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Structural Design and Fabrication of a Rocket

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Structural Design and Fabrication of a Rocket
March 24, 2016

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Executive Summary:
As members of The University of Akron's rocket design team our group designed and fabricated the structure of a single stage rocket. We define the structure of the rocket to be the body tube, motor mounts, as well as, mounting of any other components inside the rocket.

Our team began by setting goals, as well as, selecting constraints for our design. Our primary goals were to reduce weight, improve accessibility to the rockets internals and improve the overall craftsmanship of the completed rocket. Some constraints that defined our design were time, budget, and manufacturing capabilities of the team members.

Once our goals were set and our constraints defined, our team began an iterative brainstorming process. During this process our design constantly changed as our team came across new problems and difficulties.

The aerodynamic and inertial forces acting on the rocket body were also calculated. These forces were then used to predict the stresses acting on the rocket during its flight. These calculations helped our team choose a material for the rocket body.

Our final design consisted of a fiberglass tube, which could be purchased commercially. Four aluminum bulkheads mounted our motor, as well as supported our recovery system. A fiberglass coupler allowed the rocket to be separated on the ground for maintenance. Finally polycarbonate bulkheads supported the electronics bay and attached the coupler.

With a design in place our team purchased the necessary materials and began to fabricate the structure. First, team members learned how to operate a lathe. The lathe was used to face, turn and bore our aluminum and polycarbonate bulkheads. Next, the fiberglass tube was cut, and the bulkheads mounted in the tube. Finally, the coupler was installed and the recovery and electronics systems attached to there respective bulkheads.

![Figure 1: Final Overall Rocket Design](image)
Introduction:

The Akronauts
The University of Akron Rocket Design Team (Akronauts) is closing in on completing its second year as a student design team at The University of Akron. Last year a group of around 55 students, from many different disciplines, were able to fabricate a two-stage rocket to compete in the Intercollegiate Rocket Engineering Competition or IREC. This competition is made possible by the Experimental Sounding Rocket Association or ESRA. ESRA has been an organization for 13 years and started hosting the IREC competition for the past 12 in Green River, Utah. The competition has two categories, advanced and basic. Each category must make a ten pound payload experiment and launch it to a predetermined height depending on the rocket category, 10,000 feet for basic and 25,000 feet for advanced. The rockets that are used in these competitions can be propelled in one of three different methods, solid, liquid, or hybrid fuel. The design teams are judged in a number of categories including, novelty of payload, accuracy of apogee and craftsmanship.

Figure 2: Last Years Team at the Competition in Utah

Our Senior Design
A rocket is a complex vehicle consisting of many different subsystems including, propulsion, payload and recovery to name a few. Our senior project will focus specifically on the structure of the rocket. This includes the rocket body, and securing any subsystems. The motor, electronics bay, and recovery system are example of components which will need to be mounted. The project consists of two parts.
First, we will examine the design process used to arrive at a functioning rocket structure. This includes setting design constraints, and goals, as well as, demonstrating the iterative design process and performing calculations to verify crucial components. Secondly, our report will detail how our team members fabricated the rocket structure. This very important to the Akronauts team because the competition places an emphasis on the rocket being student designed and built.

![Last Year's Rocket Descending After Launch](image)

**Figure 3:** Last Year's Rocket Descending After Launch
**Design Parameters and Goals:**
The Akronauts competitive design team consists of seven separate teams: Structure, Guidance, Propulsion, Recovery, Payload, Electronics, and Research and Design. Each team must operate cooperatively amongst the groups in order to achieve a successful design. The purpose of the structure team is to design an effective system to in-capture the internals during flight. The structure must secure these parts while at the same time allowing these components to operate as intended. Each group puts out specific restrictions, which must be taken into consideration.

**Structure**

The structure team has set certain goals of its own for this year’s competition.

Each team is allocated a specific amount of money to build their components for the rocket. The structure team was allocated approximately 1500 dollars.

Some parts used must be purchased commercially due to the complexity of them, however others must be manufactured in house by the structure team. While in the design phase, this must be taken into account.

The next design parameter that has to consider is the weight of the rocket. This applies to both the total weight of the rocket as well as the distribution of weight. This is done to maximize the performance of the rocket during lift-off and flight. According to calculations performed by the propulsion team, the total weight of the rocket should be less than 100 lbs. to reach our goal altitude of 10,000ft.

**Guidance**

The guidance team is responsible for the design of the nosecone and fins. The rocket’s structure system must incorporate these components inside its design. The guidance team determined that the fins will be supported by a “fin can” around the motor. The structure must allow slots in the body tube for the mounting of the fins.

**Propulsion**

The motor to be used is the Pro 98 rocket motor, which is the same as the previous year’s rocket. The rocket’s structure must be designed to secure this motor within the body. Challenges include the necessity for some type of bulkhead to withstand the thrust forces created. Since the Pro 98 rocket motor has an outer diameter of 3.880”, the structure’s skin must be larger than this size in order to fit the motor.

**Payload**
According to the Intercollegiate Rocket Engineering Competition a payload of no less than 10 pounds must be carried during the rocket’s flight, and released at apogee. The structure of the rocket must be designed to allow for the release of the payload. Furthermore, since this payload must complete some task, the structure must protect the payload from any unnecessary forces, which may be created during flight.

**Recovery**

Similar to the payload, the recovery systems on the rocket must be deployed at apogee. To do this the structure again must allow for this release of any parachutes used.

