University of Windsor High Speed Launch Vehicle Technical Report

Team 119 Project Technical Report for the 2019 Spaceport America Cup

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The University of Windsor is competing in the 2019 Intercollegiate Rocket Engineering Competition (IREC) Spaceport America Cup. The team is participating in the "30,000 ft AGL apogee with COTS solid propulsion system" category, and the rocket will be transporting a payload adhering to the CubeSat 3U standards. This report will outline the design, analysis, and build of such a rocket capable of fulfilling the aforementioned project requirements. A sensitivity analysis was performed for preliminary aerodynamic sizing, using empirical drag coefficients from existing literature. Then, a more in-depth analysis on the fin airfoil shape and the nose cone shape was performed using Ansys FLUENT. From the analysis, the team concluded that a fin with a diamond airfoil and a nose cone with a tangent ogive with a fineness ratio of 4 were the optimal candidates for the mission. The rocket structure was built using composite materials and laid against student researched and developed (SRAD) molds to achieve the desired shape. Material samples were constructed and subjected to shear tests defined by NASA-TM-X-73550 and tension tests defined by ASTM3039. Based on the results of those tests, the wet-layup method and a 90 degree fiber orientation were used to build the rocket.

Nomenclature

AGL	=	above ground level
ASL	=	above sea level
CFD	=	computational fluid dynamics
COTS	=	commercial of the shelf
ESRA	=	Experimental Sounding Rocket Assoication

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MAME = Mechanical, Automotive, and Materials Engineering
c_d = Total coefficient of drag
c_{di} = Total coefficient of drag on the ith body component of the rocket
σ = Tensile stress
σ_y = Yield stress
σ_{UTS} = Ultimate tensile stress

I. Introduction

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THE goal of the project is to design and construct an experimental sounding rocket, within the design constraints put in place by ESRA for the IREC. The rocket will take part in the 30,000 ft AGL apogee with COTS solid propulsion system category. The rocket will carry a functional payload that will serve a telemeter for flight and atmospheric properties, with a weight of 4 kg. Advanced engineering analysis methods such as CFD software has been employed for the selection of a variety of aerostructures. Most of the rocket components, such as the body tubes, nose cones, fins, and internal structures have been manufactured in house. Extensive material testing was conducted to determine optimum manufacturing methods and exact dimensions of the rocket components.

To manage a project of this size the team divided itself into six subdivisions of responsibility. Each subdivision has its own lead, as they distribute work amongst their subdivision they also reported back to the technical and project leads. The subdivisions are aerostructures, materials & manufacturing, finance, recovery, aesthetics, and electronics. The project lead is responsible for the smooth functioning of the team's communication, arranging test launches, making sure that deadlines are being met. The technical lead is responsible for assigning technical duties to other members and highlighting technical challenges. Team meetings are held once a week where tasks previously assigned are followed up on and upcoming challenges are highlighted. Meeting minutes are noted down during every meeting. In addition to weekly team meetings, the team meets with the capstone advisor weekly. The capstone advisor provides insight into conceptual design. Each team member chose their roles for the project based on their strengths and interests.

The project is sponsored by GC Painting, Ventra Plastics, AP Plasman, Windsor Mold Group, Windsor Engineering Society, University of Windsor Student Life Enhancement Fund, and University of Windsor Alumni Association. Without the stakeholder's support and the support of the University of Windsor the project would not be possible.

II. System Architecture Overview

"True North" is shown in Fig. 1. It is the topic of this report.

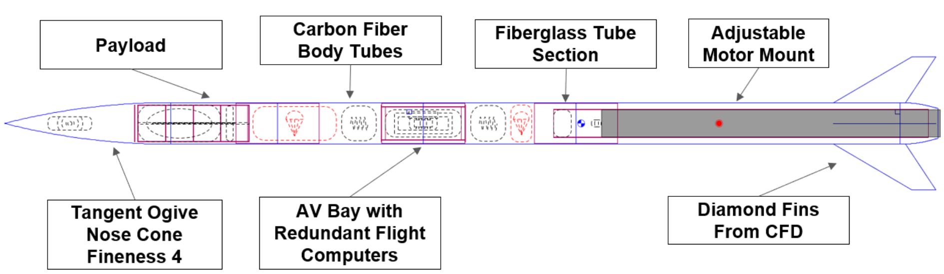

Figure 1. Cutaway View of "True North"

A. Propulsion Subsystems

The Cesaroni O3400 motor is chosen for the mission. It has the largest total impulse amongst the 98mm L3 classification motors at 21,062 Ns. Sizing up in diameter, at 150mm and 30,095Ns significantly overshoots the apogee. Furthermore, the mounting hardware for the 150mm motors is not readily available for purchase. The motor is characterized with a long burn time of 6.2 seconds.

The 6GXL Cesaroni motor casing is used to structurally support the motor. This casing has a forward closure that can be threaded into a retainer. The Aeropack 98mm minimum diameter forward motor retainer is placed at the front of the motor mount tube. The motor casing slides into the tube, and screws into the retainer. This configuration allows the team to use a shorter length motor for the test launch, as the shorter length motor can be extended with aluminium rods. The aft closure of the motor has a slightly larger diameter than the motor casing. The aft closure rests against the motor mount tube, and the load is transferred from the aft closure, to the motor mount tube, to the centering rings, and finally to the airframe.

B. Aero-structures Subsystems

1. Preliminary Sizing

Preliminary sizing was done using OpenRocket[1], a software which allows setting various physical parameters of the rocket and then calculates the trajectory with 6 Degrees of Freedom (DoF). The relevant output parameters used to rank the designs are the minimum stability margin and the apogee. The minimum stability is 1.5 body calibers and the target apogee is 30,000ft AGL. The simulation parameters are set based on the geographical location of the launch, at Spaceport America, NM. The launch pad is located 1400m above sea level and the winds average 10 mph at the ground with an average temperature of 87 °F. The weather data is the average for the month of June[2].

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First, a stability sensitivity analysis was performed to determine the contributing geometric factor in the rocket's stability. A baseline rocket was chosen, and each geometric parameter was varied one at a time from -25% to 25% in step sizes of 5%. The limitation of this procedure is that is does not show the effect of interaction between the parameters, but it is sufficient for an initial starting point. Fig. 2 shows the percentage change in a geometric parameter versus the percentage change in the stability. The rocket diameter is kept fixed at 6 inches, since that is the minimum size that would allow a 3U Cubesat payload to fit. The straight lines between the points were added for ease of viewing, they do not represent a continuous change in the stability. The fin span has the most significant contribution to the stability, followed by the fin sweep length. Continuing forward, the nose cone and boat tail will be sized for their aerodynamic performance and the fins will be sized for stability.

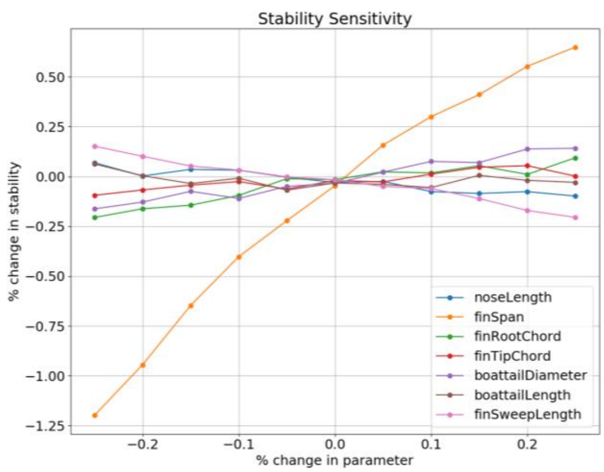

Figure 2. Stability Sensitivity Analysis

Many of the internal components of the rocket take up a fixed length, and thus, the minimum length to package all the components could be determined. The total length of the rocket is 342 cm (~11 ft 3 in). Many of the internal components also have a fixed mass since they are off-the-shelf products. The mass breakdown of the motor can be found in Table 1. An additional 1 kg of ballast mass was added to provide a more conservative design. Once the main dimensions are chosen, adding and removing ballast is the easiest way to alter the trajectory of the final design.

Table 1. Mass breakdown before the build phase

Component	Mass (g)	% of total mass
Nose cone	594	1.66
Forward Body Tube	1099	3.08
Aft Body Tube	2787	7.8
Boat tail	214	0.6
Fins	304	0.85
Motor	16842	47.16
Main Parachute	1362	3.81
Main Harness	470	1.32
Drogue Parachute	81.3	0.23
Drogue Harness	450	1.26
AV Bay	984	2.76
TRS Bay	681	1.91
Payload	4000	11.2
Tube Coupler	1577	4.42
Motor Mount	2954	8.27
Motor Retainer	289	0.81
Launch Lugs	26.6	0.07
Additional Mass	1000	2.8
Total Mass	35714.9	

2. Boat tail

The boat tail aft inner diameter was set to fit snug with the diameter of the motor, at 10.2cm. To determine the length of the boat tail, an iterative approach was taken. The boat tail length was increased by 1cm and the body length was decreased by 1cm. This ensured the space allocated to the motor mount remained constant. The boat tail length that was chosen was the one that maximized the apogee of the rocket. According to Fleemen[3], the boat tail's half angle should be below 10 degrees to prevent flow separation. The chosen length, 14 cm, and diameter, 10.2 cm, lead to a half angle of 7.8 degrees, in agreement with the recommended value.

3. Airfoil

To determine the optimum airfoil for the application, advanced engineering analysis was needed, as OpenRocket lacked the capability to specify an airfoil shape. ANSYS Fluent was used to determine which airfoil had the lowest coefficients of drag. To narrow down the possible comparison metrics for the designs, the flight regime was split into a subsonic portion, with a time-average Mach number of 0.45 and a subsonic portion, with a time average Mach number of 1.4. From the Mach vs. Time curve of the baseline rocket, the average subsonic Mach number and average supersonic Mach number were determined. The rocket spends 75% of its ascent going subsonic and 25% of the ascent going supersonic. This data comes from an OpenRocket simulation of a baseline rocket. In the 2D CFD analysis that was conducted, the $K - \omega$ SST turbulence model was used, since the boundary layers will be turbulent given the high speed nature of the flight. The density based solver along with the energy equation was opted for due to the compressible nature of airflow, mostly above Mach 0.3. A rectangular fluid domain that was large enough to capture upstream flow and wake was set up around the airfoil. The reference values were altered with respect to the dimensions of the simulated airfoil. Convergence of the residuals, coefficient of drag, volume integrals were monitored to ensure that the results were accurate. Two airfoils were tested, the diamond, the biconvex. The drag comparison results are shown in the table below. As such, the diamond airfoil is the most efficient at supersonic speeds where the fin will experience shockwaves.

Table 2. Comparison of coefficient of drag for biconvex airfoil and diamond airfoil at Mach 0.4 and Mach 1.4

Airfoil	Mach Number	Coefficient of Drag
Biconvex	1.4	1.45e-2
Biconvex	0.4	3.05e-3
Diamond	1.4	1.05e-2
Diamond	0.4	3.00e-3

4. Nose Cone

The nose cone design was guided by the same time-averaged Mach numbers approach as taken with the airfoils. Comparing nose cone shapes with the same length to diameter (fineness) ratio, the drag forces due to friction above Mach 0.8 will largely be the same[4]. Toft[5] reported that increasing the nose cone fineness past 5 results in marginal reduction in the wave drag. At that point, the skin friction drag becomes the dominant factor. From the same report, the tangent ogive and the ¾ power series were found to result in the lowest drag at the average mach numbers. When looking at packaging constraints, and wanting to fit the payload inside the nose cone, the tangent ogive offers more usable space by about 10cm. A CFD analysis was conducted to explore the tangent ogive in more detail. The experiment was setup as a 2D axisymmetric model using the k-ε turbulence model. The length of the body was kept at 3m and the nose cone fineness was changed between trials. The data are presented in Table 3. By performing a mesh convergence study, a y^+ value of less than one was found to be required for proper drag results. The trends show that at Mach 0.45, increasing the nose fineness will increase the total drag, since the viscous drag increases faster than the pressure drag decreases. At Mach 1.4, the opposite trend is observed. The trends observed from the CFD experiment match the results from the OpenRocket simulations. The nose cones with larger fineness ratios have less usable volume, and they would require a longer fuselage to offset that effect. Therefore, a nose cone fineness ratio of 4 was chosen since the rocket spends most of the flight at subsonic speeds, and the benefit in increasing the fineness ratio does not offset the loss in usable space.

Table 3. Drag coefficient of tangent ogive nose cone at nose fineness 4, 4.5, and 5

			Drag Coefficient		
nose cone	fineness	mach	pressure	viscous	total
tangent ogive	4	0.45	0.002640	0.218392	0.221033
tangent ogive	4.5	0.45	0.002011	0.220267	0.222278
tangent ogive	5	0.45	0.001680	0.222696	0.224377
tangent ogive	4	1.4	0.065494	0.157695	0.223190
tangent ogive	4.5	1.4	0.053188	0.158513	0.211701
tangent ogive	5	1.4	0.043714	0.160053	0.203767

5. Fin Planform

With the nose cone and boat tail lengths determined, the length of the fuselage is set to meet the length minimum length. The fins now need to be sized. OpenRocket features an optimization tool that iterates over given length parameters and finds the optimum design. The tool was run to find the fin span, root chord, tip chord and sweep length that would maximize the apogee and keep the stability at a minimum of 1.5 body calibers. However, the tool is very sensitive to finding a local optimum and settling at that position. Using the results from the sensitivity analysis in Fig. 2, an initial set of dimensions was input to the tool. The results from the optimization are shown in Table 4.

Table 4. Fin geometry

Root Chord (cm)	26.3
Tip Chord (cm)	8.89
Span (cm)	16.7
Sweep Length (cm)	28.6
Sweep Angle (deg)	59.7

6. Stability

The minimum stability of the final rocket is given in Fig. 3. The average weather conditions at Las Cruces, NM in June are used for the simulation, as described in the beginning of Section II.B. The minimum stability is 1.925 body calibers, and it occurs once the rocket first leaves the launch rail.

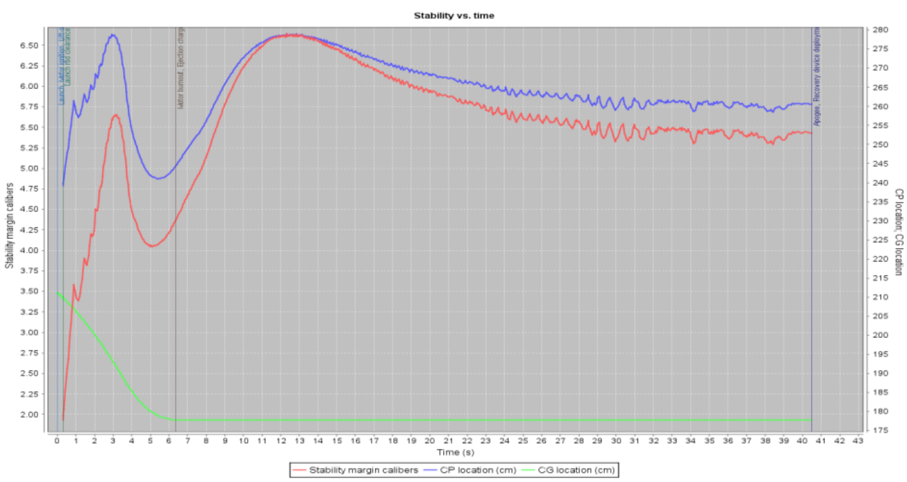

Figure 3. Stability margin for the rocket at Spaceport America launch pad.

7. Material Testing

The materials chosen to form the body of the rocket were a plain weave carbon fiber, twill carbon fiber, and S-glass fiberglass. The plain weave carbon fiber was chosen because it provides the most support in 2 directions. This is ideal for the rocket due to the largest forces experienced along its axis, and perpendicular to its axis, hence, the material would need to have high strength in multiple directions. Furthermore, carbon fiber was chosen because of its high strength to weight ratio, making it ideal for the rocket. The twill carbon fiber is best for shaping to complex contours and was necessary in constructing the desired shape for the boattail component. S-glass fiberglass was selected as being another material to make up the body of the rocket because it also has a high strength to weight ratio, as well as allowing radio frequency signals to pass through it, unlike carbon fiber. This makes it an ideal material to form the body of the rocket to ensure that the GPS signal can be received and tracked.

With the final shape, and length of the rocket determined, a choice of material was needed to finalize the manufacturing process, as well as, determining whether or not the rocket would be able to support all the necessary loads. To accomplish this, multiple tests were conducted, these tests include tensile and shear tests. For the tensile test, the ASTM D3039[6] was selected due to it yielding the best result for composite materials such as carbon fiber. The shear test is a 10 degree off-axis test[7] and is not officially standardized, however it is recognized by the community as being an accurate method to test shear properties of a material. It was determined that a thickness of 0.1 in (2.54mm) was needed for structural integrity of the rocket. The tests showed that the carbon fiber can withstand the forces experienced by the motor at maximum power, and the impact when it finishes its flight. During a test, a video extensometer was utilized in order to obtain the strain the carbon fiber would experience in 2 directions so that the Poisson's ratio could be calculated. This allowed for improved accuracy on how the material would react when exposed to similar forces. A summary of the data obtained from the test results can be seen in Table 4: Material Test Results for Plain Weave Carbon Fiber. Table 5 shows the yield strength of the material and maximum strength in tension and shear.

Table 5. Material Test Results for Plain Weave Carbon Fiber

Test	$Yield\ Stress$ (MPa)	$Max\ Stress$ (MPa)
Tension, σ	274.552	291.044
Shear, τ	174.209	206.418

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8. *Manufacturing*

Manufacturing the rocket was the second largest hurdle after completing the design. Fortunately, some parts were easier to make than others. One of the simplest parts of the entire rocket, the couplers, were the first major part to be manufactured in house. According to our design, three couplers were called for; one coupler joins the aft body tube with the forward body tube, the other connects the forward body tube with the nose cone, and the final one connects the Radio Frequency Window to the aft body tube. The couplers that are not permanently attached are made of carbon fiber. The remaining coupler is permanently attached to the aft body tube with a fiberglass body tube, and is made of fiberglass. To calculate the amount of material needed for the couplers, three rectangular sheets of the fiber were cut into dimensions where its length, the longest side, is 4 times the circumference of the tube (4 layers thick) and the shorter length is the desired height of the coupler. The male molds were prepared by coating the tube's outside surface with 3 layers of a wax gel called mold release, a fourth layer of Petroleum Jelly, and a fifth layer of vacuum bagging. All of which is designed to aid in the separation of the mold and the carbon fiber (once hardened in the desired shape). Next a two-part epoxy was created using PT2520 A (epoxy resin) and PT2520 B (hardener) of about 250g for use in all three couplers. The most delicate and time sensitive part of the process begins when a layer of epoxy coats the surface of the tube followed by wrapping the carbon fiber tightly around the tube while new layers of epoxy are applied to the outside surface of the fiber. It is important to mention that the epoxy and carbon fiber layers were made into a single smooth surface at every opportunity using a tape wrapped cooking roller and a tape wrapped plastic jar. These devices were used to compress the layers together and bring the excess epoxy from below to the surface. Once wrapped all the way around the tube, a final layer of epoxy covers the fiber and is left to dry for about 18 hours. After this time period the carbon fiber (now hardened into the shape of a coupler) can simply be pulled off with its vacuum bagging. Once the bagging is pulled off, one is left with a pristine coupler.

Figure 4. Preparing the Mold with Mold Release


Figure 5. Preparing the Mold with Petroleum Jelly


Figure 6. Preparing the Mold with Vacuum Bagging

The aft body tube, the forward body tube, the radio frequency window (RF Window), the motor mount, and even the cylindrical portion of the nose cone (before the curve) were made in house using a method similar to that of the couplers. There were however some changes that had to be made to accommodate the larger length and radius of these parts compared to the couplers. To begin with, the mold was changed for the cylindrical part of the nose cone from a tube to a custom-made CNC wood male mold which was designed so that when wet fiberglass layup was applied to it, the tangent ogive portion of the cone would be made at the same time as the cylinder part of the nose cone. This was accomplished using wooden planks that were glued on top of each other and lathed into a cylinder. For the motor mount tube, the cylinder of the aluminum motor mount itself was used as the male mold. The added bonus to using the aluminum motor mount as a mold is that it ensured the motor mount tube would fit over the aluminum motor mount and it cut down on cost and time needed to build a mold for this component. Another major difference is that a crane was used to slide the carbon fiber body tubes off their molds. This was done by creating a square plate with a centered hole large enough so that it can fit over the body molds snugly, but be small enough so that they can grab all the carbon fiber on the mold. Once slid onto one side of the mold, a crane (on opposite side of the plate and the mold) can be used to pull the plate upwards which then pulls on the carbon fiber. This setup can be seen in Fig. 7. This results in a tube of carbon fiber which can be used as a body or aft tube once the vacuum bagging is removed.

Figure 7. Removing Tube from Mold

A significant difference also exists in thickness in that the forward body tube and the couplers were 8 layers thick instead of 4 layers thus requiring the longest side of the carbon fiber to be twice as long (8 times the circumference of the mold it sits on).

