NORTHVILLE HIGH SCHOOL
AEROSPACE CLUB

Rocket Optimization through Minimization of Variable Effects

Northville High School TARC Team

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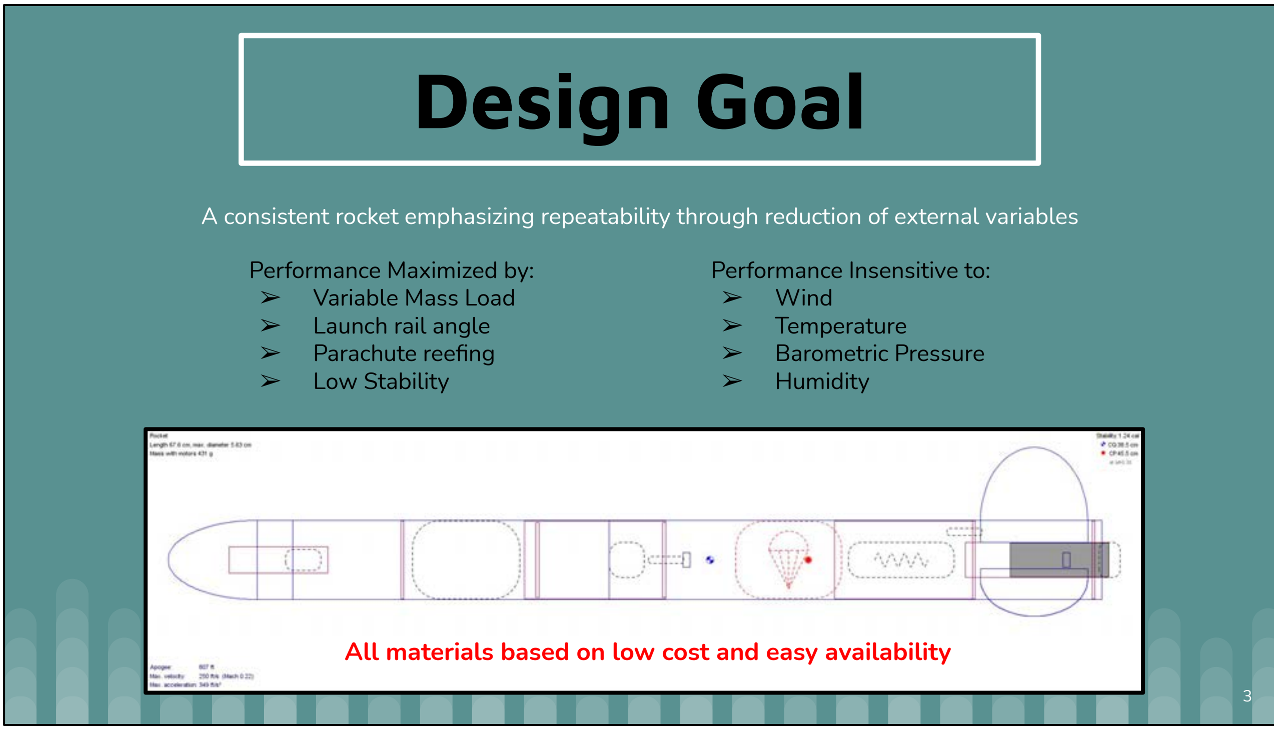
Team Summary and Roles

- **NHS Aerospace Club**
  - 17 Members
  - Completely Student Run with One Faculty Mentor.
- **NHS TARC Team**
  - The TARC Team is a spin-off of the NHS Aerospace Club.
  - First year team (not including the partial year in 2020) of 4 members.
  - The team structure is based on an inclusive process where everyone can work on all aspects.
    - Parallel rocket designs by each student.
    - We built individual rockets, then slowly tested and selected the best to ensure participation by all.

NHSAEROSPACECLUB

- The NHS TARC team is a small subdivision of the NHS Aerospace Club
- We pride ourselves in being student run
- We are a first year team, having attempted to compete last year, but the competition was cancelled due to COVID
- Even during COVID quarantine orders, we still attempt to be inclusive
  - Group design reviews
  - Everyone gets the opportunity to build a rocket
  - Group launches

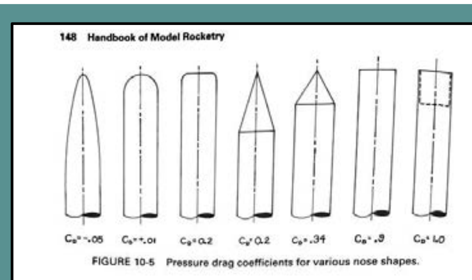


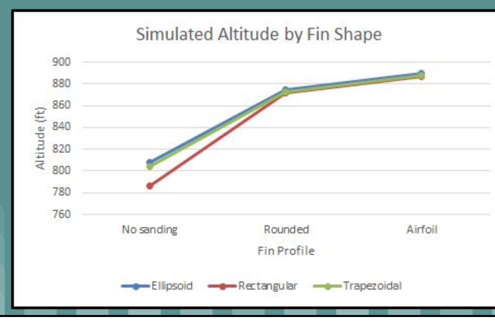
- Initially, our attempts at creating the best possible rocket were hindered by the sheer number of variables that we didn't control or have optimized
- Original rockets were approximately 2 or more calibers of stability, leading to flight variations
- We had to go about designing a rocket that minimizes variation in order to consistently gather useful data

Coefficient of Drag Optimization

➢ Drag is a function of humidity and barometric pressure. By reducing drag, we reduce sensitivity to these variables.