**Electronics**

The electronics system requires the ability for wiring throughout the rocket. Also, the electronics bay should be accessible externally. The structure of the rocket should be designed to allow for both of these.
Design:
Any design that is produced on the shop floor or drawn in modeling software is the result of an iterative design process. This means that based on defined constraints, such as cost, time, and performance, designers come up with many ways to satisfy a particular constraint. The final design is a combination of all the best solutions. The following paragraphs show how our team developed specific crucial areas of the rocket's structure.

External Structure
The external structure of a rocket is crucial to the rocket's overall weight, strength, and stiffness. Our team’s goal was to maximize strength and stiffness while minimizing weight and cost.

First, the team had to examine how the external structure would be loaded. The free body diagram, shown below, clearly illustrates that the rocket body will be subjected to an axial force as well as a bending moment. The axial force is generated by thrust from the motor, the weight of the rocket and drag. The rocket moving through the air with an angle of attack α, creates the bending moment.

![Free Body Diagram](image)

Next a cross sectional geometry was picked. Our team selected a circular cross section. This was done because tubes are easily purchased with various wall thickness and lengths. Also, a circular cross-section offers good stiffness in bending.

Finally a material had to be selected that was lightweight, strong and stiff in bending. These constraints narrowed our choices to carbon fiber reinforce polymer (CFRP), Aluminum and fiberglass. When only performance is examined CFRP is the best option. It offers a superior E/ρ and stiffness in bending. However, CFRP is very
expensive and it would be impractical given our team’s budget. Aluminum is within our team’s budget but would be harder to work with given our team’s limited machining experience. This left fiberglass as the material of choice for our external structure. Fiberglass has a good $E/\rho$ and stiffness. In addition it is the cheapest of the three options and the most forgiving to work with. In other words a mistake would be less costly than with CFRP for example.

**Internal Structure:**
The internal structure of the rocket has to secure the various systems to the external structure. These systems included the motor, the electronics bay, the recovery system and the payload. Our initial ideas could be organized into two categories, an internal skeleton design and a component design.

**Skeleton Design**
The skeleton design consisted of bulkheads that are connected to another mechanically. In this design the connected bulkheads are the structural base of the rocket. In other words, the rocket derives its strengths and rigidity from the internal skeleton. The external skin is not considered structural. It is merely an aerodynamic covering. This would allow for a very lightweight skin to be used. A sketch of the skeleton design is shown in Figure 5. (Large figures of all our sketches can be found in the appendix.)

![Figure 5: Internal Skeleton Concept](image)
Skin-Based Design
The skin-based design is a structure with the strength and stiffness derived from the skin of the rocket. This means that an internal skeleton connecting the rocket’s various subsystems would not be needed. Because the different components were not mechanically connected, this design permitted the subsystems to be modular. This means that one individual component could be removed and worked on at a time.

Figure 6: Skin-Based Design

Internal Structure Decision
Ultimately, the skin-based design was chosen over the internal skeleton design. There were several reasons why our team came to this decision. First, the skin-based design offered superior properties in bending due to its large cross section. Secondly, the skin-based design permitted the rockets subsystems to be removed modularly. This satisfied one of our main design goals, which was easy access to the internals of the rocket. Finally, the internal skeleton was more complex. Our design team has learned from past experience that an intricate design can be very difficult to actually fabricate.

Payload Deployment:
The principle goal of a rocket is to successfully carry a payload to a specified altitude and return it to Earth. This means the design of the rocket’s structure is closely tied with the payload. Our rocket’s payload had to be deployed at apogee and would then descend separately from the rocket. This means that the payload and the rocket’s main parachute would be deploying at the same time. We came up with three designs to achieve a smooth deployment of the payload.
**Top Deployment**
This way to deploy the payload is to simply eject it through the top of the rocket via the nosecone. This design is attractive because the body tube and internal rocket structure does not need to be modified in anyway. However, in this configuration the ejection system must push out the nosecone and the 10lb payload. This may be at the upper limit of the planned ejection system.

**Side Deployment**
In this deployment scheme the payload is ejected out of the side of the rocket. This means that the payload could be ejected without interfering with the deployment of the rockets main parachute out of the nosecone. However, in this design a large section of the rockets body tube must be cut. This would significantly weakens the body tubes strength in bending. Further, the ejection would put a side force on the rocket which could cause instability.

**Coupler Deployment**
The rocket would separate in the center at apogee and eject the payload from the center of the rocket. This means the parachute could be deployed from the top of the body tube with ease. The main issue with this design is that the separation of the rocket adds a layer of complexity to the flight. Also the strength of the body tube could be compromised by the addition of a coupler.

![Figure 7: Top Deployment Concept](image1)
![Figure 8: Coupler Deployment Concept](image2)
Payload Deployment Decision
Our team decided to implement a top deployment method. The main driving force of this decision was simplicity. Both the coupler and side deployment methods added a layer of complexity with benefits that did not justify the risk.

Motor Mount:
In order to secure the motor in place during flight a motor mount is required. The motor mount must be designed to locate the motor within the skin tube, as well handle the thrust force caused from the motor. Since the rocket mount is located between the skin and the rocket, both the inner and outer diameters are restricted and must be considered during the design phase. It was decided that the motor mount should constrained at both the top and the bottom

The first part of the motor mount should be a thrust plate of some sort. This bulkhead should be capable of taking most of the thrust force during flight. It was determined that the thrust plate should be located at the end of the motor since there is a large bearing surface on the motor casing. Ultimately, the design was a bulkhead that could be tapped and secured to the skin via hardware. There was discussion of using an epoxy to secure it, however it was decided that aluminum to fiberglass epoxy would be difficult because of the dissimilar materials. Also the bulkhead would be loaded in shear, the weakest loading scenario for epoxy. An early design of the thrust bulkhead may be seen below in Figure 9.