The manufacturing process of the boat tail is closer to the body tube process but it also stands alone as different because of the shape and material the mold consisted of. To elaborate, the boat tail of this rocket has a cylindrical portion, and then a decreasing radial cone but this portion starts with a sudden increase in radius of about 1/8th of an inch. This can be seen in the Fig. 8. The process starts by creating the boat tail mold with high density foam. This is a complex process where rectangular stacks of the foam are bonded together using a product called 3M Spray Adhesive. This results in a large rectangular box made of foam. To transform this into the desired shape with high accuracy, the foam was cut with a CNC machine. The result is a very accurate mold but the wet layup method had to be modified in order to deal with the properties of carbon fiber when it comes to complex shapes. Furthermore, the mold had a different preparation process as it was a one-use mold. This process forgoes the need for mold release, vacuum bagging, and petroleum jelly and it starts by considering this mold as two molds instead of one, the cylindrical section and the curved boat tail section (both being 8 layers thick). The cylinder section follows the normal wet layup method of applying a thin coat of epoxy to start and then tightly wrapping the carbon fiber around it, reapplying the coat to each new freshly applied coat of carbon fiber. The curved section will require more cutting of the carbon fiber sheet as it is being wrapped around due to the change in radius. This results in a warped frontline very soon around the curved surface. To resolve this, the carbon fiber sheet was cut and reapplied in such a way that the new frontline that replaces the wrapped frontline will cover most of the surface area that that warped surface line did not cover resulting in minimal extra thickness (which will mostly disappear once sanding takes place). Since no lubrication technique was used, the high-density foam was carved out resulting in a neat outside surface but a messy inside one with patches of the foam still there. All in all, this surprising level of deviation from the main manufacturing method still results in an aerodynamic and accurate shape.

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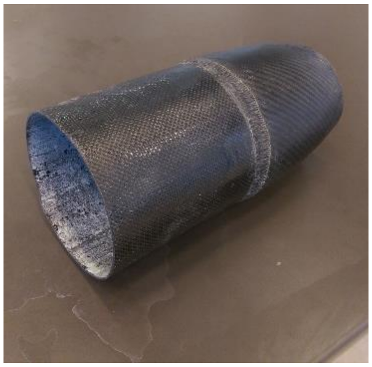

Figure 8. Boat tail

The nose cone is a part that relies highly on the precision of its tools during manufacturing. This is why, in order to manufacture this part, a CNC was used to obtain the aerodynamic shape. The cylindrical part of the mold, as stated previously, was cut on a lathe. The Nose Cone mold was made using two molds which were then glued together to form one mold. This was done due to the limitations of the machines available in the shop, as a one-piece mold would have been too large for any of the available machines. The two pieces were centered and glued together using 3 dowels 1 inch in diameter, and spaced evenly apart. All dowels, holes, and faces were glued together to ensure the two parts would not come apart when utilizing the crane. The mold was then prepared by sanding and polishing the wood to 2000grit with the use of a palm sander. Then the mold was sealed and prepared using the same method mentioned above for the various body tubes. The fiberglass needed to be cut a different way as well to ensure proper tangent ogive shape of the nose cone using a CAD flat layout. It was cut to the proper length, with multiple sections cut out along its width to account for the changing diameter. It was also cut into 8 sheets instead of 1 long sheet. This allowed for easy application and control over the layering and layup of sheets.

Figure 9. Nose cone mold (left) and the fiberglass nose cone (right)

The centering rings were manufactured in a very simple fasion, they were made on a flat sheet of aluminum. This aluminum mold was prepared by applying 3 layers of mold release. Once the mold release was applied, the carbon fiber was then layered using the methods discussed earlier. This sheet was made to be 8 layers thick. Once the sheet finished curing, it was then removed from the mold, then cut on a water jet to proper sizing.

The fins were manufactured using a female mold. First, two halves were created separately using a vacuum bag method in the mold. Then, once the two halves cured, they were placed on top of each other and sandwiched in the mold. Another few layers of carbon fiber and epoxy were applied between the two halves so they would bond to each other. The two halves are secured to each other through the bolt holes. There is a channel on the lower mold where an o-ring can be placed to prevent the epoxy of different parts from mixing and bonding to the aluminum.

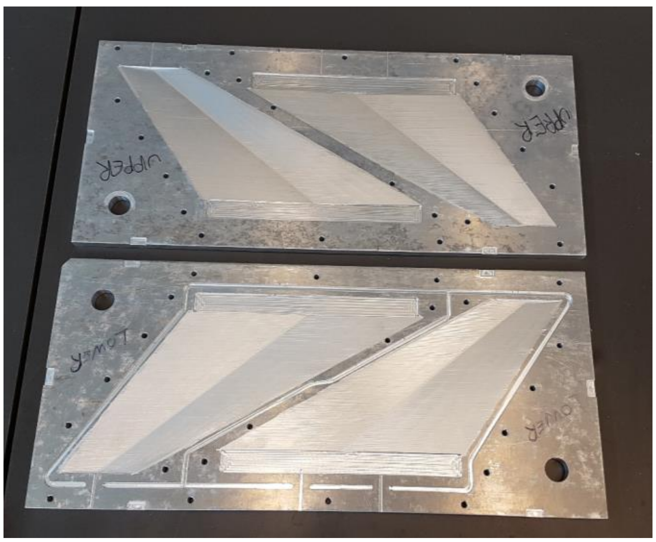

Figure 10. Upper and lower halves of the fin female mold

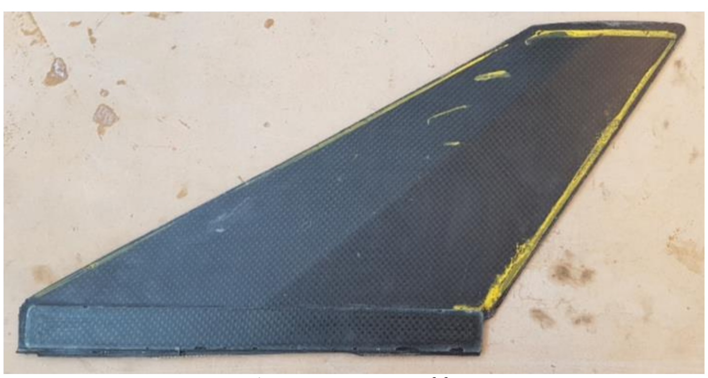

Figure 11. Top view of fin

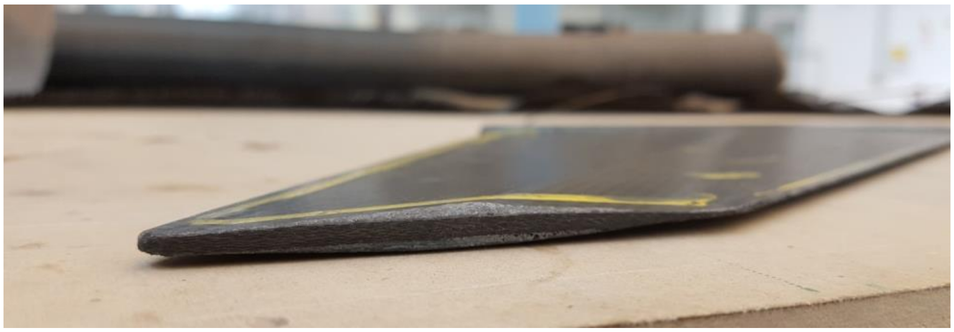

Figure 12. View of diamond airfoil

C. Recovery Subsystems

The Rocket's recovery system consists of a dual deployment parachute system. The designed sequence is characterized by drogue parachute deployment at apogee and main parachute deployment at 1650 ft (1500 ft x safety factor of 1.1). Both open rocket and Simulink were used to simulate the descent speed of the rocket with respect to the changing air density. Both of the ejection systems operate using black powder. Above 20 000 ft ASL the low atmospheric pressures cause a lower heat transfer coefficient this affect lowers the burn rate of black powder (Cheng[8], Leypunskiy[9], and White[10]) Since this rocket is designed to reach an apogee of 30 000 ft AGL our drogue ejection canisters have been designed to operate at high altitude conditions.

1. Parachutes, Descent Rates and Shock Cords

The dual deployment parachute system allows for a quicker and easier recovery of the rocket by allowing the rocket to fall faster during its initial descent. According to the IREC rules, the drogue parachute is allowed to fall between 23-46 m/s. Since the target apogee is 30 000 ft AGL it was decided to be more liberal with the rocket's initial descent speed. The drogue parachute is released 1 second after apogee and has been sized to fall at a maximum rate of 44 m/s. This was achieved by using a 36-inch diameter parachute with a 3-inch spill hole. The main parachute needs to be released before the rocket reaches 1500 ft AGL and fall at a rate of less than 9 m/s. Due to fluctuations in atmospheric pressures and gauge reliability it was determined to use a safety factor of 1.1 for the main ejection altitude. Therefore, the main parachute is set to be released at 1650 ft. The main parachute's descent speed was decided to be 7 m/s to avoid damage to the rocket upon impact with the ground. The size for the main parachute's diameter was determined to be 109 inches.

The Simulink model that was used to size the parachutes is based on Eq. (2) which calculates the force of drag and compares it to the force of gravity to determine the changing terminal velocity. Where F_D is the force of drag, A is the projected horizontal area of the respective parachutes, m is the dry mass of the rocket in kilograms, 23.8 kg, g is the acceleration due to gravity (9.81 m/s^2), π is a constant, and rho is the density of air which changes with respect to altitude, v is the velocity of the rocket, starting conditions are v_0=0 m/s and C_d is the coefficient of drag of the drogue and main parachutes given by the manufacturer of 0.75, and 2.59, respectively. Simulink modeled the change in air density via a logarithmic line of best fit based on data easily found online about altitude and air density. The area is determined through Eq. (1).

$$A = \frac{1}{4}\pi(D^2 - d^2) \tag{1}$$

$$F_D = \frac{1}{2}C_d S_{ref}\rho \tag{2}$$

After the parachutes are ejected, a 12 m shock cord attaches the separated rocket components together this length was determined by a 7:2 ratio with the total rockets body length. This ratio was determined via experience and advisor advice, as it prevents different sections of the rocket to descend without possibly-damaging in-air collisions.

The materials considered for the parachutes and shock cords were nylon, Kevlar, and mylar. The material needed to be as light as possible and strong enough to resist the forces applied to it during recovery. Mylar was being considered due to its extremely lightweight characteristics but after consulting rocketry mentors it was determined to be too weak of a material for high powered rockets. Both Kevlar and nylon are strong enough to withstand the forces applied to the parachutes and shock cords during recovery. However, since weight is a constraint and Kevlar materials are heavier than nylon, both chosen parachutes, and their respective shock cords, are made of Nylon due to its strength and weight benefits. The nylon cord chosen is rated to 17kN of tensile strength.

2. Ejection system

The ejections of both of the parachutes in the dual deployment parachute recovery system are characterized by a forced decoupling and parachute ejection. Specifically, the drogue parachute will be ejected at apogee and the main parachute will be ejected at 1650 ft. The drogue parachute ejection is characterized by the decoupling of the forward body tube from the aft body tube. The drogue parachute is ejected at low atmospheric conditions and requires a 1 atm pressure vessel for complete combustion of the BP. The main parachute ejection is characterized by the decoupling of the nosecone from the forward body tube. Both ejections are driven by bay pressurization via black powder gas combustion. The combustion of the black powder needs to create enough axial force to break the shear pins.

3. Shear Pins

After the burnout of the motor, the three detachable sections of the rocket will each be exposed to a respective drag force which diminishes as the rocket decelerates and approaches its apogee. The differences between these drag forces acting on mating sections must be addressed in order to prevent them from causing the sections to separate. An estimate of the drag on each body component, c_{di}, was obtained from OpenRocket. Since c_{di} is a function of the mach number, the values were recorded at the maximum velocity of the rocket following burnout. It is important to stress that these drag coefficients are only an estimate, since OpenRocket does not take into account the angle of attack when reporting the drag coefficient through the "Component Analysis" interface. The total axial force, F_A, acting on a single component is equal to the sum of its axial weight force, W_a, and the drag force, F_D. This process is used to calculate F_A for the nose cone, the forward body tube, and the aft body tube. Then, the force acting to separate the coupler is equal to the difference in the axial forces for each component. Through these calculations, it was found that the separation force on the forwardmost coupler is equal to 629.6N and the separation force on the aft-most coupler is equal to 415.1N. To keep the components of the rocket together, nylon screws will be used to fasten the couplers to the body tubes. These screws effectively act as shear pins, since they have low load resistance. Since the separation force on the aft-most coupler is smaller, that section should break first. To take advantage of that, since the drogue parachute needs to deploy first, it will be placed in the aft-most compartment. It follows that the main parachute will be placed in the forward compartment.

To size the shear pins, a factor of safety of 1.5 against the drag separation force is used. From previous single lap shear testing[11], 6-32 nylon screws shear at 250N of force and 4-40 nylon screws shear at 190N of force. Therefore, to secure the nose cone to the forward body tube, four 6-32 nylon screws should be used. To secure the forward body tube to the aft body tube, four 4-40 nylon screws should be used.

4. Black powder

When combusted, the mass of black powder should create enough pressure to break the nylon screws and propel the mating components away from each other. The mass of black powder necessary to break the drogue compartment shear pins should not be able to break the main parachute compartment shear pins, otherwise, that would cause a premature deployment of the main parachute. It was determined that the nose cone would experience a larger separation force due to drag and required larger shear pins. Therefore, the main parachute was placed here to mitigate the problem of a premature ejection during the drogue ejection phase.

The mass of black powder was sized using the Eq. (4) where P is the resultant pressure, V is the volume of the section being decoupled, m is the mass of black powder, R is the universal gas constant for combusted black powder, and T is the combustion temperature of black powder. The required pressure for decoupling the rocket is determined by the total force required to shear the shear pins for a given section divided by the cross-sectional area of the rocket, as shown in Eq (3).

$$P = F/A \tag{3}$$

$$PV = mRT \tag{4}$$

Fully combusted black powder is as powerful at high altitudes as it is at sea level, however, the low heat transfer coefficient at high altitudes impedes complete combustion. To test the drogue canister a vacuum chamber was designed to simulate the low-pressure conditions of a high-altitude ejection. The expected atmospheric conditions are ~ -77 kPag and the vacuum chamber operated at – 80 kPag. The test concluded that the design was capable of ~97% combustion up to 3 grams. Since, the combustion of black powder under atmospheric conditions is also ~97%, and the ground test showed the required mass of black powder to be 1.5 grams to eject the drogue parachute. Therefore, no adjustments are needed to be made to the results of the ground test to account for changing atmospheric pressures.

5. Recovery altimeters

There will be two altimeters used, which will be mounted in the Avionics Bay of the rocket. The primary altimeter used will be the PerfectFlite Stratologger CF. This altimeter logs the altitude by measuring atmospheric pressure using its barometric pressure sensor. Ematches will be ignited based on the altimeter logging pressure and correlating the data with altitude.

The redundant altimeter is the Featherweight Raven3. The Raven3 ignites Ematches based on multiple conditions. Unlike the Stratologger CF the Raven3 has an onboard accelerometer. Launch is detected if the experienced acceleration is more than 3Gs. This data, coupled with the pressure data, is how the Raven3 ignites Ematches.

6. GPS Tracking

The rocket is equipped with the T3 Tracker System. The system includes a GPS whose operational range is up to 50,000 m and 500 m/s. The radio operational range is up to 14 km. These operating conditions are all within the range of the mission of the rocket, and as such, it is an appropriate device for recovery.

D. Payload Subsystems

A payload device is under development to fit inside of the 3U "CubeSat" form factor. The primary payload is an Arduino Mega with a custom PCB used as an Arduino hat for the variety of supported sensors. The sensors used in the aerodynamics data acquisition payload include: 9-DOFAbsolute OrientationBME055, SparkFun Environmental Combo Breakout - CCS811/BME280, SparkFun Single Axis Accelerometer Breakout - ADXL193. A PowerBoost 500 is on the PCB for battery changing control. A microSD card breakout card is connected to the Arduino for storage of the sensor data, all timestamped for later data analysis. The data are to be collected post-launch for processing. A Unity program is to be developed to combine our CAD model of our rocket and aerodynamic data from our payload for visualization of the launch & decent in a 3D environment. An RF system is to be developed to support the capabilities of transmitting the sensor data in near real-time (NRT) to the ground station. The purpose is to be able to visualize all the stages of the rocket launch in NRT using the Unity program.

III. Mission Concept of Operations Overview

The mission of "True North" is depicted in Fig. 13. The total ascent of the rocket will take 40.2 seconds and the total flight time is 433 seconds.

Commented [ER5]: This section shall identify the mission phases, including a figure, and describe the nominal operation of all subsystems during each phase (e.g. a description of what is supposed to be occurring in each phase, and what subsystem[s] are responsible for accomplishing this). Shall define what mission events signify a phase transition has occurred (e.g. "ignition" may begin when a FIRE signal is sent to the igniter and conclude when the propulsion system comes up to chamber pressure). Phases and phase transitions are expected to vary from system to system based on specific design implementations and mission goals and objectives.

Commented [ER6R5]:

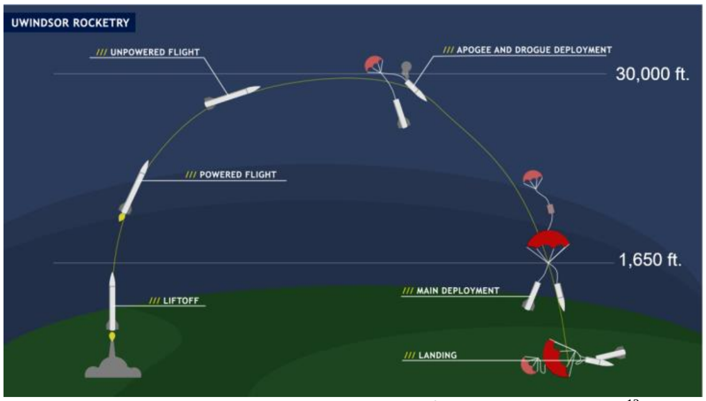

Figure 13. Mission CONOPS diagram, adapted from a previous mission[12]

A. Vehicle Preparation

The steps in the Hazard Analysis Appendix are followed. After this stage in the mission, the rocket is fully assembled, but all subsystems are disarmed. The rocket is now ready to be installed on the guide rail.

B. Launch Rail Guide Loading

The phase begins with the rocket being installed on a 1.5in x 1.5in launch rail guide. At this point, the igniter is inserted into the motor and connected to deactivated ignition cables. The flight computers are armed by turning the rotary switches. At the end of this stage, the rocket is in a state where it can be armed for ignition.

C. Ignition

The Safety Monitor will begin this phase by clearing the area of all non-essential personnel and spectators. The Safety Monitor is then responsible for arming the igniter and initiating a countdown to launch the rocket. The motor is ignited with a black powder charge after which the propellant will begin to burn, marking the end of this phase. The propulsion subsystem is solely responsible for this phase.

D. Liftoff

The beginning of the liftoff phase is marked by the rocket first moving up along the launch rail. The phase is concluded when the rocket leaves the launch rail guide. The propulsion subsystem is responsible for generating the thrust required to achieve motion. The guide rail buttons in the aero-structures subsystem guide the rocket along the launch rail. In the background, the payload and recovery subsystem are recording various flight data.

E. Powered Flight

The powered flight phase is active starting from the moment the rocket leaves the guide rail until the motor burns all the propellant. For a Cesaroni O3400 motor, this will last approximately 6.2 seconds. This represents 15.4% of the 40.3 second ascent. The propulsion subsystem is accelerating the rocket. The aero-structures subsystem is responsible for ensuring the rocket is stable throughout the ascent. The end of this phase is also the instance of maximum dynamic pressure, so the structure should be strong enough to withstand the loads experienced in flight.

F. Unpowered Flight

Unpowered flight begins once the motor is fully depleted of consumables and ends at apogee. In other words, it ends once the rocket starts descending. Although the propulsion subsystem is no longer active, the momentum gained from the powered flight phase is responsible for the motion. The shear pins in the aero-structure system are keeping the three pieces of the rocket attached together, thus preventing separation due to the difference in the drag force acting on the bodies. Again, the aero-structure system is responsible for the stability of the rocket.

G. Apogee: Drogue Deployment

The apogee phase is triggered once the flight computers determine that the rocket is no longer ascending. The computers in the recovery subsystem are responsible for this decision. The Stratologger obtains data using barometric pressure sensors and the Raven3 makes the decision using an accelerometer. Then, the flight computers will send current through the drogue channel e-matches, thus igniting the black powder charges. The pressure created by this blast will break the shear pins, cause the rocket to separate into two pieces, and deploy the drogue parachute. Only one computer is needed for this deployment, however two are used for redundancy. This event will end at an altitude of 1650 feet AGL.

H. Main Parachute Deployment

The main parachute phase is triggered once the flight computers register that the rocket has reached an altitude of 1650 feet AGL. The same deployment steps as outlines in the Apogee: Drogue Deployment section are observed. The rocket is now split into three pieces and the main parachute is deployed. This phase ends when the rocket has landed.

I. Landing

This phase begins when the rocket has landed on the ground. Once it is deemed safe to do so by the range officials, the team will locate and retrieve the rocket. The T3 GPS Tracking System, part of the recovery subsystem, will send out the GPS location of the rocket to a transponder. The proper safety procedures outline in the Assembly, Preflight, and Launch Checklists Appendix should be followed while retrieving the rocket.

