Team members: Paul L, Jacob R, Andrew M, Alizah L.

The Team

FIREBREATHER ROCKETRY

• SATO ACADEMY OF MATH & SCIENCE •

Advisor: James Mills

Students:

- Paul L.
  - Design lead, launch coordinator
- Jacob R.
  - Manufacturing lead, CAD
- Alizah L.
  - Avionics Lead, programming
- Andrew M.
  - Technical Lead, data analysis

Figure 1

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Figure 1: Our team next to our final rocket. The team members are (left-to-right) Mr. Mills (our advisor), Andrew M, Paul L, Alizah L, Jacob R.

Our team is a subsidiary of our school's rocketry club, Firebreather Rocketry. This helped us secure funding for motors and materials.

Paul: Managed the design and took the lead prototyping components. Planned potential launches and maximized our test time. He worked closely with Andrew to come up with novel solutions. Worked with Jacob to ensure all parts were satisfactory.

Jacob: Managed the manufacturing of parts on the rocket. Throughout the process, half a dozen bottom sections and four top sections were manufactured. Worked with the whole team to ensure specifications were met.

Alizah: Coded and designed the avionics, ensuring that the air brakes would open at the proper altitude and close during the descent. Worked with Paul to make sure the hardware was compatible with the software. Also worked with Andrew to refine software.

Andrew: Analyzed the flight data to find issues and determine how they could be solved. Worked with Paul to guide component design and with Alizah to ensure software reliability. Worked with Jacob to determine the feasibility of potential solutions.

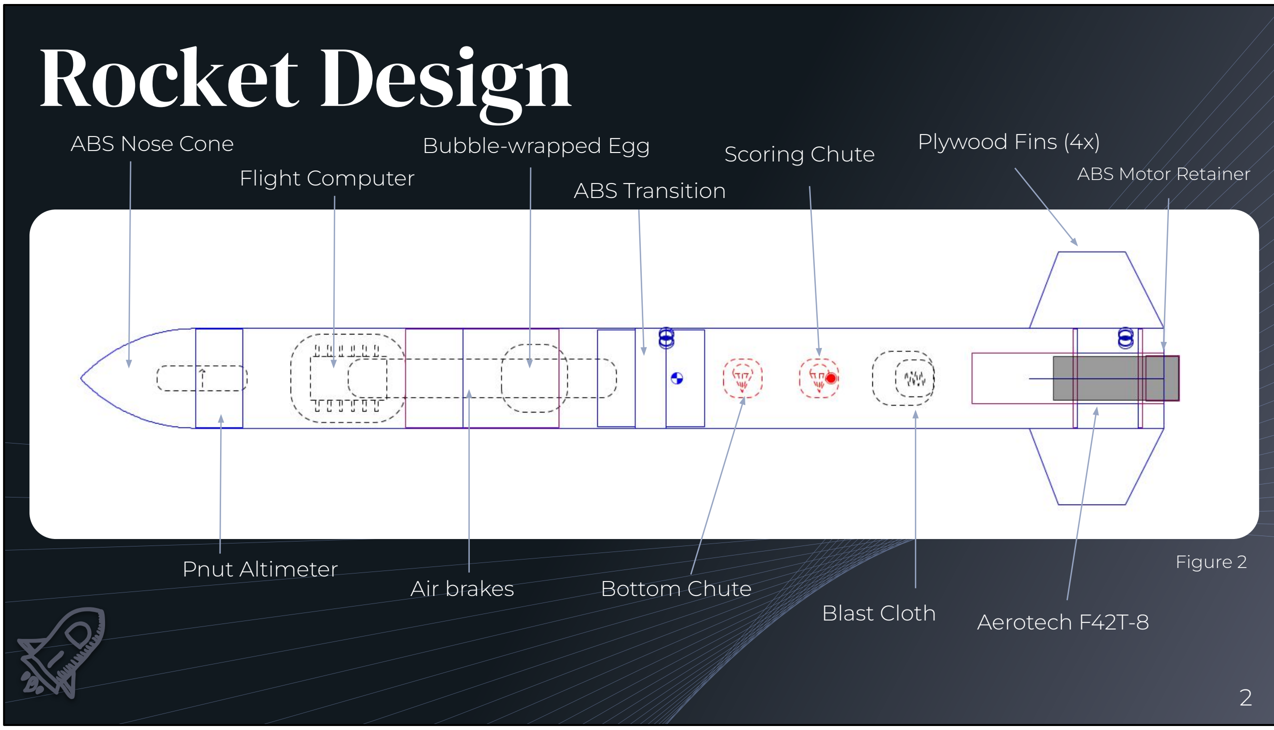


Figure 2: Final rocket design, simulated with OpenRocket.

Technical Specifications:
Stability: 1.55 cal
Length: 28.7” (729mm)
Empty Mass: 480g
Takeoff mass: 556g
Predicted OpenRocket Apogee: 1007 ft using Aerotech F42T-8

We started off the year by designing a rocket that matched TARC specifications. We included a blunt, 3d printed nose cone to ensure its survivability across multiple flights. It also housed the PNUT scoring altimeter, isolated to ensure accurate altitude readings. We chose BT-80s as our rocket body tubes to ensure a liberal amount of work room while being lightweight. The airbrake control circuitry was stored under the nose cone, allowing for easy access for post-flight analysis. The egg was wrapped in 3 layers of bubble wrap and enclosed by external air brakes ensuring high chances of survivability. The bottom section stored the two parachutes, both protected by a blast cloth. Laser Cut fins and centering rings ensure durability and resistance to any damages on touchdown. Finally, to comply with TARC regulations, a 3d printed cap on the end ensured active motor retention. These were the parts shared by all versions; it took us a lot of time and modifications to end up at this final design.