![Figure 9: Early Version of Thrust Plate](image)

The second part of the motor mount, called the retaining bulkhead, should be used to both secure and locate the motor. This bulkhead must allow for the removal of the motor as well. The retaining bulkhead will use a step on the motor near the bottom as seen in Figure 10.
Initially a ring style bulkhead was designed. The bulkhead had an L-shaped cross section and would be attached to the skin wall by hardware. In will clamp onto the step with the assistance of a plate between the step and L-shaped bulkhead. Since the fins required a slots for mounting, the bulkhead had to be cut into 3 separate sections. Figure 11 shows this design in an isometric view.

It soon became apparent that the L-cross sectioned part would both take a long time to manufacture and generate a tremendous amount of wasted material. Because of these problems the team began brainstorming alternative ideas. It was decided that two simple ring bulkheads could be used. The upper retaining mount would be tapped and attached to the skin via hardware. The lower mount will then screw into the upper mount making a clamping force on the shoulder. To remove the motor, all that must be done is remove the lower retaining mount. This allows the motor to simply slide out. Figure 12 shows a sectional view of this final design.
**Coupler:**
Although our team had decided not to use a coupler to deploy the payload it still could be beneficial to have a coupler. If the rocket had a coupler, the body tube could be separated into two sections on the ground. This means it would be easy to access the systems, which were located in the middle of the rocket. There where several iterations of the design. The first was two internal aluminum cylinders, which were secured to the wall by hardware. This idea was scraped because it would be costly and inefficient to machine an aluminum tube to the proper dimensions. The second design was comprised of a commercially available coupling tube. This tube is made of woven fiberglass. Our team decided to use this design because the length of the coupling tube meant the joint would be very stiff in bending. Also, because both the coupler and the rocket body were fiberglass the two parts could be epoxide together. This would eliminate the use of some hardware, slightly reducing the aerodynamic drag.
**Electronics Bay Access:**
Safety is always the most important consideration taken into account when designing. In order to make our rocket safe to transport to the competition, the electronics, which controlled the firing of the main engine as well as the recovery system, have to be disconnected from any voltage source prior to launch. This means that once the rocket is erected on the launch tower the electronics must then be connected to the appropriate voltage source. The electronics team requested we design a doorway, through which the arming mechanism could be reached.

The first iteration of the electronics bay door consisted of a simple square hole, cut into the rocket's fiberglass skin. Then a cylinder would be inserted inside the rocket. This cylinder had a hole in it, which would be aligned with the hole in the rocket skin. Then a metal door would cover the outer hole. The door was secured by magnets, which were epoxied into the inner cylinder.
Figure 14: Early Electronics Door Concept Help on with Magnets

Figure 15: Drawing of Electronics Bay Concept

This design was ultimately not used because the pressure change generated inside the rocket body by traveling to 10,000ft was much stronger than the magnetic force holding the door shut. (Please see calculations section for the details of this) Instead it was decided to use rivet nuts. These rivet nuts could be crimped into the skin of the rocket and then a door held on by hardware threaded into the rivet nuts.
Polycarbonate Bulkhead:

Since many of the bulkheads in the structure are not subjected to high loads, there was a freedom in material selection. Ultimately, Polycarbonate was the material of choice. It was decided that the lightweight properties of polycarbonate would allow more freedom in the design of the rocket. It is also a material, which may be purchased at a low price per volume. One focus while designing the bulkheads was to keep the parts simple.

If a part begins to get overly complicated, the potential problems increase. Further, the fabrication of the part must be kept in mind. The design chosen consisted of a ring which could be fixed to the skin via hardware. Although using epoxy could be possible, the freedom of hardware helps achieve the goal of a modular design. One of the features in the hardware design includes brass threaded insert components. Threaded inserts are specifically made to work in a plastic part. To install them, the bulkhead must holes, which the inserts get pressed into. As a screw turns into the insert, the insert expands pressing into the polycarbonate. The knurl features on the insert catch into the plastic to resist pulling out. Below in Figure 16 and 17, the brass insert and polycarbonate bulkhead design may be seen.

![Figure 16: Threaded Brass Insert](image-url)

Figure 16: Threaded Brass Insert
Evolution of Full Rocket Assembly

The following models were made in Open Rocket software (Open Rocket Software is a flight modeling software that will be introduced in the calculations section). The progression of our model serves as a good summary of the overall progression of the design. Several major changes can be seen to the overall structure of the rocket, and the distribution of weight.

Figure 18 was made at an early date and acted as a kick-off model. The nosecone and fins were designed as a placeholder. This is reflected by the center of pressure being so close to the bottom of the rocket. Note that the overall length is also nearly 20 inches shorter than the other designs.

Figure 19, 20 and 21 all show an updated fin and nosecone design, which more closely resembles the final design. Other notable changes are the location of the interior bulkheads. As sizes of internal systems change, the bulkheads must also be altered so they configure to the new geometry.

At one point, seen in Figure 20, a guide tube was designed to sit just below the nose cone. The payload team requested this guide tube. The guide tubes purpose was to secure the payload during flight, as well as help it eject smoothly at apogee. The final design, however, does not include the guide tube. It was determined that the skin of the rocket could act as a natural guide tube, and that the nosecone could have a feature built into it where it would restrict the payload from rotating during flight.