IV. Conclusion and Lessons Learned

Commented [ER7]: Include the lessons learned during design, manufacture, and testing of the project, both from a team management and technical development perspective. Furthermore, this section should include strategies for corporate knowledge transfer from senior student team members to the rising underclassmen who will soon take their place.

The IREC 30,000ft COTS category is especially challenging. This is the first time the University of Windsor is participating in this category. The team members had to conduct extensive research into low cost manufacturing methods and the design and analysis of aero structures for the complicated flow regimes and the extreme compressive loads that the rocket will experience due to the nature of the rocket engine used. The O3400 motor is the motor with the highest total impulse in Cesaroni Pro 98 series. Previously, the University of Windsor had participated in the 10,000ft category. As such, a number of precedents had been set with respect to manufacturing methods and the logistics required to run a successful engineering project of this scale. The manufacturing methods did not have to be redesigned entirely, although new techniques had to be implemented due to nature of the category.

A. Lessons Learned - Management

Financial prudence, anticipation of forth coming challenges, and the design of respective contingencies are imperative to running a large engineering project. This year's rocket team from the University of Windsor has a budget lower than the previous two years' teams, by thousands of dollars. In large part, the team was able to cut down on wasteful spending, improved on low cost molding techniques, and reused certain components from previous teams. However, there could have been be more emphasis on fundraising events. The school and most sponsors do not pay for the travel expenses. This resulted in the students having to pay for most of their own travel and accommodation. Having to pay hundreds of dollars in short notice may not be convenient for all students. This can be avoided with more creative private fundraisers being held.

A clear division of labor and responsibilities and following up on them weekly is crucial to the smooth functioning of the team. Having a small team, of around 10 students will certainly help. Larger teams tend to have certain group members not fulfilling their duties making it difficult for the leaders of the team to move the project forward.

Ensuring that each student team member has an important responsibility will put pressure on them to produce results. Moreover, timely follow ups are mandatory to ensure that the results produced are of acceptable quality. Follow ups could have been better with this year's team early on. However, this aspect got better as the team got closer to competition. If it were done earlier, major delays on certain technical duties could have been avoided. For example, meetings should start with follow-up sections.

Coordination with out of school mentors, such as high-powered rocketry experts, hobbyists, composite manufacturing experts is very important. Though this year's team fulfilled these duties diligently, it was not until the later stages of the project did this happen in a more complete manner. Earlier outreach to experts and previous team members is vital in order to, not only repeat the same mistakes again, but also not to make new ones.

From a management perspective, a feasibility study of any new or challenging technical task needs to be conducted foremost. This year, a lot of interesting ideas and tests were designed. However, these tests were never conducted or materialized as the team realized how improbable there were to be implemented given the budgetary constraints and the logistical challenges they posed.

B. Lessons Learned - Technical Duties

As previously mentioned, the team this year was particular about cutting down on wasteful spending and as a result had to improvise to create low cost molds. Research on this could have been done months before the design freeze. Instead, research on molds and manufacturing did not happen until close to the design freeze. This led to the eleventh-hour crunch time where many team members working till late night for weeks close to competition. A suggestion here is optimally reuse previous materials testing data and diligently finish materials testing in a timelier fashion by coordinating with experts if challenges are faced.

The aerostructures subsystems team had to make use of ANSYS Fluent, an advanced and challenging computational fluid dynamics software. The steep learning curve was not anticipated by the team members and this resulted in delays with producing the necessary designs. A suggestion will be to start earlier and networking with professors who are well versed with the software.

With regards to recovery subsystems, for very high-altitude flights like the 30,000 ft category, implementing COTS CO2 ejection canisters will save a lot of time as they are tried and true methods. This year, custom airtight black powder canisters were implemented. Though the design is sound, extensive testing was required to ensure its functioning at very low atmospheric pressures. Implementing COTS CO2 canisters would have had the recovery subsystems team members focusing on other aspects of the project.

Lessons learned during manufacturing process include a timeframe to build the components, epoxy to fiber ratio, mold preparation, types of molds to use, and type of carbon fiber to use. During the manufacturing process, it was observed that the components made could have been optimized by the time, or order that they were made in. For example, the couplers should be made last to ensure they fit inside the body tubes and nose cone snuggly. Secondly, the epoxy to fiber ratio could be optimized to ensure highest strength with lowest amount of epoxy to decrease the overall weight of the rocket, and decrease the amount of material needed. This can be done quickly at the beginning of manufacturing by constructing small 10x10 cm square carbon fiber sheets. Each sheet may contain different layer and epoxy quantities until a proper formula is realized for the required applications. Also, when preparing the nose cone mold for the first layup, no vacuum bagging was applied before laying up the fiberglass. This caused a waste of material and time since the nose cone could not be pulled off the mold. Hence, it was learned that vacuum bagging is a necessary component needed for molds that are cylindrical in shape to ensure easy removal of part. Furthermore, the original plan was to create the motor mount tube using a high-density foam for the mold. This plan was then rejected due to the length and diameter of the motor mount tube. If the high-density foam had been utilized, the part may not have been made properly due to buckling of the mold since the motor mount tube was so long which would have resulted in material and time being wasted. This idea was rejected after making the mold and realizing that there was no guarantee in the accuracy of the concentricity of the mold, and when pressure would be applied to the layers, the mold would begin flexing possibly causing deformations in the final shape. Finally, it was observed that utilizing plain weave carbon fiber when laying up a shape that is not symmetric, such as a cylinder with gradual decreasing radius such as the boat tail, the fibers begin to bunch up, and part in areas causing deformations in the part. For future projects, whenever a non-symmetrical shape is used, either repeat the same process with the nose cone, or switch to a different type of weave, such as twill, for easy maneuverability of the fibers.

Lessons learned through the design and implementation of the recovery subsystems include testing types and protocols and black powder efficacy with respect to altitude. Testing and validation of the components of the recovery subsystems is crucial to their successful performance. Testing should replicate the predicted in-flight conditions as genuinely as feasible. Therefore, the prospect of utilizing a weather balloon to conduct testing of the recovery subsystems was well-received among our team. Such testing was ultimately foregone for the reason that compliance with the aviation regulations was not possible without the intent of the testing being comprehensively prepared and finalized. A design team intending to conduct such testing should contact their governing body's transport division early in the design stage in order to understand and consider the numerous regulations and restrictions when designing their experiments. Alternatively, a team intending to conduct a weather balloon test could commission an organization from nearby a region with high flight clearance to conduct the test on the team's behalf either by manufacturing test apparatus according to plans provided by the team or by having the test apparatus shipped by the team. As for the black powder, our review of literature led us to realize that black powder mass is not effectively ignited at altitudes exceeding 20,000 ft AGL due to the rarity of air molecules impeding conductive heat transfer. This should be noted by teams intending to utilize black powder in their recovery systems for rockets designed to reach apogees exceeding 20,000 ft AGL.

The team underestimated small purchases that quickly add up. During the build phase, it was not uncommon to go through a box of gloves and paint brushes per day. A large stock of equipment should be purchased ahead of time to avoid any delays due to last minute purchasing.

C. Knowledge Transfer.

This year's team has placed special emphasis on documenting all reports, tests and simulations by saving the data on Google Drive. It is important for future teams to not repeat any of the research already conducted. Instead, they should build on the knowledge amassed already and implement new designs. During the time between the end of the competition and the end of the semester, this years team will actively participate in recruitment and training. Throughout the build, the team has been taking lots of pictures and building a training document that can be used by new members to quickly get up to speed. The team has also put a lot of effort into creating technical drawing for components and the molds that were used to make them. That way, even if a mold is lost, it can easily be recreated.

System Weights, Measurers, and Performance Data Appendix

Spaceport America Cup

Intercollegiate Rocket Engineering Competition

Entry Form & Progress Update

Color Key | SRAD = Student Researched and Designed | v19.1

IMPOTANT CHANGE EFFECTIVE IMMEDIATELY FOR SA CUP 2019 EVENT

All inputs are mandatory for all submitions of this document. We undestand some data may change over time, this is completely acceptable.

Feel free to add additional commanets where needed, and be sure to fill out the last page. Treat the last page as a "cover letter" for your project.

Date Submitted:	19/05/2019
Team ID:	119
Country:	Canada
State or Province:	Ontario

* You will receive your Team ID after you submit your 1st project entry form.

State or Province is for US and Canada

Team Information

Rocket/Project Name:	True North
Student Organization Name	University of Windsor Rocketry Team
College or University Name:	University of Windsor Rocketry Team
Preferred Informal Name:	
Organization Type:	Senior Project
Project Start Date	9/1/2018
Category:	30k – COTS – All Propulsion Types

Projects are not limited on how many years they take

Member	Name	Email	Phone
Student Lead	SaiPrashanth Ramesh	ramesh3@uwindsor.ca	(226) 506-6900
Alt. Student Lead	Emanuel Raad	raade@uwindsor.ca	(519) 992-1452
Faculty Advisor	Dr. Jeff Defoe	jdefoe@uwindsor.ca	519 253 3000 ext 5961
Alt. Faculty Adviser			

For Mailing Awards:

Payable To:	University of Windsor
Address Line 1:	401 Sunset Avenue
Address Line 2:	Windsor
Address Line 3:	Ontario
Address Line 4:	Canada
Address Line 5:	N9B 3P4

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	10
Undergrad	10	Female	1
Masters	1	Veterans	0
PhD	0	NAR or Tripoli	1

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

1) Team partened with United Way to host after-school program for children ages 5-12 years old. The team will present the rocket and how it was built. With this project, we hope to spark an interest in STEM amongst the younger generation.

2) Open Houses and Similar Events: The team hosts a booth at open houses and orientation events at our university and neighbouring college. We explain the project and answer questions of students interested in enrolling in STEM programs.

Rocket Information

Overall rocket parameters:

	Measurement	Additional Comments (Optional)
Airframe Length (inches):	134.6	
Airframe Diameter (inches):	6	
Fin-span (inches):	6.575	*This is the span of 1 fin from the root to the tip*
Vehicle weight (pounds):	43.65	
Propellent weight (pounds):	24.05	
Payload weight (pounds):	8.8	
Liftoff weight (pounds):	76.5	
Number of stages:	1	
Strap-on Booster Cluster:	No	
Propulsion Type:	Solid	
Propulsion Manufacturer:	Commercial	
Kinetic Energy Dart:	No	

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

1st Stage: Cesaroni O3400, 21062O3400-P, O Class, 21062.2Ns

Total Impulse of all Motors: 21062.2 (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	Calculated using OpenRocket
Liftoff Thrust-Weight Ratio:	13.92	Calculated using OpenRocket
Launch Rail Departure Velocity (feet/second):	115.5	Calculated using OpenRocket
Minimum Static Margin During Boost:	1.954	OpenRocket with 10mph winds
Maximum Acceleration (G):	14.3	Calculated using OpenRocket
Maximum Velocity (feet/second):	1874	Calculated using OpenRocket
Target Apogee (feet AGL):	30K	
Predicted Apogee (feet AGL):	30325	Calculated using OpenRocket

Payload Information

Payload Description:

A payload device is under development to fit inside of the 3U "CubeSat" form factor. The primary payload is an Arduino Mega with a custom PCB used as an Arduino hat for the variety of supported sensors. The sensors used in the aerodynamics data acquisition payload include: 9-DOFAbsolute OrientationBME055, SparkFun Environmental Combo Breakout - CCS811/BME280, SparkFun Single Axis Accelerometer Breakout - ADXL193. A PowerBoost 500 is on the PCB for battery changing control. A microSD card breakout card is connected to the Arduino for storage of the sensor data, all timestamped for later data analysis. The data is to be collected post-launch for processing. A Unity program is to be developed to combine our CAD model of our rocket and aerodynamic data from our payload for visualization of the launch & decent in a 3D environment. An RF system is to be developed to support the capabilities of transmitting the sensor data in near real-time (NRT) to the ground station. The purpose is to be able to visualize all the stages of the rocket launch in NRT using the Unity program.

Recovery Information

The flight computers that will manage the recovery are the Stratologger CF (barometric sensor trigger) as the primary and Featherweight Raven 3 (accelerometer sensor trigger) as the redundant system. The T3 Tracker System will be used as our GPS flight computer.

Drogue Parachute: Spherachutes 36"
Altitude of deployment: 30,000 ft AGL (apogee)
Altitude of decomission: 1,650 ft AGL
Means of deployment: black powder charge. Separation of rocket into two sections attached by harness
Parachute diameter: 36 inches
Descent velocity (max): 42 m/s
Descent velocity (min): 30 m/s

Main Parachute: B2Rocketry Cert3 XL
Altitude of deployment: 1,650 ft AGL
Altitude of decomission: 0 ft AGL(landing)
Means of deployment: black powder charge. Separation of rocket into three sections attached by 2 harnesses
Parachute diameter: 109 inches
Descent velocity: 5.4 m/s

Shear pins:
Nosecone-Forward Body Tube: Four 6-32 nylon screws
Forward Body Tube-Aft Body Tube: Four 4-40 nylon screws

Planned Tests

* Please keep brief

Date	Type	Description	Status	Comments
10/21/18	In-Flight	Launch of Red Wolf	Successful	TRA L1 Certification (Aerotech I-140)
4/22/19	Ground	Altimeter Testing	Successful	Ematch continuity and pressure test
3/1/19	Ground	CFD for nosecones	Successful	Tangent Ogive chosen
3/1/19	Ground	CFD for fin airfoils	Successful	Diamond Airfoil chosen
3/15/19	Ground	Tension, and Hoop Stress tests for carbon fiber	Successful	Outcome: young's modulus, poisson's ratio
5/12/19	Ground	Black Powder detonation in vacuum chamber	Successful	Test black powder at reduced pressures
5/18/19	Ground	Ground Test	Successful	Body tube and nose cone seperation
5/25/19	In-Flight	Test Launch, Muskegon, Michigan	TBD	13,000 ft apogee

Any other pertinent information:

For airfoils, we are considered 3 different shapes. Namely, a flatplate, biconvex and diamond(double wedge). For nosecones, the von Karman and tangent ogive were tested. After extensive simulations at an average subsonic and average supersonic mach number, the tangent ogive nosecone and the diamond airfoil were chosen. The reason is the flight regime the rocket will undergo, where signifcant portions of time will be spent in both subsonic and supersonic flow. The airfoil will be slightly rounded in the leading and trailing edges. This is to aid ease of manufacturing and more importantly, for safety, which we cannot guarantee with sharp leading and trailing edges. However, due to this modification of the airfoil, we do expect some trade-off with aerodynamic efficiency. The airfoils were simulated under viscous conditions at 2 time averaged mach numbers. Mach 1.4 for supersonic regime and Mach 0.4 for the subsonic regime. The fin planform is a clipped delta which will have a taper ratio of 1:7 and a sweep angle of 70 degrees. Swept back fins are known to reduce drag due to the increase in the drag-divergence mach number. This decreases the amount of time the fins experience high drag in the transonic phase of the flight. Moreover a swept back fin essentially results in a thinner airfoil. CFD for nose cones is also being conducted simultaneously.

Previously, we had considered including a non-functional payload. However, we have electrical engineers who are working on an active payload that will serve as a telemeter for flight properties such as pitch, yaw, roll and also atmospheric properties. We will be building a fully functional AV bay, as this is mandatory for the deployment of of our parachutes, and a TRS bay, which is also mandatory for the GPS.

High temperature epoxy will be used in manufacturing our components due to the high temperatures that will be experienced during flight. Most of our components will be manufactured in house using previously tried and tested methods such as the wet layup proceedure.

End of File

Project Test Reports Appendix

A. Recovery System Testing

1. Verification of On-Board Electronics' Functioning

The first test was done with the Stratologger CF. This test was conducted to verify the e-match continuity for both main and drogue deployment. The flight computer connections were completed using a breadboard setup as shown in the figure below. The red and yellow LEDs are meant to mimic E-matches. The proprietary software of the flight computer, Perfect Flight Data Camp, allows users to verify the continuities with a click of a button. The test resulted in both LEDs lighting up when the continuities were tested. This indicated that a signal could be sent to the e-matches.

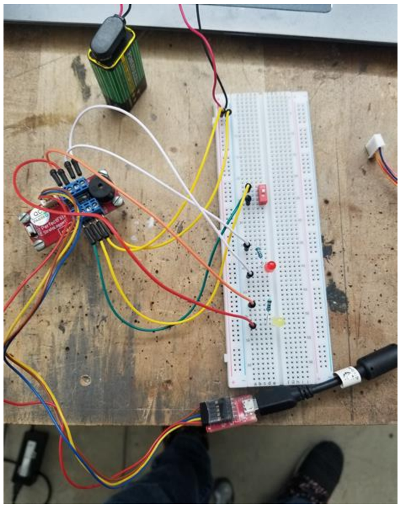

Figure 14. Breadboard setup of the Stratologger CF

The second test conducted was to verify the correctness of the barometric pressure sensor on the Stratologger CF. The flight computer along with the completed connections on the breadboard setup, were placed in a vacuum chamber shown below. A pressure of 2.9psi or 20Kpa was simulated inside the vacuum chamber and was slowly pressurized again to simulate descent.

Figure 15. Vacuum pump and chamber setup for Stratologger CF

The results, as expected, showed that the drogue deployed a few seconds after apogee was reached. The reason for this is the implementation of the flight computer itself. When using the vacuum pump for these tests, the sudden pressure increase activates the ‘Mach lock’ feature [Page 38, Stratologger CF User's Manual] on the computer. This causes the flight computer to prevent itself from setting off the e-match at apogee. However, the test was still successful considering the pressure logged by the computer correctly translates into the appropriate altitude. E-match continuities were also verified by the 3 continuous beeps sounded by the computer to signify that both main and drogue continuities were complete. The graph below shows the results.

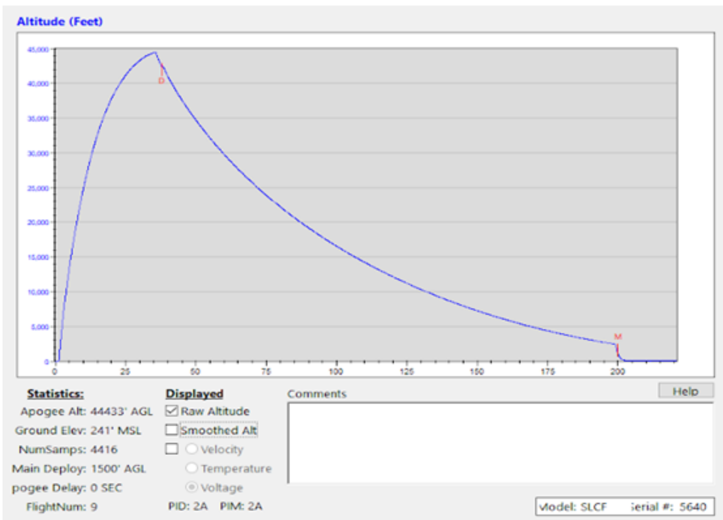

Figure 16. Altitude vs Time plot for Stratologger CF obtained from altitude simulation testing

The Raven3 was tested using the proprietary software, Featherweight FIP. Only e-match continuities were tested using the flight simulation option. This is due to the implementation of the flight computer itself. The Raven3 only registers launch when an acceleration of more that 3Gs are registered. This will be hard to simulate outside of an actual flight. As such, the Ematch continuities were successfully verified due to the fact that the LEDs lit up at the right periods of time. The breadboard setup of the Raven3 is shown below.

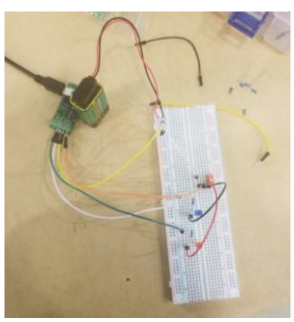

Figure 17. Breadboard setup of the Raven3

These particular Stratologger CF and Raven3 have been validated multiple times in the past due to previous successful flights that used these computers as recovery flight computers. Namely, the successful University of Windsor's Over 9000 rocket that participated in IREC 2018.

2. Vacuum Chamber Testing of Black Powder Pressure Vessels

Black powder combusts inconsistently at altitudes greater than 20,000 ft ASL due to the reduced pressure. This phenomenon is caused by the reduced heat transfer coefficient of the air at high altitudes. The drogue ejection canisters are designed to hold 1 atm of air up to apogee in order ensure complete combustion. To determine how effectively the drogue ejection canister helps the black powder to combust in low pressure conditions, the drogue ejection canisters were placed in a custom-built PVC vacuum chamber, where the pressure was reduced to -80 kPag. increasing amounts of black powder were placed in the canisters and were ignited. As seen from the table below, more than 97% burn rate was achieved with the canisters at the given pressures. This showed that by using the drogue ejection canister 1.5g of black powder will completely combust at the reduced pressures expected at 35 000 ft ASL.

Table XX: Data for Vacuum chamber Testing of Black Powder Pressure vessels.