➢ Methods for decreasing drag:
  - Optimize for Subsonic flight
  - Smallest Diameter Body Tube to Still Fit Egg
  - Ellipsoid Nose Cone
  - Elliptical Fins
  - Rounded and Sanded Fins
  - Smooth paint
    - Fill Spiral Seams in Body Tube
    - Sandable, Fillable Primer
    - Gloss Paint



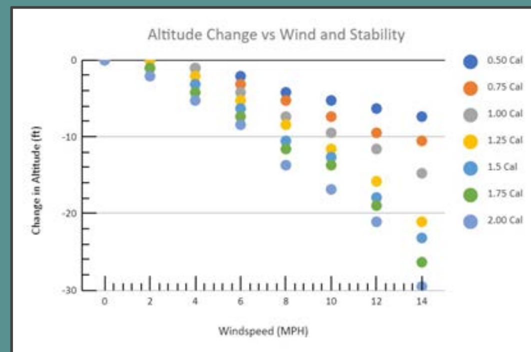


- Originally looked at sharp components and items modeled off of real missiles and rockets. A little research showed that these were optimized for supersonic flight.
- When actually looking at the drag coefficients of nose cone designs, elliptical or elongated nose cones actually have much lower drag coefficients than the traditional triangular nose cone.
- We swept the data for similar fin designs, and selected the best possible altitude variant. Delta fins and swept deltas were excluded, due to how easy they are to break on a hard landing (which we've had plenty of)
- All in all, we went with rounded elliptical fins due to how they were slightly more efficient than the others, as well as harder to break on landing.
- We rounded our fins, due to the relatively small comparative gain between rounding and airfoiling them (as well as the difficulty of getting a proper airfoil)

Drag coefficients from figure 10-5 came from the Handbook of Model Rocketry Seventh Edition, by G. Harry Stine and Bill Stine

CP and CG Optimization

- ➢ **Weathercocking** in high wind initially caused inconsistencies
  - ○ Rockets were overstable
- ➢ Qualifying rocket compromised at a stability of approximately **1.25 calibre**
  - ○ Any lower than 0.5 calibre would be too unstable
  - ○ High stability = large deviations in altitude depending on wind

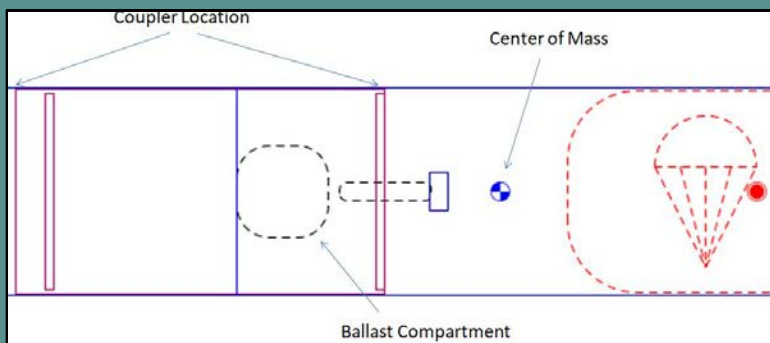


Low stability (Cal) = little altitude change in wind

- Original rocket designs were based on suggestions from TARC guides and discussions with mentors suggesting a stability of 2 calibre or higher. These rockets resulted in excessive altitude variations due to weathercocking.
- Some research and simulation models in OpenRocket made us realized that over-stability was the primary cause.
- The more stable the rocket was, the more variation we simulated based on wind variation.
- We decided to test newer designs in the 1.5-1.25 caliber range, due to the decrease in wind variation exhibited.

Location of Mass/Coupler

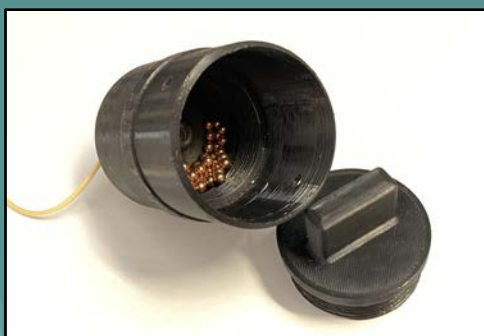
- ➢ Mass coupler located near the rocket’s CG
  - ○ Adding/removing mass would not affect rocket’s CG
  - ○ Stability will remain constant regardless of ballast