One of the main changes internally is the change in how the rocket separates during flight. The original idea was that the rocket would separate at the nosecone at apogee for the payload to eject. Shortly after, the rocket would separate at the coupler to deploy the drogue and main chute. This is reflected from Figure 18 to 21.
This design however was changed after a design team meeting. Instead, it was decided that the rocket would only separate at the nosecone during flight. The coupler was kept however for ease of access. The open rocket model in Figure 21 represents this.

**Figure 18**: Open Rocket Model Date: August 2015

**Figure 19**: Open Rocket Model Date: October 2015
Calculations:

Introduction
Our rocket will encounter three predominate forces throughout its flight: gravity, thrust, and aerodynamic forces. Gravity’s effect on the rocket can be found by locating its center of gravity or CG. The CG of an object is when all the forces and moments generated by gravity are resolved into a single force acting on a single point (Open Rocket Tech Doc). This means to calculate gravity’s effect on our rocket we simply need to find its mass and apply the force at the CG. The motor will generate the thrust force acting on our rocket. Our team is using a commercially available motor (See Appendix). This means that thrust data from a static test will be available for our team to use. This thrust value can then be treated as a simple axial force. Finally, our rocket will encounter a number of aerodynamic forces. These aerodynamic forces will change with the rocket’s speed, shape, and angle of attack. The following section will explain how the aerodynamic forces and moments were calculated with the aid of a rocket modeling software, Open Rocket.

Aerodynamic Forces on Rocket
Figure 20 shows the loading scenario of our rocket. In addition to thrust and gravity there are two aerodynamic forces, normal force and drag. The normal force is the force that generates a correcting moment around the CG. This corrective moment keeps the rocket flying straight with no angle of attack. The normal force acts at the rocket’s center of pressure or CP. Similar to the center of gravity, the CP is the single point at which a single resultant normal force acts. Drag forces are resistive forces acting in the opposite direction of thrust. For our analysis drag forces were assumed to be perfectly axial. Finally, Figure 20 shows that a rocket can pitch, yaw and roll in flight. During our analysis it was assumed the rocket would not roll. This was done because the forces generated from rolling are negligible when compared to those generated by pitching or yawing. In our calculations an angle of attack of 2 degrees was used.

**Drag**

In our analysis, two types of drag forces were considered, the pressure drag and skin friction. The pressure drag is caused by protrusions from the rocket body, such as mounting hardware and fins, as well as vortices at the base. Drag due to shock waves was ignored because our flight will be below Mach one and fin-tip vortices drag was also disregarded because of its small magnitude. Figure 23 shows the various types of drag and where they act on a rocket.
The drag force was calculated using Equation 1. In this equation $A_{ref}$ is a reference area, which was taken to be the area of the base of the nose cone. The velocity $v$ was taken to be the maximum velocity projected by our Open Rocket model. Density is the density of air.

$$C_d = \frac{D}{\frac{1}{2} \rho v^2 A_{ref}} \quad \text{Equation 1}$$

$$C_{d\alpha} = \frac{C_d}{\alpha} \quad \text{Equation 2}$$

*Equation 2* is derived from the Barrowman’s method and is only valid given the following assumptions (Open Rocket Tech Doc):

- The angle of attack is very close to zero
- The flow around the body is steady and non-rotational
- The rocket is a rigid body.
- The nose tip is a point
- The fins are flat plates
- The rocket is axially symmetric.

In this manner, the drag force was found at several crucial points of the rocket.

<table>
<thead>
<tr>
<th>Element</th>
<th>Drag Coefficient</th>
<th>Drag Force (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Cone Drag Coef.</td>
<td>0.03</td>
<td>6.38</td>
</tr>
<tr>
<td>Fin Drag Coef.</td>
<td>0.07</td>
<td>1.24</td>
</tr>
<tr>
<td>Upper Stage Drag Coef.</td>
<td>0.13</td>
<td>27.64</td>
</tr>
<tr>
<td>Lower Stage Drag Coef.</td>
<td>0.1</td>
<td>21.26</td>
</tr>
<tr>
<td>Base Drag Coef.</td>
<td>0.21</td>
<td>44.65</td>
</tr>
<tr>
<td>Total Drag</td>
<td></td>
<td>101.17</td>
</tr>
</tbody>
</table>
Notice that the base of the rocket generates the largest drag force, followed by the skin friction on the upper stage. This came as a surprise to our team. We expected the largest drag force to be generated by the nose cone because of its large cross sectional area. However because we are using a commercially available nosecone, which is optimized for our rockets speed, pressure drag from the nose in very low.

**Normal Force**

The normal force acting on the rocket was found using Equation 3 shown below. In this equation $d$ is a reference length, which we took to be the outer diameter of the body tube.

$$C_N = \frac{N}{\frac{1}{2} \rho v^2_A r_{ref} d} \quad \text{Equation 3}$$

We utilized Open Rocket to calculate the normal force coefficient derivative, $C_{N\alpha}$, at various locations along the rocket. Next Equation 4 was employed to convert the normal force coefficient derivative to total normal force coefficient.

$$C_{N\alpha} = \frac{C_N}{\alpha} \quad \text{Equation 4}$$

*Equation 4* is derived from the Barrowman’s method and is only valid given the following assumptions (Open Rocket Tech Doc):

The results of our normal force calculations can be seen in Table 2 shown below.