Test #	Pressure [kPag]	Cannister Setup	Starting Amount of BP (g)	Mass of wadding (g)	Mass of residue (g)	Ending amount of BP (g)	BP burnt (g)	% Burnt
1	0	Plugged	1.0	unknown	0.1	unknown		N/A
2	-80	Plugged	1.0	unknown	0.09	unknown		N/A
3	0	unplugged	2.0	1.5	1.54	0.04	1.96	98.00%
4	-80	unplugged	2.0	1.5	1.56	0.06	1.94	97.00%
5	0	unplugged	3.0	1.5	1.61	0.11	2.89	96.33%
6	-80	unplugged	3.0	1.5	4.37	2.87	0.13	4.33%
7	-80	plugged	3.0	1.5	2.91	1.41	1.59	53.00%
*8	-80	plugged	3.0	1.5	1.59	0.09	1.41	97.00%
9	-80	plugged	3.0	1.5	1.57	0.07	1.43	97.67%

*During test #8 The position of the E-match was changed from a vertical to a horizontal position which yielded a higher burn percentage. The increased yield was confirmed in test #9.

3. Ground Test of Body Tube and Nose Cone Separation

The purpose of this ground test is to ensure that the black powder amounts have been appropriately sized to effectively decouple the rocket body. Decoupling involves the shearing of the respective shear pins installed on the couplers and body tubes. The first test is the drogue deployment test, which needed the forward and aft body tubes to be decoupled. 1.5grams of black powder were placed inside the black powder pressure vessel. The charges were detonated and the shear pins sheared off. The nose cone was not yet built at the time of these tests, so a chamber with equivalent volume and mass was used instead. A dummy payload weighing 8.8lb was put inside the nose cone compartment. This way, the effect of the black powder on the nose cone would be identical to the effect on the equivalent chamber. The test was successful since only the aft most nylon screws sheared off, and the nose cone compartment remained attached.

Figure 18. Aft, Forward Body tube and nose cone sections primed for ground testing

Figure 19. Separation of drogue section after detonation

The second ground test was done to verify the decoupling of the forward body tube and nose cone section. The aft section of the rocket is not needed, since it will have already deployed. 3 grams of black powder were placed in the main deployment canisters and were made to detonate. The nose cone section was successfully decoupled from the forward body tube due to the shearing of the nylon screws.

Figure 20. Forward body tube and nose cone sections primed for detonation.

Figure 21. Separation of main section after detonation

4. Dual Redundancy of Recovery System Electronics

As mentioned, the 2 recovery flight computers that will be used for parachute deployment will be the Stratologger CF as the primary and the Raven3 as the redundant. The connections made on the AV Bay are in accordance with the manufacturers' suggestions. The connections between the computers have been kept entirely separate. This is to avoid failure of e-match ignition should any of the terminal blocks be faulty. Since the Stratologger CF is the primary flight computer, the e-match ignition will occur at apogee and at 1650 ft for drogue and main parachute deployment respectively. The Raven3 will be configured with a 2 second delay for each deployment.

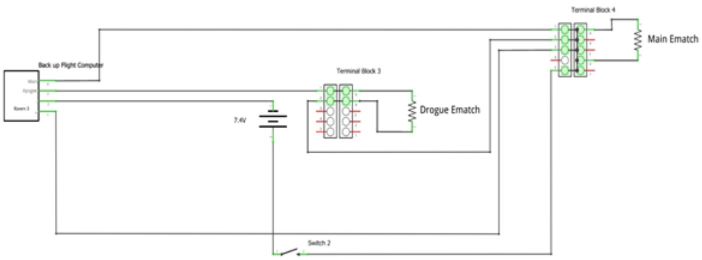

Figure 22. Schematic of Redundant Altimeter, Raven3

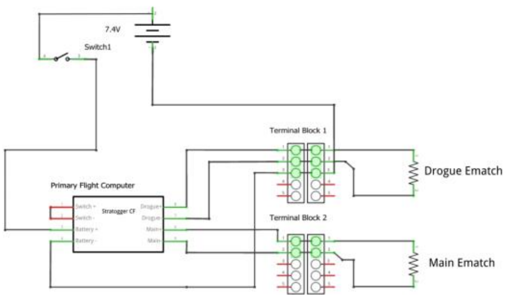

Figure 23. Schematic of Primary Altimeter, Stratologger CF

B. SRAD Propulsion System Testing

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C. SRAD Pressure Vessel Testing

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Hazard Analysis Appendix

Phase	Scenario	Risks	Mitigation	Risk Assessement
Pre-Competition Risk	Storage of high power rocket motors	1. Explosion risk if not stored in an appropriate environment 2. Toxicity risks if ingested or inhaled 3. Highly flammable substance	The team will learn how to handle the propellant from an L3 licensed club member. Store all propellants in the package that they were originally shipped in.	Medium
Pre-Competition Risk	High power rocket motor transportation and handling	1. Explosion risk if not stored in an appropriate environment 2. Toxicity risks if ingested or inhaled 3. Highly flammable substance	Store in a secure, cool and dry place, away from flammable substances and any sources of ignition with limited access. Transport in the original package that the propellant was originally shipped in.	Medium
Pre-Competition Risk	Ignition of high power rocket motors	1.Explosion risk 2.Highly flammable, controlled substance	Practice ignition process with test launch - Rehearse and be aware of - Follow a launch checklist	Medium
Pre-Competition Risk	Collection of rocket vehicle components post-launch	1. Components are fractured on landing, and have sharp edges 2. Rocket surface is hot to the touch after laying in the desert for long times 3. Plants are sharp and can scratch the skin	Wear oven mitts when touching landed rocket. Wear long pants to protect against desert shrubbery	Low
Pre-Competition Risk	Battery short circuits during assembly	1. The leads touch and create sparks 2. Wires can get tangled with other metal parts	Keep working are clean. Use good quality connectors. Minimize the use of conductive metal mounting equipment near electronics	Low
Pre-Competition Risk	Unexpected environmental conditions	Wind, rain, desert storm, heat wave	Up to the range coordinator to cancel flights. In case of excess winds, check simulation to confirm stability of rocket	Medium
Materials and Tools Risk	Electric Handheld Sander	Burns, cuts, skin abrasion	Avoid loose clothing or exposed skin. Make sure the part that is being sanded is firmly securced. Use ventilation system	Low
Materials and Tools Risk	Soldering Iron	Burns	Do not touch wires after soldering, as they can still be hot	Low
Materials and Tools Risk	Table Saw	Cut fingers	Avoid loose clothing. Do not push pieces in with fingers, use piece of scrap wood instead	Medium
Materials and Tools Risk	Wood Lathe	Cuts, broken appendages	Avoid loose clothing. Use low speeds for sanding	Low
Materials and Tools Risk	Drill Press	Cuts, abrasion	Avoid loose clothing. Firmly clamp part	Low
Materials and Tools Risk	Belt Sander	Burns, skin abrasion	Avoid loose clothing	Low
Materials and Tools Risk	CNC Waterjet cutter	Cuts	Only shop technicians will operate this tool	Medium
Materials and Tools Risk	Fiberglass cutting and sanding	Fiberglass inhalation or fiberglass abrasion of the skin	Wear safety glasses, gloves, respirator and cover skin	Low
Materials and Tools Risk	Black powder storage	Highly flammable and will explode	Store in a secure, cool and dry place, away from flammable substances and any sources of ignition. Make sure cap is tightly secured before storing.	Low
Materials and Tools Risk	Black powder transportation & handling	Unintended ignition due to Impact, friction, or static	- Clean up spills carefully with hand broom - Black powder is stored isolated from any source of ignition - Do not leave black powder unattended in hot vehicle or sunlight	Low
Materials and Tools Risk	Black powder ejection charge testing	Detonation produces hazardous overpressures and possibly fragments	Be well away from charge during ignition - Eggtimer suggests 10ft between anyone and the rocket when testing - No personnel stands in front or behind the rocket	Medium
Materials and Tools Risk	Igniter storage	Potential explosion risk	Store in isolated container, away from any black powder or sources of power	Low

Risk Assessment Appendix

Risk Assessment Matrix

Category according to Mission CONOPS	Hazards	Possible Faliures	Risk of Mishap and Rationale (Possible causes)	Mitigation Approach
Recovery	Zippering	Body tube will be ripped and unable to relaunch	Deployment charge was too large after apogee or shock cord was not long enough	Swab epoxy around the inside edges of the rocket tube to stop zippering
Recovery	Dual deployment fails	Rocket hit ground with high velocity	Amount of black powder not enough to break the shear pins and seperate the rocket	Ground test of dual deployment before rocket launch
Recovery	Loose electrical connection	Parachute wont deploy	Wire connections not double checked	Tug on all wires to make sure connections are sturdy
Recovery	Shock Cord Breaks	Rocket components seperate and sections without a parachute land at high velocities	Shock cord was not attached properly	Verify that the slip knot is appropriately tied
Recovery	Shear pins don't shear	Body tube or nose cone not seprated during deployment, rocket lands at high velocity	1. Shear pins installed at an angle. 2. Too much friction between coupler and body tube 3. Wrong size shear pin used	1. Make sure before flight that all shear pins are installed perpendicular to the body tube 2. Sand coupler and body tube contact interface 3. Refer to engineering drawing for proper sizes
Recovery	Flight computer fails	1. Sensor readings aren't correct 2. The ejections charges won't go off 3. Not enough power	1. Sensor damaged in previous flight 2. Pin outputs damaged in previous flight 3. Battery dislodged due to vibrations	1. Perform ground test in pressurized chamber to test barometric sensor 2. Perform ground test to check e-match pin outputs are working 3. Secure battery snugly
Powered Flight	Payload shifts during flight	This may cause Centre of Gravity to shift and which will lead to Flight Instability	Not well defined constraining methods for fastening the hardware or mounting methods	Shake the nose cone prior to flight to ensure the payload is properlly secured. If not, tighten all the nuts holding the bulkhead in place
Powered Flight	Fins that pop off during flight	Rocket will be unstable and veer off course	Fins were poorly secured to the body of the rocket	Create fillets on all connection surfaces between the fins and the rocket body on the inside and outside of the rocket
Powered Flight	Rocket stages seperate before apogee	Forces during ascent will rip apart the shock cord and destroy the body	Shear pins not large enough to counter the drag seperation	Size the shear pins with large factor of safety
Powered Flight	Rocket unstable	Rocket would not maintain calculated trajectory and may crash or break during flight	Center of gravity not properly calculated	Measure center of gravity once rocket is built to double check the computer predicted value. Add balast to nose cone if necessary
Powered Flight	Fins flutter and fail through shear	Rocket will experience unstable flight	This is typically caused by the fins made from very thin material or having low stiffness	Add a "tip-to-tip" layer of carbon fiber between the fins. In the design phase, increase the thickness of the fins
Powered Flight	Rocket spins too quickly	Lift forces on one side of the rocket might be greater than other side	Fins are installed asymetrically	Use a rig for installed the fins and ensure they are correctly aligned before applying epoxy
Powered Flight	CG that is off axis	Rocket would experience unstable flight	Components not installed such that their CG is aligned with the rocket axis	Determine CG of rocket before flight and adjust mounting of components

Risk Assessment Matrix

Category according to Mission CONOPS	Hazards	Possible Faliures	Risk of Mishap and Rationale (Possible causes)	Mitigation Approach
Powered Flight	Thrust is off axis	Structure fails due to shear	Centering rings not concenteric or installed at an angle	Measure concentricity and add shims to ensure correct alignment
Powered Flight	Components are not placed accurately according to the CAD model	Weight distribution wont be uniform	1. Measurement tools not adequate 2. Human measurement error	1. Use higher precision measurement tools like digital calipers 2. Measure several times
Lift Off	Off the rail velocity too slow	Rocket trajectory can be easily influenced by the wind	Thrust levels not sufficient or rocket too heavy	Perform simulations to check that lift off velocity is safe
Lift Off	Explosion of solid-propellant rocket motor during launch	Rocket explodes before lift off	Cracks in propellant grain	Visually inspect motor grains for cracks, debonds and gaps during and after assembly
			Debonding of propellant from wall	Clean motor casing with isopropyl alcohol before assembly
			Gaps between propellant section or nozzle	Visual inspection during assembly
			Chunks of propellant breaking off and plugging nozzle	Inspect motor case for damage during final assembly before launch
			Motor case unable to contain normal operating pressure	Use manufacturer recommended hardware
			Motor end closures failed to hold	Clean threads with isopropyl alcohol on closure and casing before assembly
Lift Off	Hang fire: Rocket does not ignite when command is given, but does ignite after some time	Propellant will not ignite at all or will ignite with a delay	Propellant or igniter not properly assembled	While arming, ensure that the propellant is correctly assembled. If a hang fire occurs, do not approach the rocket. Wait a sufficient amount of time (5 minutes) before attempting to disarm
Lift Off	Rocket falls from launch rail during prelaunch preparations, causing injury	Rocket could damage equipment as it falls down	Launch rail guides not able to support weight of rocket	Reinforce the connection with threaded insert. Check that each rail guide can support the rocket's own weight
Lift Off	Rocket launched at undesirable angle	Rocket does not reach the desired apogee	Rail inclined at an angle other than the reported standard	Adjust weight of rocket with ballast to correct apogee if it is overshooting
Lift Off	Motor failure	Rocket wont launch from the launch pad	Manufacturer sent malfunctioning motor	Have an extra motor from different company
Landing	Fins are damaged on landing	Unable to relaunch the rocket	Fins are too thin or material strength not enough to resist the impact of landing	Perform material tests to size the thickness of the fins appropriately. Mount the fins such that they are removable

Risk Assessment Matrix

Category according to Mission CONOPS	Hazards	Possible Faliures	Risk of Mishap and Rationale (Possible causes)	Mitigation Approach
Landing	Nose cone breaks or tip become blunt	Unable to relaunch the rocket	Rocket lands nose cone down first	Attach the main parachute to the nose cone
Landing	Engine Retainer Breaks	Engine might shoot forward through the rocket	Epoxy not properly applied. Inadequate hardware used	Visually inspect the epoxy bond. Make sure all surfaces are bonded are there are no air gaps. Use large factor of safety when designing motor assemby
Manufacturing	Crooked or Cracked Fins	Unexpected lift forces generated	Not enough pressure applied in the mold	Secure all the bolts holding the mold together. Visually inspect the fins.
Manufacturing	Fins where airfoil are different	Rocket will experience unstable flight	Fins were not checked for their designs or different molds were used for maunfacuring a same size fin	Use the same mold for manufacturing all of the fins
Manufacturing	Fin tip chord not straight	Will create unnecessary drag	Proper tools were not used to cut the fin	Mold is constructuted so the fin is longer than needed. Cut down to size
Logistics	Run out of supplies or component breaking during manufacturing	Rushed assembly or no time to test	Didn't order the correct quanity of parts or inexperiencing in assembly	Order more components or supplies than needed in order to avoid any errors
Logistics	Components arrive late or damaged due to shipping	No time to test	Parts not ordered early	Order parts early in order to avoid delays and keep records of purchase requisitions. Follow up with university administration daily

Assembly, Preflight, and Launch Checklists Appendix

ASSEMBLY CHECKLIST

Electronics

- ❏ Record Voltage:

Part	Required Voltage	Measured Voltage
T3 GPS Battery	3.5V to 7.4V	
Stratologger Battery	4V to 16V	
Raven3 Battery	3.8V to 16V	
Payload Battery	7.4V	

Nose Cone Tip

- ❏ Turn ON the rotary switch in the TRS Bay by turning it counterclockwise to the 110V position with a flat head screwdriver
- ❏ Slide the nose cone tip assembly into the nose cone from the top, and screw in until the nose cone is flush with the body

Payload Bay

- ❏ Place payload in nose cone from the bottom
- ❏ Slide payload bulkhead onto aluminum rods. Secure with 4x 1/4 inch - 20 nuts

Electronics

- ❏ Remove the bulkhead with the aluminum canisters
- ❏ Calibrate Raven3
    - ❏ Place avionics bay in 4 different standing positions for 30 s each at different orientations to calibrate gyroscope and accelerometer
        - ❏ 1st
        - ❏ 2nd
        - ❏ 3rd
        - ❏ 4th
- ❏ Check all wire connections are made
- ❏ Make sure all avionics are off/unpowered and switches turned OFF (220V position)
- ❏ Disconnect batteries from the terminal block
- ❏ Screw wires from igniters and flight computers into their respective terminal blocks
- ❏ Inspect bay for frayed or broken wires
- ❏ Secure batteries to AV Bay
- ❏ Connect the battery leads to the barrier block
- ❏ Do tug test on all wires
- ❏ Tighten all bolts and screws with a wrench
- ❏ Slide the AV Bay into the forward body tube, with the end without the bulkhead facing towards the bottom. Keep sliding until the remaining bulkhead rests against the coupler

- [ ] Install the bulkhead with the aluminum canisters into the threaded rods
- [ ] Secure bulkhead with 1/4 inch - 20 wing nuts

Motor

- [ ] Slide motor into motor mount tube from the boat tail
- [ ] Turn the motor until it is fully threaded into the forward retainer. This is indicated by the rear closure making contact with the motor mount tube

Black powder - Drogue Parachute

- [ ] Measure 1.5g of black powder required for each drogue canister
    - [ ] Aluminium Canister #1
    - [ ] Aluminium Canister #2
- [ ] Take E-match and bend 180 degrees where the igniter starts, halfway down the igniter bend 90 degrees to both previous wire and the wire itself.
    - [ ] Aluminium Canister #1
    - [ ] Aluminium Canister #2
- [ ] Feed copper wire end of E-match first through the open end and then the same end through the pinhole at the bottom of the canister.
    - [ ] Aluminium Canister #1
    - [ ] Aluminium Canister #2
- [ ] Place the E-match igniter at the base, right at the level of the black powder if it was in the canister.
    - [ ] Aluminium Canister #1
    - [ ] Aluminium Canister #2
- [ ] Fold the copper wire end of the E-match along the canister
    - [ ] Aluminium Canister #1
    - [ ] Aluminium Canister #2
- [ ] Apply Teflon tape radially across wires 1 inch from the pinhole end of canister. Make sure wires are straight.
    - [ ] Aluminium Canister #1
    - [ ] Aluminium Canister #2
- [ ] Pour the measured 1.5g of black powder into the canister
    - [ ] Aluminium Canister #1
    - [ ] Aluminium Canister #2

Black powder - Main Parachute

- [ ] Measure 2g of black powder required for each drogue canister
    - [ ] PVC Canister #1
    - [ ] PVC Canister #2
- [ ] Take E-match and bend 180 degrees where the igniter starts, halfway down the igniter bend 90 degrees to both previous wire and the wire itself.
    - [ ] PVC Canister #1
    - [ ] PVC Canister #2

- ❑ Feed copper wire end of E-match first through the open end and then the same end through the pinhole at the bottom of the canister.
    - ❑ PVC Canister #1
    - ❑ PVC Canister #2
- ❑ Place the E-match igniter at the base, right at the level of the black powder if it was in the canister.
    - ❑ PVC Canister #1
    - ❑ PVC Canister #2
- ❑ Fold the copper wire end of the E-match along the canister
    - ❑ PVC Canister #1
    - ❑ PVC Canister #2
- ❑ Pour the measured 2g of black powder into the canister
    - ❑ PVC Canister #1
    - ❑ PVC Canister #2

Main Parachute

- ❑ Make sure all parachute lines and shock cords are undamaged, looking particularly for frayed, burnt and/or rotted fibers. Verify that the shroud lines are all equal length
- ❑ Partially fold parachute using burrito folding technique. Leave the shroud lines exposed (Refer to "BURRITO FOLDING TECHNIQUE" document)
- ❑ Tie an overhand knot using the shroud lines of the parachute
- ❑ Put the kevlar shock cord sleeve on one end of the shock cord
- ❑ Put the kevlar chute protector through the shock cord end with the kevlar sleeve
- ❑ Tie a butterfly knot 4m from the end that the kevlar protector is on
- ❑ Connect the overhand knot with the butterfly knot with the swivel link
- ❑ Finish the burrito folding of the parachute
- ❑ Attach the shock cord end with the kevlar sleeve to AV Bay U-bolt using a slip knot (Refer to "SLIP KNOT TECHNIQUE" document)
- ❑ Attach shock cord to nose cone eye bolt using a slip knot (Refer to "SLIP KNOT TECHNIQUE" document)
- ❑ Daisy chain the shock cord
- ❑ Wrap the chute protector around the parachute and the shock cord
- ❑ Slide the parachute assembly into the forward body tube
- ❑ Slide nose cone on top of forward body tube
- ❑ Align the holes for the shear pins
- ❑ Screw in 4x 6-32 shear pins

Drogue Parachute

- ❑ Make sure all parachute lines and shock cords are undamaged, looking particularly for frayed, burnt and/or rotted fibers. Verify that the shroud lines are all equal length
- ❑ Partially fold parachute using burrito folding technique. Leave the shroud lines exposed (Refer to "BURRITO FOLDING TECHNIQUE" document)
- ❑ Tie an overhand knot using the shroud lines of the parachute
- ❑ Put the kevlar shock cord sleeve on one end of the shock cord

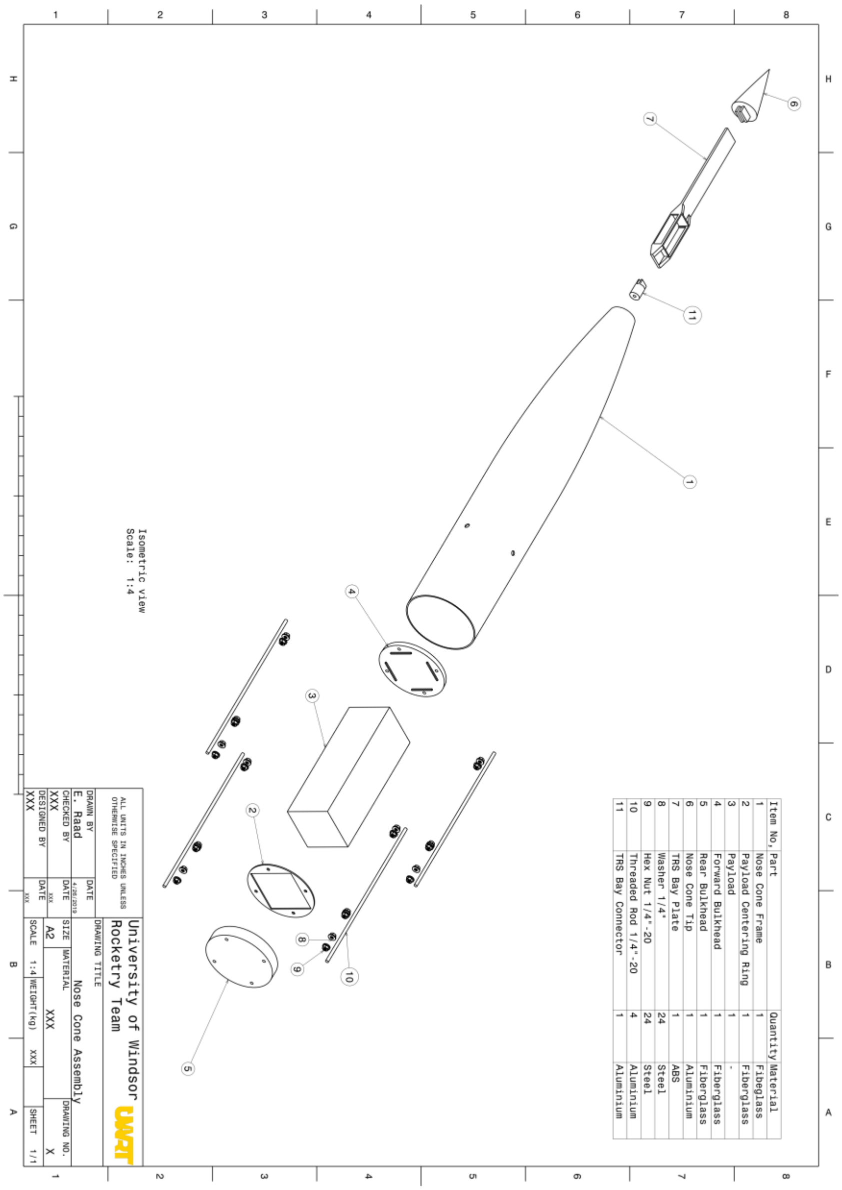
- ❑ Put the kevlar chute protector through the shock cord end with the kevlar sleeve
- ❑ Tie a butterfly knot 4m from the end that the kevlar protector is on
- ❑ Connect the overhand knot with the butterfly knot with the swivel link
- ❑ Finish the burrito folding of the parachute
- ❑ Attach the shock cord end with the kevlar sleeve to AV Bay U-bolt using a slip knot (Refer to “SLIP KNOT TECHNIQUE” document)
- ❑ Attach shock cord to motor retainer eye bolt using a slip knot (Refer to “SLIP KNOT TECHNIQUE” document)
- ❑ Daisy chain the shock cord
- ❑ Wrap the chute protector around the parachute and the shock cord
- ❑ Slide the parachute assembly into the aft body tube assembly
- ❑ Slide aft body tube on forward body tube
- ❑ Align the holes for the shear pins
- ❑ Screw in 4x 4-40 shear pins

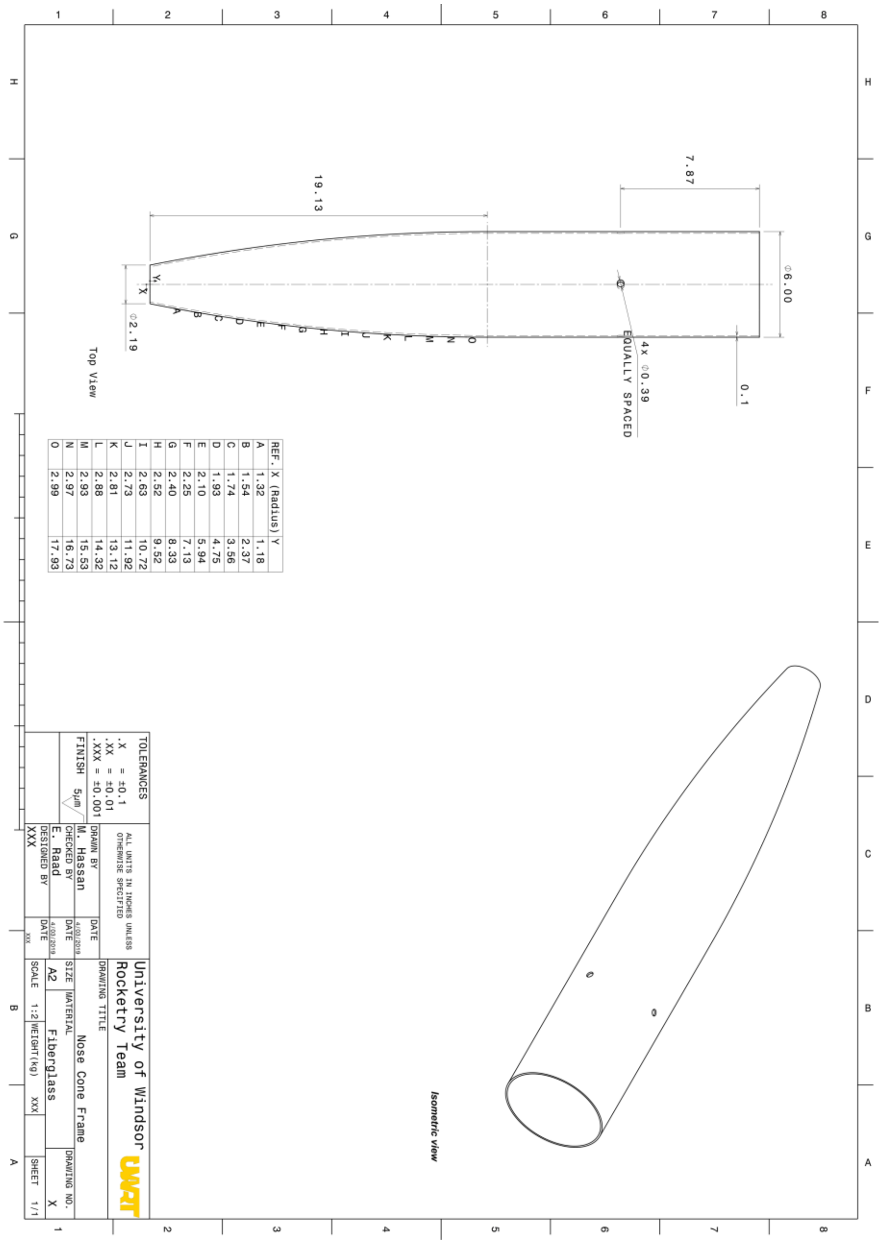
Inspection:
- ❑ Inspect the vehicle for damage in the nose cone, air frame, & fins
- ❑ Verify that the fins are secured. Wiggle them slightly to check
- ❑ Verify that the motor mount is secured with no loose parts
- ❑ Ensure that the guide rail buttons are aligned

At this point, the rocket is fully assembled. The GPS is armed. The recovery electronics and the motor are NOT armed.

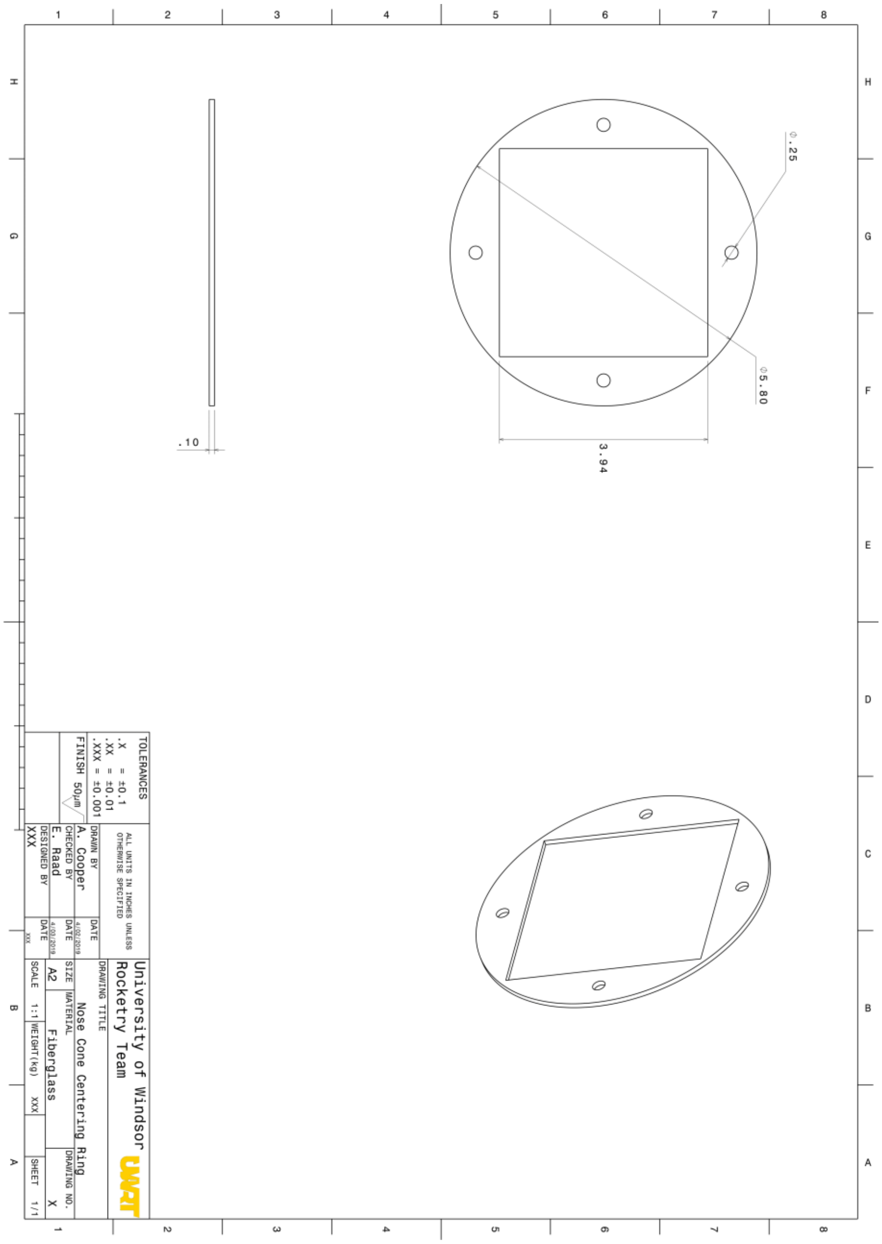
LAUNCH CHECKLIST
- ❑ Load the rocket on on guide rails
- ❑ Ensure rails are at angle from horizon at 84±1 degrees, or whichever angle the range officer dictates
- ❑ Arm electronics in AV Bay by turning the flat head screwdriver counterclockwise. Arm one at a time to listen for beeps
    - ❑ Stratologger: Sets of 3 beeps. Each set is 1 second apart
    - ❑ Raven3: Sets of 2 high pitched beeps followed by 2 low pitched beeps. Each set is 1 second apart
    - ❑ If beeps are not correct:
        - ❑ Turn OFF all the electronics (turn clockwise) and remove the rocket from the stand
        - ❑ Remove shear pins
        - ❑ Remove AV Bay
        - ❑ Check electrical checklist again
- ❑ Setup and install igniter

