Space Technologies & Rocketry (STAR) | Berkeley, CA

BART Project Report

Abstract

This rocket is designed and built as one of the Universal Intro Projects (UIP) for Berkeley's Space Technologies and Rocketry (STAR) team. This semester-long onboarding project introduced new members to all elements of rocket design and fabrication through launch through building a K-class high powered rocket. Workshops led by experienced STAR members introduced concepts on airframe design & CAD, avionics PCB design, recovery, payload, and more allowing us to apply those skills towards our rocket.

For all eight members of Berkeley Aerial Rocket Transport (BART) team, this is the first rocket we've ever built. The primary objective of this project is to construct a Level-2 rocket capable of achieving an apogee of approximately 5000 feet within a single semester. This rocket carries a custom-designed payload: an arduino-powered ice cream maker roughly the size of a 2U CubeSat.

To accomplish this goal, we utilized advanced engineering tools and manufacturing techniques. Starting in mid-September of 2024, OpenRocket was employed for the initial layout and simulations. From this layout a 3D CAD design was made through Onshape. Altium was used to design custom printed circuit boards (PCBs) for avionics systems. Manufacturing processes included waterjet cutting, laser cutting, and soldering, all conducted at UC Berkeley facilities.

This project provides our team with the foundational skills and experience to build rockets, enabling us to specialize further in preparation for ambitious rocketry competitions such as the Intercollegiate Rocket Engineering Competition (IREC). By scaling up the expertise gained from designing, building, and launching this Level-2 rocket, we came out better-equipped to tackle the challenges of larger, more complex systems and contribute to cutting-edge collegiate rocketry projects.

The rocket is slated to launch in February of 2025 at the Friends of Amateur Rocketry (FAR)'s Mojave Test Area.

Berkeley Aerial Rocket Transport

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Nomenclature

Apogee: The highest point in the rocket's trajectory.

Arduino: Open-source electronics platform used for building digital devices.

Avionics: The electronic systems used for flight control, telemetry, and data acquisition.

CubeSat: Standards for satelite and payload sizes.

FabLight: A fiber laser cutter used for precision cutting of metal components.

Friends of Amateur Rocketry (FAR): Non-profit providing infrastructure for static test firing

K-Class Rocket: Category of high-powered rockets with impulse of 1280 - 2560 Newton-seconds.

OpenRocket: A free, open-source software tool for designing and simulating rockets.

Payload: The functional cargo carried by a rocket, such as scientific experiments or technical demonstrations.

Recovery System: The system, including parachutes, used to safely return a rocket to the ground after flight.

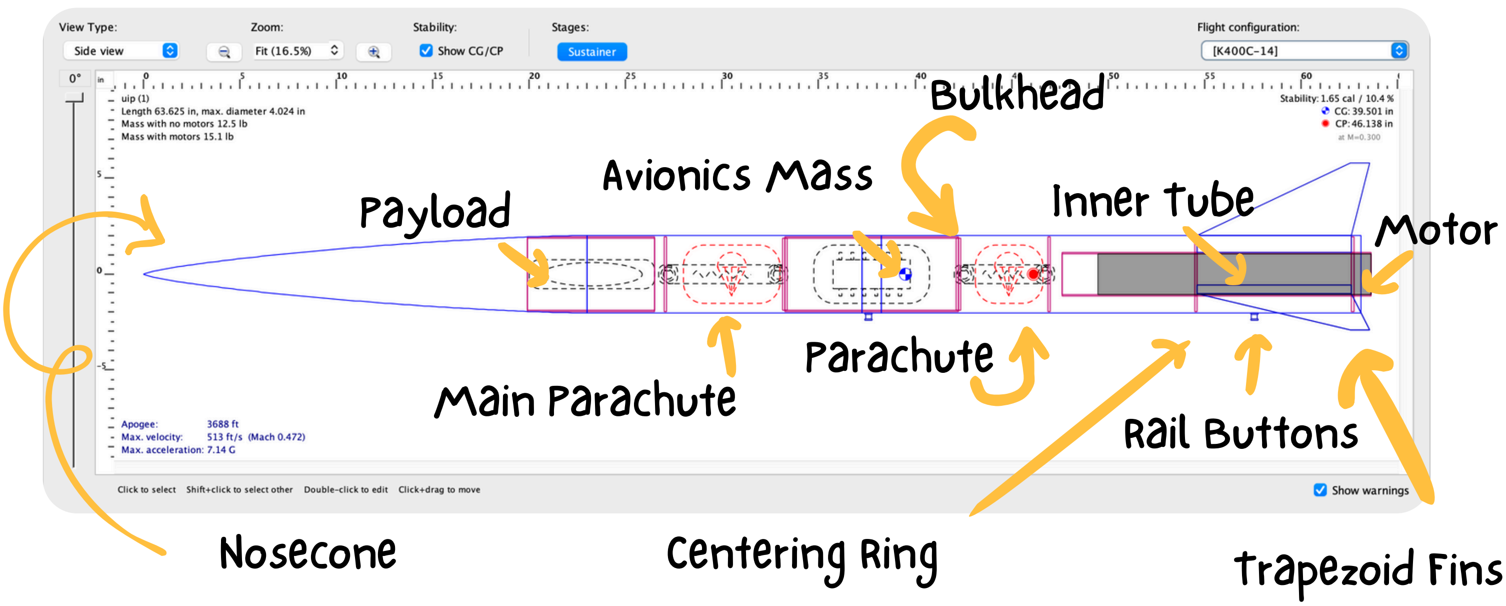
Space Technologies and Rocketry (STAR): UC Berkeley's competition rocketry team

BART Project Report

System Architecture

Following the design process of the rocket, the overarching architecture starts with a 2D Open Rocket layout, which sets the specs for propulsion, airframe, and recovery. Development for the avionics and electronics happened concurrently alongside the fabrication process for the rocket, as well as payload development and iteration.

Open Rocket ORK

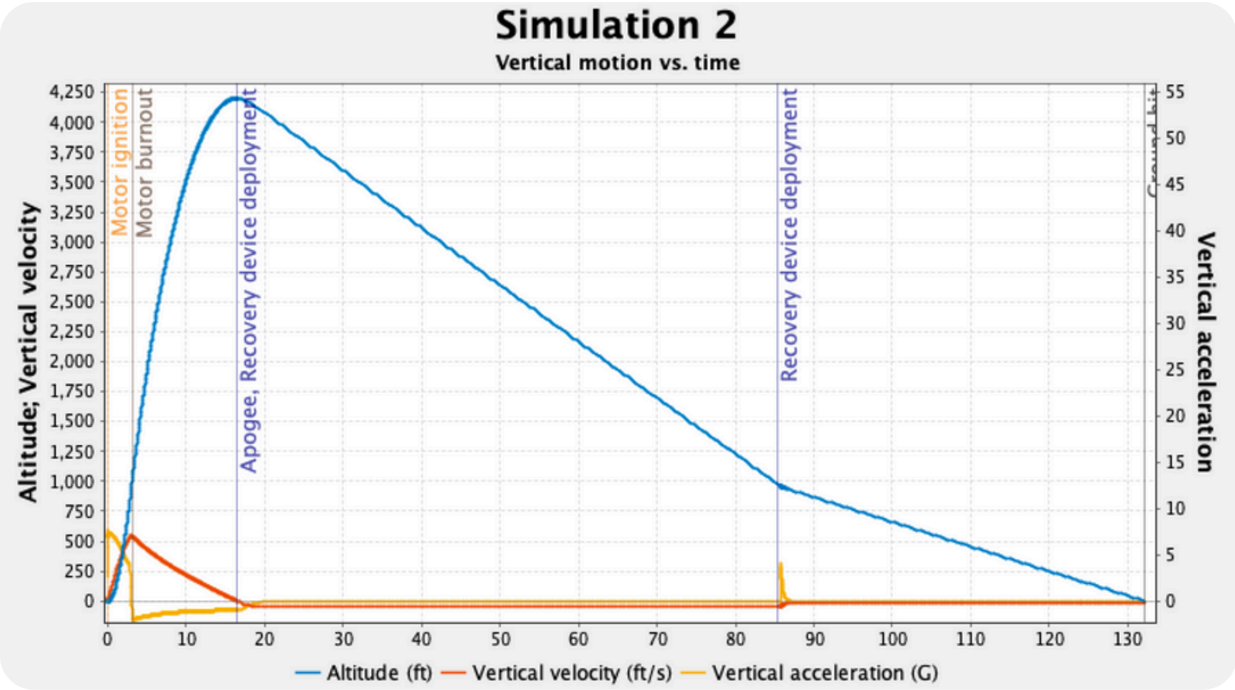


OpenRocket is a rocketry simulation tool that enables us to design and simulate the rocket's behavior at various stages of its launch. Many of the parts were dimensioned based on the stock materials available and propulsion motor. Starting with the base layout, each rocket component—such as body tubes, nose cones, fins, bulkheads, and recovery systems like parachutes and shock cords—were added to fit the overall design goals.

By adjusting the dimensions, material properties, and placement of each component, we could repeatedly run simulations to iteratively refine and optimize the rocket's performance. The simulations provided critical data on motor configurations, flight apogee, velocity, and acceleration, helping ensure the rocket met the necessary design and flight stability requirements.