**Table 2:** Normal Force Coefficients Given a 2-Degree Angle of Attack

<table>
<thead>
<tr>
<th>Element</th>
<th>$C_{n \alpha}$</th>
<th>Normal Force Coef.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Cone</td>
<td>2.15</td>
<td>0.08</td>
</tr>
<tr>
<td>Body Tube Upper</td>
<td>0.48</td>
<td>0.02</td>
</tr>
<tr>
<td>Body Tube Lower</td>
<td>0.38</td>
<td>0.01</td>
</tr>
<tr>
<td>Fins</td>
<td>9.00</td>
<td>0.31</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.42</td>
</tr>
</tbody>
</table>

**Table 3:** Normal Forces Along Rocket

<table>
<thead>
<tr>
<th>Element</th>
<th>Lift Force (lbs Force)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
One can clearly see that the fins generate the largest normal force on the rocket by a large margin. This is because the fins function is to keep the rocket flying with no angle of attack. The large normal force, created by the fins, imposes a corrective moment on the rocket, forcing it back to an angle of attack of zero.

Axial Forces Analysis
The rocket has three forces acting upon it axially during flight. These forces are drag, thrust and inertial forces. The previous section shows how the drag force was calculated for each component of the rocket. Our rocket thrust force is known because it is a commercially available motor. According to a data sheet from Cessaroni Technology Inc. our motor produced a maximum of 577lbs thrust. Finally, the rocket’s structure will experience an inertial load from the acceleration during lift off. According to the model of our rocket, constructed in the Open Rocket software, there will be a maximum acceleration of 5.2G.

Our team decided to examine how these three forces interact with one another. 

Equation 5, below, describes how axial force can be calculated at an arbitrary point or “station” along the length of the rocket. Notice that the thrust force is taken to be negative, while the drag and inertial forces are taken to be positive.

\[
F_{axial} = -F_{Thrust} + D_{Nose\ cone} + D_{Fuselage} + D_{Fin} + a_{axial} \sum_{base}^{x} m
\]

Equation 5

Using Equation 5 the resultant axial force was calculated at several key locations along the rocket. These stations and the resulting axial force can be seen in Table 4.

<table>
<thead>
<tr>
<th>Station</th>
<th>Axial Force (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of Upper Stage</td>
<td>30.35</td>
</tr>
<tr>
<td>Middle of Upper Stage</td>
<td>115.64</td>
</tr>
<tr>
<td>Recovery Bulkhead</td>
<td>161.31</td>
</tr>
<tr>
<td>Electronic Bulkhead</td>
<td>204.08</td>
</tr>
<tr>
<td>Coupler</td>
<td>224.77</td>
</tr>
<tr>
<td>Thrust Bulkhead</td>
<td>-318.38</td>
</tr>
</tbody>
</table>
To better illustrate how the axial load changes with position along the rocket the result from Table 4 were plotted against position in Figure 24.

The above plot shows that the axial force starts and ends at zero. The axial force rose linearly from the nose cone to the thrust bulkhead. At the thrust bulkhead the thrust force from the rocket motor is introduce, acting in the opposite direction. This creates a large jump in the graph. The large drag forces created by the fins and the base of the rocket then bring the axial force back to zero. The graph reveals that the max axial force occurs at the location the motor mounts to the body tube. The possibility of the body tube bulking was also considered because of the presence of a compressive load. However, the flexural modulus of the tube and the moment of inertial of the cross section are very large. This, combined with the fact that the length is relatively short, means the critical bulking load is approximately 40,000lbs. Obviously this load will not be seen during flight.

**Normal Force Analysis**

The previous section showed how the normal forces, generated by certain components of the rocket, were calculated with the aid of Open Rocket software. Our analysis of the normal force assumes that the rocket is a beam in equilibrium. This assumption allows the normal forces to be treated as an applied load on a simply supported beam.
Next, *Equation 6*, seen below, was used to sum the normal forces acting at crucial stations along the rocket. Notice that the normal forces generated by the nose cone and fins are taken to be a lift force $L$. Also, the equation takes into account inertial forces generated by a lateral acceleration. Lateral acceleration is simply an acceleration perpendicular to the rocket body. A crosswind most commonly causes this acceleration. Finally the last term in the equation takes into account roll characteristics of the rocket. As previously stated our team disregarded this term due to its relatively small magnitude.

\[
F_{Normal} = L_{Nose} + L_{Fin} - a_{Lateral} \sum_{base}^{x} m - R \sum_{base}^{x} m(x_{CG} - x_m)
\]

*Equation 6*

The results at the various stations may be seen in *Table 5*.

<table>
<thead>
<tr>
<th>Station</th>
<th>Normal Force (Lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of Nose Cone</td>
<td>12.26</td>
</tr>
<tr>
<td>Base of Nose Cone</td>
<td>-10.64</td>
</tr>
<tr>
<td>Payload Location</td>
<td>-10.62</td>
</tr>
<tr>
<td>Recovery Bulkhead</td>
<td>-5.52</td>
</tr>
<tr>
<td>Electronics Bulkhead</td>
<td>-6.41</td>
</tr>
<tr>
<td>Coupler</td>
<td>-3.25</td>
</tr>
<tr>
<td>Thrust Bulkhead</td>
<td>-12.92</td>
</tr>
<tr>
<td>Middle of Fins</td>
<td>45.40</td>
</tr>
<tr>
<td>Base of Rocket</td>
<td>-17.54</td>
</tr>
</tbody>
</table>

The results seen in the above table can then be plotted against there position in the rocket. As you can see, the graph of these points produces several interesting facts. First, and most importantly, the normal force acting on the rocket starts at approximately zero and ends at zero. This is crucial because our previous assumption that the rocket is a beam in equilibrium holds true.
It is important to note that the normal force does not change in the step fashion depicted in the graph. This was done only to help ease the generation of the bending moment graph.