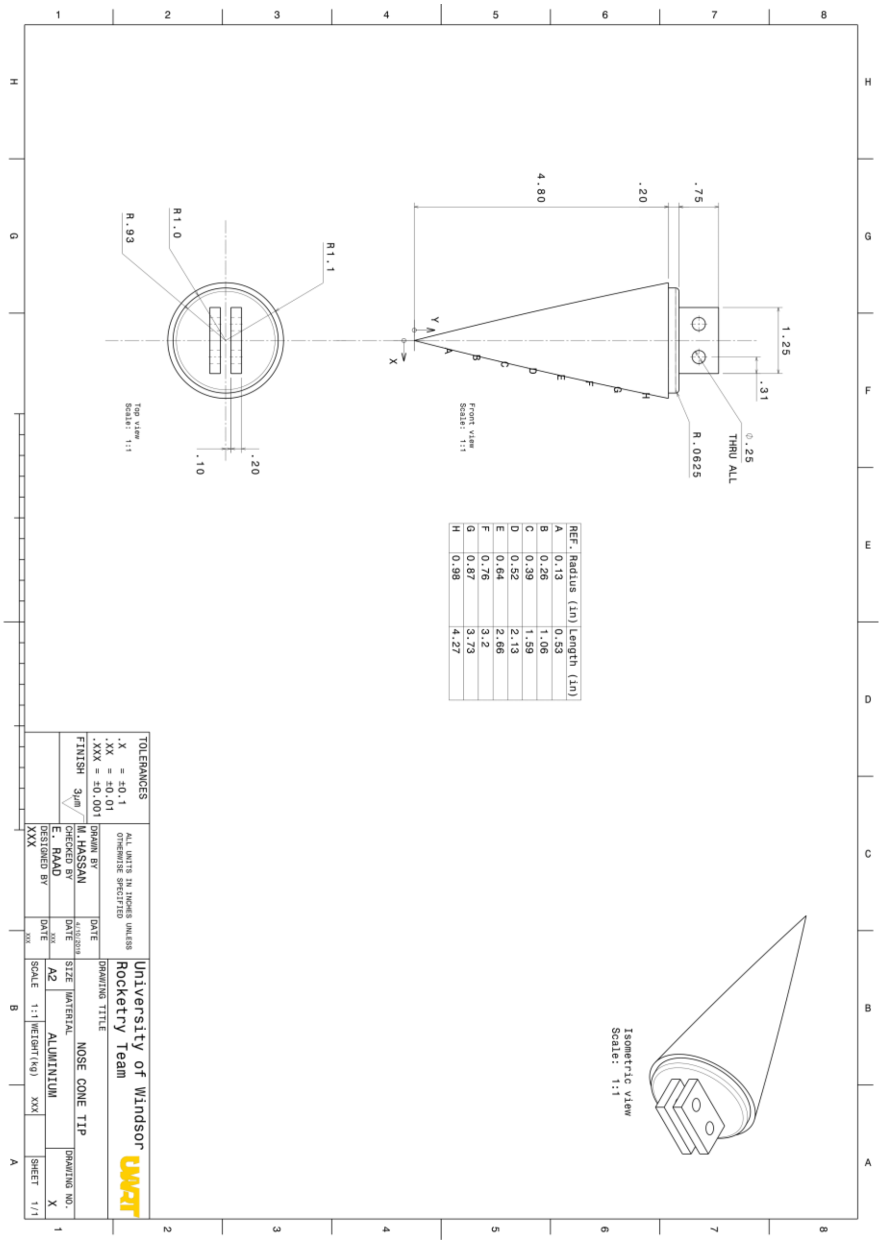
Engineering Drawings Appendix

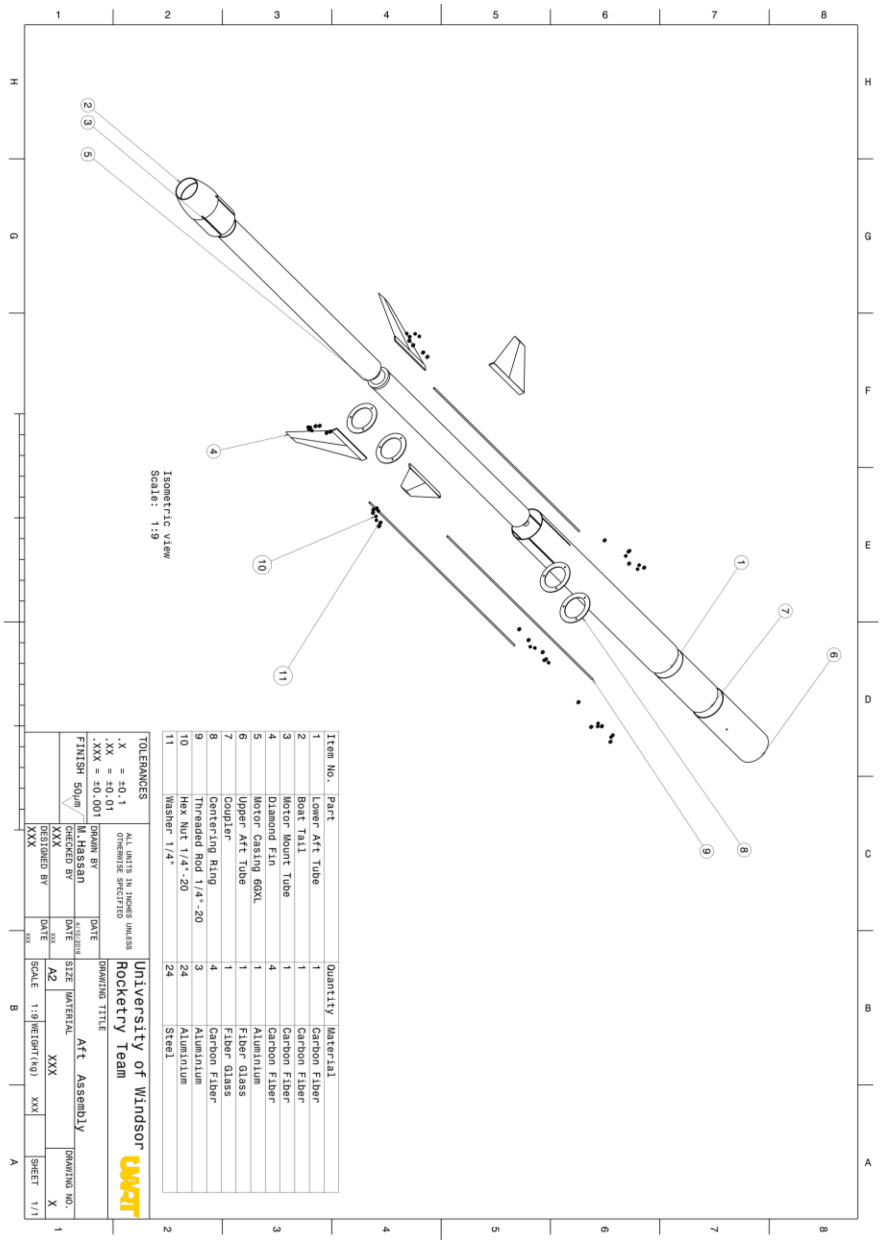


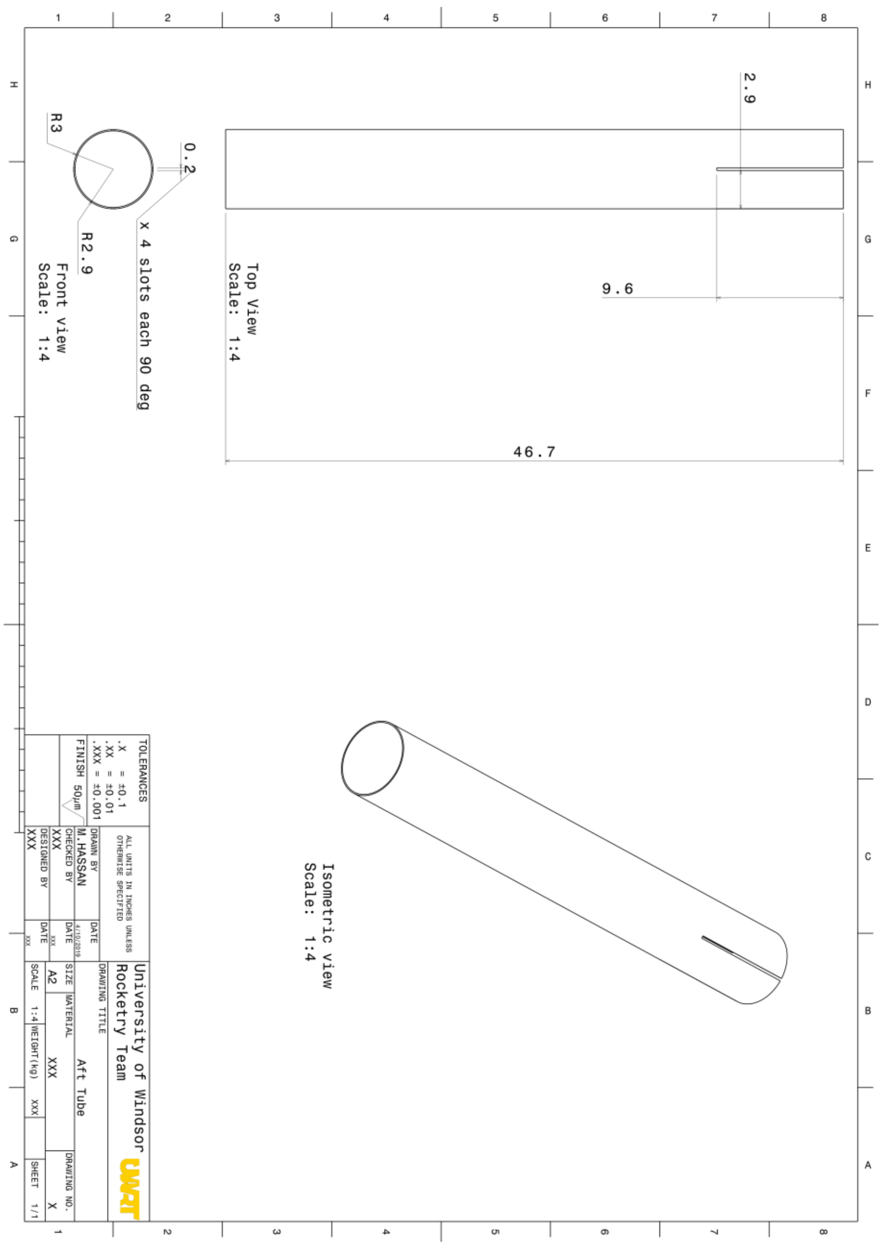


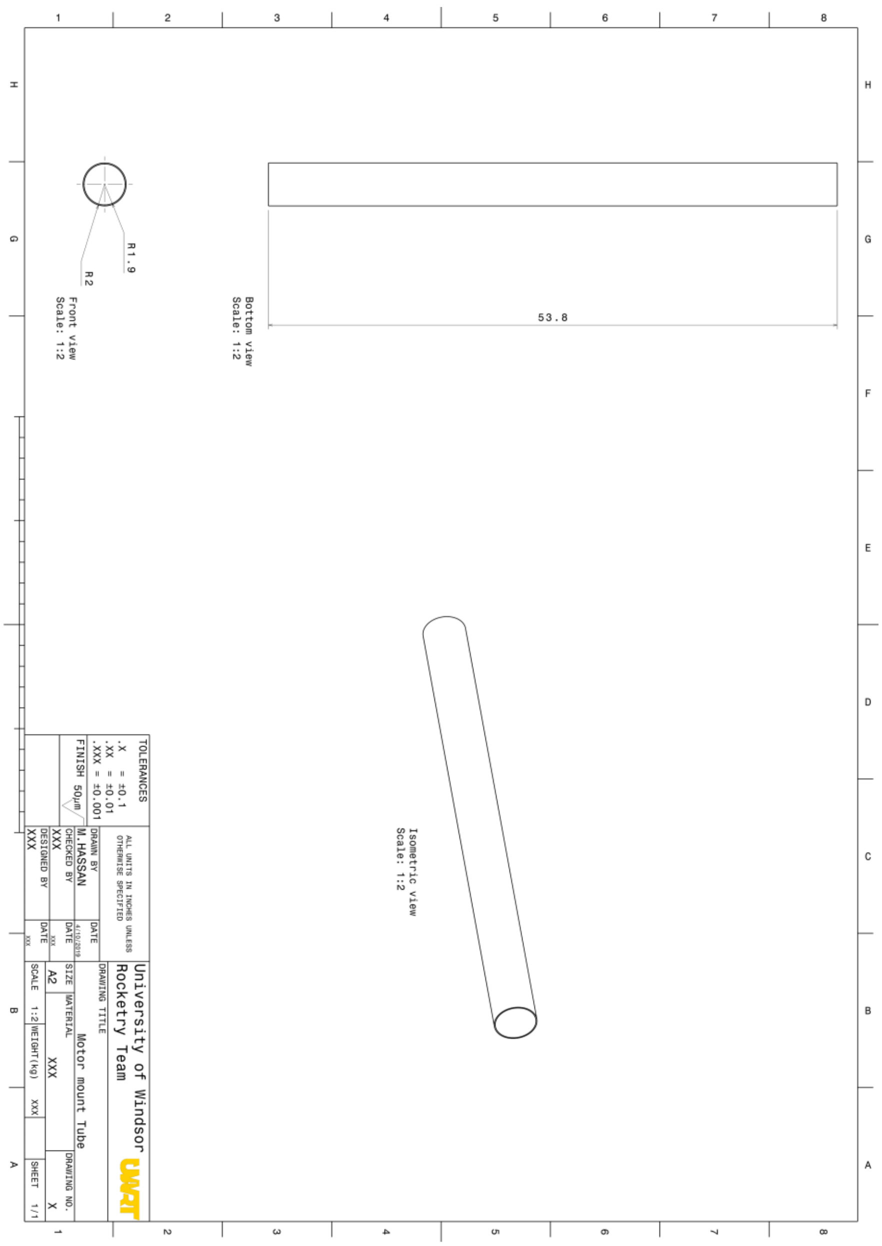
19.13
7.87
⌀6.00
⌀2.19
4x ⌀0.39
EQUALLY SPACED
0.1
Top View
REF. | X (Radius) | Y
A | 1.32 | 1.18
B | 1.54 | 2.37
C | 1.74 | 3.56
D | 1.93 | 4.75
E | 2.10 | 5.94
F | 2.25 | 7.13
G | 2.40 | 8.33
H | 2.52 | 9.52
I | 2.63 | 10.72
J | 2.73 | 11.92
K | 2.81 | 13.12
L | 2.88 | 14.32
M | 2.93 | 15.53
N | 2.97 | 16.73
O | 2.99 | 17.93
Isometric view
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 5μm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY M. Hassan
CHECKED BY E. Raad
DESIGNED BY XXX
University of Windsor Rocketry Team
DRAWING TITLE Nose Cone Frame
SIZE A2
MATERIAL Fiberglass
DRAWING NO. X
SCALE 1:2
WEIGHT(kg) XXX
SHEET 1/1

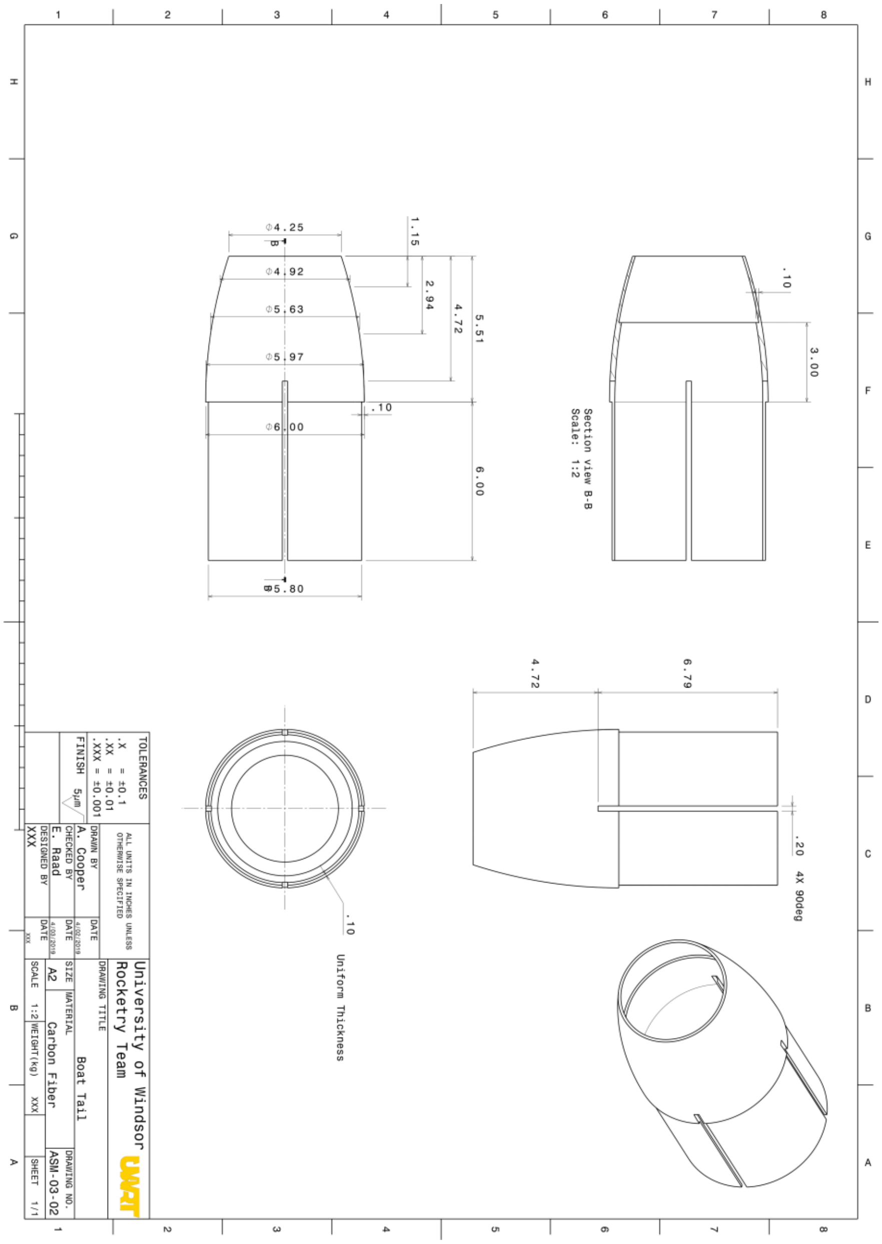

.10
3.94
⌀5.80
⌀.25
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
A. Cooper
CHECKED BY
E. Raad
DESIGNED BY
XXX
DATE
University of Windsor Rocketry Team
DRAWING TITLE
Nose Cone Centering Ring
SIZE
A2
MATERIAL
Fiberglass
DRAWING NO.
X
SCALE
1:1
WEIGHT(kg)
XXX
SHEET
1/1

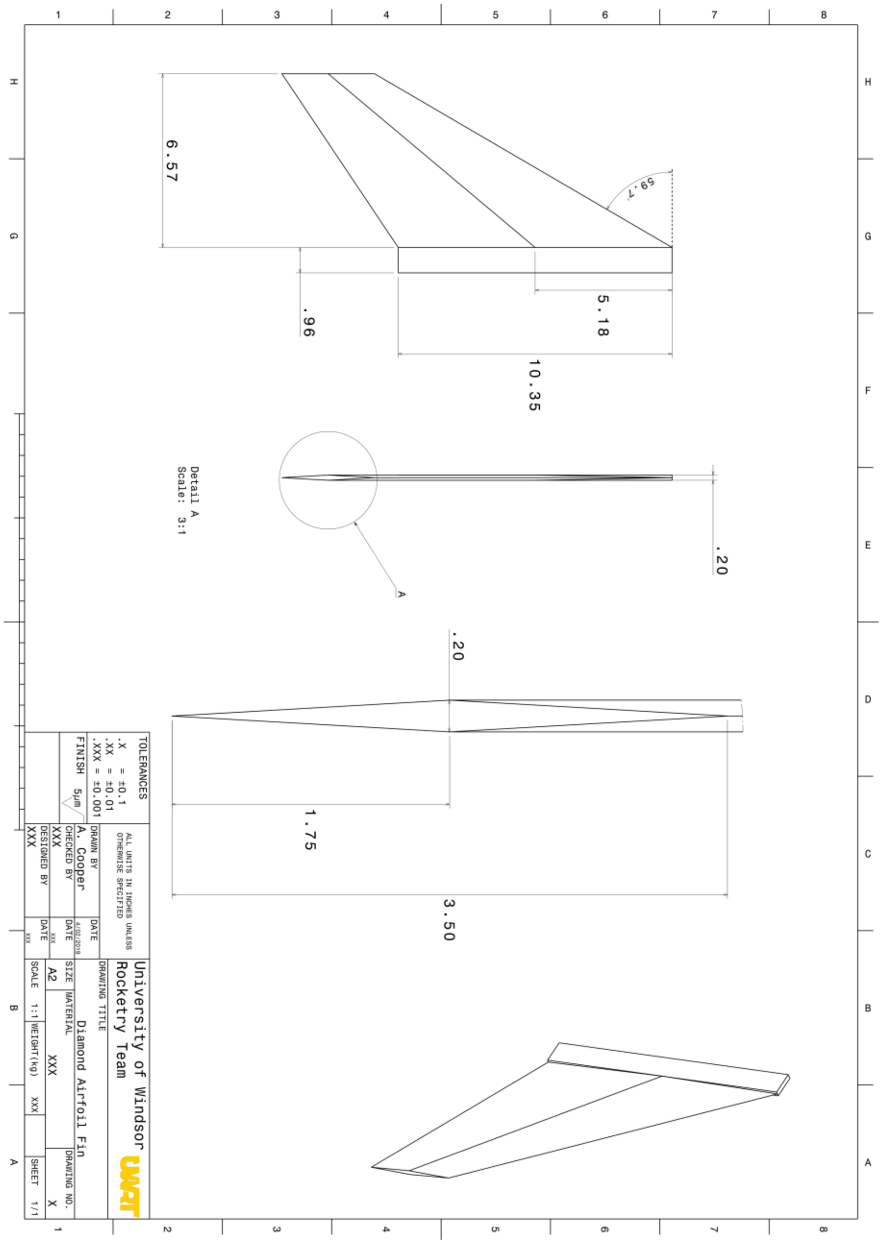

REF. | Radius (in) | Length (in)
A | 0.13 | 0.53
B | 0.26 | 1.06
C | 0.39 | 1.59
D | 0.52 | 2.13
E | 0.64 | 2.66
F | 0.76 | 3.2
G | 0.87 | 3.73
H | 0.98 | 4.27
Top view Scale: 1:1
Front view Scale: 1:1
Isometric view Scale: 1:1
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 3µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY M.HASSAN
CHECKED BY E. RAAD
DESIGNED BY XXX
University of Windsor Rocketry Team
DRAWING TITLE NOSE CONE TIP
SIZE A2
MATERIAL ALUMINIUM
DRAWING NO. X
SCALE 1:1
WEIGHT(kg) XXX
SHEET 1/1


Isometric view
Scale: 1:9
Item No. | Part | Quantity | Material
1 | Lower Aft Tube | 1 | Carbon Fiber
2 | Boat Tail | 1 | Carbon Fiber
3 | Motor Mount Tube | 1 | Carbon Fiber
4 | Diamond Fin | 4 | Carbon Fiber
5 | Motor Casing 6GXL | 1 | Aluminium
6 | Upper Aft Tube | 1 | Fiber Glass
7 | Coupler | 1 | Fiber Glass
8 | Centering Ring | 4 | Carbon Fiber
9 | Threaded Rod 1/4"-20 | 3 | Aluminium
10 | Hex Nut 1/4"-20 | 24 | Aluminium
11 | Washer 1/4" | 24 | Steel
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY M.Hassan DATE 4/10/2019
CHECKED BY XXX DATE XXX
DESIGNED BY XXX DATE XXX
University of Windsor Rocketry Team
DRAWING TITLE Aft Assembly
SIZE A2
MATERIAL XXX
SCALE 1:9
WEIGHT(kg) XXX
DRAWING NO. X
SHEET 1/1

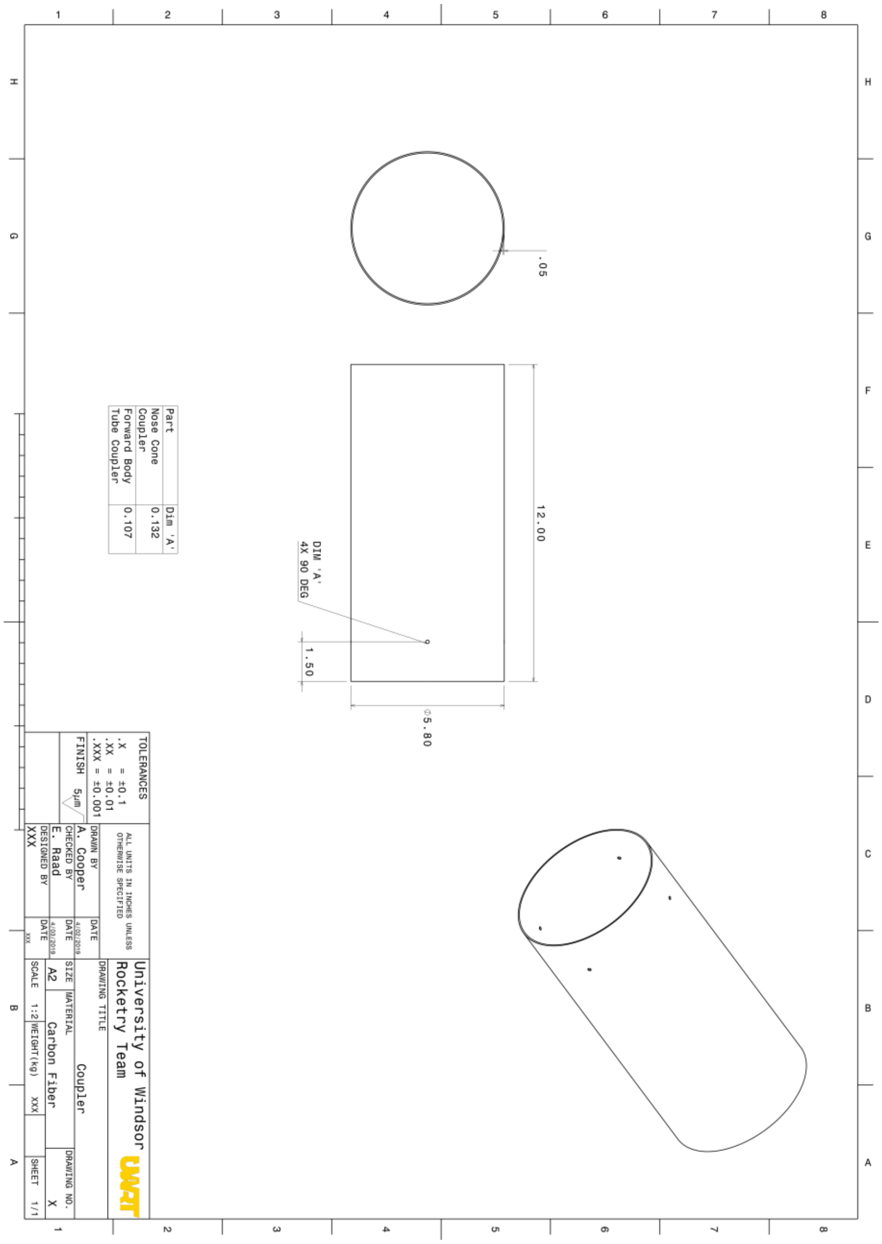

R3
0.2
x 4 slots each 90 deg
R2.9
Front view
Scale: 1:4
Top View
Scale: 1:4
2.9
9.6
46.7
Isometric view
Scale: 1:4
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50μm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
M.HASSAN
DATE
4/10/2019
CHECKED BY
XXX
DESIGNED BY
XXX
University of Windsor
Rocketry Team
DRAWING TITLE
Aft Tube
SIZE
A2
MATERIAL
XXX
SCALE
1:4
WEIGHT(kg)
XXX
DRAWING NO.
X
SHEET
1/1


R1.9
R2
Front view
Scale: 1:2
53.8
Bottom view
Scale: 1:2
Isometric view
Scale: 1:2
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
M.HASSAN
DATE
4/10/2019
CHECKED BY
XXX
DESIGNED BY
XXX
University of Windsor Rocketry Team
DRAWING TITLE
Motor mount Tube
SIZE
A2
MATERIAL
XXX
DRAWING NO.
X
SCALE 1:2
WEIGHT(kg) XXX
SHEET 1/1

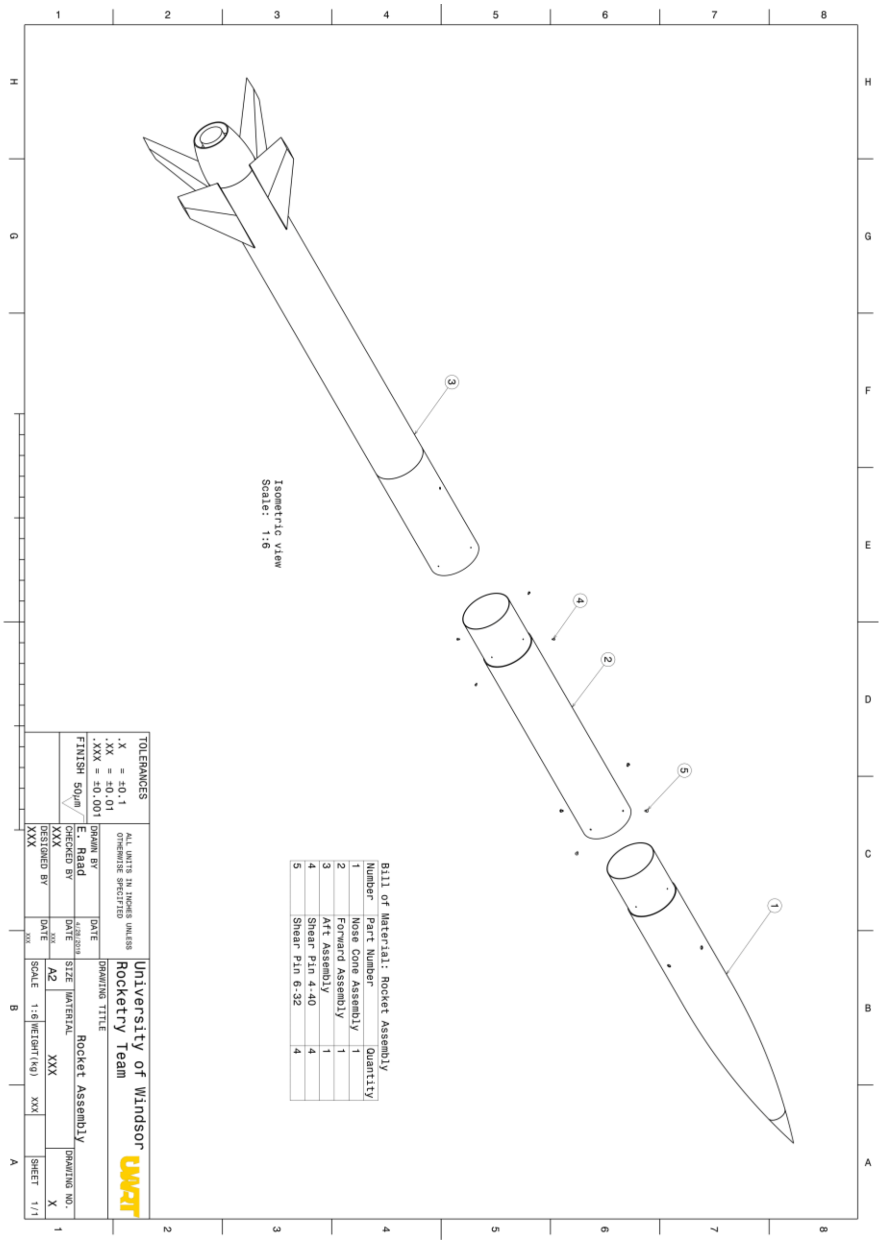

University of Windsor Rocketry Team
DRAWING TITLE
Boat Tail
MATERIAL
Carbon Fiber
DRAWING NO.
ASM-03-02
SIZE
A2
SCALE 1:2
WEIGHT(kg) XXX
SHEET 1/1
DRAWN BY
A. Cooper
CHECKED BY
E. Raad
DESIGNED BY
XXX
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 5µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
Section view B-B
Scale: 1:2
Uniform Thickness
4X 90deg

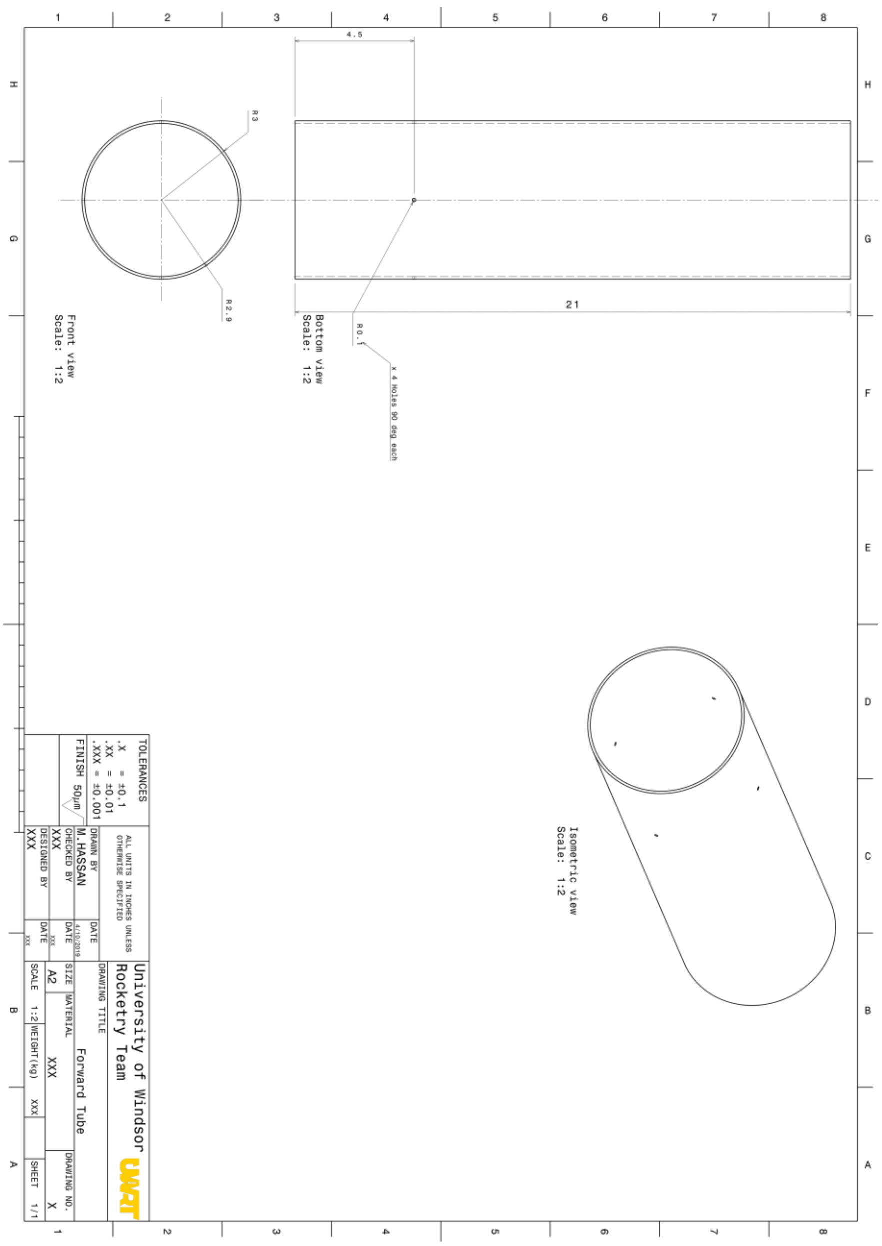


6.57
59.7°
.96
5.18
10.35
Detail A
Scale: 3:1
.20
A
.20
1.75
3.50
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 5µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
A. Cooper
DATE
CHECKED BY
XXX
DESIGNED BY
XXX
University of Windsor Rocketry Team
DRAWING TITLE
Diamond Airfoil Fin
SIZE
A2
MATERIAL
XXX
DRAWING NO.
X
SCALE
1:1
WEIGHT(kg)
XXX
SHEET
1/1

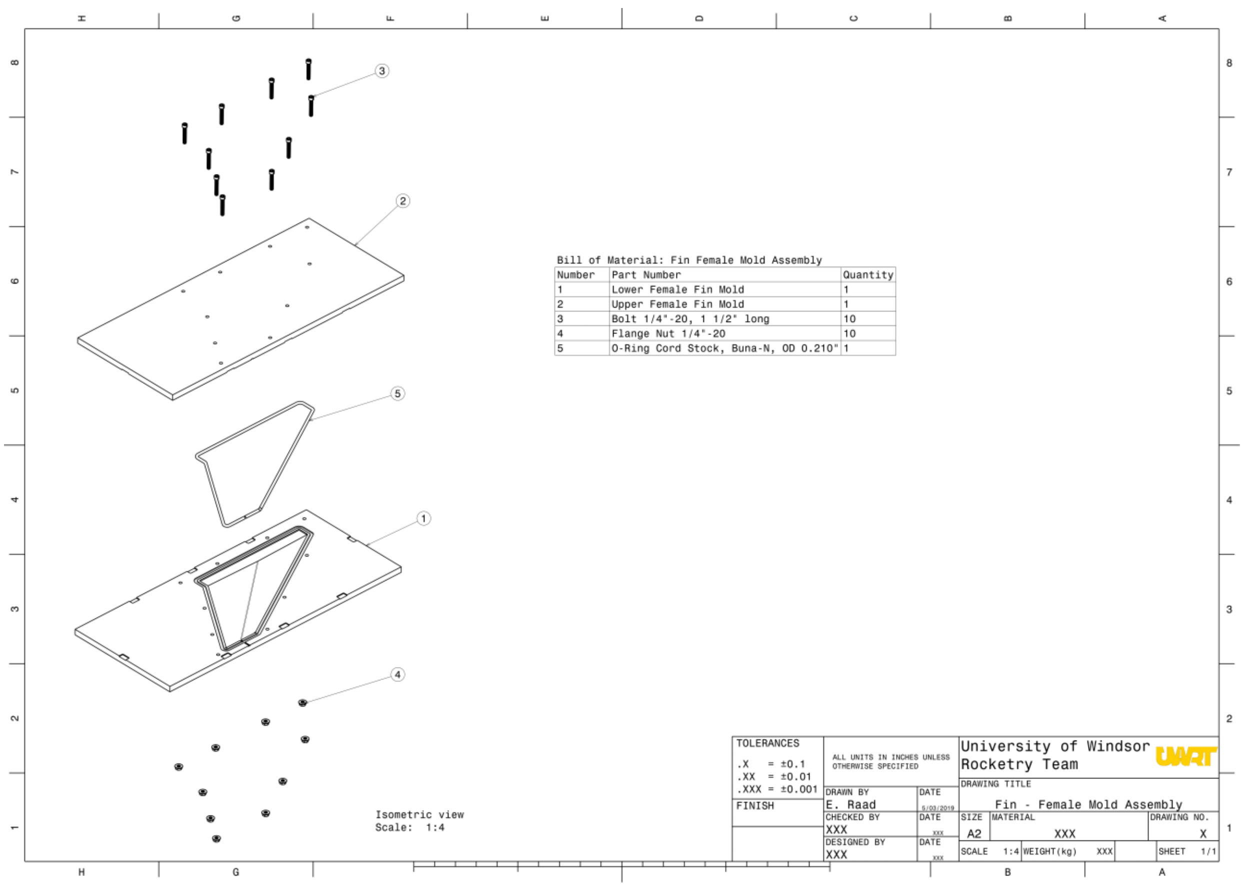


.05
12.00
DIM 'A'
4X 90 DEG
1.50
∅5.80
Part
Nose Cone
Coupler
Forward Body
Tube Coupler
Dim 'A'
0.132
0.107
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH
5μm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
A. Cooper
CHECKED BY
E. Raad
DESIGNED BY
XXX
DATE
University of Windsor
Rocketry Team
DRAWING TITLE
Coupler
SIZE
A2
MATERIAL
Carbon Fiber
DRAWING NO.
X
SCALE
1:2
WEIGHT(kg)
XXX
SHEET
1/1


Isometric view
Scale: 1:6
Bill of Material: Rocket Assembly
Number | Part Number | Quantity
1 | Nose Cone Assembly | 1
2 | Forward Assembly | 1
3 | Aft Assembly | 1
4 | Shear Pin 4-40 | 4
5 | Shear Pin 6-32 | 4
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
E. Raad
DATE
CHECKED BY
XXX
DATE
DESIGNED BY
XXX
DATE
University of Windsor
Rocketry Team
DRAWING TITLE
Rocket Assembly
SIZE
A2
MATERIAL
XXX
SCALE
1:6
WEIGHT(kg)
XXX
DRAWING NO.
X
SHEET
1/1

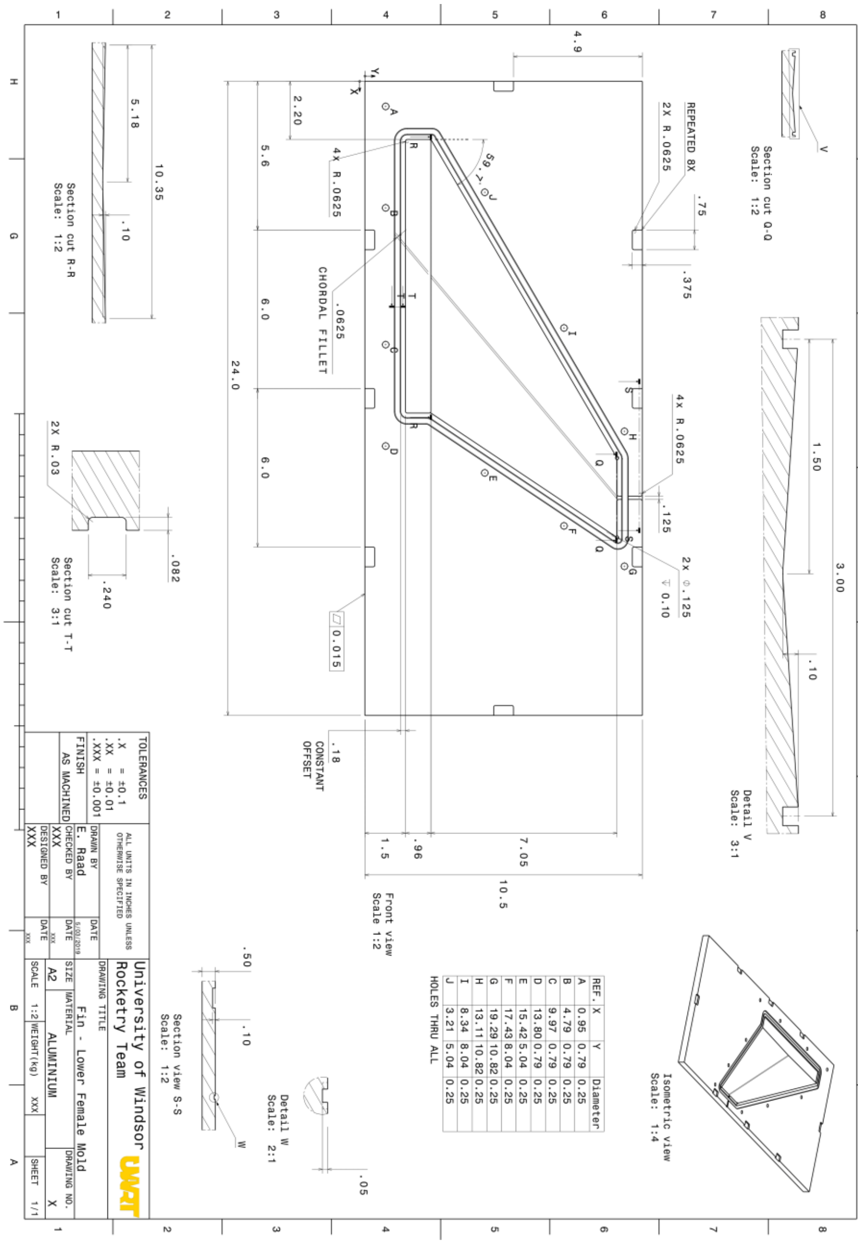


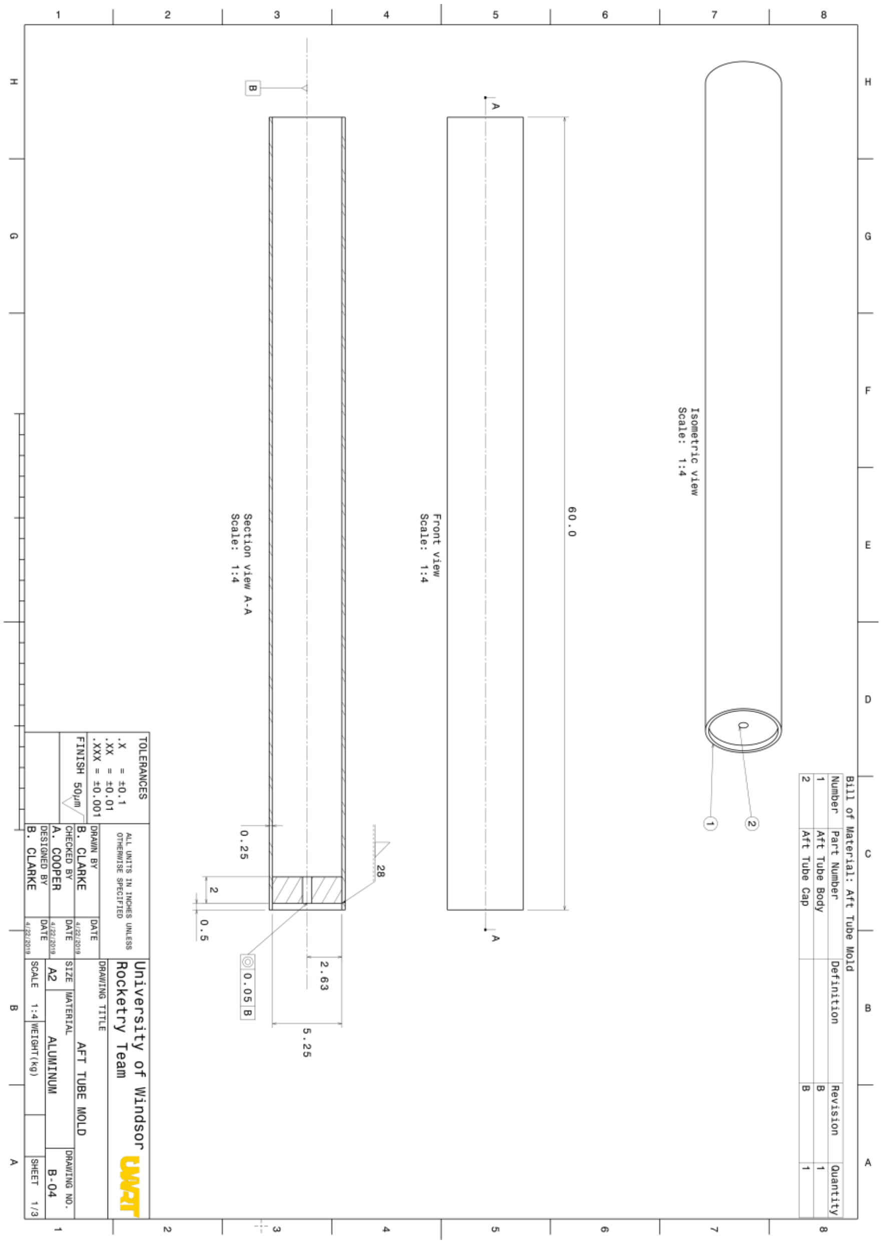
4.5
R3
R2.9
21
R0.1
x 4 Holes 90 deg each
Front view
Scale: 1:2
Bottom view
Scale: 1:2
Isometric view
Scale: 1:2
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
M.HASSAN
DATE
4/10/2019
CHECKED BY
XXX
DATE
XXX
DESIGNED BY
XXX
DATE
XXX
University of Windsor
Rocketry Team
DRAWING TITLE
Forward Tube
SIZE
A2
MATERIAL
XXX
DRAWING NO.
X
SCALE
1:2
WEIGHT(kg)
XXX
SHEET
1/1



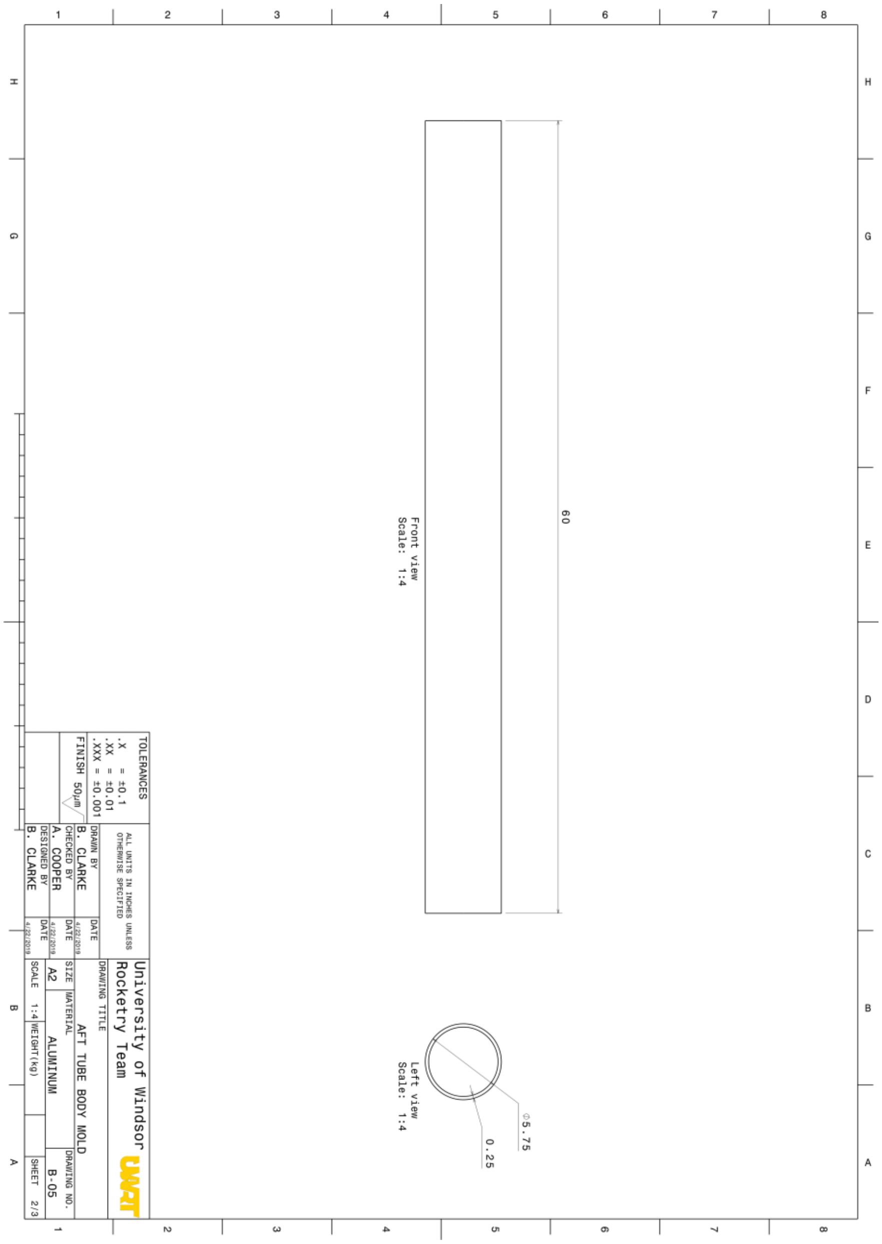
Bill of Material: Fin Female Mold Assembly