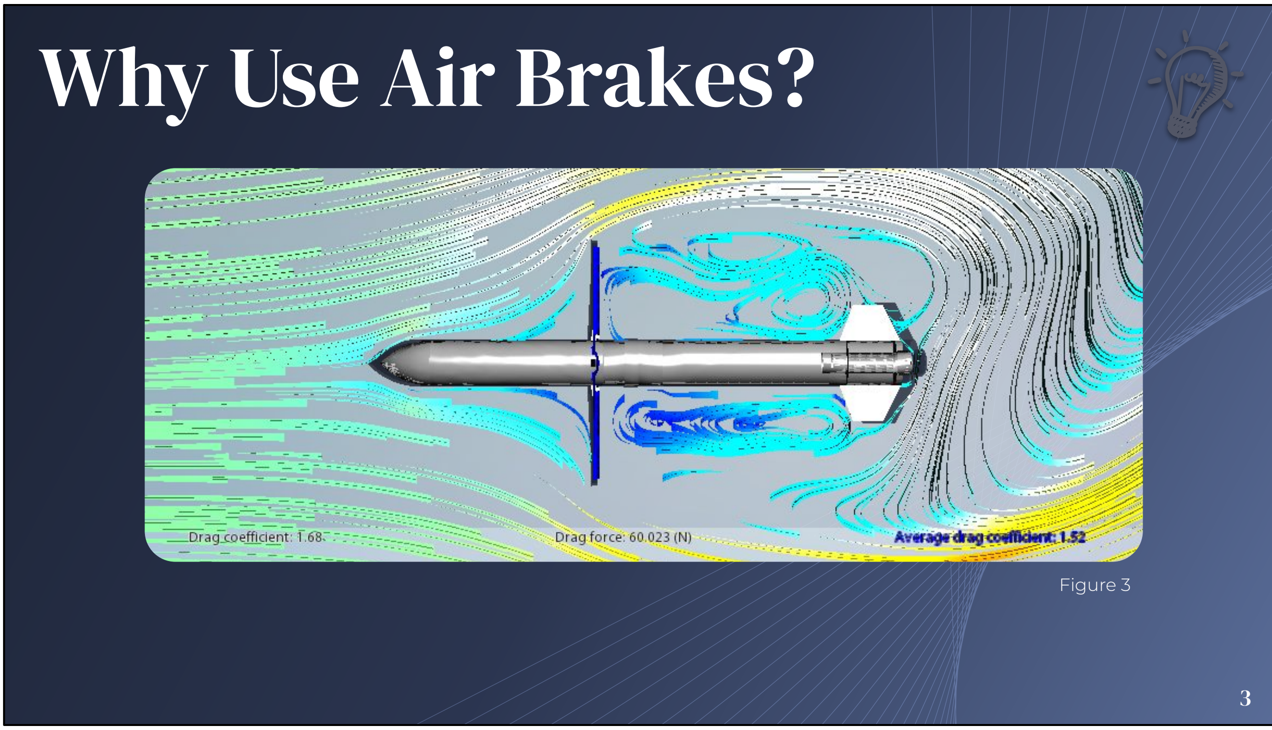


Figure 3: Simulation of our airbrake design using Autodesk Flow Design software.

Our first goal was to design large air brakes with a comparative increase in drag force when opened. We first wanted to gather an estimate of the rocket's drag with the airbrakes closed. According to the simulation, the rocket has an average drag coefficient of 1.16, with a drag force of 15N in 10 m/s flow speed. However, with the air brakes opened, the drag coefficient jumps to 1.52, and the drag force quadruples to 60N. Combined with the equations used to determine stopping distance (shown on the next slide) and velocity graphs from OpenRocket simulations, we were able to determine the ideal time to deploy the air brakes in different scenarios.

In addition to having a powerful stopping force, we found airbrakes to be the ideal solution due to their resilience to launch site factors such as humidity and temperature, ensuring reliable results with just a simple modification of air brake deployment altitude in the software.

Why Use Air Brakes?

$$(stopping\ distance) = -\frac{1}{2\beta}\left(\ln(9.81) - \ln\left|-9.81 - (\beta)(velocity)^2\right|\right)$$