The bending moment graph was found by taking the integral of the normal force line. The resulting moment graph can be seen above. The graph starts and ends at
approximately zero, reinforcing the assumption that the rocket acts as a simply supported beam in equilibrium. The fins create the initial negative moment value and the geometry of the fins can be altered to shift the moment graph up or down to insure stability. The maximum moment of 68 ft-lbs occurs at the coupler tube. This means that the largest moment location coincides with the weakest point of the structure in bending.

**Stress Analysis**

Now that the force and moment distribution along the rocket is known, a stress analysis can be performed at the same locations along the rocket.

**Total Axial Stress**

The total axial stress is a combination of the flexural stress and axial stress. Axial stress can be defined as the force over the cross sectional area of the rocket body tube. The loading is both compressive and tensile depending upon the stations location in the rocket.

\[
\sigma_{\text{axial}} = \frac{F_{\text{axial}}}{A_{\text{cross section}}}
\]

<table>
<thead>
<tr>
<th>Station</th>
<th>Stations (inches from nose cone)</th>
<th>Axial Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of Nose Cone</td>
<td>15</td>
<td>N/A</td>
</tr>
<tr>
<td>Base of Nose Cone</td>
<td>30</td>
<td>11.79</td>
</tr>
<tr>
<td>Payload Location</td>
<td>55</td>
<td>48.10</td>
</tr>
<tr>
<td>Recovery Bulkhead</td>
<td>70.75</td>
<td>67.10</td>
</tr>
<tr>
<td>Electronics Bulkhead</td>
<td>89.25</td>
<td>84.89</td>
</tr>
<tr>
<td>Coupler</td>
<td>97.5</td>
<td>93.50</td>
</tr>
<tr>
<td>Thrust Bulkhead</td>
<td>106.25</td>
<td>-132.44</td>
</tr>
<tr>
<td>Middle of Fins</td>
<td>130.5</td>
<td>-84.00</td>
</tr>
<tr>
<td>Base of Rocket</td>
<td>146</td>
<td>-19.63</td>
</tr>
</tbody>
</table>

The flexure stress is defined as the stress induced by a bending moment. In our case, *Equation 7* solves for the flexural stress produced in a simply supported beam.

\[
\sigma_{\text{Flexure}} = -\frac{F}{2l\left(\frac{l}{z}\right)} \alpha(l - x)
\]

*Equation 7*
In this equation $F$ is load, $I$ is the moment of inertia, $z$ is the distance from the neutral axis to a point, $l$ is the beam length, and $x$ is the axial distance to the evaluation point. Applying this equation yields the values in Table 7.

**Table 7: Flexural Stress**

<table>
<thead>
<tr>
<th>Station</th>
<th>Stations (inches from nose cone)</th>
<th>Flexure Stress (Psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of Nose Cone</td>
<td>15</td>
<td>N/A</td>
</tr>
<tr>
<td>Base of Nose Cone</td>
<td>30</td>
<td>43.16</td>
</tr>
<tr>
<td>Payload Location</td>
<td>55</td>
<td>43.16</td>
</tr>
<tr>
<td>Recovery Bulkhead</td>
<td>70.75</td>
<td>147.34</td>
</tr>
<tr>
<td>Electronics Bulkhead</td>
<td>89.25</td>
<td>225.87</td>
</tr>
<tr>
<td>Coupler</td>
<td>97.5</td>
<td>225.87</td>
</tr>
<tr>
<td>Thrust Bulkhead</td>
<td>106.25</td>
<td>225.29</td>
</tr>
<tr>
<td>Middle of Fins</td>
<td>130.5</td>
<td>53.33</td>
</tr>
<tr>
<td>Base of Rocket</td>
<td>146</td>
<td>13.36</td>
</tr>
</tbody>
</table>

The total axial stress may then be found by summing the axial stress and the flexural stress.

<table>
<thead>
<tr>
<th>Station</th>
<th>Stations (inches from nose cone)</th>
<th>Total Axial Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of Nose Cone</td>
<td>15</td>
<td>N/A</td>
</tr>
<tr>
<td>Base of Nose Cone</td>
<td>30</td>
<td>54.95</td>
</tr>
<tr>
<td>Payload Location</td>
<td>55</td>
<td>91.26</td>
</tr>
<tr>
<td>Recovery Bulkhead</td>
<td>70.75</td>
<td>214.44</td>
</tr>
<tr>
<td>Electronics Bulkhead</td>
<td>89.25</td>
<td>310.76</td>
</tr>
<tr>
<td>Coupler</td>
<td>97.5</td>
<td>319.37</td>
</tr>
<tr>
<td>Thrust Bulkhead</td>
<td>106.25</td>
<td>-357.73</td>
</tr>
<tr>
<td>Middle of Fins</td>
<td>130.5</td>
<td>-137.33</td>
</tr>
<tr>
<td>Base of Rocket</td>
<td>146</td>
<td>-32.99</td>
</tr>
</tbody>
</table>

The largest total axial stress is 357.73 psi and occurs at the thrust bulkhead. This location makes sense because it is where the thrust of the motor is applied to the body tube and is close enough to the base of the rocket for there to be significant inertial forces.