Additionally, the OpenRocket file (ORK) defined constraints for payload and avionics, such as mass and dimensional boundaries. These constraints acted as a framework, allowing concurrent development of subsystems and allow for smooth integration between the different parts.

Vertical Motion V. Time Plot

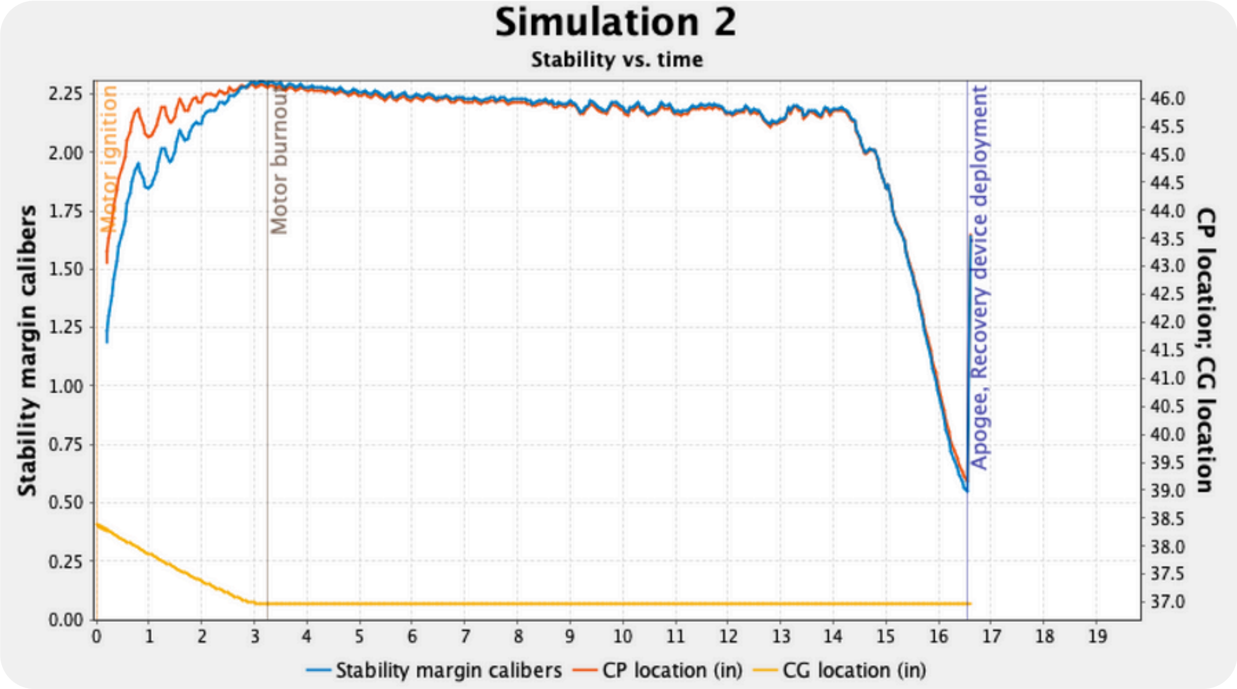


The simulation plot illustrates the vertical motion of the rocket over time, showing altitude, vertical velocity, and vertical acceleration throughout its flight. The key events of the launch are shown in the plot such as motor ignition, motor burnout, and recovery deployment. We can find the altitude using the blue curve, which peaks at approximately 4,201 feet in this graph. The red curve shows vertical velocity, which rises sharply during motor thrust, decreases after motor burnout, and transitions to zero at apogee. The yellow curve represents vertical acceleration, which show the high G-forces experienced during thrust and a spike during recovery device deployment.

To determine whether the deceleration force is safe using the plot, we focus on the yellow curve representing vertical acceleration (in Gs). The spikes in this curve indicate moments of rapid deceleration, particularly during recovery device deployment. By reading the maximum value of vertical acceleration during these events, we can assess whether it falls within a safe range for the rocket's structural integrity and payload.

Safe deceleration forces depend on the rocket size and specs. Through research, we found that safe decelerations are specific to the structure and payload. The rocket frame and connections must withstand these forces without buckling or separating. Typically, hobby rockets are designed to safely tolerate deceleration forces up to 20–30 Gs. This is far above the simulation deceleration from the the plot.

Stability V. Time Plot



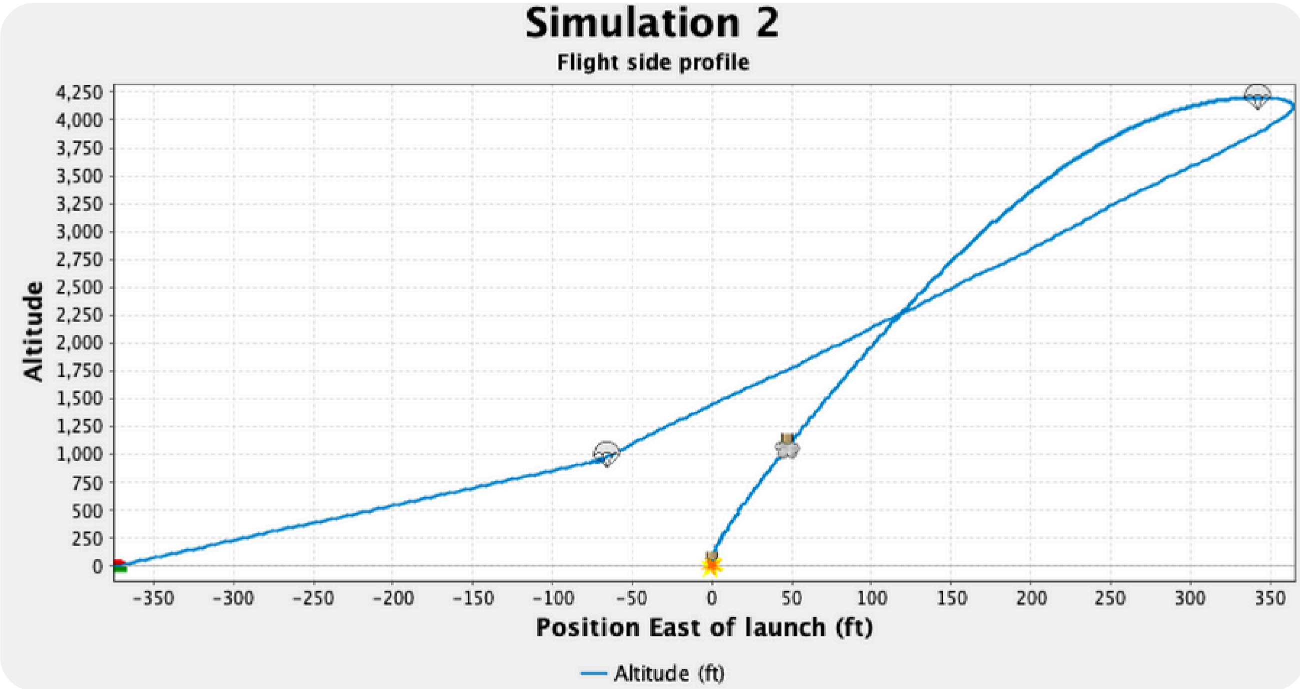
As the rocket's velocity changes, the center of pressure (CP), represented by the orange line, shifts forward and backward due to the consumption of fuel by the motor. Simultaneously, the center of gravity (CG), shown by the yellow line, moves as the mass distribution changes over time. Increasing the surface area of the fins can help shift the CP further backward, increasing the distance between the CP and CG. This distance determines the rocket's static stability, which is calculated using the formula: (CP-CG) / (Body Diameter)

For our rocket, the stability margin is 1.65 calibers or 10.4%. A "caliber" is the diameter of the rocket's body, meaning the CP is located 1.65 times the body diameter behind the CG. The 10.4% figure offers an alternative way to express this margin relative to the rocket's dimensions.

A good stability margin typically falls between 1.0 and 2.0 calibers. Margins below 1.0 indicate under-stability, leading to potential tumbling, while margins above 2.0 can result in over-stability, causing weathercocking or reduced adaptability to flight conditions. With a margin of 1.65 calibers, our rocket is within the ideal range, providing sufficient stability for a straight flight path without excessive resistance to changes in trajectory. Adjusting the fins to increase surface area helped optimize this balance. Additionally, the Mach number varies during the flight due to velocity changes, but the stability margin ensures consistent performance throughout.

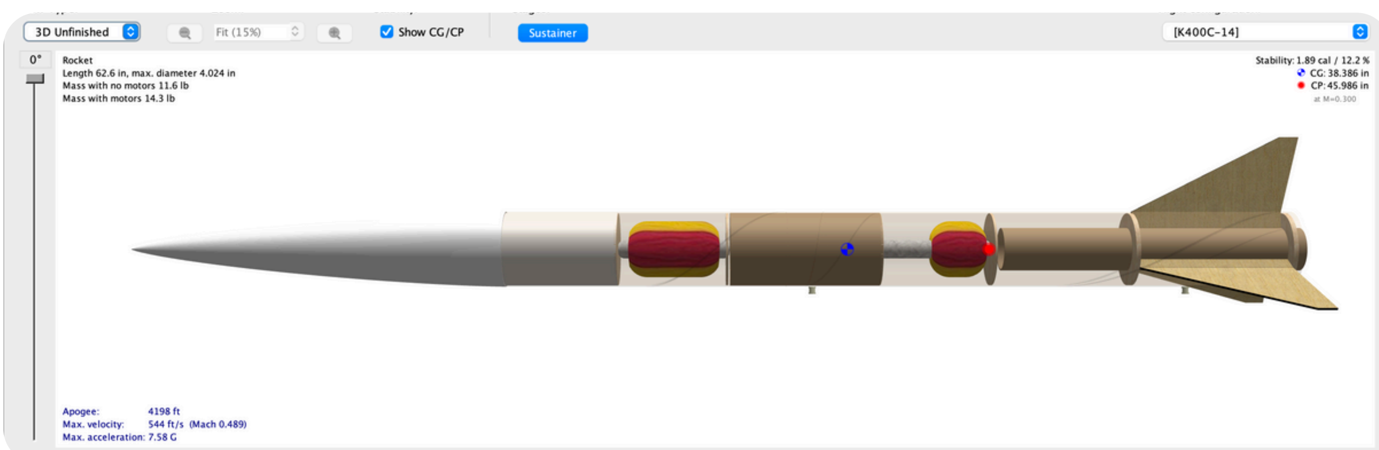
The reason for this is in the fins: in order for a rocket to fly straight without oscillating back and forth, the fins need to “overcorrect” each other. The fins counteract deviations in the flight path by applying corrective forces. These corrections must slightly exceed the disturbance to ensure the rocket remains stable without oscillating back and forth, which can occur if the corrections are too aggressive or insufficient.

Flight Side Path Plot



This graph indicates how much the rocket will drift during flight. The axis graph is heavily skewed, meaning that it will be a lot more vertical than horizontal. The plot shows the rocket's eastward drift from the launch pad, which reaches approximately 375 feet at the point between when the two parachutes are released. This displacement is heavily influenced by wind conditions, while we cannot accurately predict at this point in the process.

However, this information is still useful to understanding the safety of the flight path and the feasibility of recovering the rocket safely. We can see from the graph that the drift follows a smooth, predictable curve with minimal oscillations. This indicates that the rocket is stable and well-balanced. We can also see that the descent rate is decreasing steadily after the parachutes are deployed, which is what we want. Irregularities in the trajectory might suggest issues with drag, stability, or thrust misalignment.



Propulsion

Motor: Aerotech 54mm HP SU DMS Motor - K400C-14A

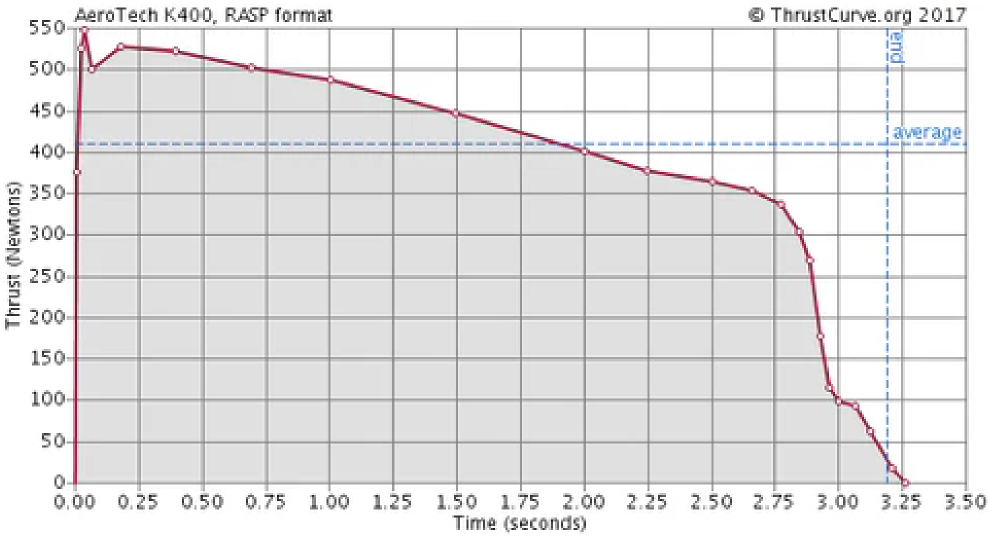
Motor Diameter: 2.125 inches (54mm)
Casing Length: 14.10 inches (358mm)
Total Impulse: 1361 N-sec
Average Thrust: 400 newtons
Peak Thrust: 549 N-sec
Thrust Duration: 3.3 seconds
Delay Time: adjustable up to 14 seconds
Propellant Weight: 650 grams
Motor Weight: 1194 grams

For our Level 2 (L2) rocket project, we chose the AeroTech K400C-14 motor due to its ideal thrust profile, high performance, and compatibility with the rocket's design parameters. The K400 motor is a composite propellant motor categorized in the K-class, delivering an average thrust of approximately 400 Newtons over its burn time. This makes it well-suited for achieving the desired altitude and velocity while ensuring structural safety and stability during the flight.

The -14 designation refers to the delay in seconds before the ejection charge activates, making it a good match for the rocket's expected coast phase duration and apogee timing. Its lightweight construction and robust design further enhance its compatibility with the rocket's propulsion needs.

The thrust plot for the K400C-14 motor shows how the thrust changes over time. Looking at the various stages of launch, the rocket goes through three main phases.

1. **Initial Thrust:** Rapidly accelerates up to 500N
2. **Sustained Thrust:** Stabilization at average of 400N
3. **Thrust Tailoff:** Trust decreases gradually then drops to zero

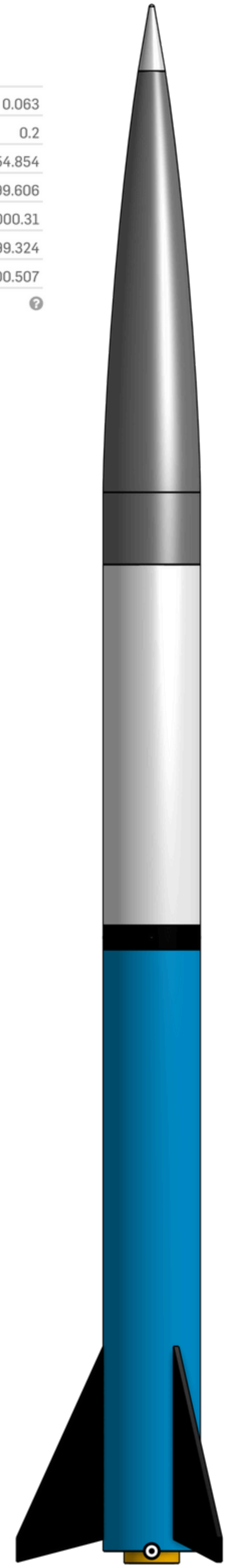


Airframe

Total height: 5' 5"
Tube Material: Fiberglass

- Top Tube: 15"
- Middle Tube: 1"
- Bottom Tube: 25"

Name	Fiberglass
Density (lb/in³)	0.063
Poisson's ratio	0.2
Young's modulus (Psi)	10587754.854
Tensile yield strength (Psi)	29999.606
Ultimate tensile strength (Psi)	50000.31
Compressive yield strength (Psi)	21999.324
Ultimate compressive strength (Psi)	35000.507



Nose Cone

Our rocket uses a COTS 5:1 Von Kármán nose cone due to its ability to minimize drag and maintain laminar airflow, particularly at supersonic speeds. The 5:1 is the length to diameter ratio, with a tapered profile derived from the Sears-Haack body. The sharp tip penetrates the incoming shock wave better than rounded shapes.

This is a proven and accessible deisgn that reduces pressure drag, heating, and shockwave formation. Additionally, it provides stable aerodynamic properties, aiding in flight stability and maximizing altitude efficiency, making it a standard choice for rockets requiring low-drag performance.

Body Tubes

The body tubes are 4" OD fiberglass tubing. Fiberglass is ideal for rocket body tubes due to its high strength-to-weight ratio, with tensile strength ranging from 30,000 PSI and a lightweight density of 0.063 lb/in^3.

Fins

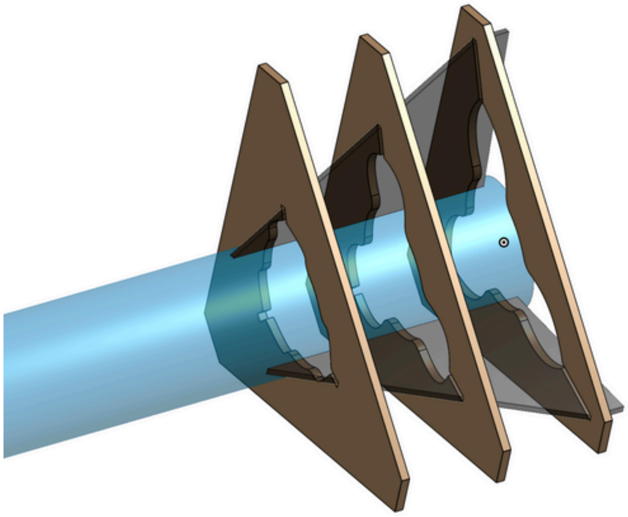
The fins are tapered swept fin, which we researched to be ideal for smaller L2 rockets given it’s ability to improve flight stability. This is because the swept design minimizes drag at higher speeds, especially in supersonic flight, while the tapered profile reduces weight and ensures a lower center of pressure. This shape also provides sufficient surface area for effective control and stability without adding unnecessary bulk or drag, making it optimal for high-performance, compact rockets.

The fins are delaminated by carefully sanding the fiberglass layers to create a smooth and even surface, ensuring proper adhesion and a clean finish. This process reduces imperfections, improves aerodynamics, and enhances the structural bond between the fins and the airframe.

Attatchment

The components of the airframe are bonded using JB Weld epoxy for its high strength and resistance to heat and vibration, ensuring durability during flight. Fillets are added at joints to improve structural integrity and reduce aerodynamic drag.

Fin Attatchment Jig
The fins were aligned using custom designed laser-cut plywood. Each piece has rounded space on the inside to enable us to add epoxy to the side of the fin and allow us to reach in with the fillet tool to round it.

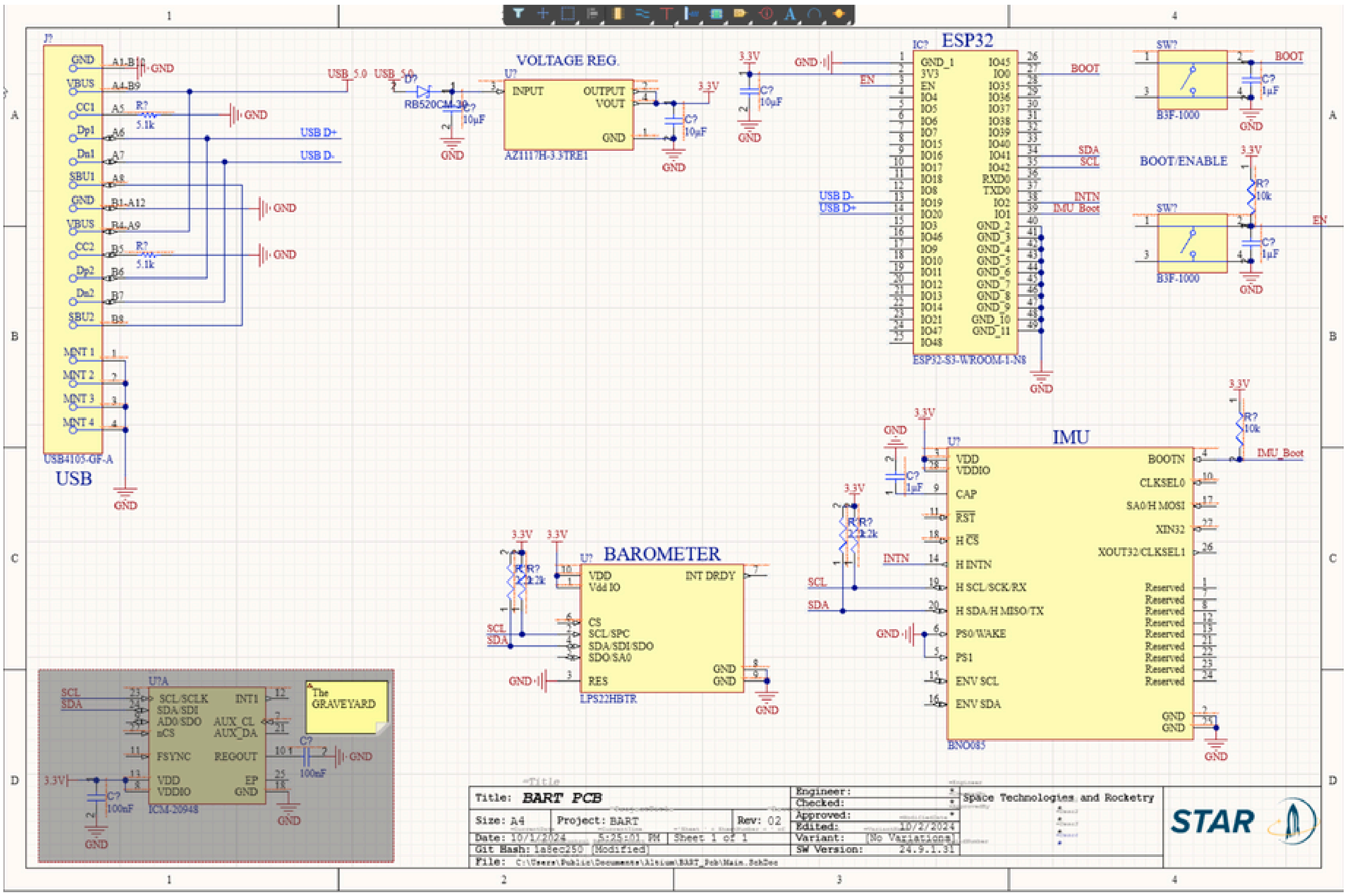


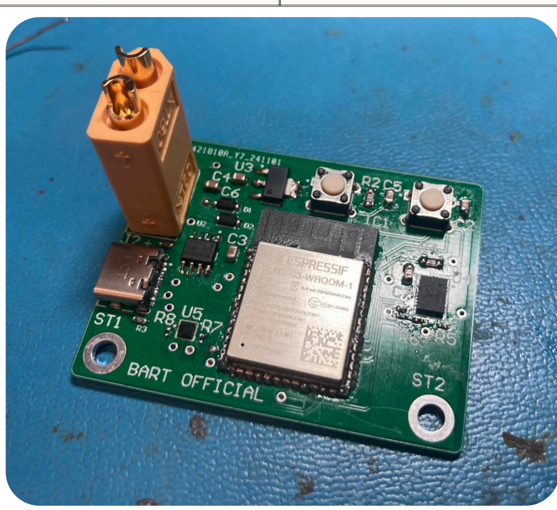
Avionics

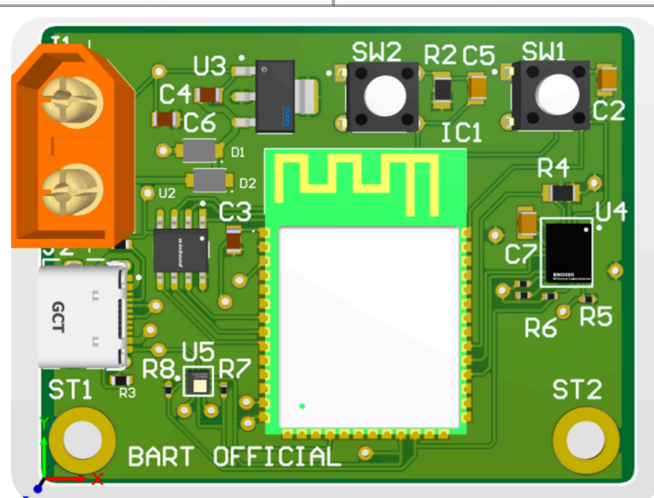
The main board and the payload board are custom-designed in Altium, then soldered and programmed through the Arduino IDE.

Main Board

The main board has a BNO085 9-axis IMU (Inertial Measurement Unit) and LPS22HBTR Pressure Sensor/Barometer. The parts are ordered through Digikey and soldered at Berkeley. The schematic features boot and reset switches for system control, pull-up resistors on communication lines for signal stability, and provisions for interfacing with external peripherals. This compact, efficient layout ensures reliable operation under the dynamic conditions of rocket flight.

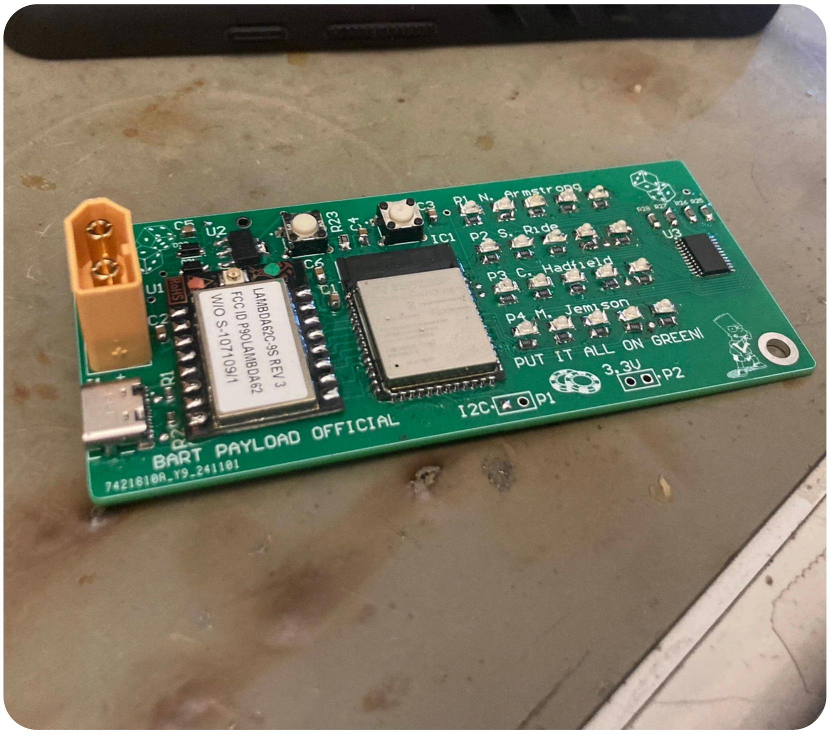






Payload Board

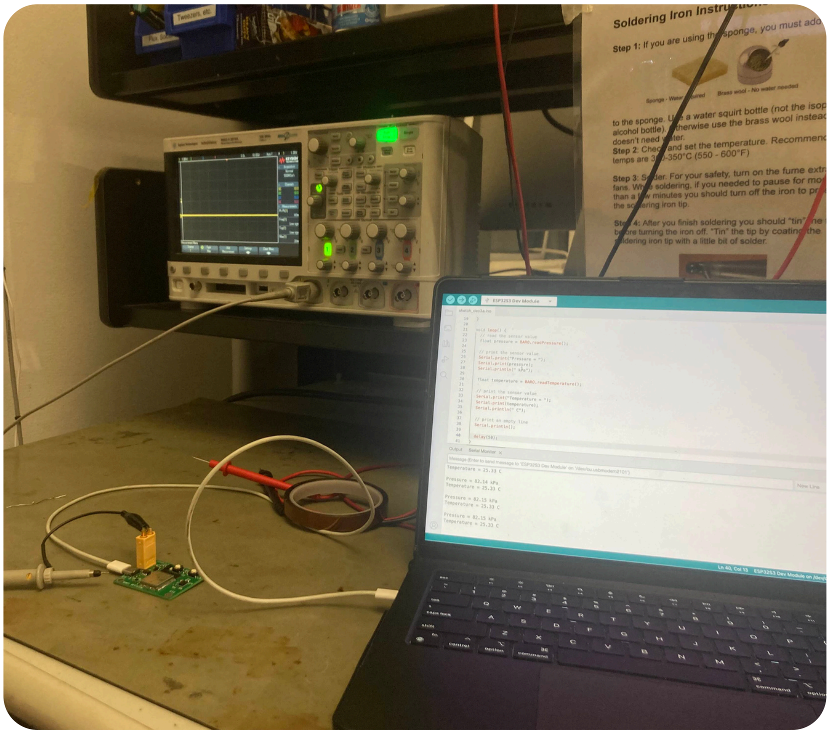
In addition to the physical payload, a custom payload board runs its own ESP32. Using this, we can run custom games on it simply by connecting it to its own power source or with other electronic segments of the rocket.



Programming

The programming is done through the Arduino IDE. The code interfaces with a W25Q16 flash memory chip to save data from the senors. The flash drive is connected with defined pins for clock, data input/output, and chip select, and the program utilizes SPI for communication.

It took a lot of hardware troubleshooting and resoldering to ensure working connections across the board.



Recovery

Using a handy spreadsheet for calculation, we found the appropiate parachute sizes to reduce descent velocity while minimizing drift caused by wind. For this system, a 24-inch drogue parachute was selected to stabilize the rocket during descent, reducing velocity by approximately 50 ft/s. A 58-inch main parachute was chosen to provide a slower terminal velocity, ensuring a safe landing while controlling lateral drift to an acceptable range. The choice of parachute sizes balances safety, drift minimization, and ease of deployment.

Constants
Wind Speed = 20mph
Coordinates: Friends of Ameteur Rocketry on Google Maps
Alt: 2069 ft
Rail Length: 10ft
Angle: 5 degrees
Parachute drag coefficient: 0.75
Main parachute deploys at 500ft altitude

Outputs	User Input			Write a formula for an output			
Parachute Options	Drogue Deployment Velocity (ft/s) ***Total Velocity at Apogee***	Main Deployment Velocity (ft/s) ***Vertical velocity before 2nd Recovery Device IREC: <65 - ~100ft/s***	Landing Velocity (ft/s) ***Vertical velocity before end of graph IREC: <36 ft/s***	KE of Upper Section (ft-lbf) ***<75 ft-lbs***	KE of Avionics Bay (ft-lbf) ***<75 ft-lbs***	KE of Lower Section (ft-lbf) ***<75 ft-lbs***	Drift in 20mph wind (ft) ***<4/5 apogee, ~4000 ft***
Main 58" Drogue 24"	104.91	71.19	26.9	73.66769923	22.33308665	79.79636601	2305.6524
Main 58" Drogue 30"	104.64	56.98	25.7	67.24171676	20.38498695	72.83578417	2640.06
Main 70" Drogue 36"	103.51	47.68	21.4	46.62298688	14.13421645	50.50171194	3138.738
Main 70" Drogue 24"	106.6	71.47	22.8	52.92273015	16.0440455	57.32555231	2464.056

Upper Section (Exclude parachute and shockcord mass)	
Component	Mass (lb)
Nosecone	1.33
Payload	3
Shoulder	0
Nosecone Bulkhead (0.25" Alum)	0.143
Main U-Bolt & Quicklink	0.1
Main Tube	0.978
Epoxy/Fasteners	1
Total	6.551

AV Bay	
Component	Mass (lb)
Coupler Tube	0.435
Switchband	0.065
Bulkheads	0.286
Sled	
Recovery Electronics + Fasteners	0.2
Avionics Component	1.00
Threaded rods and eyenuts	
Total	1.99

Lower Section (Exclude parachute and shockcord mass)	
Component	Mass (lb)
Booster Tube	1.63
Drogue U-Bolt & Quicklink	0.1
Drogue Aft Bulkhead (0.25" Alum)	0.143
MMT	0.58
Motor Dry Mass (K400)	1.55
Centering Rings	0.374
Fins	0.715
Rail Buttons	0.004
Motor Retainer	
Epoxy/Fasteners	2
Total	7.10

Formula for calculating kinetic energy = 1/2mv² in ft-lb (mass in slugs, velocity in ft/s)	Upper Section	AV Bay	Lower Section
Mass (oz)	104.816	31.776	113.536
Mass (lb)	6.551	1.986	7.10
Mass (Slugs)	0.2036116119	0.062	0.221

	Total flight time	Time to apogee	Time under parachute
Main 58" Drogue 24"	94.7	16.100	78.600
Main 58" Drogue 30"	106	16.000	90.000
Main 70" Drogue 36"	123	16.000	107.000
Formula for calculating drift = Time under parachute * wind speed (ft/s)			
20mph	29.33	10mph	14.67

The table takes into account the various dimensions and velocities to output the kinetic energy of the various rocket segments, as well as the drift under 20 mph wind. We use the descent velocities for the drogue and main parachutes, kinetic energy at deployment, drift distances under wind conditions, and total recovery time. With many of the parameters from the OpenRocket ORK, we could easily input them to get the right main and drogue parachute sizes.

Arming Sequence

The arming sequence for the rocket's recovery system involves preparing the avionics bay by installing and securing the avionics sled, connecting the recovery electronics to the power source, and ensuring proper wiring to the igniters for deployment charges. Before launch, the switches are toggled to arm the system, verifying continuity and LED indicators to confirm readiness. Redundant altimeters are used to trigger the drogue parachute at apogee and the main parachute at the preset altitude (e.g., 500 ft), ensuring a safe, reliable deployment sequence during descent.

Inputs	Length
Inner Diameter	3.9
Main Chute	6
Drogue Chute	5.125

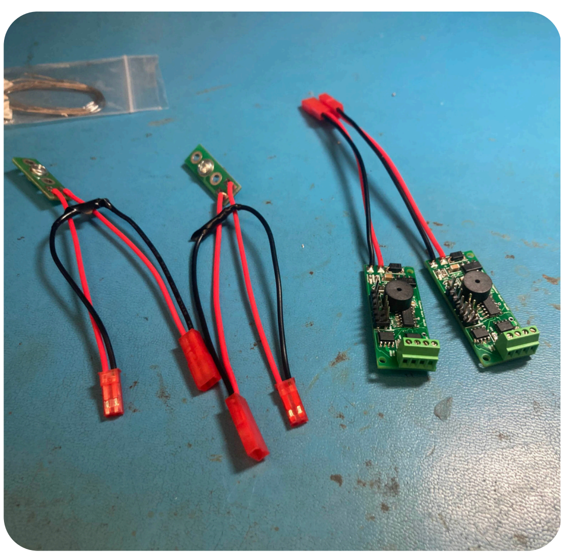
	PSI Value	Recommended BP Amt (g)	Force on Bulkhead (lbs)	Number of #2 Shear Pins	Number of #4 Shear Pins
Main Chute	8	0.29	95.5188	3	2
	9	0.33	107.45865	3	2
	10	0.37	119.3985	4	2
	11	0.4	133.33835	4	3
	12	0.44	143.2782	5	3
	13	0.47	155.21805	5	3
	14	0.51	167.15789	5	3
	15	0.55	179.09775	6	4

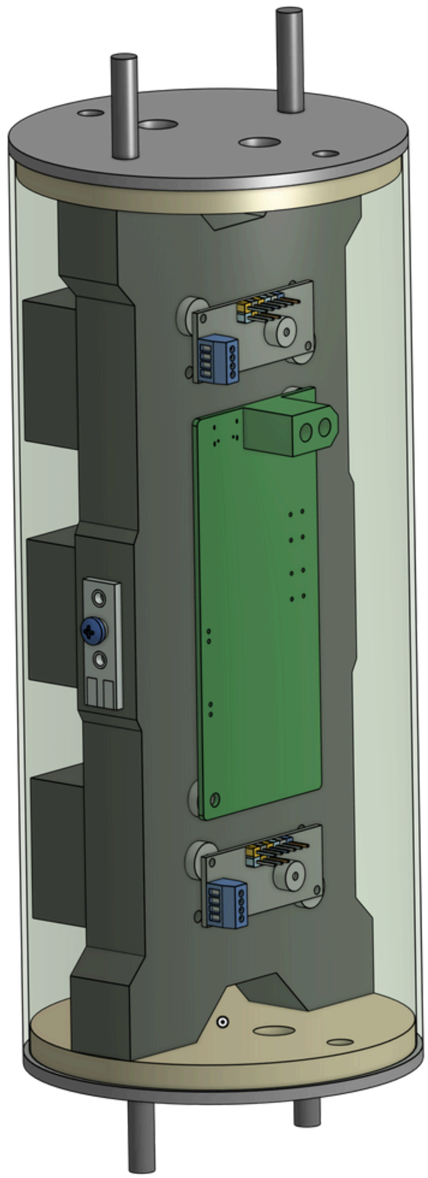
	PSI Value	Recommended BP Amt (g)	Force on Bulkhead (lbs)	Number of #2 Shear Pins	Number of #4 Shear Pins
Drogue	8	0.25	95.5188	3	2
	9	0.28	107.45865	3	2
	10	0.31	119.3985	4	2
	11	0.35	131.33835	4	3
	12	0.37	143.2782	5	3
	13	0.41	155.21805	5	3
	14	0.44	167.15789	5	3
	15	0.47	179.09775	6	4

Avionics Bay

The avionics bay lives in the middle of the rocket, and houses the avionic systems. The custom 3D printed parts allow us to securely mount the battery and boards while the holes in the bulkheads allow us to pass through wires to the black powder charges that release the parachutes stored above and below.

These quarks are used to trigger the ejection charges for parachute deployment at specified altitudes, with redundant systems for reliability.



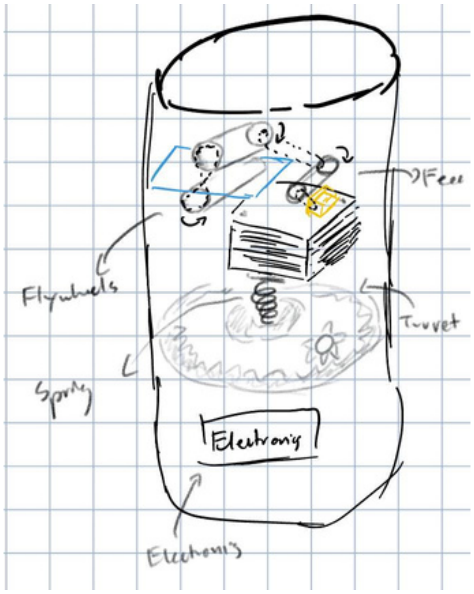


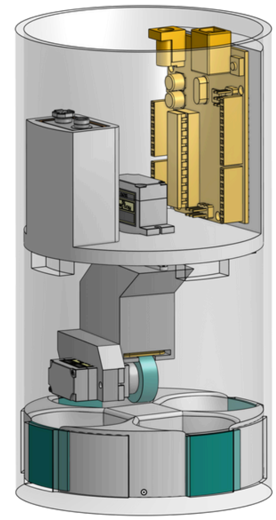
Payload

Version 1

The initial concepts of the payload was a card dispensor to play a remote game of blackjack during launch.

Concept sketches and CAD are seen to the right

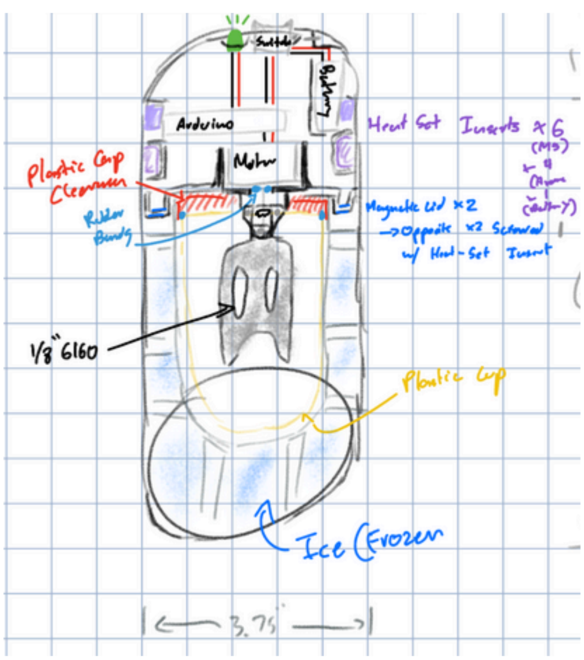


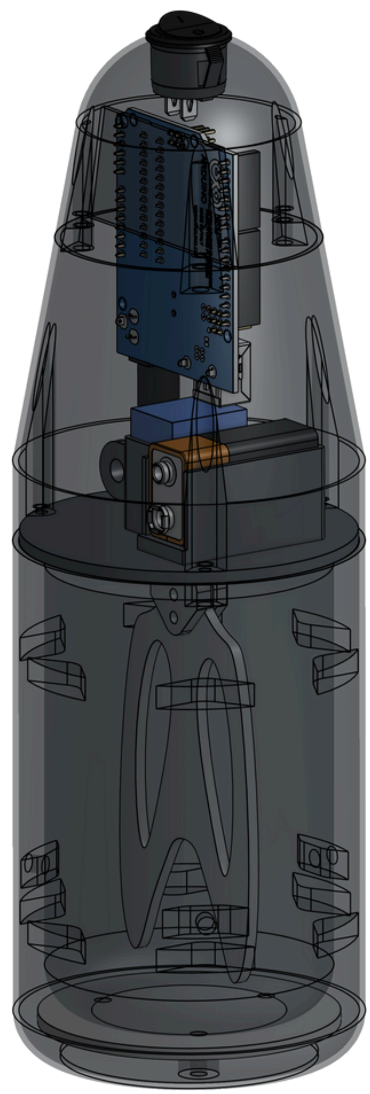


Version 2

Due to the feasibility and practicality of this idea, we choose to go with the ice cream maker payload. This payload would allow us to load in bottoms of heavy cream and sugar in a small peanut butter jar and whip it into ice cream as it's surrounded by insulated ice.

The payload is integrated into the airframe using 3x 5mm heat-set inserts that allow us to insert screws from the exterial of the rocket. The electronics are run through an Arduino hooked up to a 9V battery to power the payload through launch.





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Manufacturing

Parts for the rocket that were manufactured in-house were manufactured in Jacobs Hall, UC Berkeley's Makerspace, with electronics assembly at the Supernode in Cory Hall. These were the tools and processes we used:

OMAX Waterjet

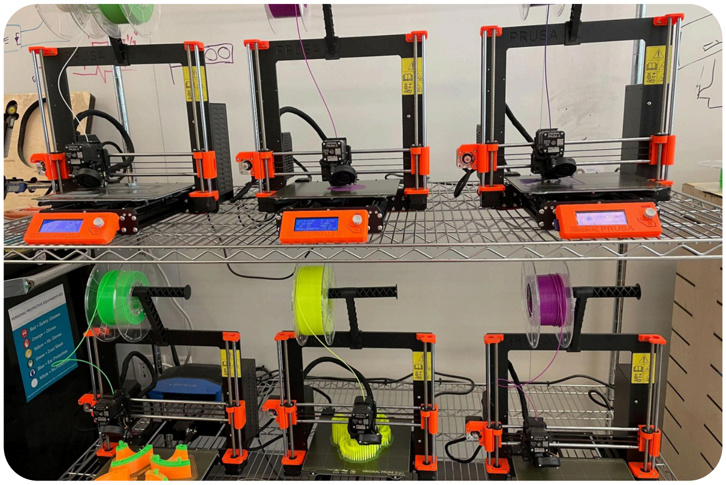
- For quickly manufacturing metal bulkheads and centering rings

Universal Laser Cutters

- Manufactured fin jigs and bulkhead centering pieces out of thin plywood

Prusa 3D Printers

- Printed payload parts quickly and inexpensively for rapid prototyping



Formlabs SLA Printers

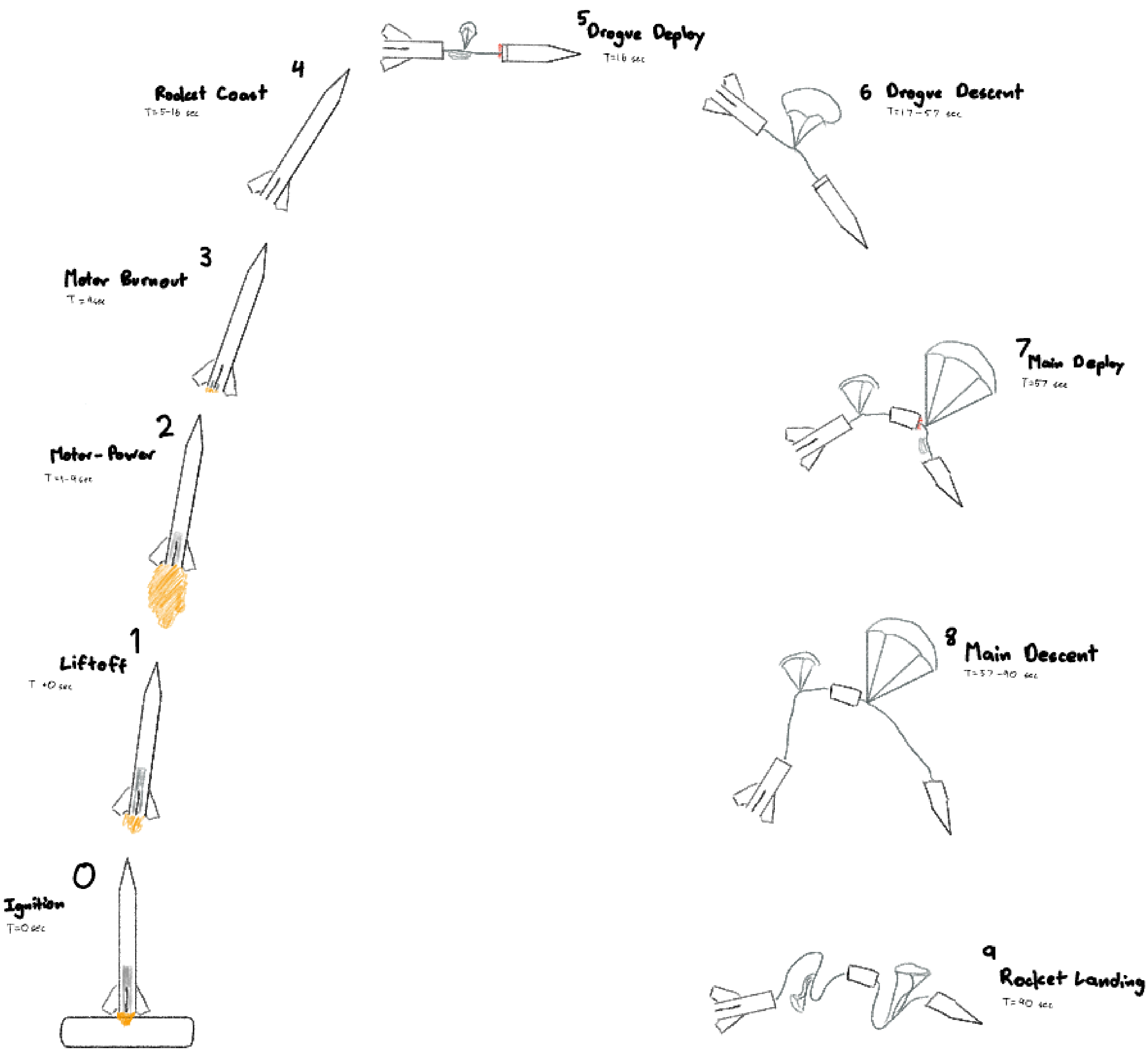
- Used to print final payload parts given high material strength and heat-resistenet proper

Soldering & Electronics

- Soldered and assembled all avionics components
- Used stencils for mounting sensors on main board

BART Project Report

Mission Concept of Operations



Rocket Events

PHASE	*DESCRIPTION*
Ignition	Motor ignites and combusts the liquid fuel
Liftoff	Thrust overcomes gravity and rockets begins ascent
Motor powered flight	The motor burns, accelerating the rocket to it’s highest velocity
Motor burnout	Rocket reaches peak motor-powered speed
Rocket coast	Coasts upward, gradually slowing as it nears apogee
Drogue deploy	Drogue parachute deploys at apogee, stabilizing the rocket's descent
Drogue descent	Slow but stable descent
Main deploy	Main parachute deploys, significantly slowing the rocket
Main descent	The rocket descends slowly and safely under the main parachute
Rocket landing	The rocket touches down on the ground

Conclusion

Airframe

- The design of the airframe following the OpenRocket worked well, with solid construction and fit throughout the manufacturing process. Due to the tight launch timeline, we had limited time to test different variables and run simulations on OpenRocket. Given more time, we'd be able to fine tune the different masses and weight distribution across the rocket, as well as test more fin options.

Avionics

- The avionics of the rocket were done through Altium with parts ordered from Digikey. Solding the sensors using the stencils was more difficult and require many attempts to get a good connection. We also had issues with the USB-C port and had to solder new ones on it to get a connection with the computer.

Recovery

- The process of the soldering and testing the quarks went very smoothly, as well as the dry ejection test that was done. This show that the components were all working as intended and helped us calibrate the lengths of the rope.

Payload

- In order to be more comparable to modern kitchen appliences, having variable speed control and an easy release mechanism of the whisk would be good additions to the payload. In addition, insulation can be improved by implementing technology used in thermoses and other materials that let in less heat.

Appendix

System Weights, Measures, and Performance Data

Basic Rocket Information

- Number of stages: 1
- Vehicle length: 65"
- Airframe diameter: 4"
- Number of fins: 3
- Fin semi-span: 3.6"
- Fin Tip Chord: 1"
- Root Chord: 8“
- Fin thickness: 1/4"
- Avbay Weight: 1.99 lb
- Empty motor case/structure weight: 1.55lb
- Payload weight: 3 lb
- Liftoff weight: 15.641 lb
- Center of pressure: 45.986"
- Center of gravity: 38.386"

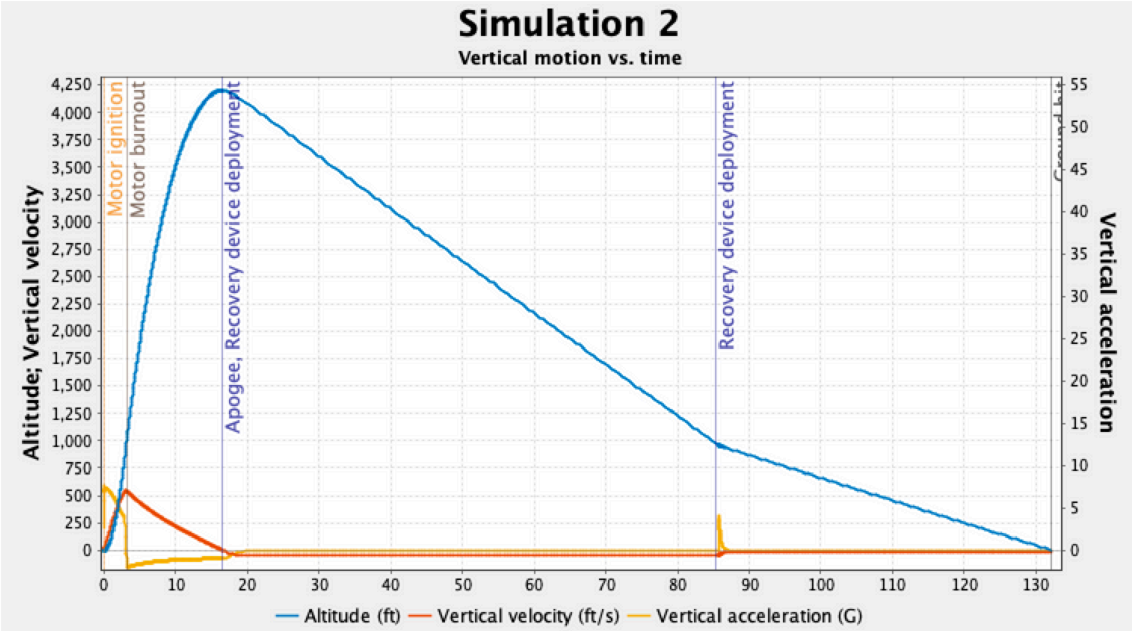
Propulsion Information

- Motor Diameter: 2.125 inches (54mm)
- Casing Length: 14.10 inches (358mm)
- Total Impulse: 1361 N-sec
- Average Thrust: 400 newtons
- Peak Thrust: 549 N-sec
- Thrust Duration: 3.3 seconds
- Delay Time: adjustable up to 14 seconds
- Propellant Weight: 650 grams
- Motor Weight: 1194 grams

Predicted Flight Data

- Launch rail length: 10'
- Rail departure velocity: 54 ft/s
- Minimum static margin: 2
- Maximum acceleration (G): 7.29G
- Maximum velocity: 543.22 ft/s
- Predicted apogee: 4201'

Preliminary calculations to shear four 6-32 nylon fasteners were done using the above formula for the drogue ejection charges. Final ejection charge sizes were determined after recovery system ground testing. Low altitude charges are made from plastic vials while high altitude charges are made from vinyl tubing. The high altitude charges are designed to act similar to an end burning motor, ensuring that as much black powder as possible is ignited.



Recovery Information

Table 1: COTS Altimeters

DROGUE	Apogee
MAIN	500' Altitude

EasyMegas were chosen because they have additional pyro channels that can be used for staging and sustainer airstart. In addition, EasyMegas offer altitude, tilt angle, and velocity lockout as safety measures for airstart.

On each stage, three ⅛” vent holes are drilled in the avionics bay section to allow the barometric sensors on the EasyMega altimeters to sample atmospheric pressure.

Table 2 Recovery Ejection Charges

DROGUE	1 gram
MAIN	1.25 gram

$$Grams\ of\ black\ powder = \frac{454\ g}{1\ lbf} * \frac{Pressure\ [psi] * Volume\ [in^3]}{266\ [\frac{in*lbf}{lbm}] * 3307 * R}$$

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Table 3 Shear Pins

MATERIAL	Nylon
SIZE	6-32 Thread
STRENGTH	~12-15 lbs per pin

On each stage, four 6-32 nylon shear pins hold the recovery bay closed until recovery deployment.

Table 4: Shock Cord

MATERIAL	Braided Kevlar
TOTAL LENGTH	25'
	18'
THICKNESS	1/4 in
RATED CAPACITY	2,800 lbs

The main parachute of each stage is closer to the end with the avionics bay of its respective stage. This means that the main ejection charge wires do not have to span the length of the entire shock cord.

The length of the shock cord for each stage takes into account the length of each stage, the length of the shroud lines, and the minimum distance required to avoid collision between airframe sections upon descent.

The two knots on either end of a shock cord are figure eight knots. All knots in the middle of a shock cord are alpine butterfly knots. Knots can decrease the maximum rated force by 50%.

Table 5: Shock Loading & Velocity

STAGE	*DROGUE DESCENT VELOCITY (FT/S)*	*LANDING AIR VELOCITY (FT/S)*	*DROGUE SHOCK LOAD INFINITE MASS (LBF)*	*MAIN SHOCK LOAD INFINITE MASS (LBF)*	*KINETIC ENERGY ON IMPACT (FT*LBF)*	*DRIFT DISTANCE (FT)*
Rocket (nominal)	104.91	26.9	7.1	6.6	79.79	2305.65

$$v = \sqrt{\frac{2 * m_{dry}}{\rho_{air} * A_{proj} * C_d}}$$

$$Shock\ Load = \frac{1}{2} * \rho_{air} * v^2 * A_{proj} * C_d * C_{shock} * F_{red}$$

$$KE = \frac{1}{2} * \frac{m_{dry}}{32.174} * v_{land}^{2}$$

$$d_{drift} = v_{wind} * t_{descent}$$

Input data for the booster stage is obtained from OpenRocket and input data for the sustainer stage is obtained from RASAero. When assuming the infinite mass condition, the shock reduction factor (Fred) is 1. The air density (air) takes into account the atmospheric lapse rate. Airstart failure indicates that the sustainer recovery system must also support the load of the unfired sustainer motor.

Table 6: Recovery Harness Rated Strength (lbs)

COMPONENT	RATING (LB)	FACTOR OF SAFETY
Shock Cord	~ 1500	5
U-Bolt	~ 2500	5
Large Quick Link	~ 2000	4
Normal Quick Link	~ 1000	4
Recovery Bulkhead	~ 3000	6
Tender Descender	~ 2000	5

Table 7: Parachute

PARACHUTE	DIAMETER (IN)	C_D	SHOCK LOADING (LBF)
Drogue	24"	0.75	30.82
Main	58"	0.75	54.16

Hazard Analysis

HAZARD	POSSIBLE CAUSES	RISK OF MISHAP AND RATIONALE	MITIGATION APPROACH	RISK OF INJURY AFTER MITIGATION
Fiberglass	Inhalation of dust during sanding or cutting; skin irritation.	Moderate - Exposure can cause respiratory issues or irritation without PPE.	Use appropriate PPE (e.g., respirators, gloves); work in ventilated areas.	Low - Proper PPE reduces exposure.
Black powder	Mishandling during ejection charge preparation; accidental ignition.	High - Highly flammable and explosive under improper handling.	Store in sealed containers; follow strict safety protocols; handle away from ignition sources.	Moderate - Proper storage and handling reduce risk.
Epoxy	Skin contact or inhalation of fumes during mixing and application.	Moderate - Exposure can cause chemical burns or respiratory irritation.	Use gloves and masks; work in well-ventilated areas or use fume hoods.	Low - Proper PPE and ventilation reduce exposure.
E-match igniters	Accidental ignition due to static discharge or improper wiring.	High - Can cause burns or trigger premature motor ignition.	Handle in static-free environment; use shorting plugs; follow manufacturer instructions.	Low - Static control measures minimize risk.
APCP solid motor propellant	Mishandling during installation; exposure to heat or sparks.	High - Highly flammable and explosive material.	Store in cool, dry place; handle with care using gloves; keep away from heat sources.	Moderate - Adherence to protocols reduces risk.
Lithium polymer batteries	Overcharging, punctures, or short circuits causing thermal runaway.	High - Can catch fire or explode if mishandled.	Use certified chargers; avoid physical damage; store in fireproof containers.	Moderate - Safety measures minimize likelihood of incidents.
Lithium ion batteries	Overcharging, improper storage, or manufacturing defects.	High - Can overheat, catch fire, or explode under certain conditions.	Use certified charging equipment; store in temperature-controlled environments; avoid physical damage.	Moderate - Risk reduced with proper care.

Risk Assessment

Rubric		Mission Impact				
		Minimal Effect	Small Effect	Moderate Effect	Significant Effect	Critical Effect
Likelihood	0-1%	A1	B1	C1	D1	E1
	1-5%	A2	B2	C2	D2	E2
	5-10%	A3	B3	C3	D3	E3
	10-25%	A4	B4	C4	D4	E4
	25%	A5	B5	C5	D5	E5

FAILURE MODE	*CAUSES*	*RISK CATEGORIZATION*	*MITIGATION*	*MITITIGATED RISK CATEGORIZATION*
Manufacturing				
Incorrect dimensions	Errors in CAD design or machining tolerances	B3	Perform double checks on CAD designs and inspect machined parts pre-assembly	A2
Weak structural bonds	Insufficient curing time or improper epoxy application	C3	Follow epoxy application protocols and conduct quality assurance checks	B2
Integration (Before Pad)				
Loose electrical connections	Improper soldering or wiring during avionics integration	C3	Conduct pre-launch continuity tests and visual inspections	B2
Misaligned components	Incorrect assembly of airframe or payload	C4	Use alignment jigs during assembly and verify fit through full-system checks	B3

Integration (on pad)				
Igniter failure	Improper installation or damaged e-match	D3	Perform pre-launch continuity checks and prepare backup igniters if needed	C3
Payload shifting	Insufficient fastening or vibrations during handling	C3	Double-check fastening mechanisms and use vibration-damping materials	B2
Main Descent				
Parachute tangling	Incorrect packing or high-speed deployment	C4	Use standardized packing procedures and test deployment on the ground	B3
Recovery harness failure	Undersized or damaged shock cords	C3	Inspect harnesses pre-flight and use appropriately rated materials	B2
Landing & Recovery				
Hard landing	Failure of secondary chute or miscalculated descent rate	C4	Conduct descent rate simulations and verify parachute sizing	B3
Damage during recovery	Mishandling by team or landing on rough terrain	B3	Train recovery team and mark safe landing areas during launch setup	A2

Assembly, Preflight, Launch, and Recovery Checklists

No Fly Conditions

- Extreme weather conditions, including high winds, heavy rain, or thunderstorms.
- Any visible damage to the rocket components that compromises structural integrity.
- Failure to meet the minimum required safety inspections as per regulatory guidelines.
- Issues identified during pre-flight checks that cannot be resolved in time for launch.

Airframe No Fly Conditions

- Presence of cracks, deformations, or any signs of structural failure in the airframe.
- Improper assembly or insecure fastening of airframe components.
- Significant damage to aerodynamic surfaces, such as fins.
- Warping or misalignment that could impact flight stability.

Recovery No Fly Conditions

- Malfunctioning or improperly packed parachute systems.
- Damage to recovery electronics or failure to pass recovery system tests.
- Incorrect deployment mechanism setup or insufficient ejection charge.
- Issues with shock cords or harnesses that could compromise recovery safety.

Avionics No Fly Conditions

- Avionics module failure to initialize or operate correctly.
- Inability to properly log or transmit flight data.
- Insufficient power supply to sustain avionics throughout the flight.
- Note: These conditions do not prevent the rocket from flying; they pertain only to the avionics module.

Payload No Fly Conditions

- Payload module failure to secure properly within the rocket.
- Malfunction of payload systems or inability to operate as intended.
- Note: These conditions do not prevent the rocket from flying; they pertain only to the payload module.

Order of Tasks

1. Conduct a detailed pre-flight checklist covering all rocket subsystems.
2. Perform a thorough inspection of the airframe for structural integrity.
3. Test recovery systems, including parachutes and ejection charges.
4. Validate avionics functionality, including data logging and transmission.
5. Secure and test the payload module within the rocket.
6. Verify environmental conditions are within acceptable limits.
7. Perform a final safety review and gain approval for launch.
8. Proceed with launch operations.