in Chapter 2 that during the 2017-18 project, the team experienced a great deal of success using a more selective application system to fill out the team. Most of the team from the 2017-18 project were once again part of the 2018-19 project, but a much different result was seen. During the first two weeks of the project, team members seemed to be engaged in the project and willing to meet the needs of the team in regards to participation. In part, this was due to work being scheduled when the most people were free, as determined by a poll sent to the group. Unfortunately, after the first few weeks, team participation dropped heavily, and the workforce was very low, which significantly slowed the progress of the build. Some major contributing factors include a high volume of required projects, and a team with many seniors nearing graduation. This method of team selection will certainly be addressed for upcoming years of the project.

Future Work

The rocket restructuring plan aims to ensure that a rocket is constructed by the completion of spring 2019, and to accomplish this, the following work still needs to be completed by the team.

1. Fins installation (In progress)
2. Parachute repair (In progress)
3. Bulkhead Installation (Waiting on previous steps)
4. Avionics Bay Installation
5. Parachute Installation (Waiting on Step 2)
6. Installation of rail buttons

While it is disappointing that the rocket was not completed in time for competition, a positive is that more time will be allowed for completion of the final steps of the project. A key factor in this year's build was focusing on quality and ensuring that the rocket would be able to successfully complete a flight. With such an increase in timeline, it is certain that a higher quality build will be able to be achieved.

Chapter 6: Project Summary

Although the 2018-19 Rocket Rebels team were not able to successfully complete a rocket in time for competition, there were many positive results that came out of the experience. While at the time of writing, the construction is not absolutely complete, the objectives of this thesis have been accomplished. I set out to discuss the procedures for assembling a rocket team, designing a rocket, and manufacturing it, and this has been accomplished.

First, the project was introduced and given basic project parameters, including discussion of past years projects. It was hoped that the 2018-19 Rocket Rebels would be able to overcome many of the difficulties seen by previous teams, and while in many ways this was accomplished, it ultimately didn't lead to a successful competition launch.

The project organization portion focused on various methods to build and organize a project team. This ranged from competition selection to team organization. It should be noted that a conclusion is that the discussed method of selective team organization was not successful during the 2018-19 project as was seen before. This will have to be re-evaluated in future years both to correct a low workforce participation issue, as well as to replace many graduating team members.

Discussion of rocket design followed, ranging from material selection to design simulation. This ranged from the process for carbon fiber hand layup to the materials and processes designed for use in 3D printing the rocket's nosecone. Design simulations were included for the selected engine in order to discuss some important launch characteristics, as well as to show how the competition requirements were met. Simulation is very important to rocket design and was stressed as such.

Discussion then turned to how the Rocket Rebels went about manufacturing the 2018-19 rocket up until the writing of this thesis. This includes the process of laying up the material, the creation of the rocket subsection, and the creation of internal components. There are many lessons to be learned here about how to better streamline the manufacturing process. Much of the work done by the Rocket Rebels during the 2018-19 project season was linear and as needed, but for efficiency this could, and should have been diversified to spread out the work more.

Finally, the team leadership's proposal to restructure the project into a two-year project was presented. Various issues that caused manufacturing delays are discussed in this portion, which highlight the difficulty in completing a project such as this.

The goal stated for this thesis was to examine the best processes used for students to manufacture a high-powered composite competition rocket. This was accomplished by compiling a detailed walkthrough of each step in the design and manufacturing process. An additional goal was to provide a guideline that future teams could reference, which I believe was also accomplished. While there was definitely room for improvement in the performance of the project, and it wasn't entirely finished at the time of writing, I believe that the goals of the thesis were accomplished satisfactorily.

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