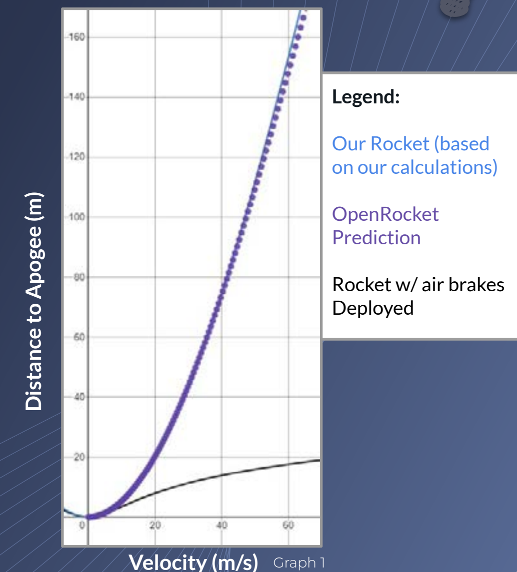
Figure 4

$$\beta_{Our\ Rocket} = \frac{(0.3)\left(1.176\frac{kg}{m^3}\right)(0.0034\ m^2)}{2(0.529\ kg)}$$

$$\beta_{with\ Air\ Brakes} = \beta_{Our\ Rocket} + \beta_{Air\ Brakes}$$

$$= \frac{(0.3)(1.176\frac{kg}{m^3})(0.0034\ m^2)}{2(0.529\ kg)} + \frac{(0.3)(1.176\frac{kg}{m^3})(0.0072\ m^2)}{2(0.529\ kg)}$$

Figure 5



Graph 1

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Graph 1: Graph depicting the distance to apogee of our rocket based on OpenRocket, our predicted rocket performance, and the rocket with air brakes deployed.
Figure 4: Equation relating stopping distance to the drag of the rocket and the velocity at deployment. This equation was derived from newtonian physics equations.
Figure 5: Calculation of the total drag of the rocket by approximating the mass and the drag coefficient of the air brakes.

Using the mass of our rocket, which is approximately 529 grams after the motor burns out, and the surface area of our air brakes, which is about 0.07 square meters when fully deployed, we can estimate how quickly the air brakes will slow our rockets.

We used these estimation graphed on the right to determine the different altitudes we should use to deploy the air brakes for both the qualifying launch and the finals.

Air Brake Design

Key Features:

- Spool rotates to unlatch air brakes
  - Can rotate to reel in air brakes
- Modified servo motor to have uncapped rotation
- Air brake material selection:

Material	Lightweight	Durable
BT-80 Tube	✓	✗
ABS Plastic	✗	✓
Fiberglass	✓	✓

Table 1

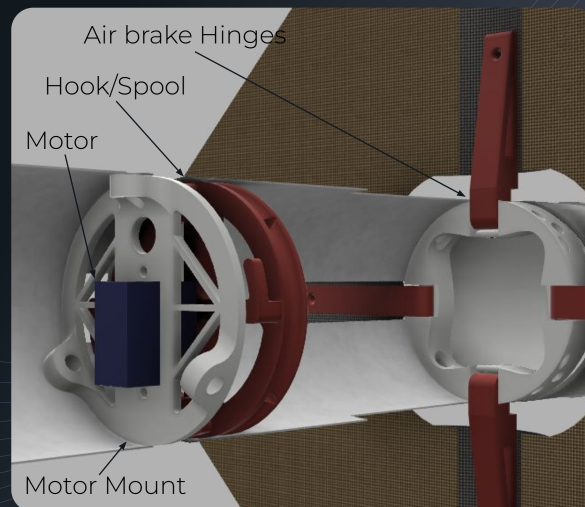

Figure 6

Table 1: A matrix comparing three different materials we considered during our air brake design.
Figure 6: A rendered 3D-model of our internal air brake mechanism

We designed a servo-actuated mechanism which can deploy and retract the air brakes.
The four hooks on the spool can turn to release the air brakes, which are pulled out using rubber bands. During ascent, the air brakes are deployed once the rocket reaches its predetermined deployment altitude.

Once deployed, the airbrakes can be retracted by winding up the spool, which pulls on strings attached to the end of each air brake..

The spool design evolved a lot throughout the year as we optimized dimensions and tolerances to prevent tangling of the strings as they wound up.

During the descent, the air brakes can either be further deployed or retracted to fine tune the descent rate.