Based upon these stress values a fiberglass tube with a wall thickness of 1/16in would more than suffice. However, because the rocket needed extra weight to achieve its goal altitude it was decided to use a tube with a 1/8in wall thickness. The properties of this tube are shown in the appendix.
**Electronics Door**

The following calculations were completed by structure team member Cody Fox and used with permission.

The team first considered using magnets to hold on the door used to access the electronics bay. However, there was concern that the pressure difference between the inside of the rocket and the atmosphere at 10,000ft would generate a force that would potentially pop off the door.

First, it was assumed that there was no pressure loss inside the rocket body. Next, the force acting on the door was determined at apogee. This would be when the pressure difference would be the greatest.

**Given**

- Pressure at 4000ft: 12.692 psia
- Pressure at 14000ft: 8.633 psia

These pressures were then applied to the surface area of the door. This yielded the force acting on the door to be 64.58 lbs, a much larger force than our group had anticipated. These calculations as well as the door loading are shown in the following figure.

![Figure 27: Free Body Diagram of Electronics Door](image)

The complete magnetic calculations can be found in the appendix, including a comparison of possible magnets.
Fabrication:
Our rocket structure’s components were predominantly fabricated in the COD lab using four of the labs machines: the cut-off saw, band saw, lathe and drill press. The structure components that we needed to fabricate in the machine shop were three aluminum bulkheads, four polycarbonate bulkheads, and some alterations to a fiberglass tube.

Polycarbonate Bulkheads
The four polycarbonate bulkheads that were produced were all made with near identical operations despite having differing sizes and functions. We started making these bulkheads by laying out each individual part. The inner diameter (ID), outer diameter (OD), center mark, and brass insert location were marked. After the parts were laid out, the sheets were clamped to a drill press. A hole saw was used to cut out the inner diameter. At this point we experienced some issues in cutting the polycarbonate sheet. At times the polycarbonate material would melt on the hole saw and we would have to stop drilling and clean off the hole saw. To avoid this cutting fluid was apply to the polycarbonate sheet to help prevent the plastic from melting.

Figure 28: Laying Out Polycarbonate Bulkheads
Next a rough cut of the bulkheads outside diameter was made on the bandsaw. Next we chucked the somewhat circular polycarbonate bulkheads on the lathe, and turned the OD. Each piece was turned until it fit within the body tube of our rocket. A slight chamfer was cut on the outside edge of each bulkhead for aesthetic appearance as well as ease of insertion into the rocket tube. Finally we were able to drill the holes for the brass inserts.

![Image](image.png)

**Figure 29: Cutting Out Bulkhead Blanks**

*Aluminum bulkheads*

The fabrication of the aluminum bulkheads was similar to that of the polycarbonate bulkheads with a couple key differences. First, the aluminum stock was cut on the cutoff saw as opposed to the bandsaw. Group members were careful to leave enough material on the bulkhead blank for the facing operation.
Next the pieces underwent many operations on the lathe. The first operation was facing the surfaces of the bulkheads. After precisely setting up the blank on the chuck, small increments of material were removed on the face.
After the parts were sufficiently surfaced they were removed from the lathe and were laid out according to their designs. If any of the aluminum bulkheads required a drilling operation the hole location was center punched. Next the part was placed back on the lathe and the inner diameter was bored. The ID’s were checked to insure a slip fit over the motor casing.

Finally the OD of the part was turned until a slip fit inside the body tube was cut. After these operations were completed, holes for the radial screws were added similarly to those in the polycarbonate bulkheads. Also weight saving holes were added to the bulkheads with the use of the drill press.
Coupler section and motor mount

The coupler section plays a vital role in accessing different parts of the rocket before launch. It is comprised of two polycarbonate bulkheads, twelve screws, and a coupler piece. The coupler piece was sanded to insure a slip fit in the body tube. After the coupler was sufficiently sanded down mounting holes were added. After this the holes were further transferred onto the body tube. During the drilling operation team members had to be careful not to crack or fracture the fiberglass matrix. Next, the coupler tube was installed into the body tube sections with hardware as well as epoxy.

Next the aluminum bulkheads, comprising the motor mount, were installed. Clearance holes for the mounting hardware were drilled in the body tube. The actual motor casing was used to make sure the bulkheads were positioned correctly.

Figure 33: Finished Motor Mount Bulkheads
Testing:

Brass Inserts
Brass inserts were used to secure screws into the rocket’s polycarbonate bulkheads. These inserts have grooved teeth on the outside. The insert expands when a screw is threaded into it, pushing the teeth into the inside of the hole and securing the insert.

The manufacturer has a suggested hole size of .250in for the inserts. However, because the position of the holes in our bulkhead left some very thin walls we wanted to test the inserts in a variety of holes sizes. The chief objective was to see if the expanding insert would crack the ridged polycarbonate if the mounting hole was too small. Conversely, in the mounting hole was too big the insert would not properly mount.

It was determined that the ideal hole was .257in because it offered good engagement with the expanded insert without putting a dangerously high load on the bulkhead. A hole size of .250in did not crack the polycarbonate but it was much too tight. Figure 34 shows the comparison between the two hole sizes.