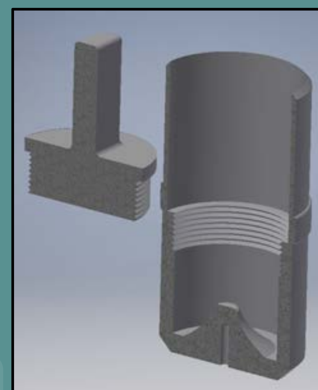


- After performing our center of pressure and center of gravity optimization, we wanted to ensure that added mass (specifically for changing the projected altitude of the rocket) changes the center of gravity as little as possible.
- In order to do this, we had to get our mass compartment as close as possible to the center of gravity, which was unfortunately within the lower body tube
- The closest point that we could fit a mass component without restricting the parachute deployment would have to be at the very end of the coupler

Variable Mass/Coupler Design

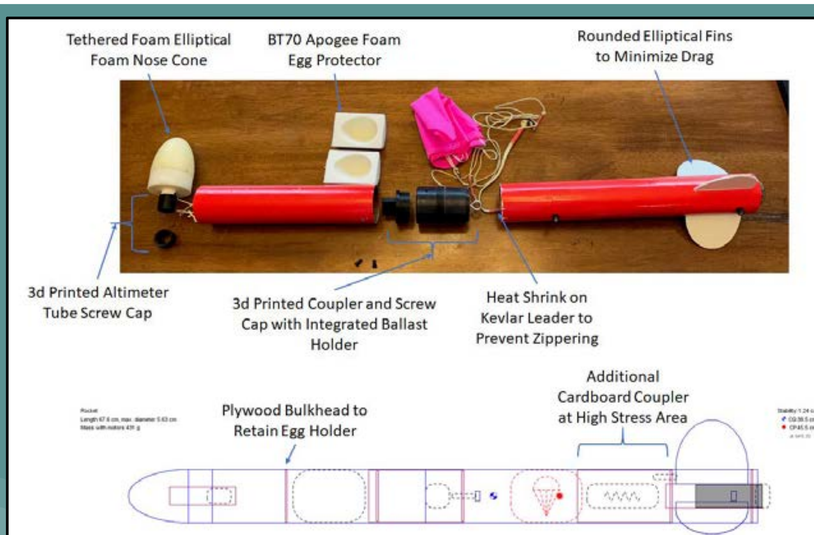
- ➢ 3D printed coupler also functions as ballast container
  - Eliminated need to separately package variable mass
  - Connected to payload section by plastic rivets





- We initially experimented with a wooden and cardboard coupler, but our mass component would either be loose or hard to secure
- In order to increase durability and secure the mass properly, we had to design and 3D print a new, custom-made body tube coupler
- By creating a hollow coupler with mass compartment, we can add BB pellets as mass as low as any payload part of the rocket can be without interfering with the parachute deployment

Final Rocket Design



- After several iterations, we believe we developed a very optimized rocket.
- Other features that have not been presented in previous designs include:
  - Adding heat shrink to the Kevlar leader where it rubs against the booster section to minimize zippering and wear on the thin-wall cardboard.
  - Adding a cardboard coupler above the forward motor mount centering ring. This area usually is the first to get damaged from landing repeatedly at 20 ft/s.
  - Designing a 3d printed screw cap for the altimeter tube.

Motor Selection

Compromised between cost, power, and motor variability:

Motor	Manufacturer	Type	Chemistry	Propellant	MMT Diameter	Total Impulse (N-s)*	1 Sigma (N-s)	1 Sigma %	Price/Motor	Comments
E15	Aerotech	Single Use	Composite	White Lightning	24 mm	35	0.3	0.86%		Not enough total impulse
E20	Aerotech	Single Use	Composite	White Lightning	24 mm	35	0.3	0.86%	$ 13.50	Not enough total impulse
E22	Cesaroni	Reloadable	Composite	Smokey Sam	24 mm	35			$ 17.38	Not enough total impulse
E23	Aerotech	Reloadable	Composite	Blue Thunder	29 mm	37	0.18	0.49%	$ 15.00	Expensive, not quite enough total impulse
E18	Aerotech	Reloadable	Composite	White Lightning	24 mm	39	0.95	2.44%	$ 9.67	Slow burn, too much variation
E16	Aerotech	Reloadable	Composite	White Lightning	29 mm	40	0.85	2.13%	$ 15.00	Expensive, slow burn
E28	Aerotech	Reloadable	Composite	Blue Thunder	24 mm	40	0.27	0.68%	$ 9.67	Good Compromise
F23	Aerotech	Single Use	Composite	Fast Jack	29 mm	41.2	0.8	1.94%	$ 17.00	Expensive, too much variation
F44	Aerotech	Single Use	Composite	White Lightning	24 mm	41.5	0.34	0.82%	$ 15.00	Expensive
F12	Aerotech	Reloadable	Composite		24 mm	45	1.14	2.53%	$ 11.00	Slow burn, too much variation
F30	Aerotech	Single Use	Composite	Fast Jack	24 mm	47	0.5	1.06%	$ 20.00	Expensive, too much variation
F62	Aerotech	Reloadable	Composite	Fast Jack	24 mm	47.6	0.73	1.53%	$ 14.50	Expensive, too much variation
F63	Aerotech	Reloadable	Composite	Red Line	24 mm	49.5	1.06	2.14%	$ 14.50	Expensive, too much variation
F15	Estes	Single Use	Composite		29 mm	49.6	0.83	1.67%		Slow burn, difficult supply.
F27	Aerotech	Single Use	Composite	Red Line	29 mm	49.6	0.8	1.61%	$ 17.00	Expensive
F51	Cesaroni	Reloadable	Composite	Blue	24 mm	49.9			$ 17.32	Expensive, no data on variation
F24	Aerotech	Single Use	Composite	White Lightning	24 mm	50	0.43	0.86%	$ 11.00	Possible, but overpowered
F37	Aerotech	Reloadable	Composite	White Lightning	29 mm	50	2.05	4.10%	$ 17.99	Expensive, too much variation
F39	Aerotech	Reloadable	Composite	Blue Thunder	24 mm	50	0.49	0.98%	$ 11.00	Possible, but overpowered