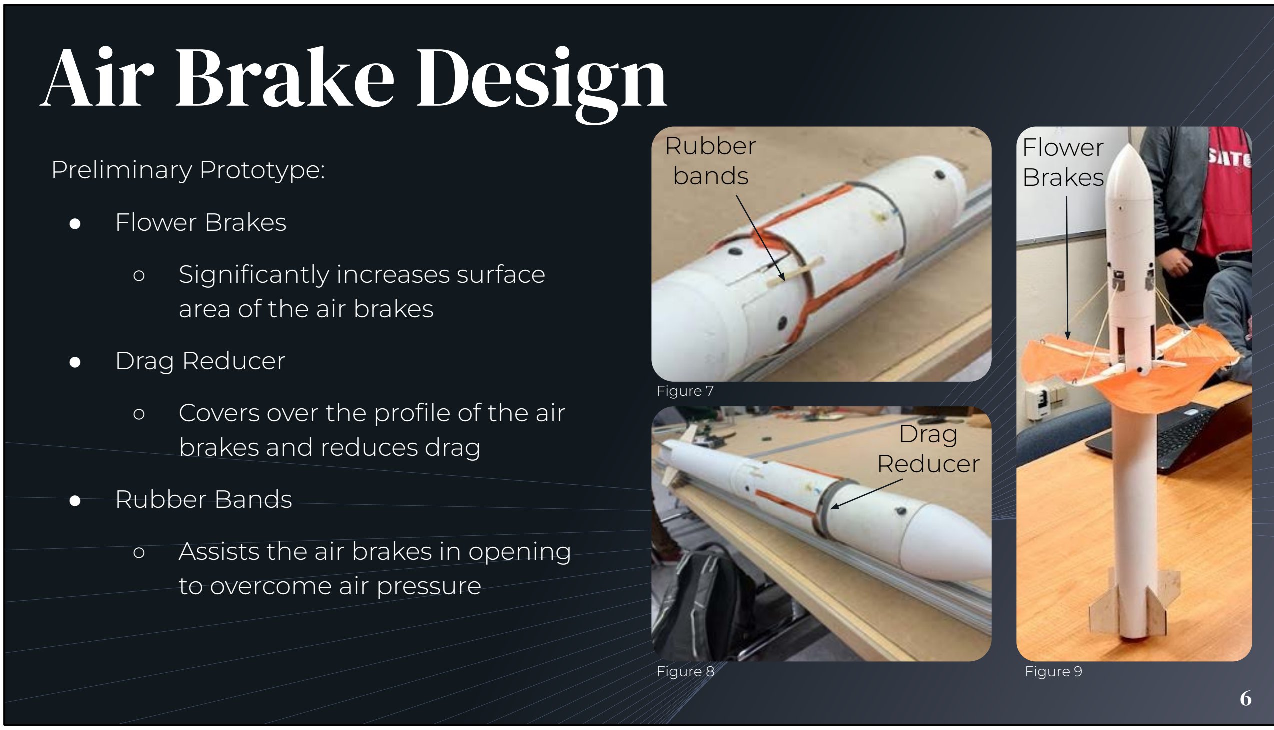

Figure 7: Rear view of the air brakes closed on our preliminary prototype rocket
Figure 8: Front view of the air brakes closed on our preliminary prototype rocket
Figure 9: Side view of the air brakes open on our preliminary prototype rocket

Brakes:
We reached the unique four-panel design after careful consideration of how to maximize deceleration across the course of the flight, and most of our early design work was dedicated to this. We also used it as a method of modulating speed on descent, and the larger surface area allowed it to substantially affect the rate of descent.

Drag Reducer:
Early tests showed the air brake construction added significant drag even when collapsed and it was a goal throughout our several iterations to reduce this. As a result, we decided to make a drag reducing flange to slide onto the rocket and sit directly above the air brakes.

Rubber Bands:
Another hurdle we encountered was occasional air brake deployment failure, which was not present during ground testing. We hypothesized this was a result of air pressure differences in actual flight. We attempted to overcome this with the use of rubber bands to assist in deployment.

Motor Selections

Motor	Type	Diameter	5 mph winds	20 mph winds	Velocity off rail	Cost per Motor
Aerotech F22	R	29mm	917 ft	808 ft	22.5mph	$ 24.60
Aerotech F42	D	29mm	1022 ft	957 ft	38.8 mph	$ 18.70
Cesaroni F79SS	R	24mm	1193 ft	1095 ft	44 mph	$ 26.02
Aerotech F50	D	29mm	1136 ft	1085 ft	57 mph	$ 30.59

Table 2

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Table 2: Sample of decision-making chart used to select the appropriate motor.

With a the usage of air brakes, it was crucial to find a motor that was reliable and could allow the rocket to surpass the target apogee. However, our motor could not be too-powerful; if the air brakes deployed when the rocket was travelling too quickly, it could cause them to disintegrate. We ran OpenRocket simulations on every TARC approved F motor to determine which motor would allow the rocket to perform the best. We also tested in different wind conditions to ensure the rocket will perform well regardless of wind speeds.

Different delays were selected with each motor to balance the maximum altitude with the parachute deployment speed.

We settled on using Aerotech F-42s with an 8 second delay, since, alongside their relative cheapness, they allowed the rocket to surpass the target apogee without going too fast. We also had a few of these motors available at the start of the year, which allowed us to cut down costs while getting started on testing.

Rocket Construction

Figure 10

Figure 11

8

Figure 10: Picture of the air brake mold being covered with PVA mold release.
Figure 11: Picture of two fin Jigs, a fin slot cutting jig, and a body tube marking jig.

Our team aimed for precisely manufactured parts during this year's competition to help speed up construction processes and reduce turnaround times. In order to ensure precision and accuracy across different rocket iterations, jigs were used throughout the construction process. We decided to 3d print all of our jigs, which ensured precision in the jigs themselves while also being easy to use and modify. They also expanded our options for rocket modifications, including canting fins and modifying the size of our fiberglass air brakes, as re-printing the jigs would not take a lot of time.