![Figure 34: .25in Test Hole Note: Brass particles can be seen in hole on the right.](image)

![Figure 35: .257inch Test Hole](image)

Polycarbonate Bulkhead Axial Loading Test
Currently our team uses aluminum bulkheads to secure the motor mount and recovery systems. These are the bulkheads that see the highest load in the rocket. In the future the team would like to move towards a lighter and cheaper material for these bulkheads such as fiberglass or polycarbonate.

Our design team wanted to prove that a polycarbonate bulkhead with threaded brass inserts could withstand the motor thrust force. Because the bulkhead joint
with the fiberglass tube is not a traditional joint, it was decided a compression test would be better than an analytic calculation. Unfortunately the test could not be performed before this report was due. Group members still plan on carrying out the test to provide future Akronauts members with information to aid in their design.

![Figure 36: Test Section of Tube with Polycarbonate Bulkhead](image)
The test will be performed by an Imada Tensile tester. The Imada will provide a compressive load on the bulkhead around its inner diameter. The load will replicate the maximum thrust of the motor. The applied load will place a moment on the bulkhead. This loading scenario could be described as a cantilever beam in bending.

If the bulkhead does not fail the load will be steadily increased until failure. The two figures below show the loading of the bulkhead.

**Figure 37**: Model of Testing Setup

**Figure 38**: Cross Section of Testing Setup
**Conclusion:**
Our team conceived, designed, reworked and ultimately built the structure of a single stage rocket. The process started by setting goals for us to strive for, as well as, boundary conditions to constrain our design. During our project we applied an iterative design technique to progressively improve our concept structure. Next, the aerodynamic and inertial loading of the rocket was considered. These force values were then used to predict the stresses acting on the rocket. This information was used to further refine our design.

Finally, with a well defined and carefully set out design in place, our team began fabricating the rocket structure. Motor mounts were turned out of aluminum. Mountings for the recovery and electronics systems were fabricated out of polycarbonate. These components were then mounted on the fiberglass tube.

Although the rocket structure is largely complete, other aspects of the rocket are currently being worked on. Members of this group will continue to help the Akronauts team complete the nose cone, fins, payload and electronics bay. The picture below shows group members with the current rocket.
Appendix:

Brainstorming Sketches:

- Internal structure
- Tower approach
- Bulkhead top view
- Offset or thinner bulkhead may be used.

Pros:
- Good for side launch
- Easy to remove, systems to work on
- Modular, adjustable

Cons:
- Requires...
Diagram of a system with labeled parts:

- **Internal Structure**
- **System Specific Clamping**
- **Top Loading Scheme**
- **System**
- **Bottom Loading Scheme**

**Pros:**
- Only 1 bulkhead
- Must be removed to remove system
- Lightweight

**Cons:**
- Relatively small
- Possible hardware threat
- Screws not enough clamping force
- Would require CNC tooling

Would require separate mounting scheme for motor:
- Mounting holes to be slotted
- Systems must have flange for attachment
integral payload/coupler

Pros

Cons
- Too complex
Simple coupler

- Aluminium
  - or fiberglass?
  - will a system be integrated into coupler?

Simple tube/cylinder

- Weak points
- Drag performance

Pros
- Easy assembly
- Light weight
- Retaining hardware

Cons
- Relent on skin cross section

Simple tube with internal Hans cylinder

Pros
- Retent
- Additional part

Cons
- Hardware
Magnetic Calculations:

**Given**
- Door surface area = 15.91 m²
- Volume of pressure vessel = 5.65 m³
- Launch altitude = 4000 ft
- Apogee = 14000 ft

1. Air pressure above sea level can be calculated as:
   \[
   p_x = 101325 \left(1 - 2.25517 	imes 10^{-5} \left(\text{m} \cdot \text{h} \right)\right) \text{atm}
   \]
   \[
   p_{4000} = 87610.836 \text{ psia}
   \]
   \[
   p_{14000} = 59523.865 \text{ psia}
   \]

2. Assuming pressure in rocket is atmospheric at 4000 ft when rocket reaches apogee at 14000 ft.

3. With (4) \( \frac{3}{4} \) in. x 1/4 in. grade N42 magnets using 16 gauge steel as the door:
   - Pull force = \( 8.96 \text{ lb} \times 4 \) = 35.84 lb
   - 64.5 lb > 35.84 lb
   - Door will fly off

Full force was obtained using K&T Magnetics Website using an online calculator found in Graph #1 on 3rd page.
4 WITH (2) 11/4" x 1/8" GRADE N32 MAGNETS USING 16 GAUGE STEEL AS DOOR:

FULL FORCE = (29.83lb)(2) = 59.66lb

\[ 64.58lb - 59.66lb \quad \text{FROM GRAPH \#2} \]

DOOR WILL FLY OFF

4 WITH (2) 11/4" x 1/8" GRADE N32 MAGNETS USING 11 GAUGE STEEL (WEIGHT OF 51lb/ft²):

FULL FORCE = (39.62lb)(2) = 79.24lb

\[ 64.58lb - 79.24lb \quad \text{FROM GRAPH \#3} \]

DOOR WILL STAY ON
## Skin Tube Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural Modulus Longitudinal</td>
<td>10000000 psi</td>
</tr>
<tr>
<td>Flexural Modulus Circumferential</td>
<td>10000000 psi</td>
</tr>
<tr>
<td>Tensile Strength Longitudinal</td>
<td>5000 psi</td>
</tr>
<tr>
<td>Tensile Strength Circumferential</td>
<td>21000 psi</td>
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<td>Compressive Strength Longitudinal</td>
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<td>Density</td>
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References:


