Design and Concepts of BYU Rocketry's Launch Vehicle

Team 84 Project Technical Report to the 2018 Spaceport America Cup

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The launch vehicle named "Wasatch 1," designed and built by BYU Rocketry, will compete in the "10k – COTS – All Propulsion Types" category of the upcoming 2018 Intercollegiate Rocket Engineering Competition at the 2nd Annual Spaceport America Cup. It will carry an 8.8 lb payload to an altitude of exactly 10,000 feet. The vehicle body is constructed of hand-wrapped carbon fiber tubes and has G10 fiberglass stabilizing fins, with wood bulkheads to bear the loads exerted on it by the shock cords upon deployment. The mission of the payload, the first iteration of a BYU cold-gas thruster, is to alter the descent of the payload under parachute. It does this by utilitizing custom electronics and off-the-shelf hardware.

Nomenclature

AOA	=	Angle of Attack
CG	=	Center of Gravity
CP	=	Center of Pressure
ID	=	Center of Pressure
LOV	=	Loss of Vehicle
OD	=	Outer Diameter
PPD	=	Personal or Property Damage
RSO	=	Range Safety Officer

I. Introduction

BYU Rocketry is student association that focuses on designing, building, and testing rockets of various sizes and lift capabilities. The High Power Team is a subset of BYU Rocketry and consists of systems teams that work together to build High Power rockets. The 2018 High Power Team consists of 3 systems teams, lead by a single High Power Team Lead. The three teams include: Structures, Payload, and Guidance Navigation and Controls (GNC). The Structures Team designs and builds the vehicle to house the payload and all other subsystems that will ensure successful launch and recovery of the rocket. The Payload Team designs a scientific payload, following CubeSat standard dimensions, that will meet competition criteria and fly to the target altitude aboard the rocket. The GNC Team designs the electronics and hardware that will control flight events, such as parachute deployment, and gather data on the vehicle's flight to compare with simulations. Together, they coordinate their effors to construct a capable launch vehicle.

II. System Architecture Overview

The vehicle was designed using *OpenRocket*, a free and open-source rocket simulation program. Both custom and off-the-shelf components were used in the construction of the rocket airframe and all major subsystems. Major subsystems of the vehicle include: the payload section including nose cone, payload containment bay, and the 8.8 lb payload; the avionics bay including coupler, all flight computers, data acquisition units, electronics mounting hardware, recovery ejections charges, and bulkheads; and the booster, including motor mount inner tube, centering rings, tailcone, and through-the-wall fins (see Figure 1).

OpenRocket allows the user to specify component geometry, dimensions, masses, densities, and surface finishes; radial placement of objects, fin quantity, and fin cross section shape; and much more. Based on these specifications, OpenRocket determines the rockets center of gravity (CG), the point along the length of the rocket at which it would balance, and center of pressure (CP), the point where the total sum of a pressure field acts on the rocket. Based on the location of these points, OpenRocket gives a static margin for the vehicle, or caliber of stability. One caliber of stability signifies that the CP is one body-diameter-length behind the CG, or that the static margin is 1.

The geometry and dimensions of the vehicle were determined based on the desired altitude, as well as several design constraints including payload dimensions, available commercial motor sizes, and available off-the-shelf building materials.

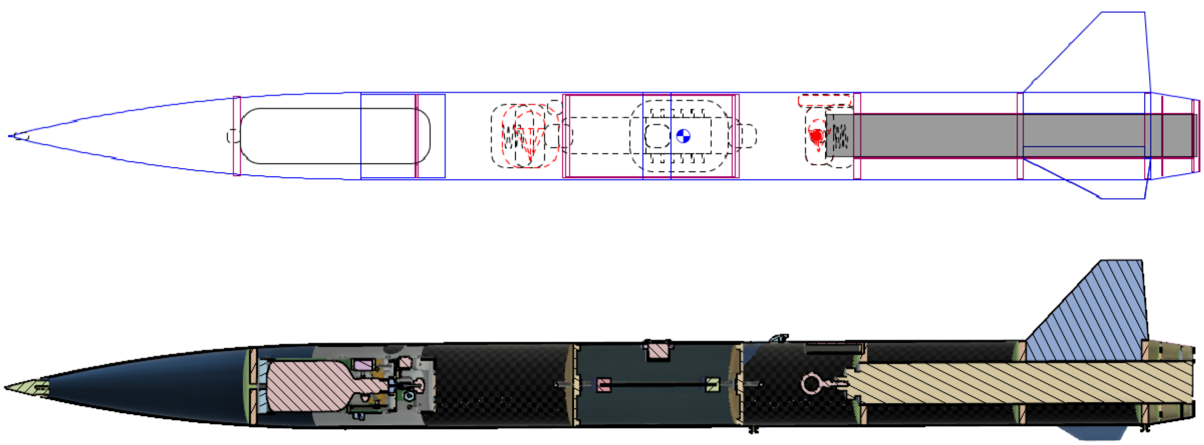

Figure 1 – Top: OpenRocket design of essential systems and locations in Wasatch I. Bottom: Cross-section of the vehicle.

A. Propulsion

One of the most defining features in any rocket is the primary booster, as this determines the class and size of the rocket. For this vehicle, the Aerotech M1297W motor was selected as the booster due to its affordable cost and appropriate total impulse. To compensate for deficiencies in the motor and simulation software and an imperfect trajectory, a slightly overpowered motor was chosen and a lightweight vehicle was built. To compensate for exceeding the target altitude in simulations, two test launches were to be conducted and the simulation modified based on those results. The competition rocket would then be given added weight near the CG to compensate for the slightly overpowered motor. Based on mass estimates and preliminary drag calculations it was determined that the total impulse requirements would be approximately 5,400 Newton-seconds and the average impulse should be approximately 1,300 Newton-seconds. In selecting a motor, numerous models were considered, which are tabulated below (see Table I-A). Aerotech motors were mainly considered due to low cost and a fairly flat thrust curve, which is desirable for a constant thrust (see Figure 2). Due to a desire to reduce cost and weight, and maximize total impulse, the Aerotech 75/5120 case was selected. The Aerotech M1297W offers a high total impulse along with an adequate average impulse for a low cost, which match the needs of the vehicle.

Table I-A: COTS Motors Considered			
MOTOR	**TOTAL IMPULSE (N-s)**	**AVERAGE IMPULSE (N-s)**	**COST**
M1500	5217	1500	$270
M1297	5439	1297	$270
M1780	5341	1780	$270
M1550	5529	1550	$310
M1315	6645	1315	$310

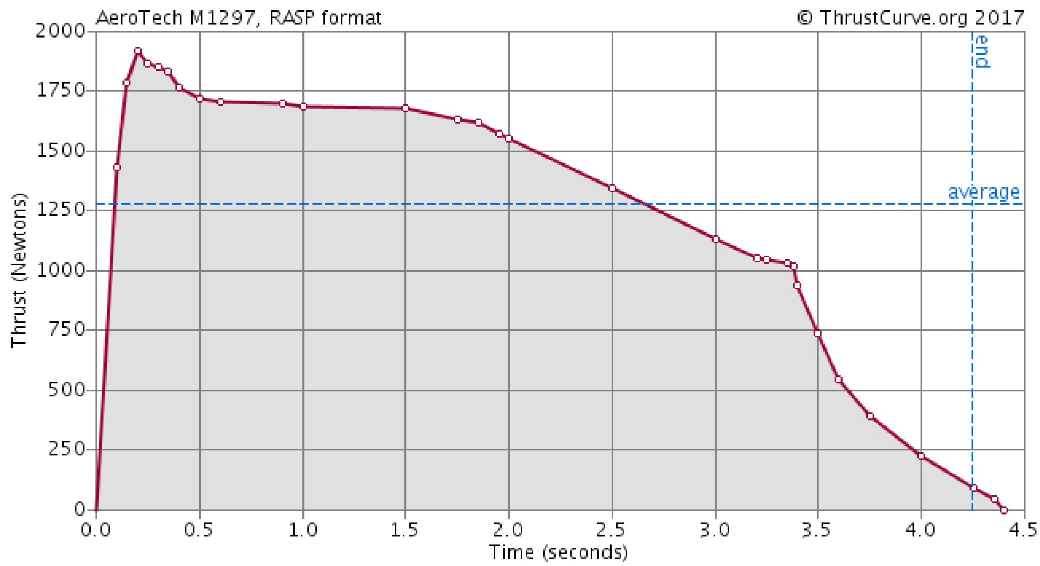

Figure 2 - Thrust Curve of the Aerotech M1297W solid rocket motor.

B. Structures

1. Nose Cone

The vehicle uses a tangent ogive nose cone profile, which is composed of a segment of a circle that is tangent to the rocket body tube and whose base is on the radius of the previously mentioned circle. The length of the nose cone is 24 inches, or four times the diameter of the rocket, not including a six inch shoulder that inserts into the airframe (see Figure 3). This 4:1 ogive nose cone is made of filament-wound fiberglass, manufactured by Madcow Rocketry, and provides additional strength to resist the effects of both flight and ground impact. Fiberglass is also easy to sand, finish, and paint, allowing for a low coefficient of drag.

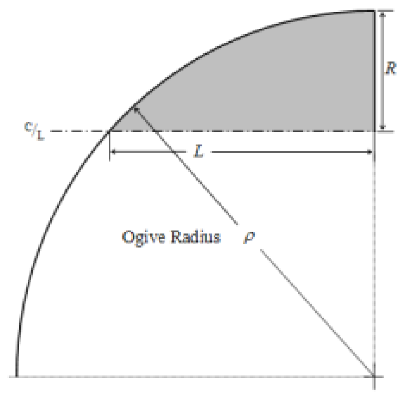

Figure 3 - Diagram explaining how the ogive nose cone shape is derived.

2. *Airframe*

The rocket airframe is composed of hand-wrapped carbon fiber tubes. Factors such as radial strength and rigidity were considered, as the use of off-the-shelf Blue Tube in the 2017 IREC resulted in a damaged airframe and a loss of competition points. Carbon fiber provides a higher strength-to-weight ratio compared to the Blue Tube used last year. Four layers of a prepreg weave were wrapped around an aluminum mandrel and covered in 20% shrink tape before curing in the oven at 300 ºF. To achieve the desired final outer diameter and surface finish, a single cosmetic layer was added using spread tow fabric and a wet layup process. Various finishing techniques were employed, including top coats of epoxy resin and sanding.

To reduce drag and achieve a higher altitude, a tailcone was manufactured and mounted at the rear end of the vehicle. The tailcone was manufactured using biaxial braided carbon fiber sleeving that was placed over a 3D printed mold to achieve the custom geometry. The mold was then removed after the part had cured at room temperature. To achieve the final fore and aft diameters, as well as a smooth surface finish, a two-part Bondo was applied to the tailcone surface and machined on the lathe.

Figure 4 - Madcow Rocketry nosecone, custom carbon fiber body tubes, reinforced Blue Tube coupler, 2-inch switch band.

The booster segment of the rocket contains the motor mount assembly and fins. It is 34 inches of 6-inch diameter carbon fiber tube and is coupled to a 20-inch length of 6-inch carbon fiber tube using a 12-inch Blue Tube coupler, manufactured by Always Ready Rocketry. The coupler was reinforced, however, with a layer of carbon fiber for added strength, and a 2-inch switch band was cut from excess 6-inch diameter carbon fiber tubing and glued to the outside at its center (see Figure 4).

3. Motor Mount

Because the rocket body has a 6-inch diameter, but the Aerotech 75/5120 case has a 3-inch diameter, the motor mount method used involves coupling a 3-inch inner diameter Blue Tube to the inside of the 6-inch airframe using centering rings (see Figure 4). The centering rings were cut from 1/2-inch plywood using a CNC router. Three centering rings were made this way and were epoxied to the inner tube. The two bottom rings were glued 8.5 inches apart, allowing for the fin tab of each of the fins to insert between them. The top ring was simply adhered to the top to ensure concentricity along the full length of the motor tube.

Figure 5 - Image depicting the centering rings mounted onto the motor mount tube.

All glue joint locations were sanded with 80-grit sandpaper, scored with utility knives and hacksaw blades, and cleaned of any particles or residue using acetone prior to the application of epoxy.

4. Motor Retention

Because a 75 mm motor was selected in favor of the 98 mm motor option, it was necessary to reduce the weight of all vehicle components to achieve the target altitude. Despite the effectiveness of a thrust plate and Aeropack retaining ring that were used last year, the aluminum components are heavy. Instead, a much simpler and lighter solution was employed for this new rocket. Within the tailcone are two fiberglass centering rings, one with 6 evenly spaced holes. A t-nut was epoxied into each of the 6 holes. A fiberglass retaining ring was manufactured on the CNC router with 6 identically spaced holes that allow it to bolt to the aforementioned centering ring. Once the motor is installed in the vehicle, the retaining ring is fixed to the rear of the rocket with 6 bolts that thread into the t-nuts, and the motor is accordingly constrained within the motor mount and tailcone subassemblies (see Figure 6).

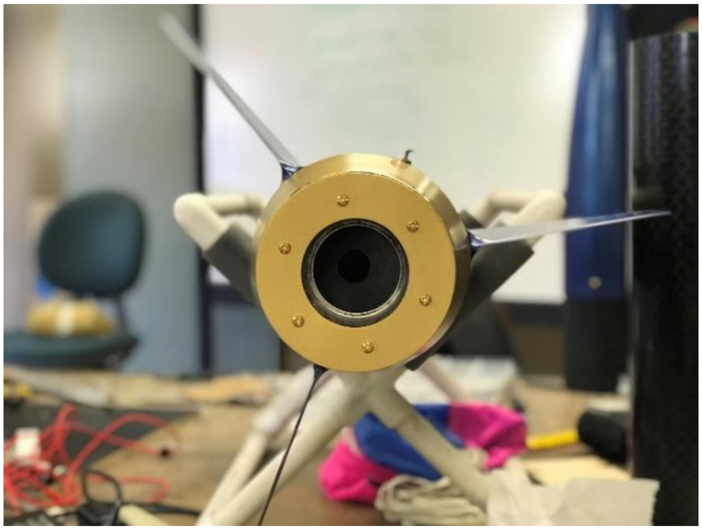

Figure 6 - Image depicting the motor retaining ring at the aft of the rocket.

5. Fins

Rockets fins are often damaged when the vehicle impacts the ground after the recovery phase of the flight. To prevent damage, the fins were cut from a sheet of high strength G10 fiberglass purchased from McMaster-Carr. A 1/8-inch thick fiberglass sheet was utilized, however, to reduce weight, and a clipped delta fin shape was used to eliminate sharp corners. The fins also have a small span, or height, of only 5.75 inches from the OD of the airframe and, instead of tall fins, a root chord, or base length, of 9 inches was used. These large, but short, fins move the CP far enough back for stable flight, yet ensure the structural integrity of the fins so as to avoid damage (see Figure 7). The high stiffness of the G10 fiberglass is also ideal to prevent fin flutter due to the aerodynamic forces on the fins as it reaches maximum velocity at motor burnout.

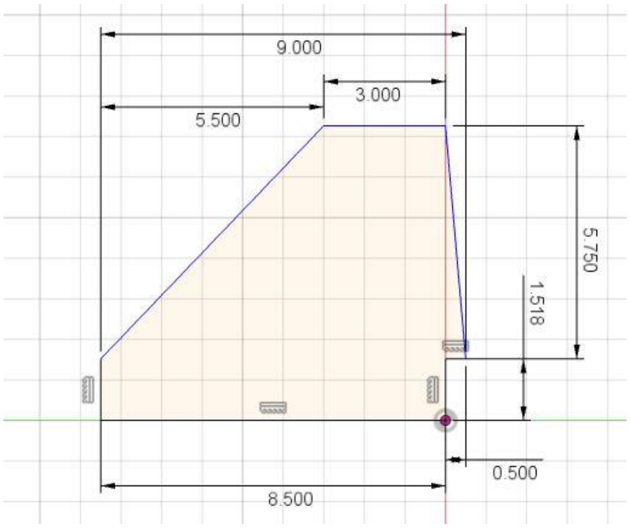

Figure 7 - Drawing showing the dimensions of the fins.

Although preventing damage when impacting the ground was critical, the primary concern with High Power rocket fins is how to attach them to the rocket so that they do not shear off in flight due to the high acceleration forces during the motor burn. The best-practices method used by those that build model rockets as a hobby is to cut slots in the airframe that allow for a fin tab to attach through the body tube instead of using a less-robust surface mounting technique. The rocket fin slots were carefully measured, marked, and cut by hand with a handheld rotary tool. The fins were then glued to the inner motor tube, the centering rings, and the body tube along the root chord (see Figure 8). To then be sure that the fins were bonded at 120° angles from one another, and parallel to the long axis of the vehicle, laser-cut acrylic fin alignment jigs were utilized while the adhesive cured (see Figure 9).

Figure 8- Image depicting through-the-wall-fins during assembly.

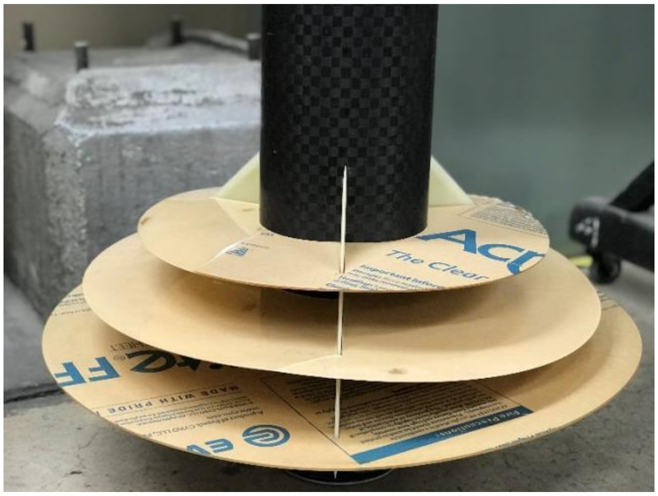

Figure 9 - Image depicting the acrylic fin-alignment jigs.

Large epoxy fillets were used along the exterior of the airframe to reinforce the fins and ensure they do not come off in flight (see Figure 10). These bonds were prepared with sanding and scoring for maximum bond surface area before being cleaned of particles using acetone.

Figure 10 - Image depicting the structural epoxy fillets on the fins.

6. Payload Containment

To eliminate the need for stabilizing nose cone weight, the payload is contained within the nose cone. This balances the rocket. A simple 1/2-inch plywood bulkhead was bonded in place within the nose cone, featuring a 3/8-16 bolt, washers, and nut. The forward bracket of the payload was drilled and tapped with the same thread as the bolt, which allows the payload to thread into the nose cone assembly.

As a result of this design choise, the payload itself becomes an anchor point for the main parachute shock cord. Therefore, it was necessary to devise a way to ensure the payload would not unthread itself under parachute descent. Physical stops were bonded to the inside of the nose cone coupler as a way to prevent rotation of the payload. Consequently, the payload can be installed within the nose cone, then the coupler slides over the payload and is bolted to the nose cone. The stops inside the coupler then prevent the payload from unscrewing itself.

C. Recovery

1. Recovery Architecture

The vehicle is divided into three sections: the booster, the avionics bay, and the payload containment bay. To ensure a safe recovery of each of section, the avionics bay is armed with a redundant dual-deploy altimeter system. These altimeters measure the altitude of a rocket and often include additional capabilities, such as triggering parachute deployment events at specific altitudes. The two commercial altimeters utilized are a PerfectFlite StratoLoggerCF and a Missile Works RRC3. Both altimeters operate based on the barometric properties of the atmosphere, measuring change in ambient air pressure to provide an accurate altitude reading.

The two altimeters are mounted to an acrylic sled, in addition to two 9-volt batteries for power A data acquisition device is also mounted to the sled to provide acceleration and rotational velocity data. The configuration of the avionics can be seen in Figure 11. The avionics sled mounts onto the the two 3/8-16 threaded rods that extend through the avionics bay, through the bulkheads, and clamp the whole system together. Once the sled is installed, wing nuts are used to clamp the bulkheads together on the avionics bay and prepare it to hold the weight of the rocket.

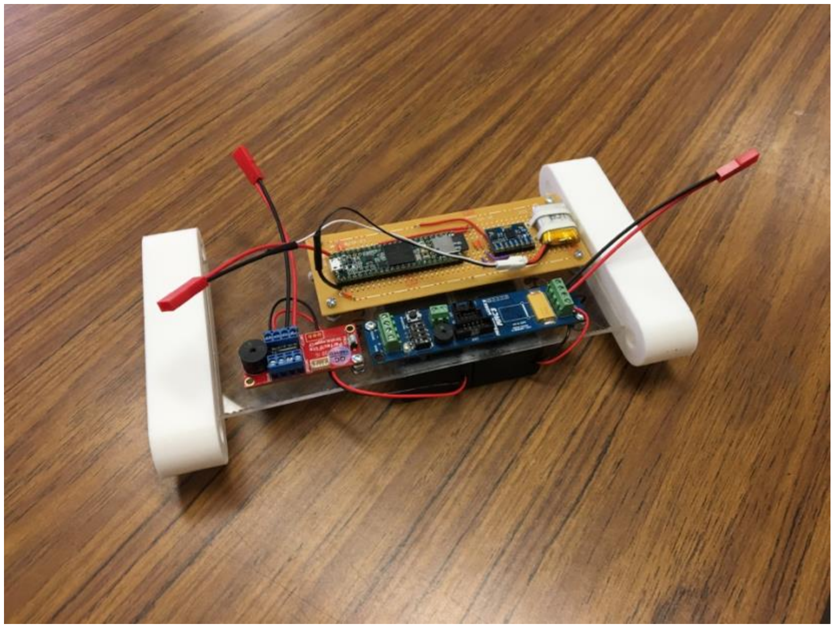

Figure 11 - Image depicting the avionics used to record flight data and trigger events.

For the altimeters to record altitudes accurately, the following equation, provided by PerfectFlite, was used to determine the size of the four static pressure sampling ports that were drilled equidistantly around the circumference of the avionics bay:

$$\text{Four ports, each hole} = \text{Diameter} * \text{Diameter} * \text{Length} * 0.0008$$

Based on the dimensions of the vehicle, this equation proved that the diameter of each of the pressure sampling port holes needed be 0.34375 inches in diameter. These holes then allow the air pressure within the avionics bay to adequately equalize with ambient air pressure outside of the rocket. Each ejection charge, for both drogue and main parachute deployment, has two commercial e-matches installed to ensure ignition (one from each redundant altimeter). The black powder ejection charges were calculated using the following equation:

$$\text{Ejection charge in grams} = \text{Diameter} * \text{Diameter} * \text{Length} * .005$$

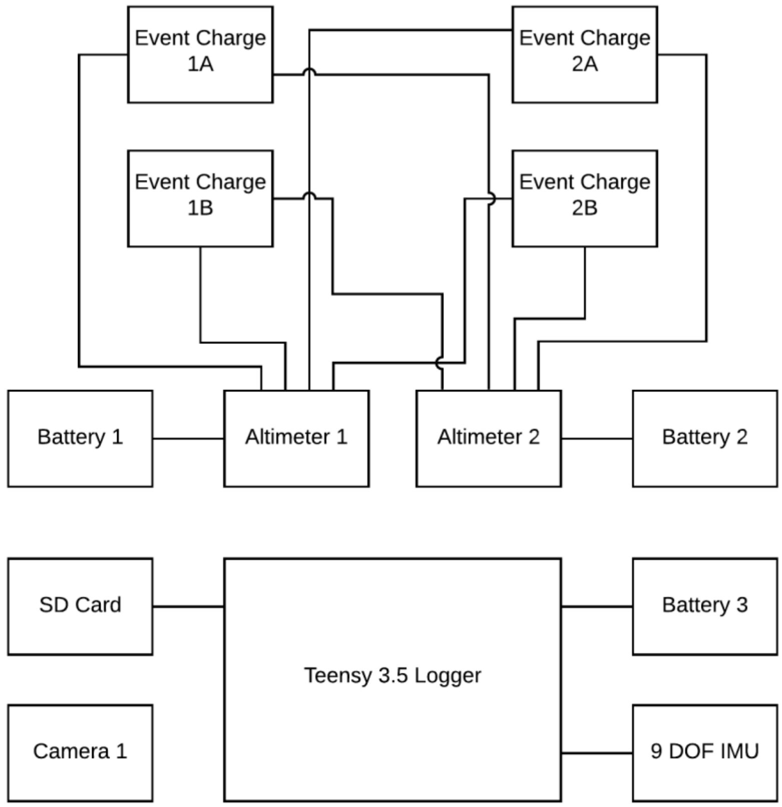

Figure 12 - Interconnect of the avionics for Wasatch I.

Charges of 1.5 grams and 3 grams were chosen for the drogue and main parachute deployments, respectively. This creates enough pressure to break the four shear pins connected to the payload section and the four shear pins connected to the booster section and ensure separation. Each nylon shear pin has a shea strength of 20 pounds.

The payload section of the rocket contains a 36-inch Top Flight Ultra-X-Type parachute that is used as the drogue chute. It is fired at apogee and is connected to the 30-foot 1/4-inch Kevlar shock cord at a point one third of the way down from the payload section. The drogue parachute gives the vehicle a descent speed of 78 ft/s until reaching the altitude of main parachute deployment, 1200 feet. At this altitude, the main ejection charge is fired, deploying the main chute, a student-designed-and-built 72-inch toroidal parachute. The main parachute is attached to the booster section and the airframe coupler by a second 30-foot 1/4-inch Kevlar shock cord at the one-third point from the booster. The descent rate of the vehicle under the deployed main parachute is 25.75 ft/s.

2. *Main Parachute*

The main parachute was made in-house to reduce cost and increase overall performance of the vehicle. The parachute is 72 inches in diameter and toroidal in shape. The toroidal shape of the parachute allows for a more steady descent than a standard hemispherical parachute due to the center hole. This hole allows air to spill through, preventing billowing of the fabric.

The parachute was manufactured using rip-stop nylon and paracord. The shape of the parachute gores were created using Solidworks and were then cut into an adhesive vinyl sheet. The sheet was used as a template to cut out the 12 gores of the parachute (see Figure 13). The rip-stop nylon was cut into 12 rough sections and sprayed with a temporary adhesive. The sections were then stacked on top of each other with the vinyl template on top, and the gores were cut to the correct size using a rotary cutter. The temporary adhesive was removed using acetone, which dissolves the adhesive but leaves the nylon intact. The gores were then sewn together on the long edges, after which the circumference of the outer and inner diameters was hemmed (see Figure 14).

Figure 13 - One of twelve gores for the main parachute.

Once the shape of the parachute was completed, the shroud lines were attached to the 12 seams of the parachute. The inner shroud lines were also attached to the inner diameter. These inner shroud lines give the parachute its toroidal shape.

Figure 14 - Detail showing the seam between two gores of the main parachute.

3. *Swivels*

Due to the potential of high wind shear at the apogee of the rocket's trajectory, low-friction ball bearing swivels were attached to the mounting points of the parachutes. These low-friction swivels provide a strong mounting point for the parachute and prevent the tangling of the shock cords, resulting in a clean and smooth recovery of the vehicle.

D. Payload

1. *Payload Architecture*

The vehicle was designed to carry an experimental payload built to official CubeSat dimensions. Since the IREC rules require a total payload mass of 4 kilograms, the experimental payload meets official CubeSat 3U standards (100 x 100 x 340.5 mm, 4 kg). The experimental payload, designed by the BYU Rocketry High Power Team, is designated the Cold-Gas Thruster Experiment (CGTE) (see Figure 15).

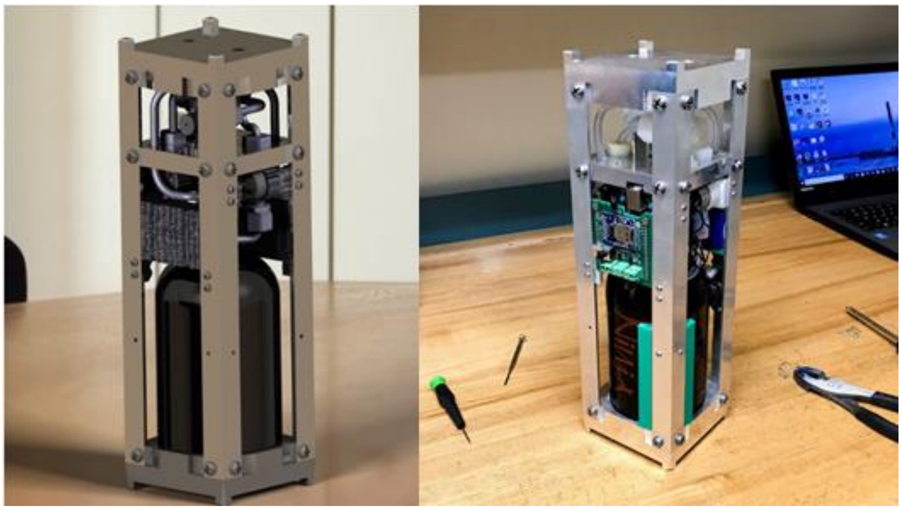

Figure 15 - Left: Payload Rendering In CAD. Right: Fully Assembled Payload.

The Cold-Gas Thruster Experiment (CGTE) is a 3U CubeSat that uses compressed gas and nozzles to demonstrate cold-gas propulsion and control. The purpose of the CGTE is to develop a platform upon which future BYU Rocketry and BYU Spacecraft cold-gas thruster systems can build. Due to limited volume, only two nozzles were utilized. The x and y axes are each controlled by one nozzle. Also, since the payload is not to affect the flight of the vehicle, the propulsive system remains dormant until after main parachute deployment. The design can be effectively divided into four subsystems: structure, Cold-Gas Thruster System, electronics, and programming.

2. *Payload Structure*

The structure includes:

- Machined Aluminum and Steel Plates (Top, Middle, and Bottom)
- Aluminum Angle Brackets
- Machine Screws
- PLA 3D printed mounting brackets

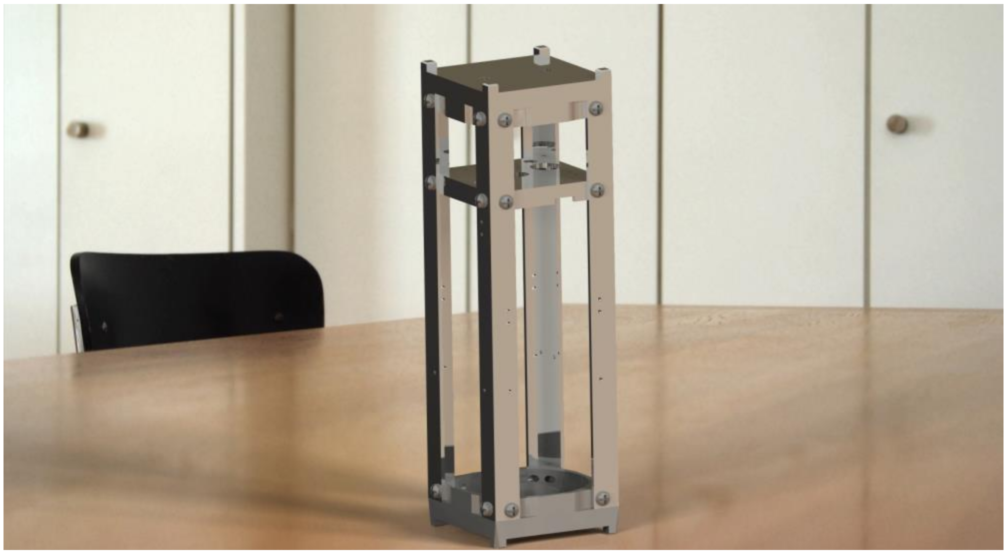

Figure 16 - Rendering of the machined structure.

The structure was designed to follow 3U cubesat specifications and to safely enclose the experimental payload. The structure was designed with manufacturability and simplicity in mind. The design was built to be modular so that it may be easily adjusted and re-assembled to handle design changes or necessary field repairs, as well as strong and durable to survive launch vibrations, turbulence, and high g-forces in both directions (for the boost phase of flight as well as the aerodynamic drag which will induce negative g's) (see Figure 16).

3. Cold-Gas Thruster System

The cold-gas thruster system includes:

- Compressed Gas Tank
- Regulator
- Adapters
- Tubing
- Solenoid Valves
- SLA 3D Printed Nozzles

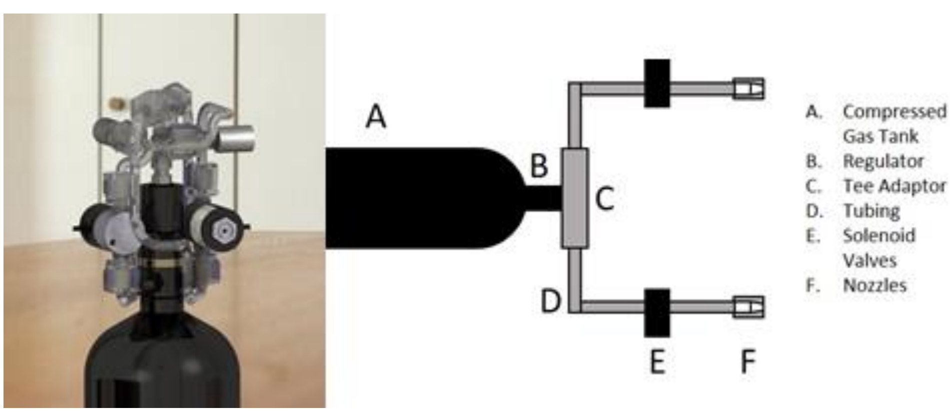

Figure 17 - Rendering of the Cold Gas Thruster System and Diagram of System.

The cold-gas thruster system was developed to demonstrate the capability of such systems. Compressed gas is stored at a pressure of 3000 psi in a pressure vessel. A regulator attached to this pressure vessel allows gas to leave the tank at 300 psi. The gas flows in two directions through adapters and tubing until it reaches a solenoid valve (see Figure 17). When the normally-closed solenoid valve opens, the gas continues flowing through the nozzles and produces thrust.

The nozzles are a simple converging nozzle design. After running tests with various nozzle designs it was determined that a converging nozzle yielded the most thrust (see Figure 18). The nozzles are 3D printed using an SLA printer for quick prototyping and fine print resolution. The nozzles have an entrance area of .125 inches that slopes down to an exit area of .08 inches. The sloping angle and exit area will continue to be modified to maximize thrust in the weeks prior to the final launch at IREC.

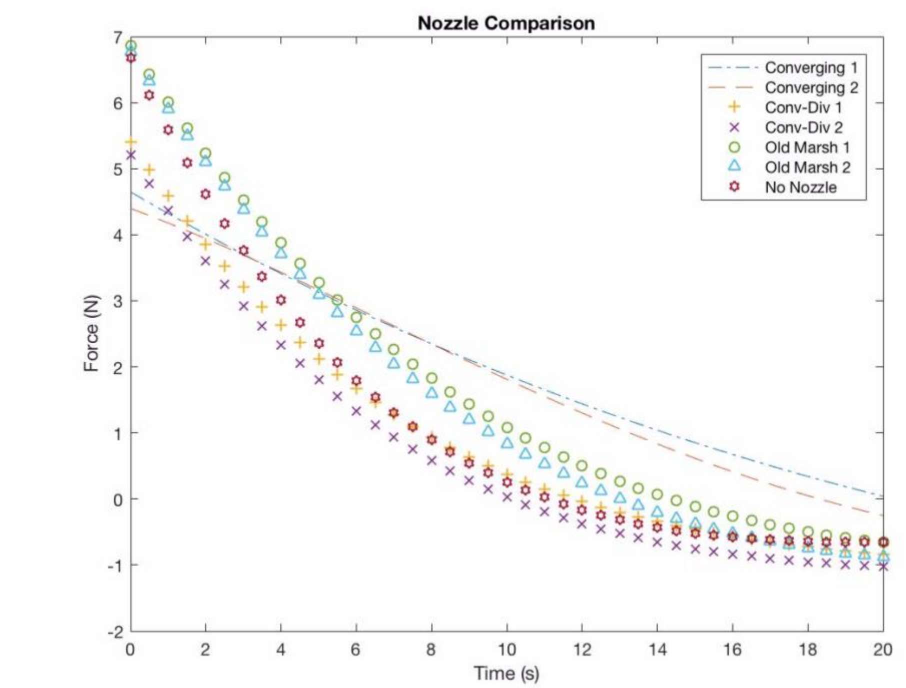

Figure 18 - Test results of various nozzle designs.

4. Payload Electronics

- Arduino 101
  - 6-axis accelerometer and gyroscope
  - Voltage regulator
  - Microprocessor
  - Thermometer
- Custom printed circuit board (Arduino shield) containing the following:
  - SD card for data logging
  - RBF pin
  - Parachute deployment pin
  - Power switch
  - Solenoid and battery connectors
- 11.1V 3 cell battery (12.6Volts fully charged)

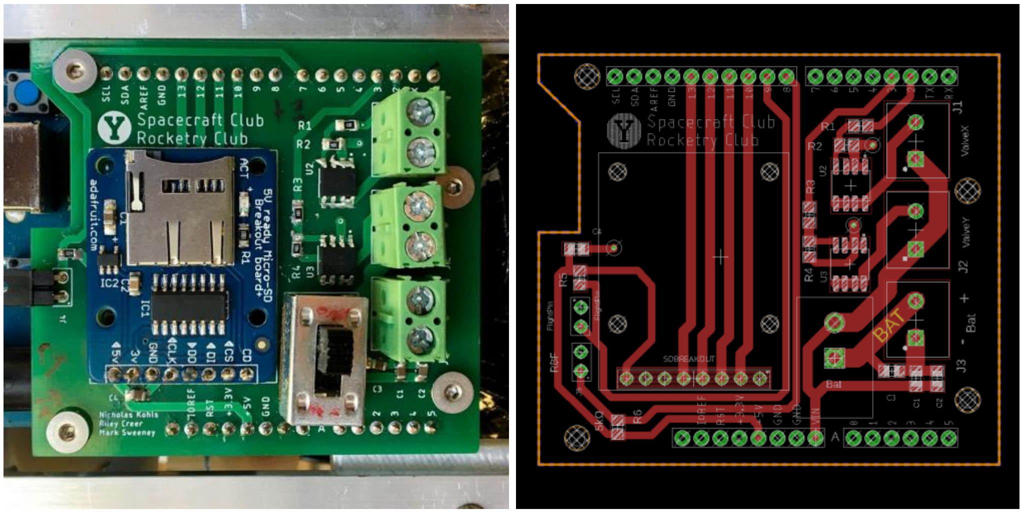

Figure 19 – Custom printed circuit board and design.

The electronics sense 3 axis movement and control the solenoid valves to stabilize the payload. The electronics primarily include two modules: the Arduino 101 and a custom PCB (custom arduino shield). Power is supplied by a battery. The battery is a 3 cell 1000mAh 20C Lipo pack. It produces over 12 volts when fully charged, ensuring that the solenoid valves have enough power to open and close.

The Arduino 101 is able to step down the 12 volts to 5 and 3 volts, and has quite a lot of functionality built into it. This includes a six-axis accelerometer and gyroscope. Using these sensors, the movement and relative orientation of the payload can be monitored.

A custom arduino shield was built to further increase the functionality of the Arduino 101 (see Figure 19). The custom PCB includes mosfets to turn on and off the valves, connectors for the valves and battery, a power switch, a RBF pin and a parachute deployment pin. An SD card slot was included so that data can be recorded and used to analyze the rocket's behavior.

5. *Programming*

The software is divided into multiple stages:

- Stage 6: The payload is turned on during assembly. The gyro and accelerometer data is calibrated relative to gravity.
- Stage 5: The RBF is removed at the launchpad. This is done through a hole in the airframe. The electronics will begin data logging and will not stop until powered off.
- Stage 4: The payload continues logging data as it experiences the loads of flight.
- Stage 3: The main parachute is deployed and the parachute pin is pulled out of the electronics.
- Stage 2: The electronics wait 8 seconds for the parachute to open up fully.
- Stage 1: The payload tests if movement in a specific direction is occurring and opens up the valves for 250 ms to stabilize the payload.
- Stage 0: The rocket lands

The data is saved onto the SD card every 50 ms and saved in CSV format. The saved data includes: the stage of the code (see above), the time, xyz accelerometer data, xyz gyroscope data, the x axis solenoid valve position (on or off), the y axis solenoid valve position, and the temperature.

III. Mission Concept of Operations Overview

The mission shall be divided into 10 Phases:

1) Preparation
2) Ignition
3) Liftoff
4) Mainstage Flight
5) Coasting Flight
6) Apogee
7) Drogue Descent
8) Main Parachute Descent
9) Landing
10) Recovery

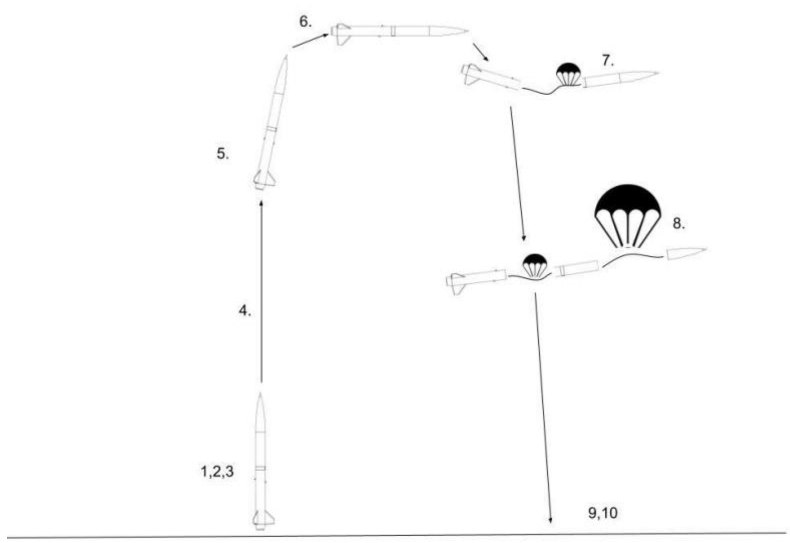

Figure 20- Image depicting vehicle launch sequence phases.

1. Preparation

Preparation shall consist of everything done to prepare the rocket for launch. It begins when the rocket is unpacked at the staging area and ends when ignition occurs.

Propulsion	The motor is built and mounted in the rocket. When the rocket is placed on the pad, the igniter is installed.
Payload	The payload is assembled and then activated at the pad to begin recording data.
Avionics	The avionics are armed.
Recovery	The parachutes are packed, the ejection charges are built, the recovery hardware is assembled and checked.
Structure	The rocket is assembled and placed on the pad.

2. Ignition

Ignition occurs when the launch command is sent to the motor and ends when the motor achieves operating pressure.

Propulsion	The motor is ignited and chamber pressure rises to operating levels.
Payload	The payload continues to record data.

3. Liftoff

Liftoff occurs when the rocket begins to move and ends when it clears the launch rail.

Propulsion	The motor has reached operating pressure. A plume of smoke and fire erupts from the tail end of the rocket as it begins to ascend up the launch rail.
Payload	The payload continues to record data.
Avionics	The avionics register launch and begin recording data.

4. Mainstage Flight

Mainstage Flight begins when the rocket clears the launch rail and ends when the motor no longer produces useful thrust.

Propulsion	The motor is providing thrust to the rocket and is at nominal operating pressure. The plume of fire continues to be visible from the tail of the rocket
Payload	The payload continues to record data.
Avionics	The avionics continue to record data.

5. Coasting Flight

Coasting Flight begins when the rocket no longer produces useful thrust and ends when vertical velocity reaches zero.

Propulsion	The motor is no longer providing thrust and there is no longer a visible plume of fire, but is providing a thin trail of tracking smoke.
Payload	The payload continues to record data.
Avionics	The avionics continue to record data.

6. Apogee

Apogee begins when vertical velocity reaches zero and ends when the drogue parachute is deployed.

Payload	The payload continues to record data
Avionics	The flight computers send fire commands to the drogue ejection charges and the charges fire, separating the sections of the rocket at the pre-defined point.
Recovery	The drogue parachute is deployed and emerges from the aft section of the rocket.
Structure	The rocket sections separate at the pre-defined point.

7. Drogue Descent

Drogue Descent begins when the drogue parachute is deployed and ends when the main parachute is deployed.

Payload	The payload continues to record data.
Avionics	The flight computers continue to record altitude data to prepare for main descent
Recovery	The drogue parachute limits descent to 50 ft/s
Structure	The rocket separates at the pre-defined point.

8. Main Descent

Main Descent begins when the main parachute is deployed and ends when the first portion of the rocket contacts the ground.

Payload	The Cold-Gas Thruster system activates as the electronic pin is pulled during the ejection charge. Following an eight second delay, the cold-gas thrusters will fire for the duration of the main descent.
Avionics	The avionics deploy the main parachutes at the pre-defined altitude.
Recovery	The main parachutes are deployed and emerge from the each half of the rocket. These parachutes limit the descent rate to 26 ft/s.

9. Landing

Landing begins when the first portion of the rocket contacts the ground and ends when all components have reached an altitude of zero AGL.

Payload	The payload continues to record data and turns the thrusters off after reading no movement for a period of time.
Avionics	The Avionics continue to record data and register landing. The avionics then begin to produce a wailing sound to aid recovery.

10. Recovery

Recovery begins when all components have reached an altitude of zero AGL and ends when the rocket has been transported back to the staging area. w

Propulsion	The motor is cleaned and disassembled.
Payload	The data is downloaded from the payload and processed.
Avionics	The data is collected from the avionics and processed.
Recovery	Any live charges are stored safely, then parachutes are packed and stored. The radio beacon aids in recovering the rocket.
Structure	The rocket is inspected and packed.

IV. Conclusions and Lessons Learned

A. Lessons Learned

BYU Rocketry is a relatively new organization, forming within the last three years. Although Brigham Young University has participated in the IREC before, these teams were involved via a different, non-aerospace university club with very little overlap between successive teams. The current group, however, is attempting to create a sustainable organization that can build upon itself year after year, allowing for progress and improvement, retention of members, and advancements in the complexity of the projects undertaken. Likewise, the focus is on space and rocketry, allowing students with a common passion to come together and work on the rocket team. Therefore, dozens of lessons were learned throughout the school year that will be applied in the coming year.

For example, effective and rapid communication is essential to the design process, as long as team members are available and willing to respond and have meaningful conversations about the team's design, plan, and short-term benchmarks. As our team began to discuss the direction the project would take, there were major issues with ensuring each team member was on the same page as decisions were being made. Because our group had multiple sub-teams coordinating their various efforts, it became necessary to utilize a central platform for communication. Slack, a team communication application available for mobile phones and desktop, helped our team effectively communicate, plan, design, and coordinate. Slack utilitzes group chats called channels. Each sub-team had a separate channel through which to communicate, allowing for quick brainstorming, file and image sharing, and more. A general channel for group discussions was created, as was an administrative channel for behind-the-scenes executive decision making. All team members had access to each channel, allowing cross-team coordination.

We also learned that accountability is key. It is important that each role is well-defined and that expectations of each team member are clear. This allows each team member to be held responsible for the tasks that they are assigned. If people are not held accountable for their work, they will either not do it well or not do it at all. Last year, many last-minute changes and design cuts were made because time simply ran out. This year we were able to mitigate these same issues by having more defined roles and holding individuals responsible for their work. This resulted in accelerated design and build phases and ultimately a better finished product that was completed on schedule.

Additionally, everyone has different strengths and weaknesses, as well as different motivators. Each team member is unique and brings something different to the table. It is important for leaders to understand that and play to everyone's strengths while still helping them stretch and grow. Personal issues and needs affect the whole team so leadership must be both aware and accommodating, while not allowing such issues to prevent the progress of the group as a whole. Reassigning tasks and responsibilities in light of such issues can allow for the affected team member to have necessary time to address any personal items while also allowing the group to proceed forward. Our team was composed of various students with different needs, talents, obligations, class loads, part-time jobs, and even one team member who is a father. Delegation of key tasks, as well as playing to the strengths, and time commitments, of each individual was essential for our success.

In terms of the design process, last year the rocket was designed backwards. Propulsion was considered first followed by the design of the airframe. The payload, which is the primary objective of the competition, was considered near the end. This year, we were able to modify the design process in a way that resulted in fewer design changes, and allowed us to design subsystems in parallel, rather than in series. This cross-team collaboration and emphasis on design allowed for a streamlined design process, a single CAD model, and a team working toward a unified goal.

Likewise, benchmarks and short term goals allowed the team to make slow and steady progress throughout the course of the year, rather than rushing to finish tasks and designs right up against the final deadline. Long term planning sessions with hard dates and multiple, achievable benchmarks along the way allowed team members to attain a vision of how and when the rocket would come together. Iterative design and protyping were then utilized to make rapid and efficient design changes throughout the process. Deadlines, or predetermined dates, by which certain subsystems needed to be finished allowed for proper planning, prototyping, testing, analysis, and iterating. Last year, many designs and ideas were instead cut out of the overall design simply because time ran out and insufficient development of the idea had been accomplished. It was not because the ideas were inherently bad ideas, but simply because the design had not evolved into a functioning, physical system, and design flaws were not realized until it was too late. Likewise, the rocket was built mostly in the month of May, just prior to the competition. This year, all of that was avoided due to proper planning and organization, allowing time for test flights and improvement of designs based on test flight results.

B. Conclusion

Building both a launch vehicle capable of carrying an 8.8-lb payload to 10,000 ft, and the payload itself, required a great deal of effort, coordination, and communication amongst team members. There were numerous design changes and modifications that happened all along the way until the final product was realized. Many lessons were learned about group dynamics, collaboration, and the design process of a large, multifaceted project such as this. Many changes are necessary that will help future teams more easily design and build rockets that perform nomically and contain more advanced characteristics and subsystems.

All team members were able to use their knowledge gained in engineering courses to design and build a capable launch vehicle. Every single team member learned many fundamental life lessons that will be applicable in any role they find themselves in, both in their careers and in their daily lives and relationships. Last, many team members landed internship and full-time positions at companies such as SpaceX, Orbital ATK, and more.

Spaceport America Cup

Intercollegiate Rocket Engineering Competition
Entry Form & Progress Update

Color Key — SRAD = Student Researched and Designed — v18.1

Must be completed accurately at all time. These fields mostly pertain to team identifying information and the highest-level technical information.

Should always be completed "to the team's best knowledge" , but is expected to vary with increasing accuracy / fidelity throughout the project.

May not be known until later in the project but should be completed ASAP, and must be completed accurately in the final progress report.

Date Submitted: 5/28/18

Team ID: 84 — * You will receive your Team ID after you submit your 1st project entry form

Country: USA

State or Province: UT

State or Province is for US and Canada

Team Information

Rocket/Project Name:	Wasatch 1
Student Organization Name	BYU Rocketry
College or University Name:	Brigham Young University, Provo
Preferred Informal Name:	BYU
Organization Type:	Academic Club
Project Start Date	9/5/17
Category:	COTS 10k

Projects are not limited on how many years they take

Member	Name	Email	Phone
Student Lead	Riley Meik	rileymeik@gmail.com	559-762-1905
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Faculty Advisor	David Fullwood	dfullwood@byu.edu	801-422-6316
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For Mailing Awards:

Payable To:	BYU Rocketry
Address Line 1:	Department of Mechanical Engineering
Address Line 2:	Brigham Young University
Address Line 3:	435 CTB
Address Line 4:	Provo, UT 84602
Address Line 5:	USA

Demographic Data

This is all members working with your project including those not attending the event. This will help ESRA and Spaceport America promote the event and get more sponsorships and grants to help the teams and improve the event.

Number of team members

High School	0	Male	7
Undergrad	7	Female	0
Masters	0	Veterans	6
PhD	0	NAR or Tripoli	7

Just a reminder the you are not required to have a NAR, Tripoli member on your team. If your country has an equivelant organization to NAR or Tripoli, you can cant them in the NAR or Tripoli box. CAR from Canada is an example

STEM Outreach Events

DiscoverSTEM Fair: Booths and activities for junior high students visiting BYU campus.

BYU EngTech Expo: Interactive booths and competitions for junior high students visiting BYU campus. Spanish Fork American Leadership Academy: Providing a rocket-building course for 8th graders

Rocket Information

Overall rocket parameters:

	Measurement	Additional Comments (Optional)
Airframe Length (inches):	84.25	Carbon fiber body tube and tail-cone. Fiberglass nose cone.
Airframe Diameter (inches):	6.16	
Fin-span (inches):	5.75	Fiberglass fins.
Vehicle weight (pounds):	18.4	
Propellent weight (pounds):	6	
Payload weight (pounds):	8.8	
Liftoff weight (pounds):	33.2	
Number of stages:	1	
Strap-on Booster Cluster:	0	
Propulsion Type:	Solid COTS	
Propulsion Manufacturer:	Aerotech	
Kinetic Energy Dart:	No	

Propulsion Systems: (Stage: Manufacturer, Motor, Letter Class, Total Impulse)

1st Stage: Aerotech 75mm, M1297W-P, M Class, 5439 Ns

Total Impulse of all Motors: 5439 (Ns)

Predicted Flight Data and Analysis

The following stats should be calculated using rocket trajectory software or by hand.
Pro Tip: Reference the Barrowman Equations, know what they are, and know how to use them.

	Measurement	Additional Comments (Optional)
Launch Rail:	ESRA Provide Rail	
Rail Length (feet):	17	
Liftoff Thrust-Weight Ratio:	8.9	
Launch Rail Departure Velocity (feet/second):	114	
Minimum Static Margin During Boost:	1.5	*Between rail departure and burnout
Maximum Acceleration (G):	12.7	
Maximum Velocity (feet/second):	1028	
Target Apogee (feet AGL):	10,000	
Predicted Apogee (feet AGL):	10,000	

Payload Information

Payload Description:

Our payload will be a functional demonstration of a CubeSat thruster. It will remain attached within the nosecone after main parachute ejection and will be attached to the main parachute line. The cold-gas thruster system will attempt to alter the motion of the nosecone section. The purpose of this payload is to test a system that could be used in future BYU CubeSats.

Recovery Information

Electronics - The main altimeter is a Perfectflite Stratologger with a Missile Works RRC3 as the backup (both barometric). Each will have its own power source (Duracell 9v battery) and triggering switch (limit switch triggered by release pin). Stratologger will be programmed to fire at apogee + 1 second for drogue and 1,500’ for main. RRC3 will be programmed to fire at apogee + 2 seconds for drogue and 1,300’ for main. Each altimeter will have its own black powder ejection charge. Charge sizes are calculated by hand and then tested to validate. Parachutes - The drogue parachute is a 36” Top Flight Recovery X-Type. The main is a custom made 72” toroidal parachute. Landing descent rate is 19 ft/s.

Planned Tests

* Please keep brief

Date	Type	Description	Status	Comments
1/16/18	Structures	Carbon Fiber Test Tube	Complete	anufacturing methods for hand wrapped carbon f
1/19/18	Structures	Carbon Fiber Test Tube	Complete	anufacturing methods for hand wrapped carbon f
4/6/18	Recovery	Deployment Test	Success	Test effectiveness of black powder charges
3/31/18	Recovery	Range Tracking Test	Complete	Distance tests to ensure tracking
3/30/18	Recovery	Parachute CD Test	Complete	Drop tests to find CD of parachutes
4/7/18	Flight	Test launch 1	Success	Test launch of full system
5/5/18	Flight	Test launch 2	Success	Test launch of full system

Appendix B – Project Test Reports

A. RECOVERY SYSTEM TESTING

The ejection charges for deploying the drogue and main parachutes were tested prior to the test flight of the rocket. The black powder charges were connected via leads to a launch controller and the charges were ignited by pressing the button on the controller from a safe distance. The test was deemed successful if the rocket's sections completely separated from one another at a significantly high velocity.

For the first test, the ejection charge inside the drogue section was filled with 1.5 grams of black powder and the main section with 2.7 grams These amounts were calculated based on the body tube's diameter and the length of the cavity inside the parachute section. In this test, both the drogue main parachute sections successfully separated, although not at a considerably high velocity. It was decided to increase the drogue section's black powder amount to 1.7 grams and the main section to 3 grams. Both sections separated with a considerably high velocity, ejecting all necessary recovery equipment. Testing of the altimeters under simulated flight conditions did not take place because of the planned flight test demonstration.

B. PARACHUTE DESCENT RATE TEST

The descent rate of the vehicle is critical in the recovery of the vehicle because a fast descent rate could inflict damage, but a slow descent rate could cause it to drift far from the launch site. Additionally, a slower descent rate requires a larger parachute, which means that the overall weight of the vehicle is greater. To better estimate the descent rate of the vehicle when descending under the main parachute, a test of the main parachute was performed.

Methods

The parachute was tested by dropping it off a 45-ft high structure with weights of various mass attached. The parachute was unfurled as much as possible before dropping the weight off the structure to ensure that the descent rate was as constant as possible throughout the duration of the test. A rod of a known height was placed near the landing zone of the parachute, and a camera was mounted 25 feet away from it. The frame-rate of the camera was known, so the frames could be counted from the time that the weight clears the height of the rod until it impacts the ground. The descent rate of the parachute with a particular weight was calculated.

C. FLIGHT TEST DEMONSTRATIONS

Two flight test demonstrations were carried out at Utah Rocket Club launches in order to test the recovery system of the rocket in actual flight conditions, as well as test the accuracy of team flight simulations. The rocket was to launch with the chosen competition motor: the Aerotech M1297W.

For the first launch, the rocket was to fly without any additional weight and reach its maximum capable altitude. The rocket was prepared for flight with the same configuration that will be used for the competition flight. The payload was replaced with a simulated mass of the same volume and shape. The simulated apogee for launch was 10,664' AGL.

The rocket performed nominally. Both parachutes were deployed, however, spinning of the rocket twisted the shroud lines of the drogue parachute, resulting in a higher deployment velocity of the main parachute. This caused a 1" zipper down the body tube of main parachute bay. No other damage to the rocket was found.

The PerfectFlite Strattologger CF altimeter recorded an apogee of 10,644' AGL and a maximum velocity of 1,003 ft/s (Mach 0.89). These values yielded a percent error of 0.2. We then used this data to calculate the additional weight needed to reach 10,000' exactly for the second test launch.

The second test launch was conducted 3 weeks later. The zippered section of body tube was removed and the rocket was prepared for flight. For this launch, ball bearing swivels replaced the swivels used in the first test launch. Additional mass was added within the avionics coupler (near the center of gravity) and the completed payload was integrated into the rocket. This time, the target was 10,000' AGL.

The ascent was straight and the recovery system performed perfectly. The rocket was recovered without issues or damage. The PerfectFlite Strattologger CF altimeter recorded an apogee of 9,880' AGL and a maximum velocity of 1,000 ft/s (Mach 0.89). The percent error increased to 2.0. It was determined that the variability in the commercial motors was the main cause of the large change in error. Simulations are currently being conducted to determine the final mass of the rocket to reach exactly 10,000' AGL in New Mexico.

Appendix C – Hazard Analysis

A. Equipment and Tools

1. The is an inherent risk in utilizing tools and equipment, especially if that equipment spins, rotates, cuts, or otherwise moves under power. The following are risks of equipment and tool handling:
    a. Lacerations
    b. Burns
    c. Punctures
    d. Blunt force impacts
    e. Crushing
    f. Other bodily injuries

2. Ways to mitigate these risks:
    a. Always wear appropriate clothing, e.g. closed-toed shoes, short sleeves, etc.
    b. Always wear appropriate safety equipment, e.g. safety goggles, gloves, etc.
    c. Always ask someone who knows the equipment if unsure
    d. Err on the side of caution

B. Composites Safety

1. Carbon fiber, fiberglass, epoxy, and other composite materials require special care when handling. The following are risks composites handling:
    a. Respiratory irritation
    b. Skin irritation
    c. Eye irritation
    d. Splinters
    e. Secondary exposure

2. Ways to mitigate these risks:
    a. Always wear face masks/respirators when sanding, cutting, grinding, etc., layups.
    b. Always wear gloves when handling pre-cured composites.
    c. Always wear puncture-resistant gloves when handling potentially sharp composites.
    d. A dust-room has been constructed, as per MIT EHS guidelines, specifically for the handling of composite materials.
    e. No team member will handle carbon fiber until properly trained.

Table C – 1: Hazard Mitigation		
Hazards	**Effect/Severity**	**Mitigation**
General Safety Guidelines	Mild to Severe	Always ask a knowledgeable member of the team if unsure about: i. Equipment ii. Tools iii. Procedures iv. Materials Handling v. Other concerns
		Be cognizant of your own actions and those of others i. Point out risks and mitigate them ii. Review procedures and relevant MSDS before commencing potentially hazardous actions.
		Safety Equipment i. Only close-toed shoes may be worn in lab ii. Always wear goggles where applicable iii. Always use breathing equipment, i.e. face masks, respirators, etc, where applicable iv. Always wear gloves where applicable, e.g. when handling epoxy and other chemicals
Epoxy	Irritation of the skin, eyes, and respiratory system from contact and/or inhalation of hazardous fumes, skin sensitization. Mild to medium severity.	Use nitrile or latex gloves when handling epoxy, and only in a properly ventilated area. If epoxy gets into your eyes, flush with water immediately. Wash any skin that has come into contact with epoxy to avoid sensitization and irritation. If excessive fumes are inhaled, call Poison Control at **(800) 222-1222** and move to fresh air immediately.
Alcohol	Irritation of the eyes and respiratory system from contact and/or inhalation of hazardous fumes. Mild to medium severity.	Use nitrile or latex gloves when handling alcohol, and only in a properly ventilated area. If alcohol gets into your eyes, flush with water immediately. If excessive fumes are inhaled, call Poison Control at **(800) 222-1222** and move to fresh air immediately.
Acetone	Irritation of the skin, eyes, and respiratory system from contact and/or inhalation of hazardous fumes. Mild to medium severity.	Use nitrile or latex gloves when handling acetone, and only in a properly ventilated area. If acetone gets into your eyes, flush with water immediately. Wash any skin that has come into contact with acetone to avoid irritation. If excessive fumes are inhaled, call Poison Control at **(800) 222-1222** and move to fresh air immediately.
Spray Paint	Irritation of the eyes and respiratory system from contact and/or inhalation of hazardous fumes. Mild to medium severity.	Only use spray paint in a properly ventilated area. If spray paint gets into your eyes, flush with water immediately. If excessive fumes are inhaled, call Poison Control at **(800) 222-1222** and move to fresh air immediately.
Fiberglass	Irritation of the skin, eyes, nose, throat, and respiratory and digestive systems from	Use gloves and wear long sleeves when handling fiberglass. Cover mouth and nose with exam mask or respirator and wear safety goggles when cutting. If

	contact and/or inhalation of particles. Mild to medium severity.	fiberglass partilces get into your eyes, flush with water immediately. Wash any skin that has come into contact with fiberglass particles to avoid irritation. If excessive particles are inhaled, call Poison Control at **(800) 222-1222** and move to fresh air immediately.
Propellant	Burns, blunt force trauma from shock wave or motor casing impact, lacerations from shrapnel. Severe.	Extreme caution is to be used when handling the motor. Only trained personnel are to handle and assemble the motor. The ignitor will remain sealed and away from the motor until the vehicle is mounted properly on the rail and all but essential personnel have evacuated the area. It must be verified that the ignition circuit is open until all personnel have moved to the designated safety zone. The motor will not be assembled until it is ready to be loaded into the body of the vehicle. Until then it will remain in a cool, dry location in a sealed and locked container away from any flame or heat source. A first aid kit with bandages and burn treatment capabilities must be readily available whenever the motor is being handled. 5 gallons of water and a fire extinguisher must remain on reserve for putting out fires and treating burns. All personnel should be trained on treating burns and lacerations. Should an emergency occur, alert the range medic immediately while first aid is applied to the victim.
Black Powder Ejection Charges	Burns, blunt force trauma from shock wave or motor casing impact, lacerations from shrapnel. Severe.	Extreme caution is to be used when handling the black powder ejection charges. Only trained personnel are to handle and assemble the charges. The charges will remain sealed and away from the ignition circuit until the vehicle is ready to be assembled. It must be verified that the ignition circuit is open while the charges are being mounted. Until it is ready for assembly, it will remain in a cool, dry location in a sealed and locked container away from any flame or heat source. A first aid kit with bandages and burn treatment capabilities must be readily available whenever the charges are being handled. 5 gallons of water and a fire extinguisher must remain on reserve for putting out fires and treating burns. All personnel should be trained on treating burns and lacerations. Flush any burns immediately with cool water. Should an emergency occur, alert the range medic immediately while first aid is applied to the victim.
Dremel	Burns and lacerations. Medium to severe.	Avoid burns and lacerations by wearing long sleeves and gloves when operating a dremel. Always wear eye protection. Keep a first aid kit ready to treat burns and lacerations. Flush any burns immediately with cool water. Depending on the level of the emergency, call 911 while the victim is being treated with first aid.
Laser Cutter	Burns, blindness, fire damage. Medium to severe.	Never leave the laser cutter unattended. Always ask if you are unsure of how to operate it. Ensure that all fans and ducts are operating properly and that the lens is not dirty before operating. Do not look directly at the beam for long

		periods of time. If a fire erupts call 911 and alert Kevin Cole 801-422-7446.
Router	Lacerations. Mild to medium severity.	Always wear eye protection when operating the router. Do not let the motor overheat. If the motor starts overheating, turn it off and unplug the router to let it cool down. Be sure it is working properly before attempting to use again. Ensure that the router is being used on a stable surface.
Drill	Lacerations. Mild to medium severity.	Always wear eye protection when operating the router. Keep a firm grip on the drill and that the part you are drilling is properly clamped. Do not hold a part with your hand while you attempt to drill it.
Soldering Iron	Burns, fire. Mild to severe.	Always use eye protection when using a soldering iron. Ensure that the soldering iron is unplugged and cool before stowing and leaving. Flush any burns immediately with cool water. Never leave a hot soldering iron unattended.

Appendix D – Risk Analysis

- LOV= Loss of Vehicle
- PPD = Property or personal damage
- AOA = Angle of Attack

Failure Mode	**Causes**	**Effect/ Severity**	**Personal Risk Mitigation Procedure**	**Failure Mitigation Design**	**Validation**
Recovery system failure to deploy at apogee	Black powder igniter does not ignite after signal is sent	Ballistic descent - LOV	AOA 5 deg. From launchpad, Safety zone	Use only dry powder from working batch	Multiple tests of black powder ignition system
	Two sections of the rocket do not separate	Ballistic descent - LOV	Test smooth release before launch	Smoothed tubes and filed down bolts	Sand till smooth - all connecting parts
	Parachute gets caught on bolts inside of rocket	Tumbling descent - potential LOV	Fold chute in chute protector cloth, wrap shock cord neatly	Use bolts with smooth edges	Smooth bolts down. Fold chute neatly in chute protector cloth
	Flight computer does not send signal to igniter	Ballistic descent – LOV	Status lights on flight computer	Redundant motor in the sled	Test delay and ignition signals preflight
Recovery system fails after deployment	Parachute cords get tangled	Tumbling descent - Likely LOV	Safety Zone	Fold shock cord into parachute neatly	Ground test, parachute deployment
	Shock cord detaches from rocket body	Tumbling descent - Probable LOV	Safety Zone	Use long, strong shock cord with a secure connection	Test flight
	Parachute gets burned from ejection charge	Rapid descent	Stand in Safety zone	Wrap parachute in fire resistant blanket	Ejection charge test
Recovery system deploys before apogee	Deploys on pad	Potential fire in parachute bay.	Safety zone around launch pad	Computer prevented deployment	Ground Test
Separation failure	Shear pins are too strong	Uncontrolled ballistic descent LOV	Safety zone around range	Use small enough shear pins	Ground test, test flight
	Ejection charge is too small	Uncontrolled ballistic descent LOV	Safety zone around range	Measure chamber volume, calculated needed powder	Ground tests

Structural failure	Fins shear off of rocket body	Severe instability, poor trajectory, LOV and PPD	AOA 5 deg. From launchpad	High strength epoxy used for both interior and exterior fillets	Test flight
	Motor explodes	LOV, PPD	Ensure people are in safety zone before ignition	Purchase a motor from a company with a low percentage failure	Test flight
	Shock cord “zippers” the body tube	Possible detachment of parachute cord, high speed descent	People in safety zone in case of parachute loss and therefore ballistic descent	Properly sized shock cord, deployment at apogee.	Test flight
	Ejection charge damages rocket body	Possible detachment of parachute cord, high speed descent	People in safety zone in case of parachute loss and therefore ballistic descent	Measure correct amount of black powder for rocket body size	Test the ejection charge on the ground to ensure that it does not cause damage to the rocket
	Rail guide separates from rocket body	Weak connection between rail guide and rocket body, poor trajectory	Safety zone	Screw one rail guide into a centering ring and the other to a block of wood that has been mounted with epoxy to the body tube.	Test flight
	Electronics bay body coupler detaches from rocket body	Weak connection between shock cord and avionics bay, poor trajectory	Safety zone	Use steel U-Bolts and carbon fiber reinforced bulkheads which attach to shock cord	Flight test
	Components detach during takeoff	Unsecured parts, unstable flight	Safety zone	Securely tighten all detachable parts	Test flight
	Motor mount failure	Motor detaches from rocket, motor could fly towards people	Safety zone	Bolt motor mount to centering ring which is mounted with epoxy to body tube.	Test flight
	Damage due to overly large ejection charge	Zippering, broken shock cord	Handle charges with care, avoid static buildup	Calculate correct charge mass	Ground ejection charge test

Motor malfunction	Ignition before installation into rocket	Exposure to extreme heat/flame, PPD	Keep people away from the motor, when it is out of its case, unless necessary	Keep the motor in a fire resistant case away from heat sources	Motor is in a fire resistant case
	Early ignition on pad	Premature ignition signal, faulty wiring, PPD	Minimize the amount of people at the launch pad when the ignitor is inserted	Do not connect the power supply until everyone has left the launch area	Power supply not attached
	Motor explodes upon ignition or in flight	Air bubble in fuel grain, PPD LOV	Keep people in safety zone	Do not connect the power supply until everyone has left the launch area	Tests done by supplier
	Failure to ignite motor	Faulty electronics, faulty igniter	Unplug power source before approaching the rocket	Buy high quality ignitors and inspect before installation	Visual inspection of igniter
Electronic failure	Flight computer does not receive accurate data	Altimeter malfunctions, flight computer does not know when to deploy parachute, PPD and ballistic descent	Keep people in safety zone	Use two altimeters for redundancy	Test flight
	Loss of power to flight computer	Battery failure, failure to deploy causing ballistic descent	Keep people in safety zone	Redundant power source, new batteries	Test with both batteries
	Wire detaches from equipement	Loss of power to flight computer, thus no ejection charge firing	Keep people in safety zone	Secure wires in terminals	Pull on wires to test connection strength

Appendix E

Assembly Checklist:

1. Check fins at the joints for strength
2. Check fittings of all interfacing parts
3. Test parachute attachment to shock cord
4. Check avionics bay cable connections
5. Check payload cable connections
6. Test delay and ignition signals for chute deployment
7. Tightly pack main parachute and properly manage shock cords
8. Insert avionics bay body coupler into booster section
9. Tightly pack drogue chute and properly manage shock cords
10. Insert payload into nose cone and attach wires
11. Insert shear pins at coupler to body tube interfaces
12. Insert nose cone into front end of the payload section
13. Check center of gravity after fully packed to verify stability

Preflight Checklist:

1. Check GPS connectivity
2. Place Go-Pro video camera in viewing area. Begin recording.
3. Place transceiver and electronic controls (cameras, ignition) in avionics bay behind blast shield
4. At this point, all but two designated technicians must return to safety zone
5. Check ignitor for quality before installing
6. Launch Control Officer places ignitor in motor
7. Activate pad cameras
8. Activate avionics and payload
9. All personnel must return to safe zone

Launch Checklist:

Launch Sequence Procedures:

1. RSO oversees ignition procedure
2. Start countdown program, T - 60
3. Sound range siren at T - 20
4. Launch command sent at T - 15. Rocket is committed.
5. T - 10 countdown
6. Motor Ignition and Liftoff at T - 0

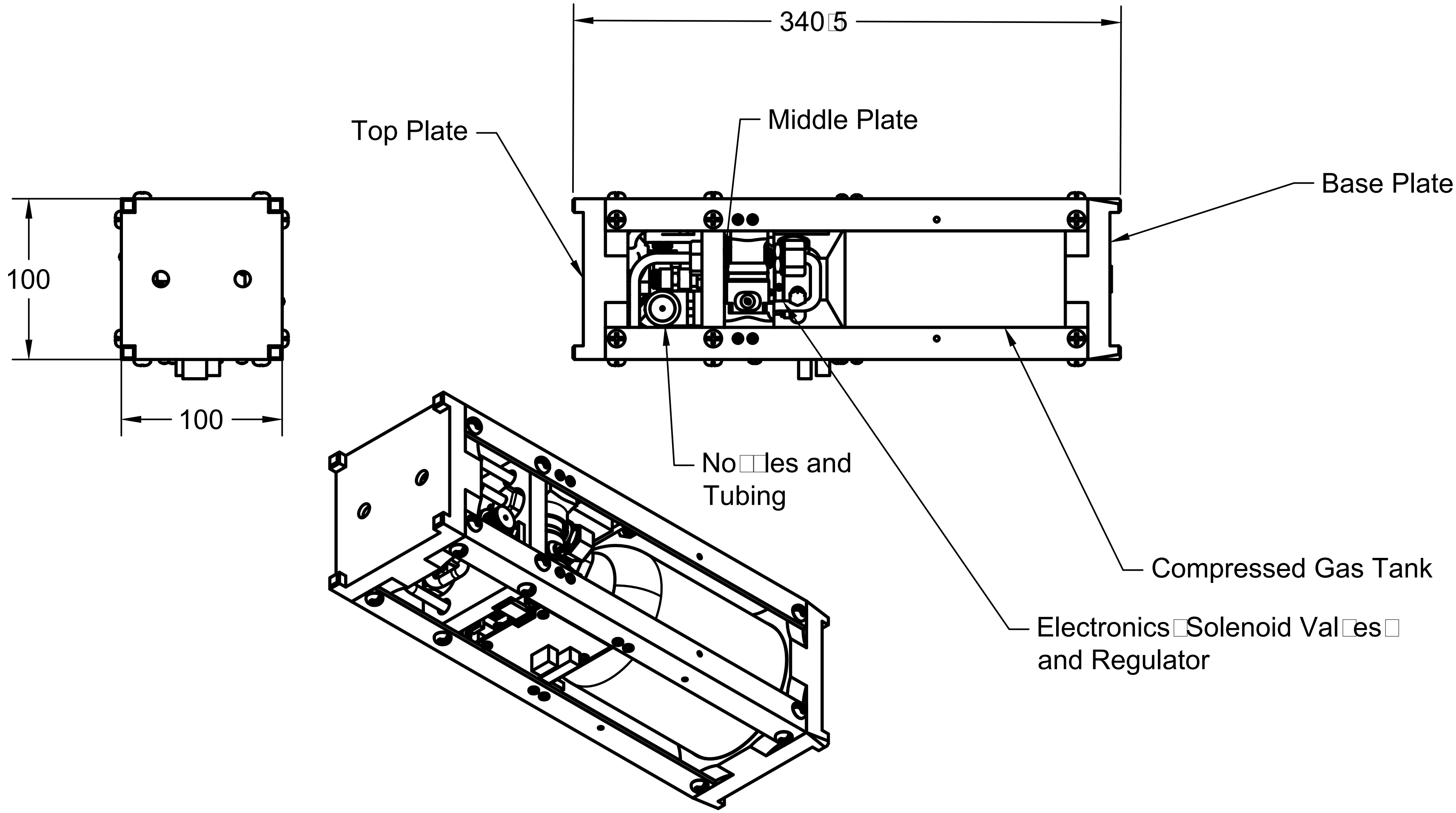
In Case of Misfire:

1. Countdown to T + 60
2. LCO removes ignitor
3. Other technicians may now approach their station
4. Check ignitor integrity. Replace if necessary.
5. Recheck all steps for launch procedure
6. Review video and audio footage
7. Start launch sequence from step

Takedown:

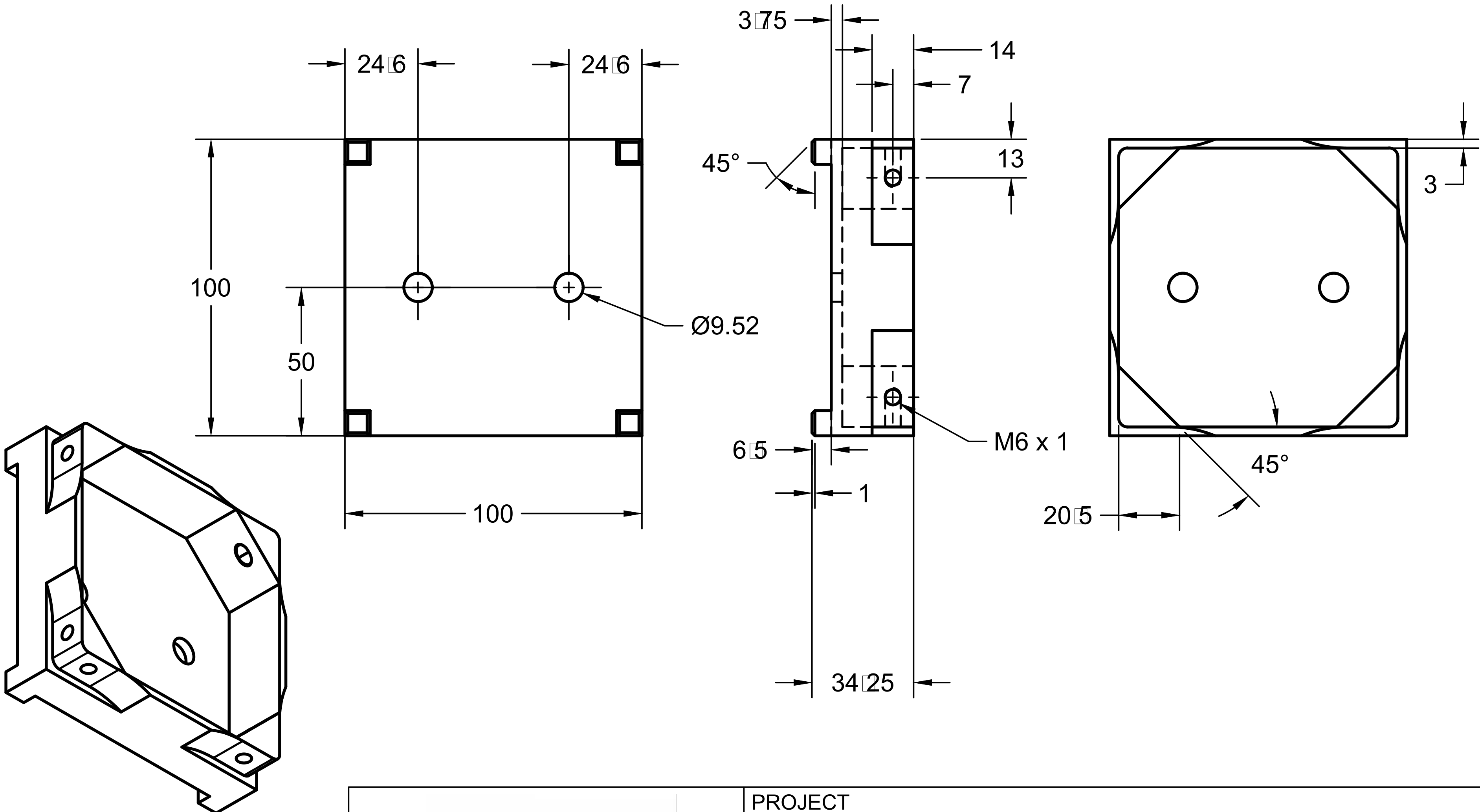
1. Shut down electronics
2. 5 min wait time before approaching site

Appendix F – Engineering Drawings

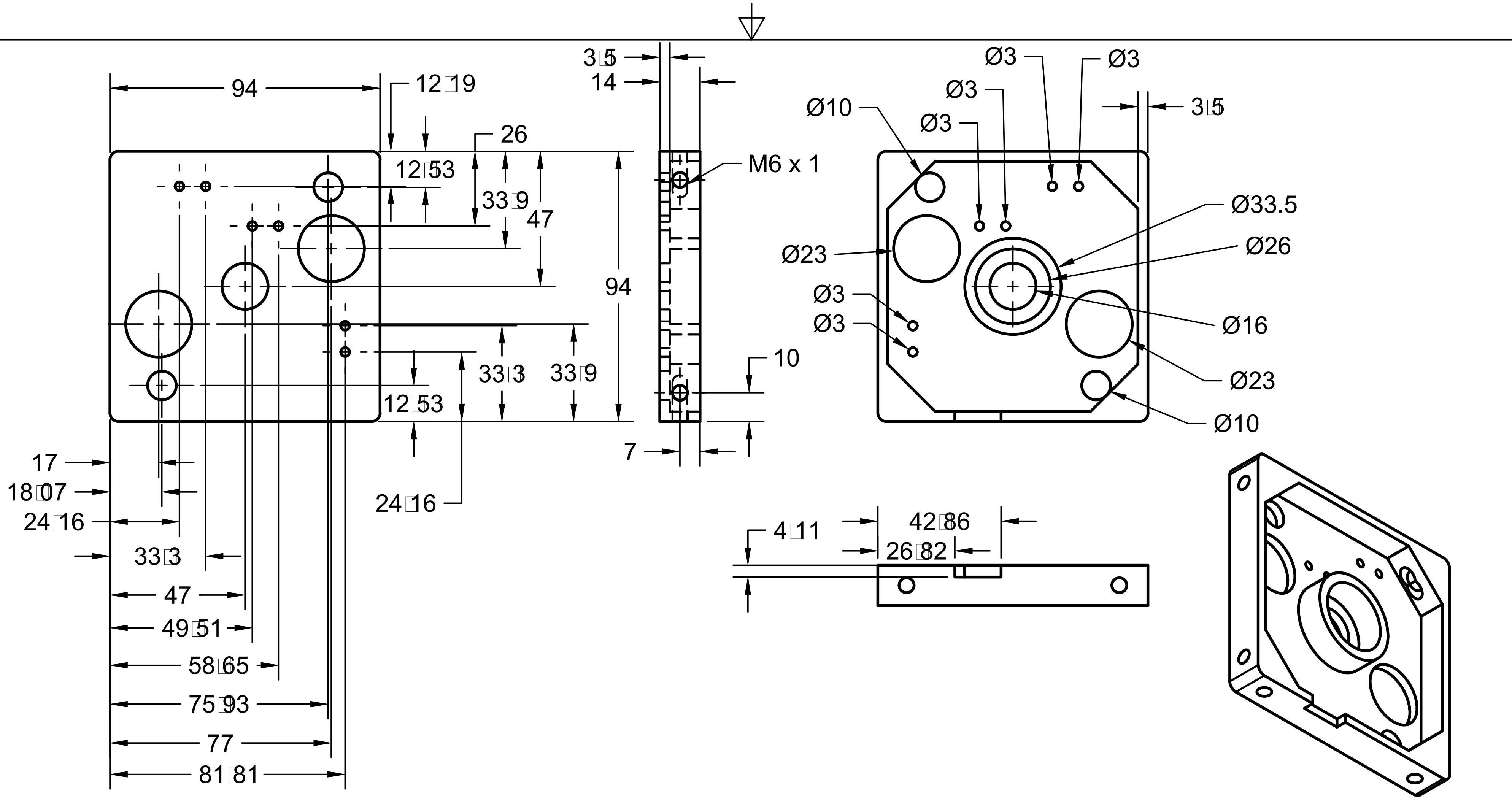


BYU ROCKETRY

PROJECT	BYU Rocketry - 2018 IREC and Spaceport America Cup				
TITLE	CGTE 3U Basic Dimensions				
APPROVED		SIZE A	CODE	DWG NO	REV
CHECKED					
DRAWN	Mark Sweeney 5/27/2018	SCALE 1:4		WEIGHT	SHEET 1/6



BYU ROCKETRY	PROJECT BYU Rocketry - 2018 IREC and Spaceport America Cup TITLE CGTE Top Plate	
APPROVED	SIZE: A	CODE / DWG NO / REV
CHECKED		
DRAWN Mark Sweeney 5/27/2018	SCALE 1:2	WEIGHT / SHEET 2/6



PROJECT

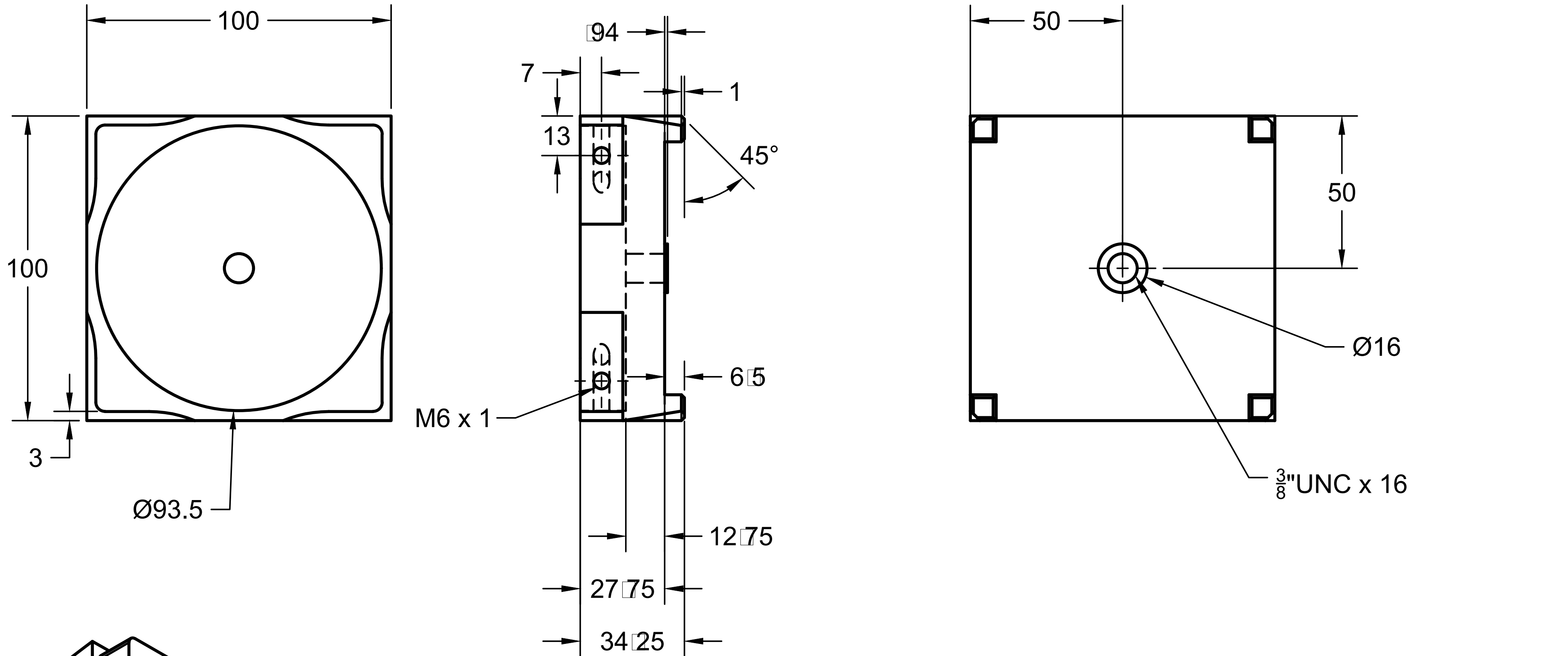
BYU Rocketry - 2018 IREC and Spaceport America Cup

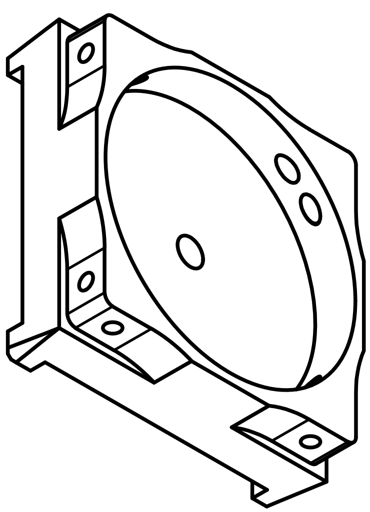
TITLE

CGTE Middle Plate

BYU ROCKETRY

APPROVED	SIZE A	CODE	DWG NO	REV
CHECKED				
DRAWN Mark Sweeney 5/27/2018	SCALE 1:2	WEIGHT	SHEET 3/6	



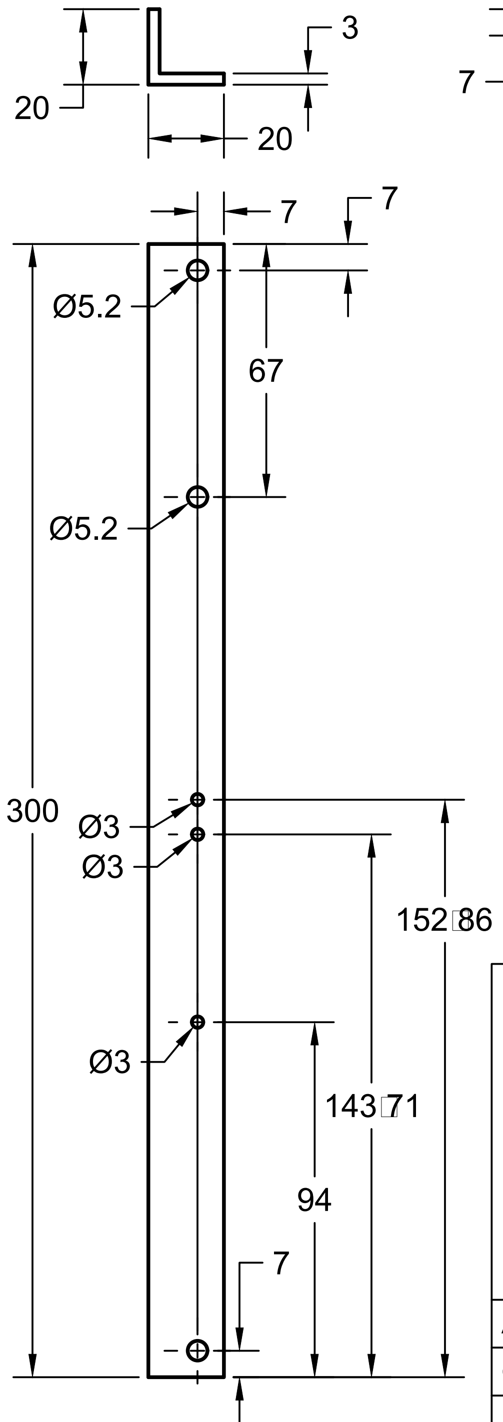


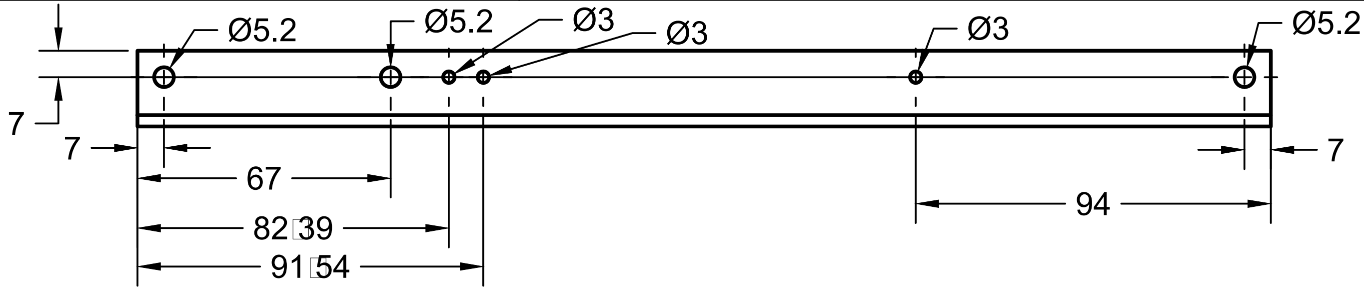
BYU ROCKETRY

PROJECT
BYU Rocketry - 2018 IREC and Spaceport America Cup

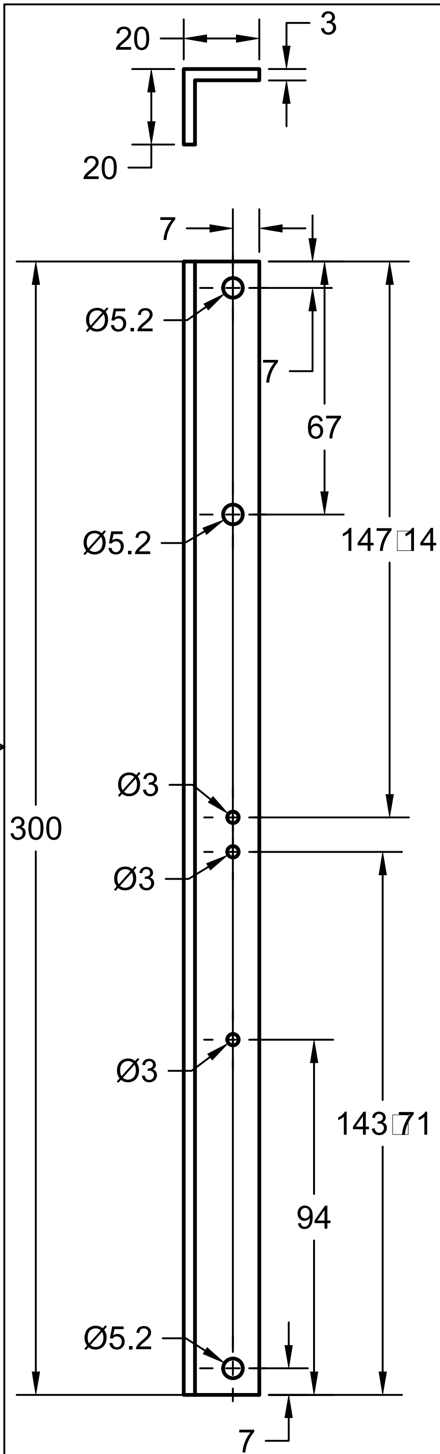
TITLE
CGTE Base Plate

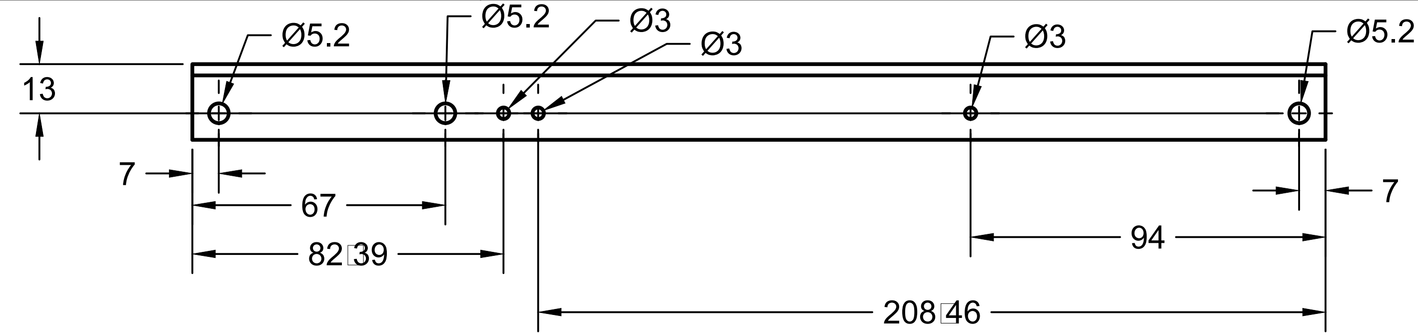
APPROVED	SIZE A	CODE	DWG NO	REV
CHECKED				
DRAWN Mark Sweeney 5/27/2018	SCALE 1:2	WEIGHT	SHEET 4/6	





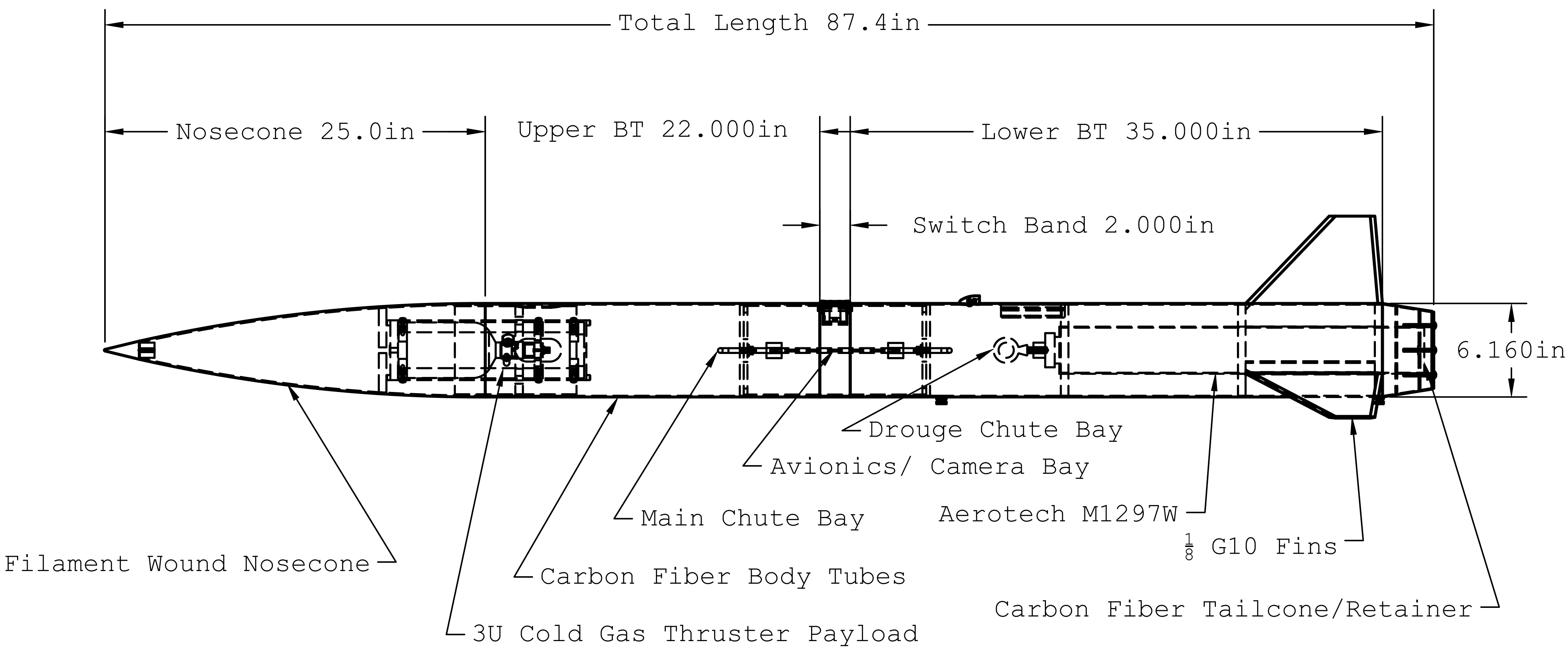
PROJECT	BYU Rocketry - 2018 IREC and Spaceport America Cup			
TITLE	CGTE Angle Bracket Type A			
APPROVED	SIZE A	CODE	DWG NO	REV
CHECKED				
DRAWN Mark Sweeney 5/27/2018	SCALE 1:2	WEIGHT	SHEET 5/6	





BYU ROCKETRY

PROJECT BYU Rocketry - 2018 IREC and Spaceport America Cup					
TITLE CGTE Angle Bracket Type B					
APPROVED	SIZE A	CODE	DWG NO		REV
CHECKED					
DRAWN Mark Sweeney 5/27/2018	SCALE 1:2		WEIGHT	SHEET 6/6	

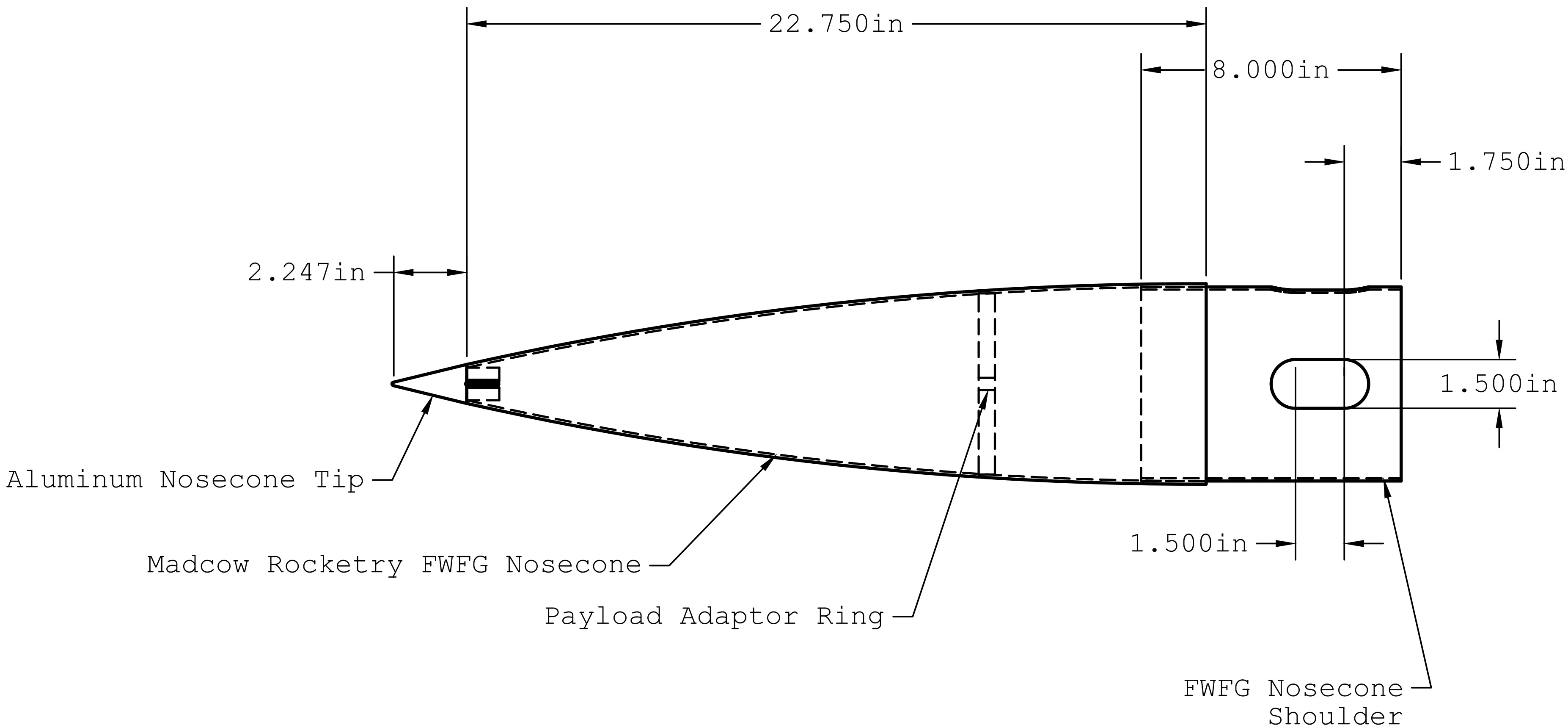


BYU ROCKETRY

PROJECT
BYU Rocketry - 2018 IREC and Spaceport America Cup

TITLE
Wasatch 1 Basic Dimensions

APPROVED	SIZE	CODE	DWG NO	REV
CHECKED	A			
DRAWN Alex Laraway 5/26/2018	SCALE 1:20	WEIGHT	SHEET 1/11	

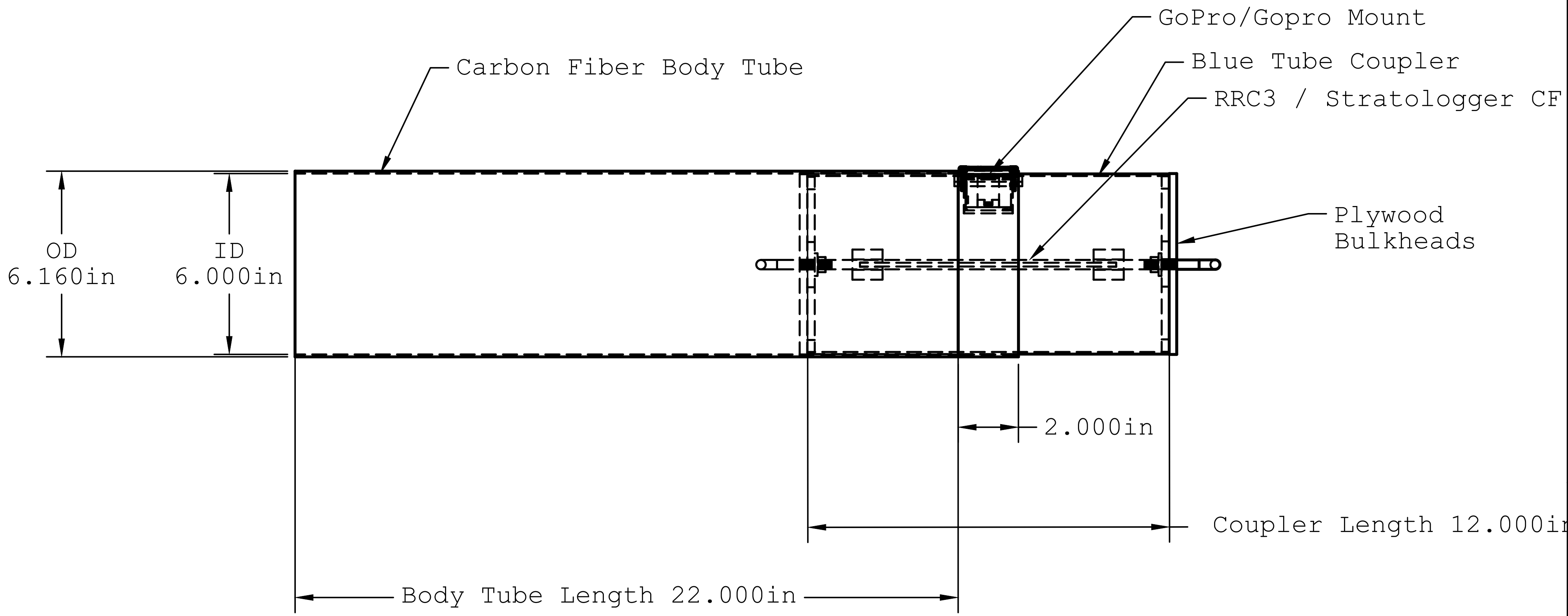


BYU ROCKETRY

PROJECT
BYU Rocketry - 2018 IREC and Spaceport America Cup

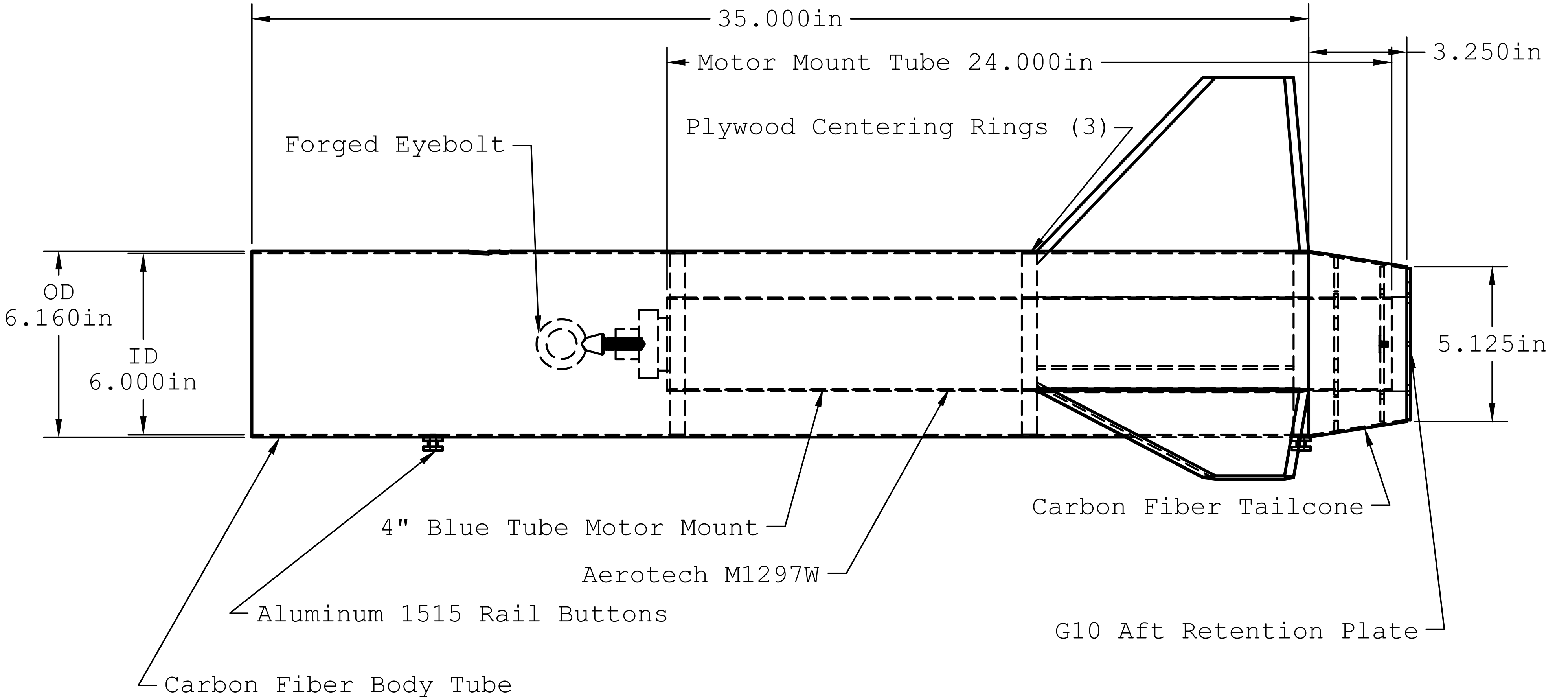
TITLE
Nosecone Assembly

APPROVED		SIZE	CODE	DWG NO	REV
CHECKED		A			
DRAWN	Alex Laraway 5/26/2018	SCALE 1:5	WEIGHT		SHEET 2/11



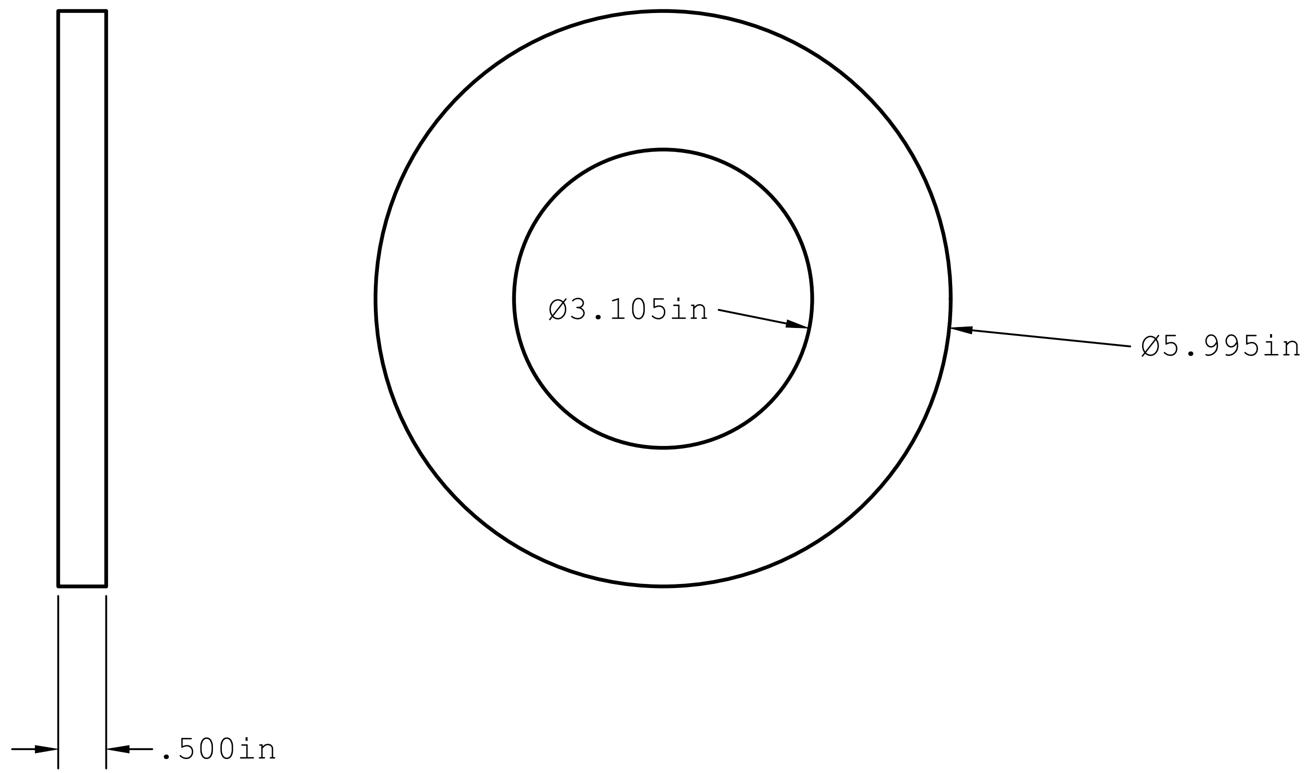
BYU ROCKETRY

PROJECT	BYU Rocketry - 2018 IREC and Spaceport America Cup				
TITLE	Upper Airframe/ AV Bay Assembly				
APPROVED		SIZE A	CODE	DWG NO	REV
CHECKED					
DRAWN Alex Laraway 5/26/2018		SCALE 1:5	WEIGHT	SHEET 3/11	



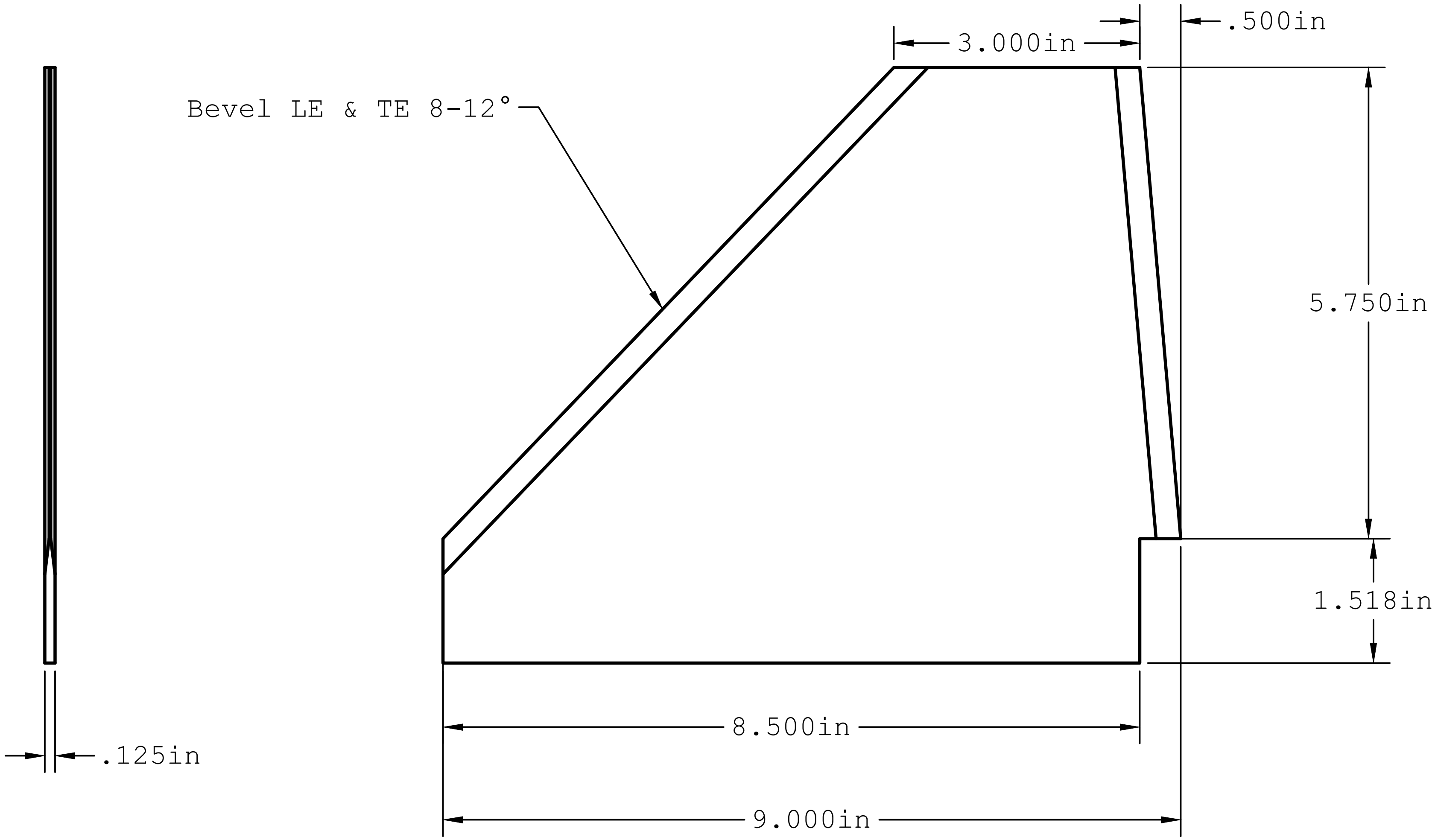
BYU ROCKETRY

PROJECT	BYU Rocketry - 2018 IREC and Spaceport America Cup			
TITLE	Lower Airframe Assembly			
APPROVED	SIZE A	CODE	DWG NO	REV
CHECKED				
DRAWN Alex Laraway 5/26/2018	SCALE 1:10	WEIGHT	SHEET 4/11	



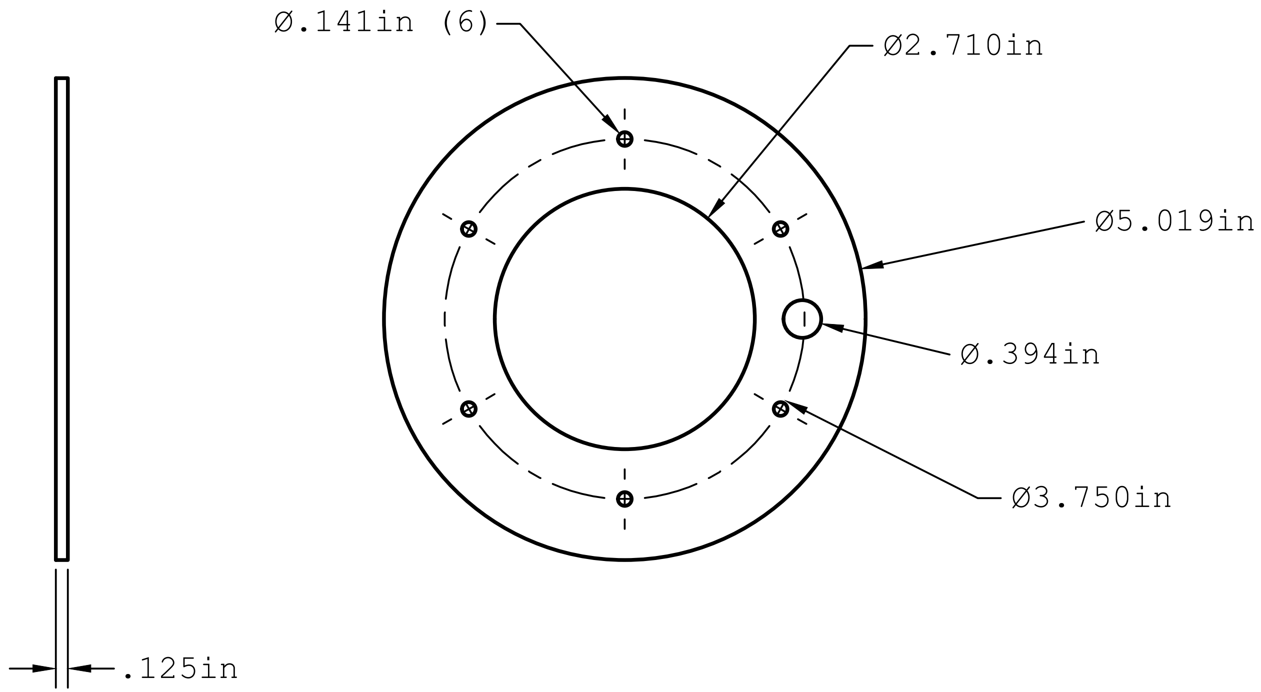
BYU ROCKETRY

PROJECT	BYU Rocketry - 2018 IREC and Spaceport America Cup				
TITLE	Centering Ring (qty 3) Plywood				
APPROVED		SIZE A	CODE	DWG NO	REV
CHECKED					
DRAWN	Alex Laraway 5/26/2018	SCALE 1:2	WEIGHT	SHEET 5/11	



BYU ROCKETRY

PROJECT BYU Rocketry - 2018 IREC and Spaceport America Cup					
TITLE Fins (qty 3) G10					
APPROVED	SIZE	CODE	DWG NO		REV
CHECKED	A				
DRAWN Alex Laraway 5/26/2018	SCALE 1:2		WEIGHT	SHEET 6/11	



BYU ROCKETRY

PROJECT
BYU Rocketry - 2018 IREC and Spaceport America Cup

TITLE
Retaining Ring
G10

APPROVED

CHECKED

DRAWN Alex Laraway 5/26/2018

SIZE A

CODE

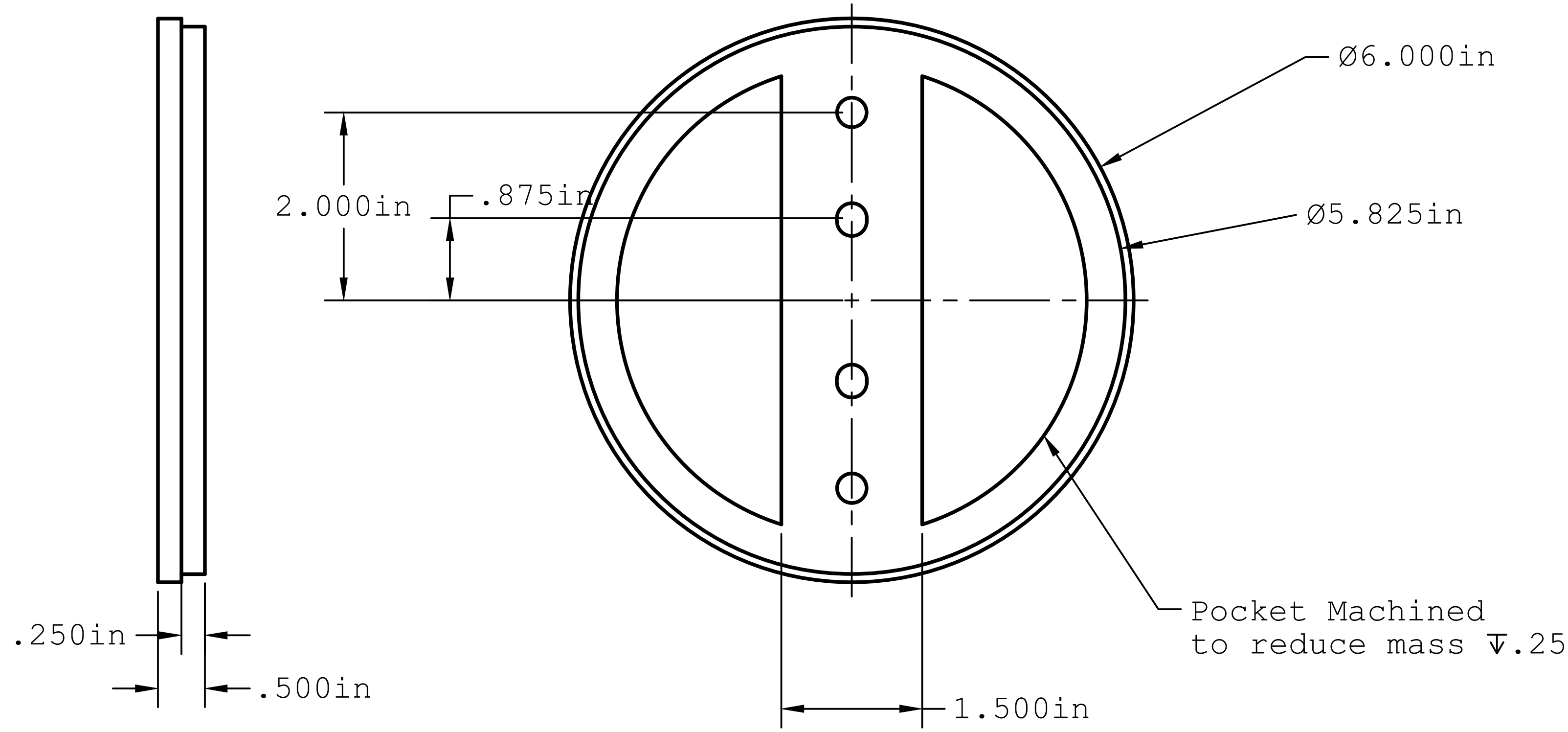
DWG NO

REV

SCALE 1:2

WEIGHT

SHEET 7/11

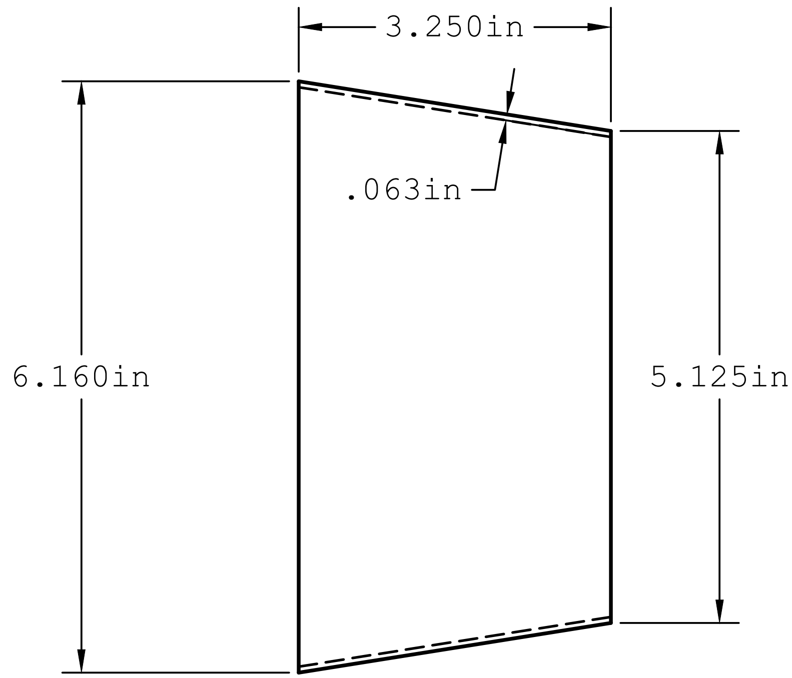


BYU ROCKETRY

PROJECT
BYU Rocketry - 2018 IREC and Spaceport America Cup

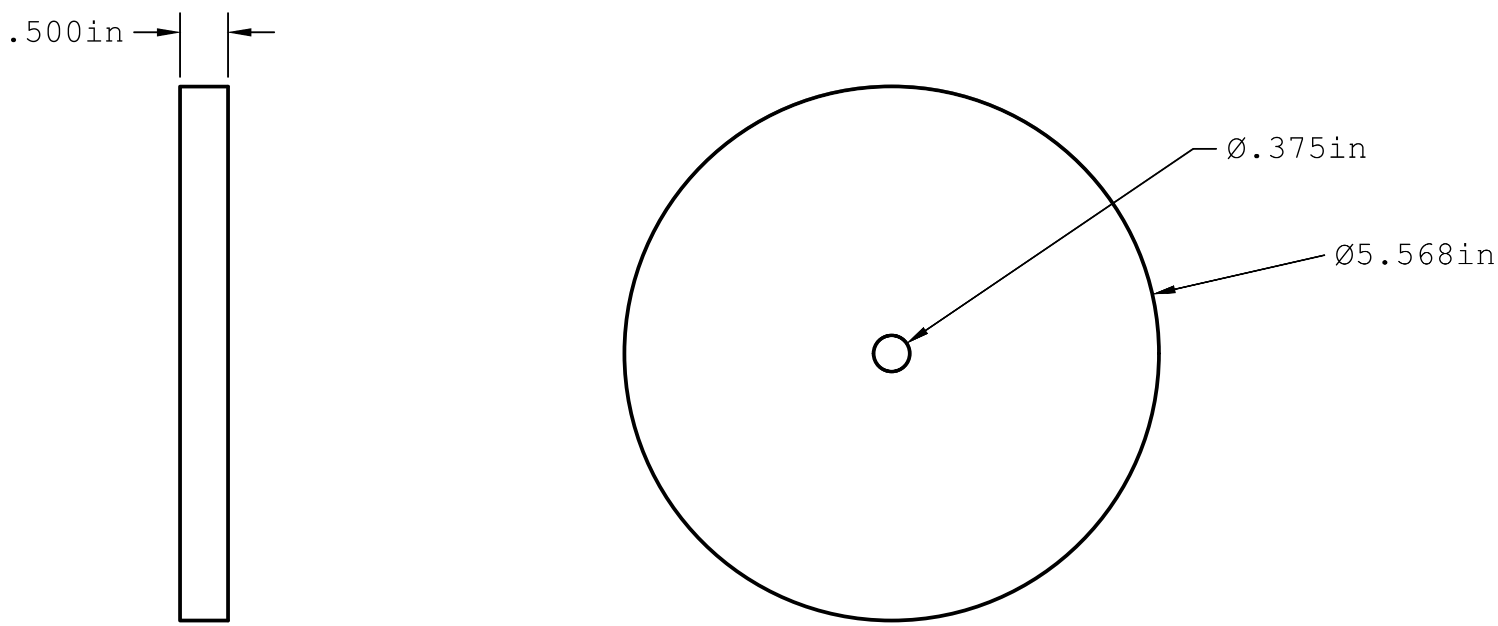
TITLE
Bulkhead (qty 2)
Plywood

APPROVED	SIZE A	CODE	DWG NO	REV
CHECKED				
DRAWN Alex Laraway 5/26/2018	SCALE 1:2	WEIGHT	SHEET 8/11	



BYU ROCKETRY

PROJECT	BYU Rocketry - 2018 IREC and Spaceport America Cup			
TITLE	Tailcone Carbon Fiber			
APPROVED	SIZE A	CODE	DWG NO	REV
CHECKED				
DRAWN Alex Laraway 5/26/2018	SCALE 1:2	WEIGHT	SHEET 9/11	



BYU ROCKETRY

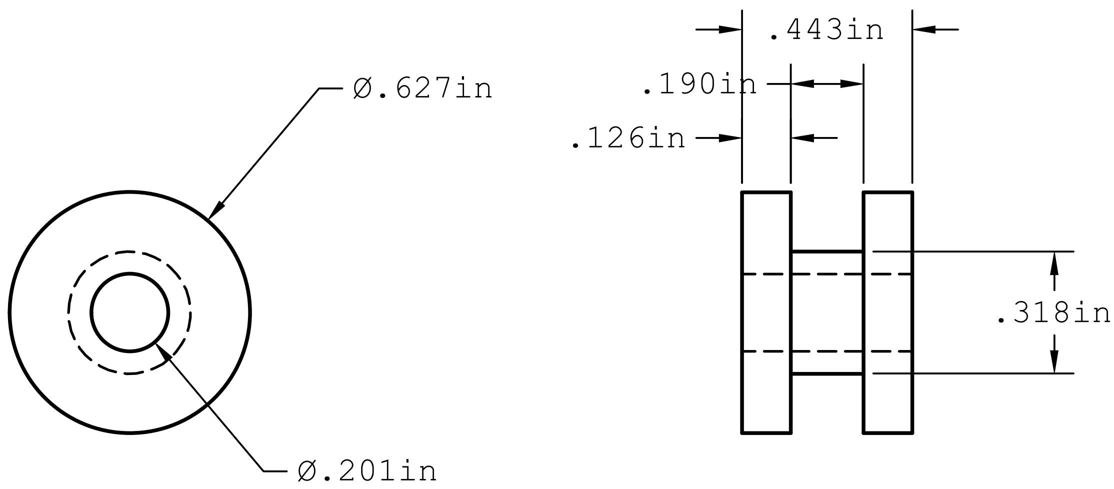
PROJECT

BYU Rocketry - 2018 IREC and Spaceport America Cup

TITLE

Payload Adaptor Ring
Plywood

APPROVED		SIZE	CODE	DWG NO	REV
CHECKED		A			
DRAWN	Alex Laraway 5/26/2018	SCALE 1:2		WEIGHT	SHEET 10/11



	PROJECT BYU Rocketry - 2018 IREC and Spaceport America Cup				
BYU ROCKETRY	TITLE Rail Button 6061 AL				
APPROVED	SIZE	CODE	DWG NO		REV
CHECKED	A				
DRAWN Alex Laraway 5/26/2018	SCALE 2:1		WEIGHT	SHEET 11/11	

Acknowledgments

Utah Space Grant Consortium

Utah NASA Space Grant Consortium and EPSCoR

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