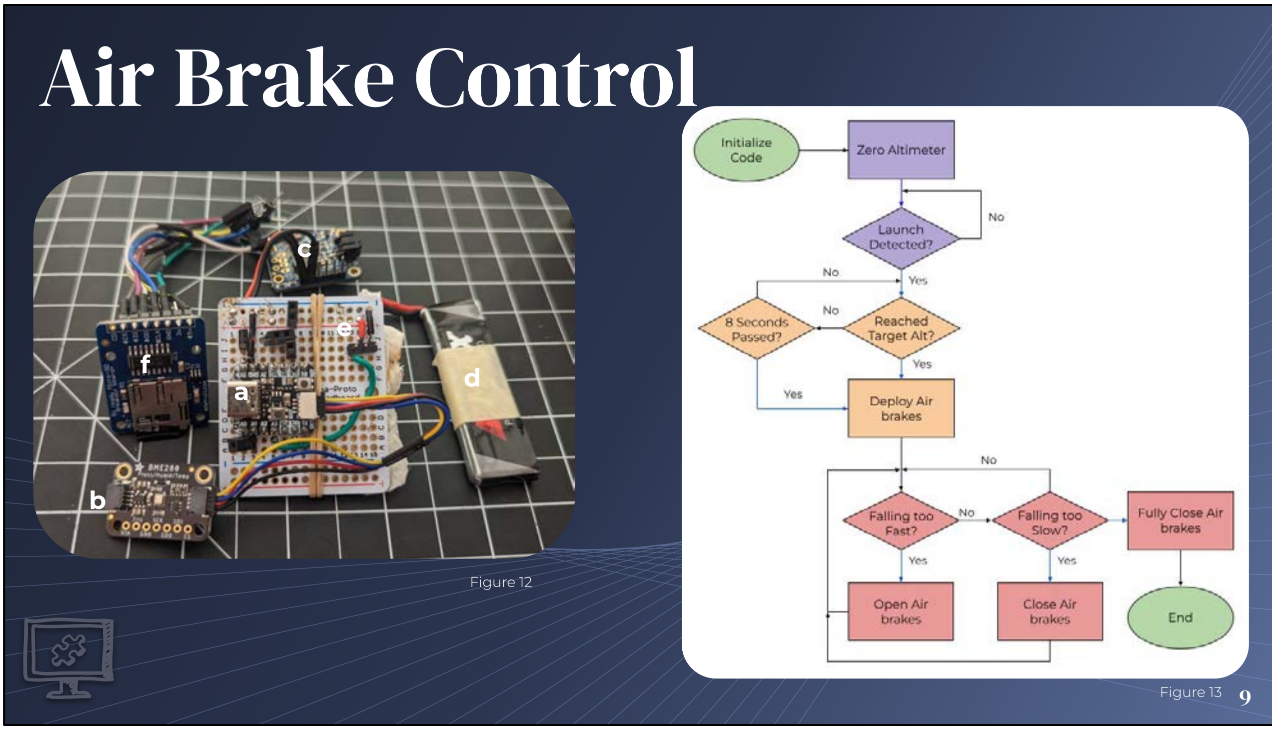


Figure 12: The circuit package used for airbrake control. Battery included, the circuit weighed 40 grams.
(a): Microcontroller
(b): Altimeter
(c): Voltage booster
(d): 3.7V battery
(e): Servo Connector
(f): SD card reader, disconnected for better viewing

Figure 13: Air brake control flowchart.

To ensure reliable control of the air brake system, we constructed a small yet powerful circuit to deploy the air brakes. This circuit was made early on in the year but the code was expanded upon throughout the year to add failsafes and improve performance. We also included an attachable SD card reader to help troubleshoot problems.

The code initializes and complete the purple cells on the pad. The orange cells were the rocket's thought process after launch. The red cells depict descent control after apogee. This guides the rocket into the correct flight time by adjusting the size of the air brakes. Finally, as the rocket reaches the ground, it closes the air brakes to shield the egg upon impact. The blue arrows in the flowchart indicate when we would upload values of different variables, such as time and altitude, to get a good understanding of what the rocket was accomplishing during fight.