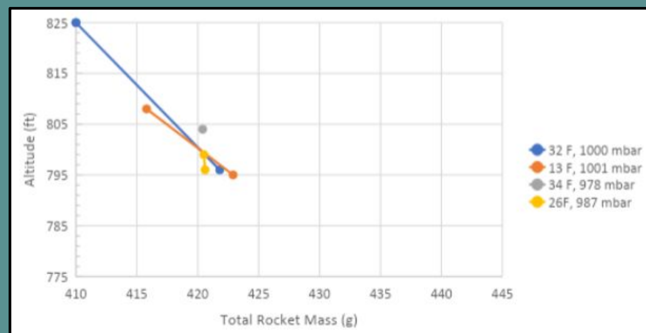
* Data from TARC Approved Motor List

** Data from NAR Motor Certification Database

- Initial designs showed that basic components at ~400 g with good aerodynamics required a total thrust of about 40 N-s.
- We pulled the certification data for relevant motors from NAR and looked at the standard deviation of total thrust. Obviously, smaller stdev is more consistent. Looking for less than 1%.
- Looked for fast burn motor (high average thrust) to get the rocket off the rail quickly (min 40 ft/s). Higher, better to reduce weather cocking.
- Some propellants, like white lightning proved difficult to ignite.
- Finally, we wanted a lot of test flights, so cost does factor. Reloadable motors tended to drive the price down.
- The E28 became the only logical choice, with an option of going to an F39 if we needed more thrust.

Initial Data

- ➢ Initial, uncorrected data had irreconcilable inconsistencies
- ➢ Did not account for
  - ○ Overstability and susceptibility to weathercocking
  - ○ Altimeter-reported altitude varies on temperature
  - ○ Motor variations



- Our initial launches went… a little less than perfect. We didn't account for changing weather, temperature, wind, or motor conditions. However, we recorded everything!
- As such, data was largely varied - we were unsure why the data we collected was varied