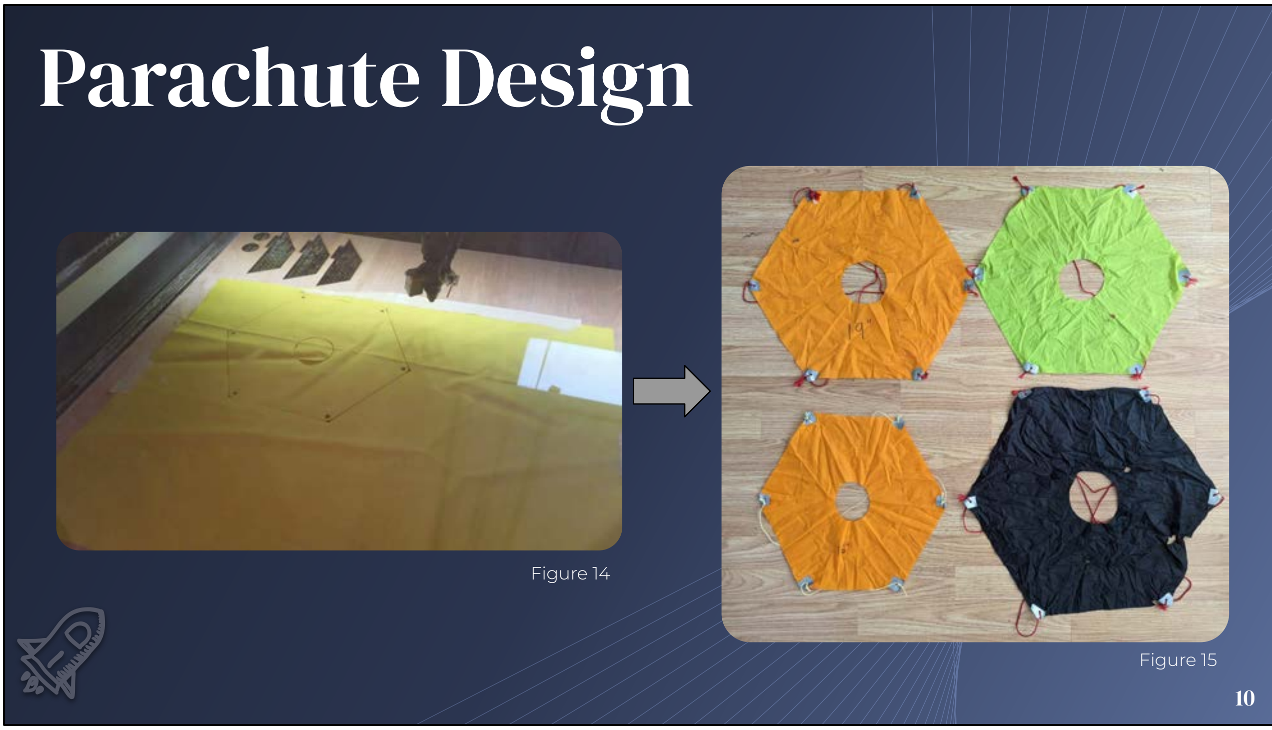
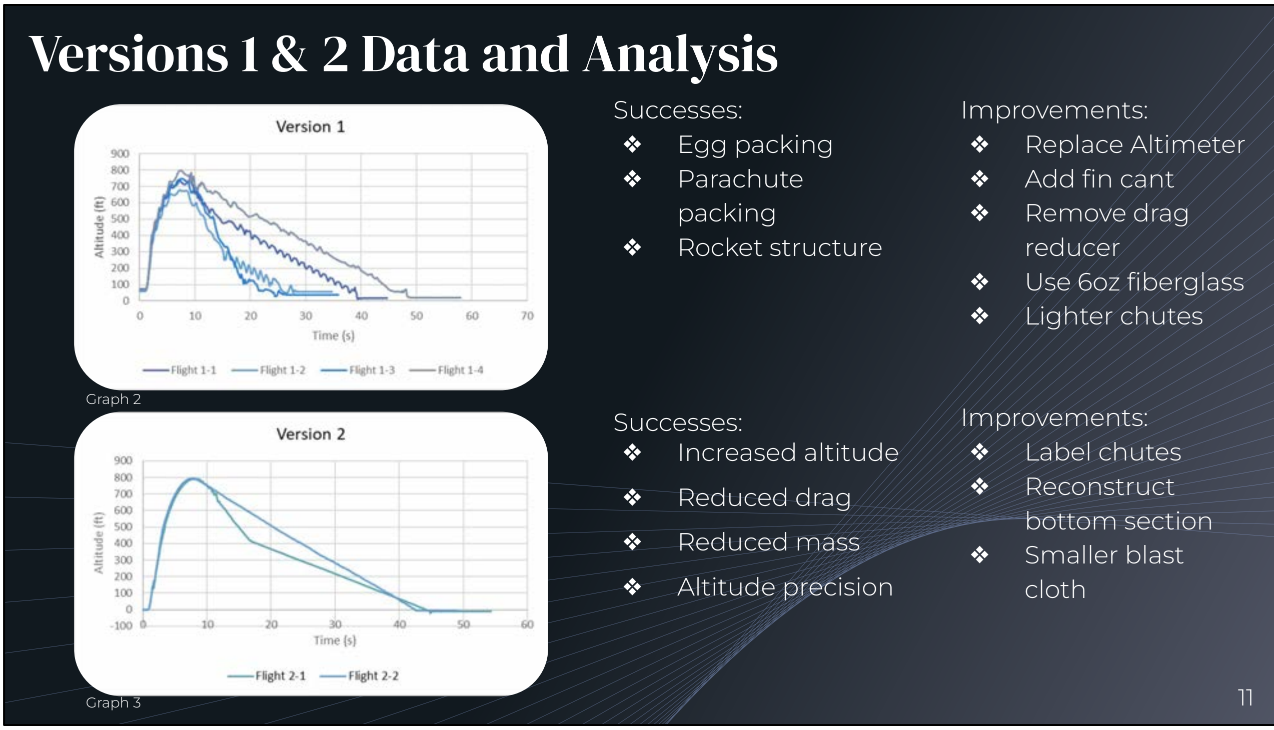


Figure 14: Frame taken from a video of our initial tests of cutting nylon fabric with a laser cutter.
Figure 15: Picture of parachutes used during our test flights. The Parachutes on the right are made out of light weight 40D Ripstop Nylon, while the parachutes on the left are made out of heavier 70D fabric.

Following down the path of precision, our parachutes were laser cut to specific dimensions. Laser cutting allowed us to rapidly construct and develop new parachutes of different sizes to ensure the rocket was descending at the target velocity. By comparing the descent rate of different sized parachutes in OpenRocket, we were able to determine a range of sizes for the top and bottom sections.



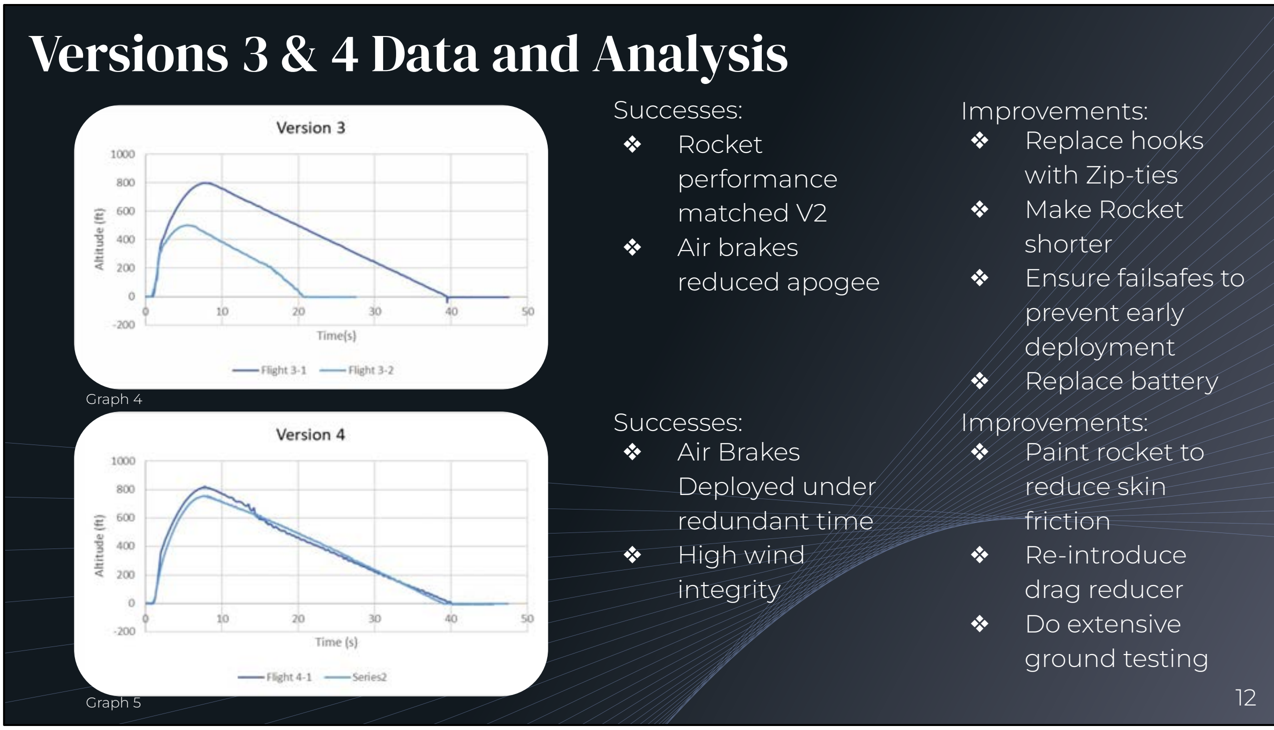
Graphs 2 & 3: Altitude over time graphs of the various flights of the 1st and 2nd version of our rocket respectively

Version 1:
Length: 30 inches
Mass: 625 grams
Stability: 1.66

Our altimeter had significant errors so we got a new for subsequent launches
We attempted to solve significant weather cocking by adding 1 degree fin cants.
We had a small flange above the air brakes to limit the drag caused by closed air brakes that ended up causing more drag than it reduced.
We started using fiberglass to create the air brake flaps to ensure they would last longer

Version 2:
Mass was reduced to 540 grams by making new, lighter parachutes.

We continuously got the top and bottom chutes confused outside of the rocket, so we began labelling to avoid any potential mishaps.
Wear and tear from numerous launches was beginning to show on the bottom section and we wanted to avoid inconsistency from wear
The blast cloth we had been using was larger than it needed to be, so we reduced its size to reduce weight

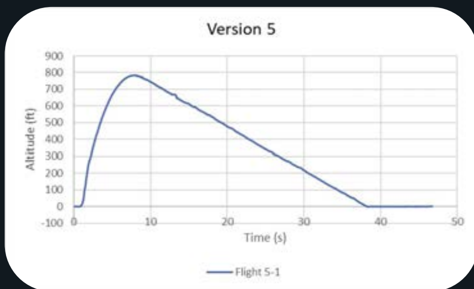


Graphs 4 & 5: Altitude over time graphs of the various flights of the 3rd and 4th version of our rocket respectively.

Version 3:
The hooks we had been using in the air brakes were deteriorating and broke during the 2nd flight, so we replaced them.
The rocket was longer than necessary, so we reduced its height to reduce its weight.
A catastrophic early deployment led to us redoubling our efforts to ensure the reliability of everything in our rocket.
During another launch the airbraked did not deploy, we traced the issue back to the battery we were using not supplying sufficient current, so we replaced it.

Version 4:
In an attempt to increase our apogee we painted the rocket to reduce friction.
We also re-introduced the drag reducer we removed, this time with a better design in attempt to create a boundary layer of air over the air brakes and reduce drag.
We created a better test chamber that allowed us to do more frequent and more efficient ground tests of the air brakes so we could improve them faster.