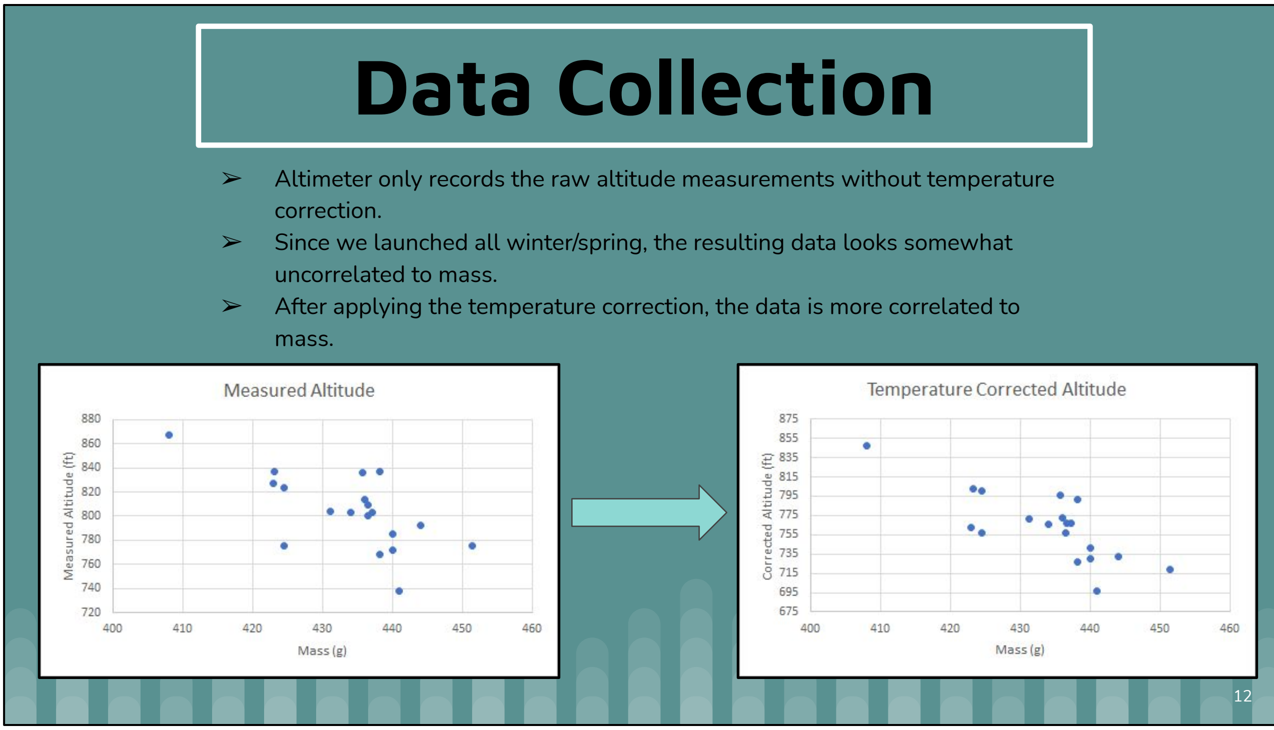
Data with Temperature Compensation

- ➢ Altimeter readings are dependent on temperature
  - Warmer day: reports under actual altitude
  - Colder day: reports over actual altitude
- ➢ Judges only use reported altitude, so compensation for variation needed
- ➢ The actual altitude that the rocket should fly to will be a function of temperature.

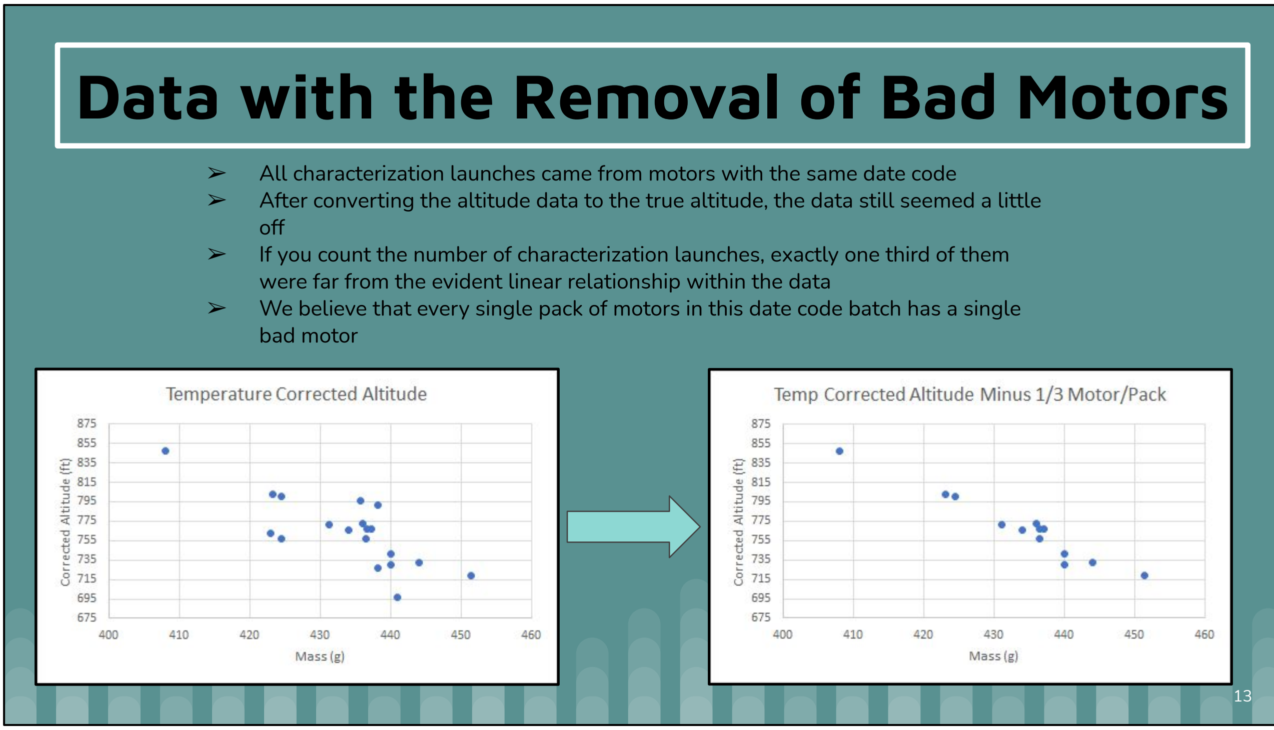
Actual Altitude = Reported Altitude * (273.15 + Launch site temp C) / 288.15

- The rules state that the altitude is determined by the reading on the altimeter, not the actual altitude.
- Reading a number of NAR and NARCON presentations it is clear that the altimeter, and all barometric pressure sensors, have a strong temperature dependence.
- We learned that it was important to fly to the altitude that would read the correct altitude, not necessarily fly to the target altitude (unless it’s 59 F!).
- We are from Michigan. Flying takes place from 0 F to 90 F!

[NARCON altimeter info PPT]



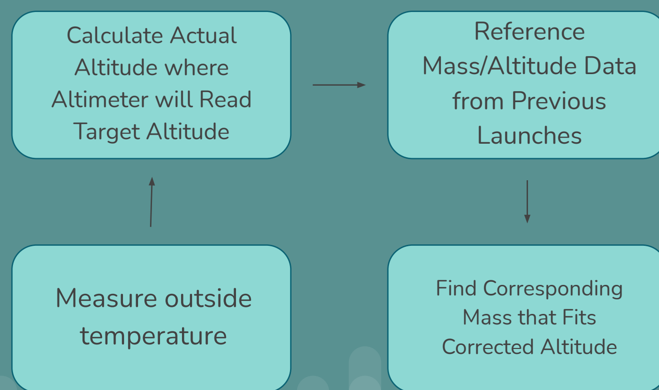
- Initial data was collected without correcting for temperature variations
- Once we convert our raw altitude data to a temperature corrected altitude, we can see that there’s a linear relationship between rocket mass and the true altitude it reaches
- However, we can see that there’s still many erroneous data points



- We originally flew on a very consistent date code of motors. However, the motors ordered for this year showed a lot of inconsistencies.
- All test launches from same date code, we still had ⅓ of the data relatively inconsistent.
- Correlated every launch to the pack that the motors came from. One launch from each pack was an outlier +/- 20-40 ft.
- Removal of one motor from each pack resulted in even stronger correlation.
- The one outlier typically had a different color marker line on the motor lining, but we are still investigating. Fuel grains are still the same mass.
- We suspect that the one fuel grain with a different color marker line/outlier may actually be different.
- During our qualification flights, we opened a new pack, determined if one of the motors was different from the others, then flew one of the two similar motors to verify if it was a good motor.
    - In the event that it was, we were willing to fly the other similar motor as a scored flight

Methodology of Calculating Mass Based on Temperature

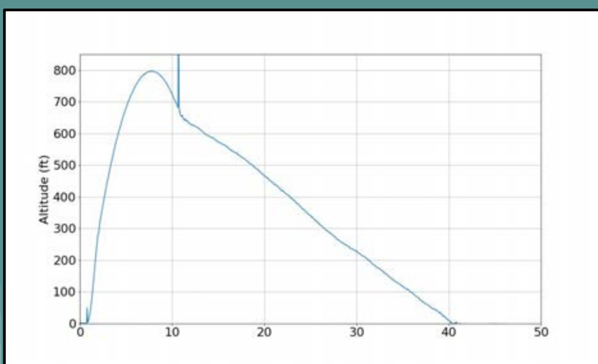
Temperature (F)	Actual-from-measure	Meas from Actual	Target for 800 ft
24	0.932	1.07	745.9
26	0.936	1.07	749.0
28	0.940	1.06	752.0
30	0.944	1.06	755.1
32	0.948	1.06	758.2
34	0.952	1.05	761.3
36	0.955	1.05	764.4
38	0.959	1.04	767.5
40	0.963	1.04	770.6
42	0.967	1.03	773.6
44	0.971	1.03	776.7
46	0.975	1.03	779.8
48	0.979	1.02	782.9
50	0.982	1.02	786.0
52	0.986	1.01	789.1
54	0.990	1.01	792.1
56	0.994	1.01	795.2
58	0.998	1.00	798.3
60	1.002	1.00	801.4

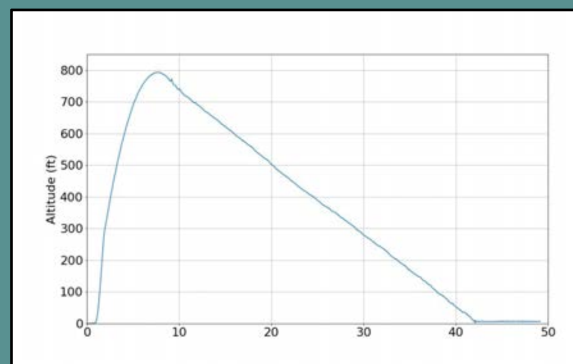


- Once test launches were complete, we developed a flow:
  - Measure outside temperature just before time of launch.
  - Calculate the actual altitude that the rocket needs to go to based on the altimeter target altitude and the temperature.
  - Determine mass required (including wadding, motor weight, etc) based on test flight data.

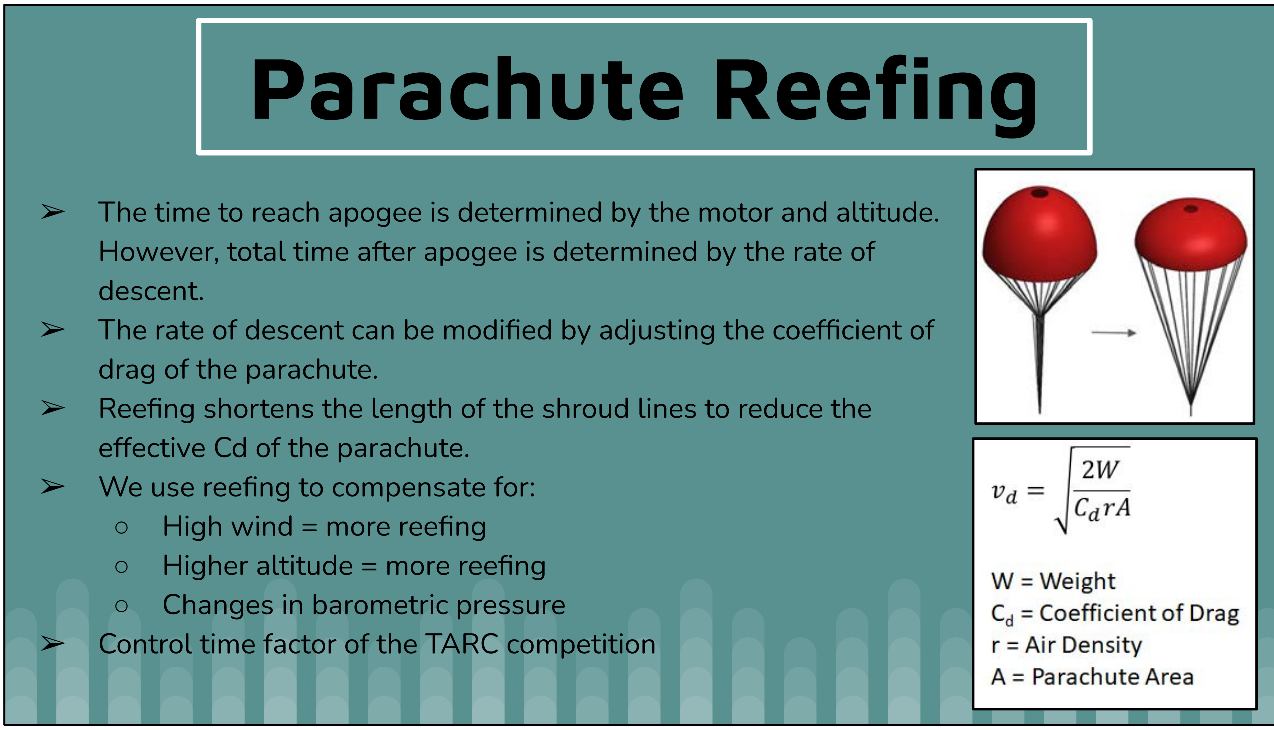
Optimization of Ejection Delay

- ➢ OpenRocket calculated an optimum delay of 7 s.
- ➢ E28-7 motors showed actual delays of close to 10 s.
- ➢ After collecting enough data, we began drilling 2 s off of each delay resulting in consistent ejection charges between 8-9 s.

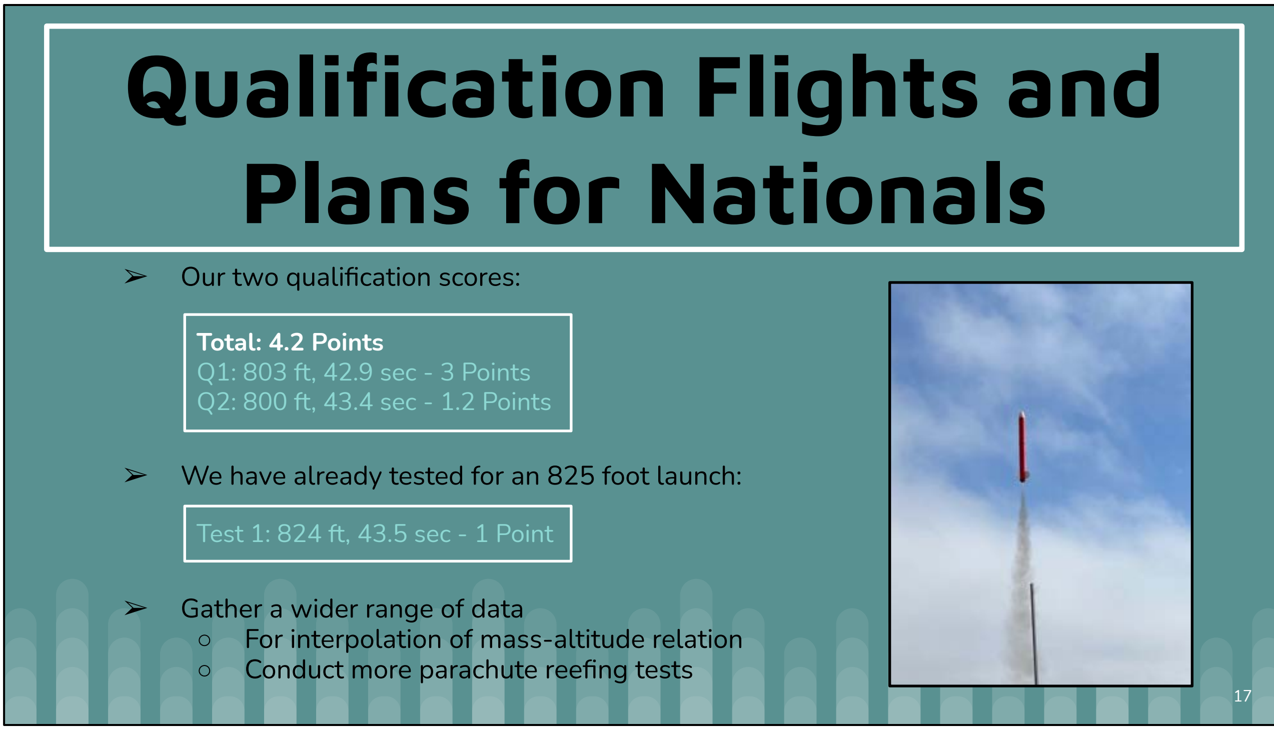




- Ideally, we would have liked the ejection charge to fire somewhere between apogee and 1 s after apogee.
- Several date codes of E28-7 motors all resulted in significantly longer delays than specified.
- Drilling the delay grain resulted in consistent ejection just after apogee.
- If ejection is too early, then the delay grain determines altitude. If too late, then time is wrong and potentially damage rocket from high speed deployment.



- During characterization launches, we did not systematically characterize reefing.
- We mainly adjusted based on test launches to get close.
- Our goal in the future is to systematically quantify rate of descent vs the amount reefed based on weather conditions and mass changes (for different altitudes).



- Thanks to our extensive characterization data, our qualifying launches resulted in a total score of 4.2 points (No, we didn't launch a third, these were on our first two tries)
- Later on that same day, we also aimed for an 825 foot launch to prove that our data was consistent throughout the National's height difference
  - Without any practice launches, our very first attempt for 825 feet went to 824 feet, proving that our data can be extrapolated to higher altitudes (and, by extension, to lower ones)
- Before Nationals, we have to collect similar data on another date code of motors (we are, unfortunately, running low on our original supply)

Pre-COVID Teamwork!

- ➢ We met weekly in the Aerospace Club meetings
- ➢ Collaboratively built rockets of different designs
- ➢ Split rocket preparations between several people
- ➢ Took turns building rocket motors
- ➢ Weekly launches, rain, shine, or blizzards!
  - ○ We have actually launched in snow… lots and lots of snow…

- We would meet every Monday, from 2:30-3:30 in a club room at school
- While the remainder of the Aerospace Club would work on building different rockets, the TARC team focused on designing and building rockets in small groups
- We held weekly launches, allowing for members to learn how to build motors, pack parachutes, and properly prep rockets for launch
- Due to the fact that we are located in Michigan, a reasonably number of our launches are in cold weather conditions (even occasionally during snowstorms!)

Post-COVID Teamwork!

- ➢ Weekly Zoom meetings to discuss changes, ideas, and schedule new launch dates
- ➢ Collaboratively designed different versions to test specific variables
- ➢ Each team member built separate rockets
- ➢ We met up on weekends to launch, making sure to maintain social distancing

- We met every Monday on Zoom at 3 pm to determine next steps, agree on the next launch date, and discuss anything aerospace-related.
- On launch days, we prepped and launched several rockets in a parallel format (preparation and launches done side by side), each working off independent data.
    - Even during the pandemic, we were able to meet nearly every weekend (weather permitting) to launch and gather data.
- Due to the pandemic, we had to shift prep work outside - we ended up setting out a table on which to build motors and prep the rocket. We made sure to maintain social distancing and wear masks during this time.
- Being in a pandemic meant we couldn't meet in person to build rockets, so each team member built their own rocket at home.
- Aside from Zoom meetings and launches, we communicate as a team through emails and a group chat.

Lessons Learned

- ➢ Learning that the altitude reported by the altimeter, not the actual altitude, made us look at this in a completely new way.
- ➢ We always knew we wanted the rocket to be stable, but overstable created problems with repeatability due to weathercocking.
- ➢ Even though you order a single date code, that lot may still have inconsistencies.
- ➢ Trust your data! With 1 out of 3 motors being off, making corrections based on a single launch is a bad idea!

- We originally thought the altimeter reported actual altitude. Learning to adjust altitude to read the target altitude was key to success.
- Most of the guides written for TARC suggest an overstable rocket with no real discussion of the disadvantages. Learning to tune stability to still be safe with enough margin, but minimize variations with wind helped make the altitude much more consistent.
- Single date code lots don’t necessarily mean consistent motors.
- Trust your data. We originally made adjustments after every launch. When we flew with a bad motor, we would then overcompensate the next launch. Record enough data, and trust it.

Next Steps

- ➢ Gather more data above and below 775-825 ft
- ➢ Fly in wider range of temperatures.
- ➢ Analyze rate of descent vs reefing, mass, and barometric pressure.
- ➢ Calculate optimum rate of descent vs target altitude, temperature, and wind, then creating an equation to determine how much parachute should be reefed.
- ➢ Possibly use thin-wall fiberglass for booster body tube.
- ➢ Build spare rockets, order new date code motors, and test, test, test!

- Even though teams for finals have not been announced, we are going to continue practicing based on National Finals rules.
- We largely neglected rate of descent as our times were typically close if the altitude was correct. However, we'd like to characterize rate of descent. We can do this based on the historical data that we have.
- Create a process for setting the amount that the parachute is reefed based on actual altitude (not target altimeter reading).
- These rockets are launched enough that they really take a beating. Definitely build spare rockets, but possibly also look into using thin-wall fiberglass.
- Order new date code of motors and fly a lot! Try to determine if new date code has the ⅓ motor problem.