Versions 5 & 6 Data and Analysis



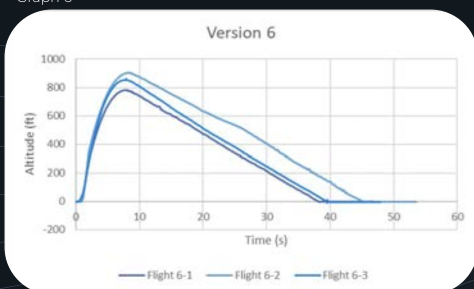
Graph 6

Successes:

- Air brakes deployed under redundant time
- Hooks prevented premature deployment

Improvements:

- Reduce bottom section length
- Make zip-tie flush with rocket
- Remove fin cant



Graph 7

Successes:

- Air brakes properly deployed
- Parachute fully opened at apogee

Improvements:

- Replaced bottom parachute
- Remove drag reducer
- Adjust airbrake deployment altitude

Graphs 6 & 7: Altitude over time graphs of the various flights of the 5th and 6th version of our rocket respectively

Version 5:
We further reduced the length to minimize the weight, trying to squeeze every foot we could out of the f-42
The head of the zip tie was sticking out beyond the drag reducer, so it was adjusted to be flush with the rocket
We also removed the fin cant, again to reduce drag, accepting the risk of weather cocking

Version 6:
The bottom parachute was larger than it needed to be so we replaced it with a lighter parachute
We compared a flight with and without the drag reducer and found negligible difference so we permanently removed it
We also found that during this launch we gained just under 100ft in average apogee, so we adjusted the deployment altitude for the air brakes

Graph 8: Roughly what scores we would have gotten if each of the flights were a timed qualifier organized by version. After version 1 there is general consistency, aside from the outlier of version 3, during which we faced a disastrous early deployment, leading to our highest score. Versions 4 and 5 also underperformed score wise as a result of modifications that failed to have any impact, however as test beds for modifications, they succeeded, culminating in version 6, which, on its last flight after minor adjustments, would have achieved a score of 22.2. This is by far our best score during testing, although with more time we would have liked to make it more consistent.

Graph 9: The altitude over time estimated by OpenRocket, our rocket simulator. This assumes no air brakes. The vastly higher apogee is likely as a result of the increased drag from overhang from the air brakes. Most of the modifications made sought to increase the apogee on an f-42 motor by minimizing both drag and weight.

Design Evolution

Figure 16

Figure 17

Figure 18

Figure 19

Figure 16: Version 1 at DART (Diego Area Rocket Team)
Figure 17: Version 2 at ROC (Rocketry Organization of California)
Figure 18: Version 5 under construction. New drag reducer was introduced
Figure 19: Version 6 at FAR (Friends of Amateur Rocketry)

Qualifying Launches

	Altitude (ft)	Time (sec)	Separation?	Egg	Score
1	817	44.14	Yes		33
2	324	16.845	Yes		626.62
3	794	41.455	Yes		58.2

Table 3

Figure 20

Table 3: Performance of our rocket for all three qualifying flights.
Figure 20: Destroyed air brakes after premature deployment during qualifying flight 2.

Launch 1 a sticky launch rail caused the rocket to underperform by 33 feet. The air brakes activated under redundant time; however, the rocket was just barely in the time range, so we enlarged the spill hole to reduce drag.

Launch 2 occurred in rapid succession, however it ended in tragedy. Two seconds into flight, the airbrakes slipped off their hooks and opened up, shredding the air brakes and stopping the rocket in its tracks. This resulted in a terrible score and time, but since the egg survived the deceleration and ground hit the flight was not disqualified.

Launch 3 was done with a version 5 top section without working airbrakes. The wear and tear from this section showed; the added drag caused it to underperform in altitude, thus impacting the total flight time as well. The egg survived this launch as well, resulting in a total score of 58.2, with a combined score of 91.2 for our best flights.

Lessons Learned

- Adaptability
- Kaizen
- Speed

Adaptability:
Being willing to make big changes, and even remove big components is very valuable. On a small scale we did make changes, but if we had been willing to readjust our view of what we needed and explore more options we may have had more success. Throughout the whole process we never really considered alternatives to air brakes, but if we had we may have found a system more reliable while just as effective. Really, adaptability is what engineering is all about, the willingness to change.

Kaizen:
Traditionally used in the manufacturing world it is a term that means consistent, small improvements, to achieve a big result. Really, that is heart of what we were trying to do. Reduce the weight and drag wherever we could, and ultimately we succeeded, reaching a total of 900 ft during our final tests. In future applying it to even more will no doubt help us achieve similar successes.

Speed:
Neither of the above matter if you’re too slow to effectively apply it. Speed is vital when making decisions. The simulations can only tell you so much, so getting on the pad or in whatever test bed quickly is very important.

Planning:
We found that throughout the competition we succeeded more when we spent more time planning. If we plan carefully we have fewer problems down the road and it is easier to fit the solutions to those problems into the design and schedule. Continuing that trend in other competitions and projects will help us to succeed even further.

Communication:
Keeping in touch with everyone can be difficult but the more effort we put into doing so the better off we are. During this project having only four members made it relatively easy to stay in touch, but having a consistent and simple place to communicate was really beneficial.

Organization:
Like when we were dealing with the parachutes staying organized requires constant effort. Continuously making sure we were following our systems helped us make this a very well organized affair. It also allowed us to over double the number of launches we had last year. We also had more documentation of our changes, which made it easier to identify issues and solve problems.

All of these lessons we will take to future projects and expand on.

Thank you, and remember…

"Perseverance is not a long race; it is many short races one after the other." -Walter Elliot

Thank you for your time