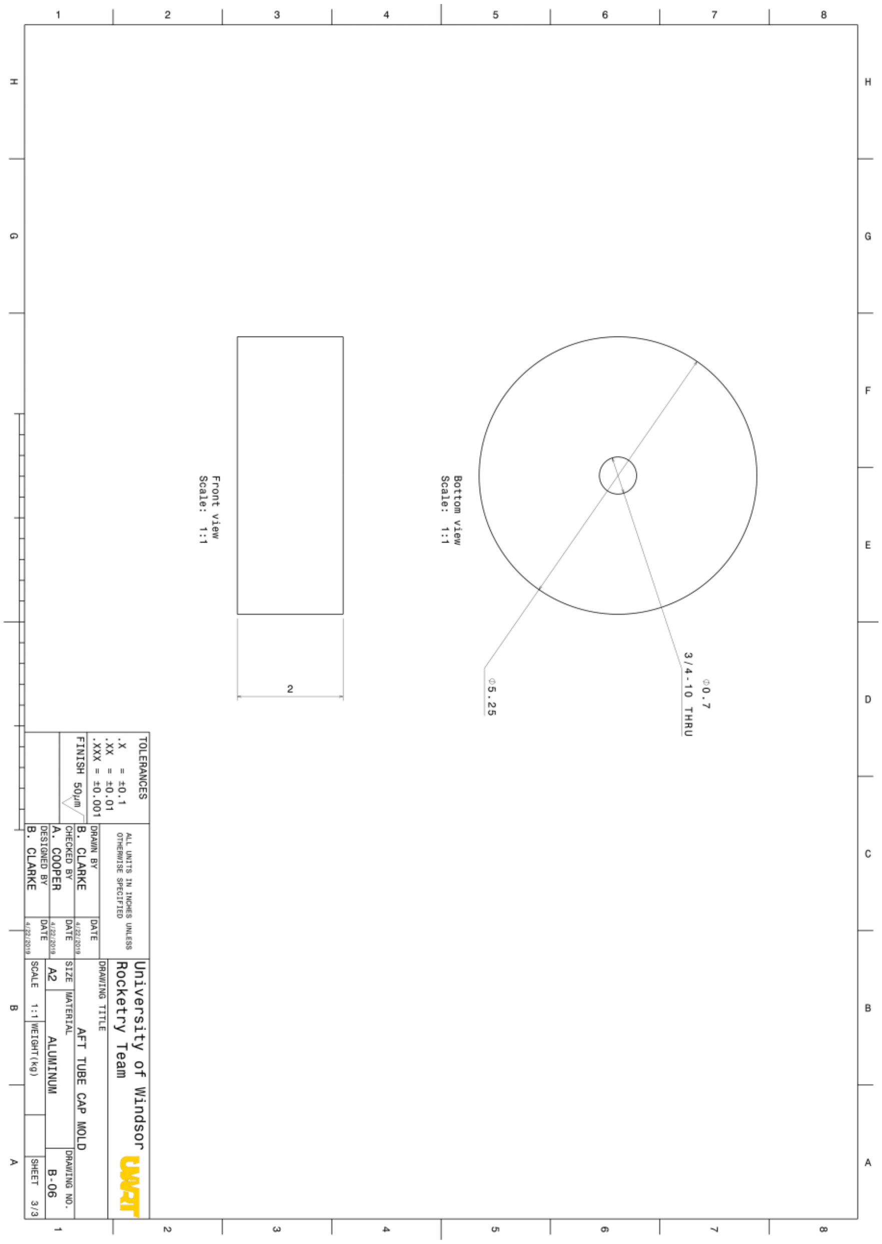
Number	Part Number	Quantity
1	Lower Female Fin Mold	1
2	Upper Female Fin Mold	1
3	Bolt 1/4"-20, 1 1/2" long	10
4	Flange Nut 1/4"-20	10
5	O-Ring Cord Stock, Buna-N, OD 0.210"	1

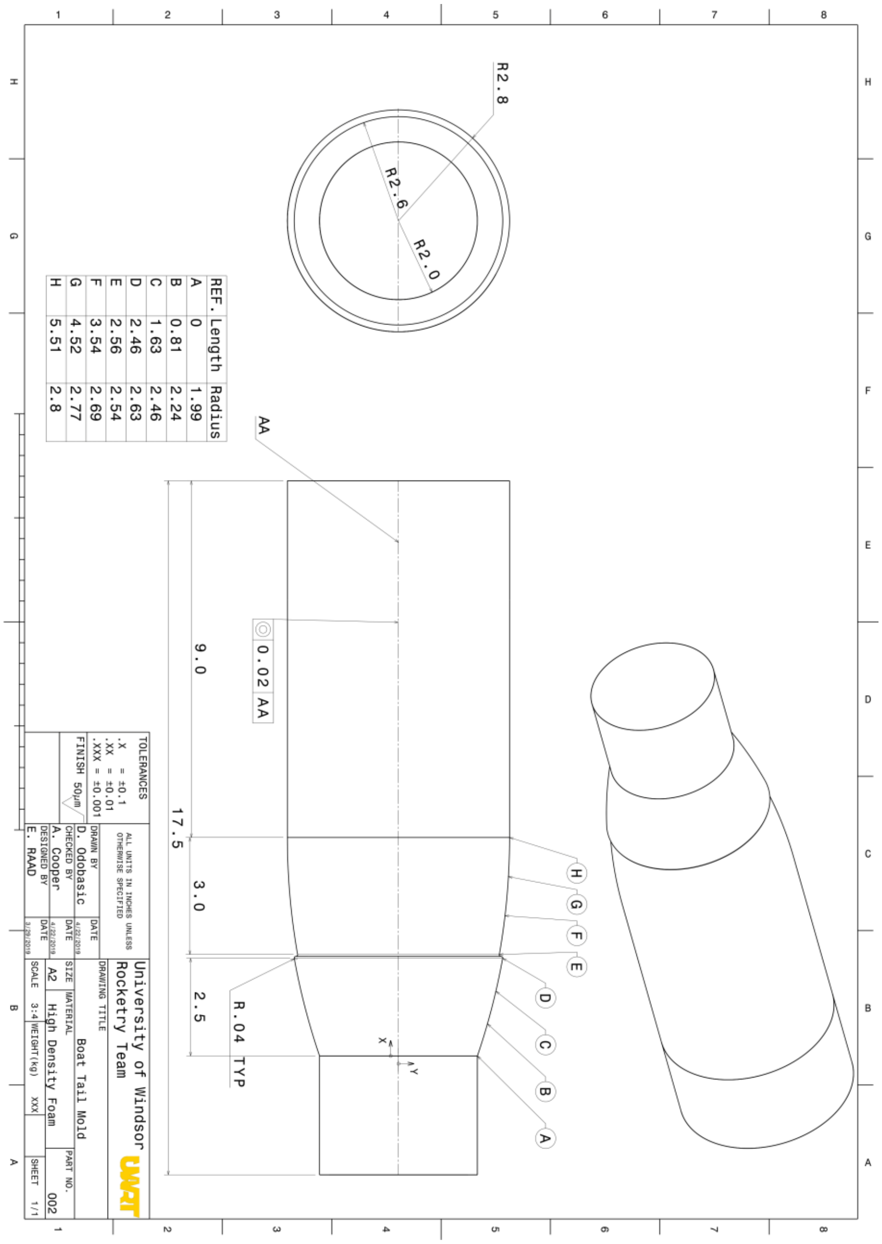

University of Windsor Rocketry Team
DRAWING TITLE
Fin - Lower Female Mold
SIZE A2
MATERIAL ALUMINIUM
SCALE 1:2
WEIGHT(kg) XXX
SHEET 1/1
DRAWING NO. X
DRAWN BY E. Raad
CHECKED BY XXX
DESIGNED BY XXX
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH AS MACHINED
Front view Scale 1:2
Section cut R-R Scale: 1:2
Section cut T-T Scale: 3:1
Section cut Q-Q Scale: 1:2
Detail V Scale: 3:1
Section view S-S Scale: 1:2
Detail W Scale: 2:1
Isometric view Scale: 1:4
CHORDAL FILLET
REPEATED 8X
.18 CONSTANT OFFSET
REF. X Y Diameter
A 0.95 0.79 0.25
B 4.79 0.79 0.25
C 9.97 0.79 0.25
D 13.80 0.79 0.25
E 15.42 5.04 0.25
F 17.43 8.04 0.25
G 19.29 10.82 0.25
H 13.11 10.82 0.25
I 8.34 8.04 0.25
J 3.21 5.04 0.25
HOLES THRU ALL

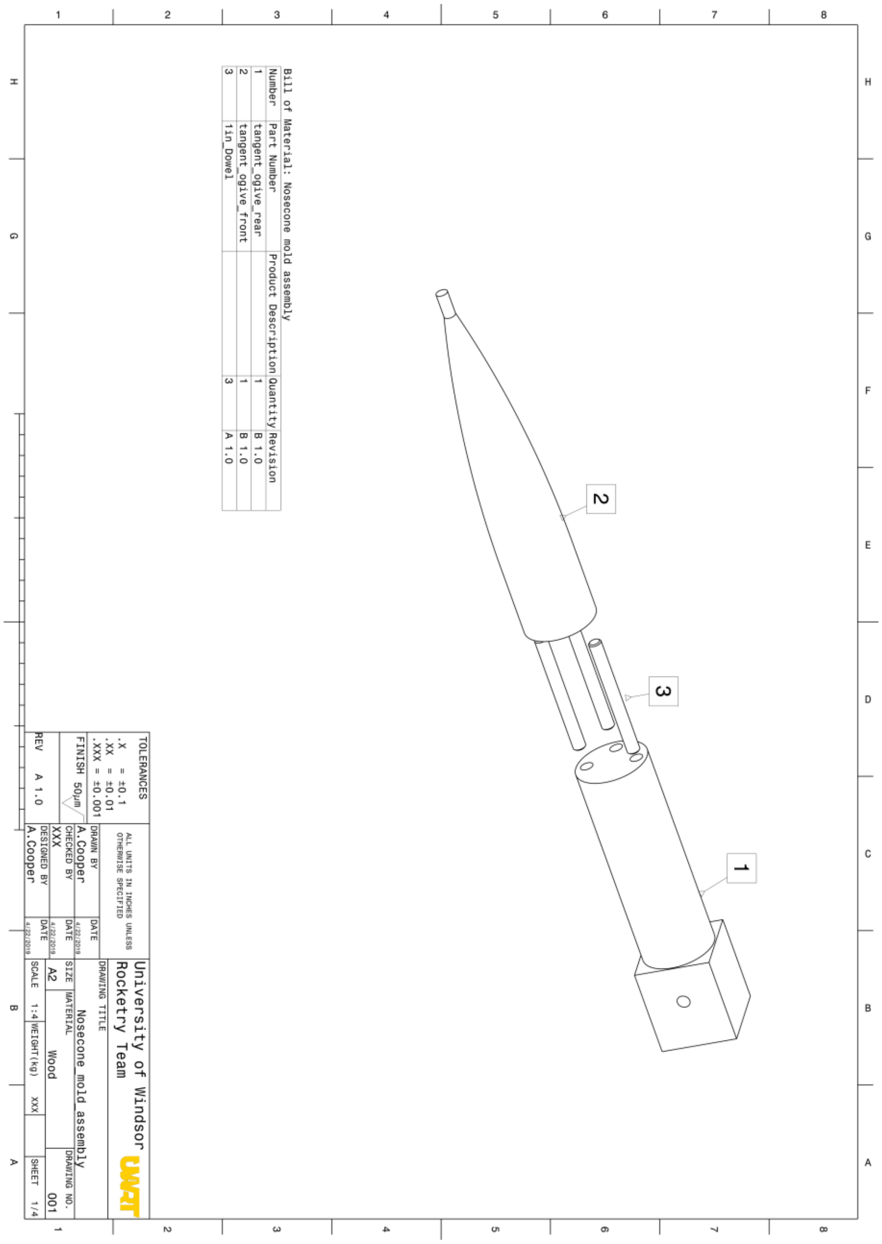


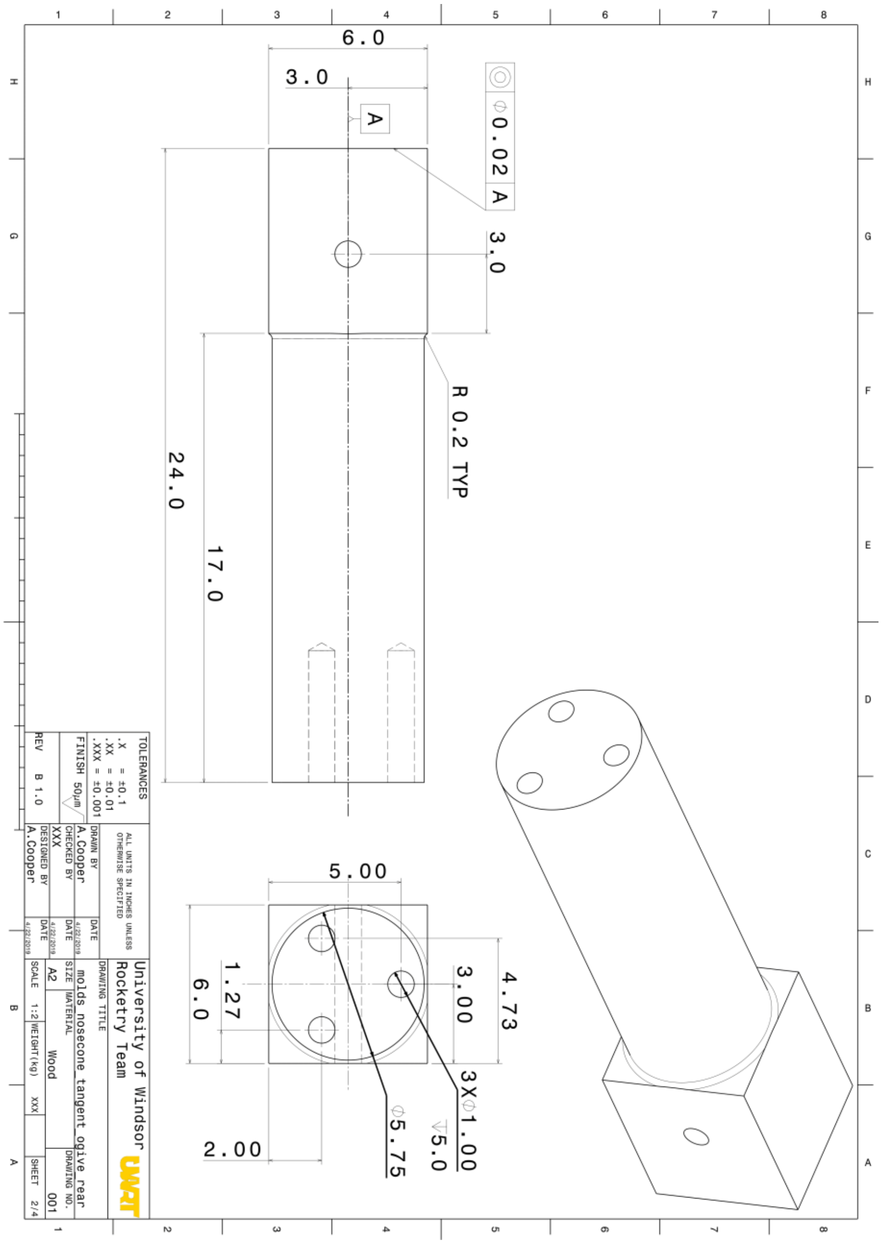
Section view A-A
Scale: 1:4
Front view
Scale: 1:4
Isometric view
Scale: 1:4
60.0
0.25
28
2
0.5
2.63
5.25
0.05 B
Bill of Material: Aft Tube Mold
Number
Part Number
Definition
Revision
Quantity
1
Aft Tube Body
B
1
2
Aft Tube Cap
B
1
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50μm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
B. CLARKE
CHECKED BY
A. COOPER
DESIGNED BY
B. CLARKE
University of Windsor Rocketry Team
DRAWING TITLE
AFT TUBE MOLD
SIZE
A2
MATERIAL
ALUMINUM
DRAWING NO.
B-04
SCALE
1:4
WEIGHT(kg)
SHEET
1/3

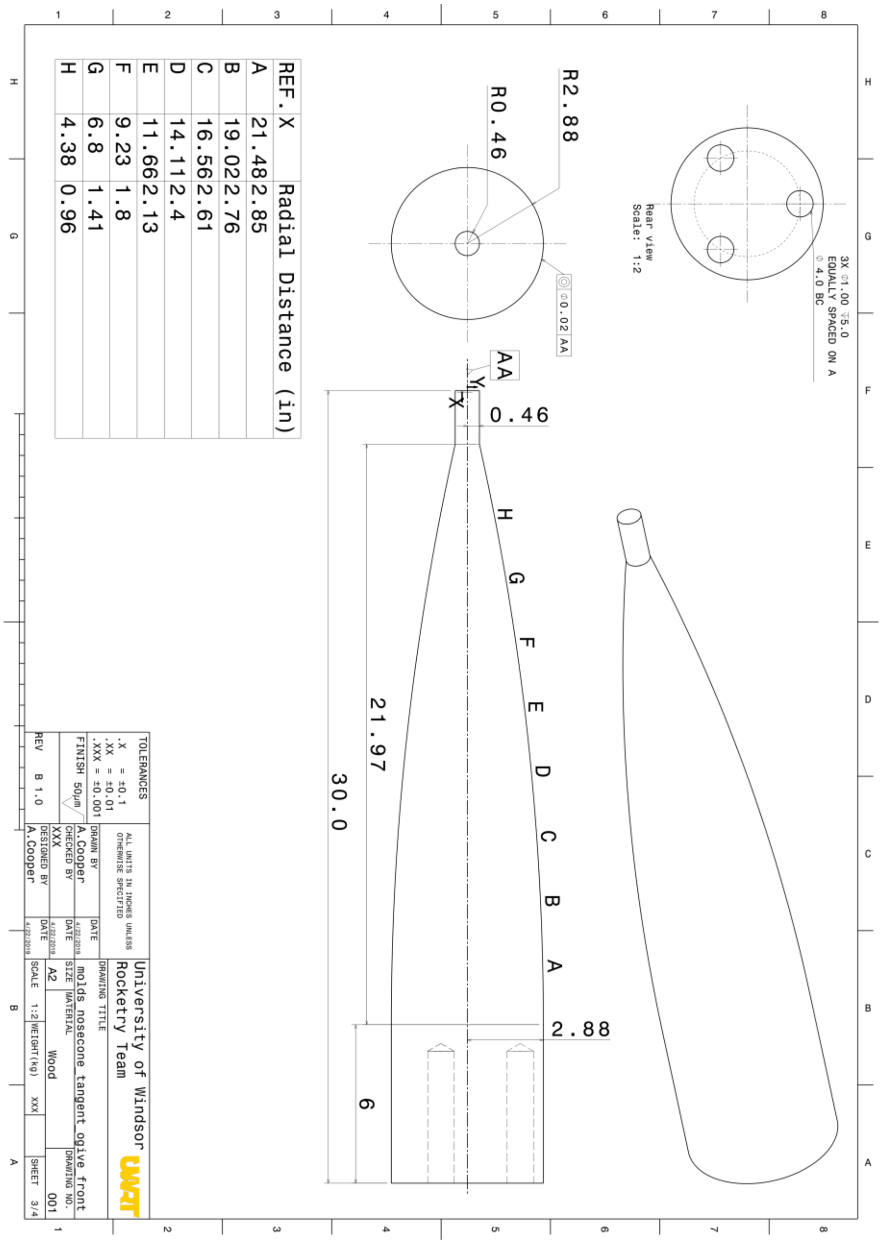

Front view
Scale: 1:4
60
Left view
Scale: 1:4
⌀5.75
0.25
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
B. CLARKE
CHECKED BY
A. COOPER
DESIGNED BY
B. CLARKE
DATE
University of Windsor
Rocketry Team
DRAWING TITLE
AFT TUBE BODY MOLD
SIZE
A2
MATERIAL
ALUMINUM
DRAWING NO.
B-05
SCALE
1:4
WEIGHT(kg)
SHEET
2/3

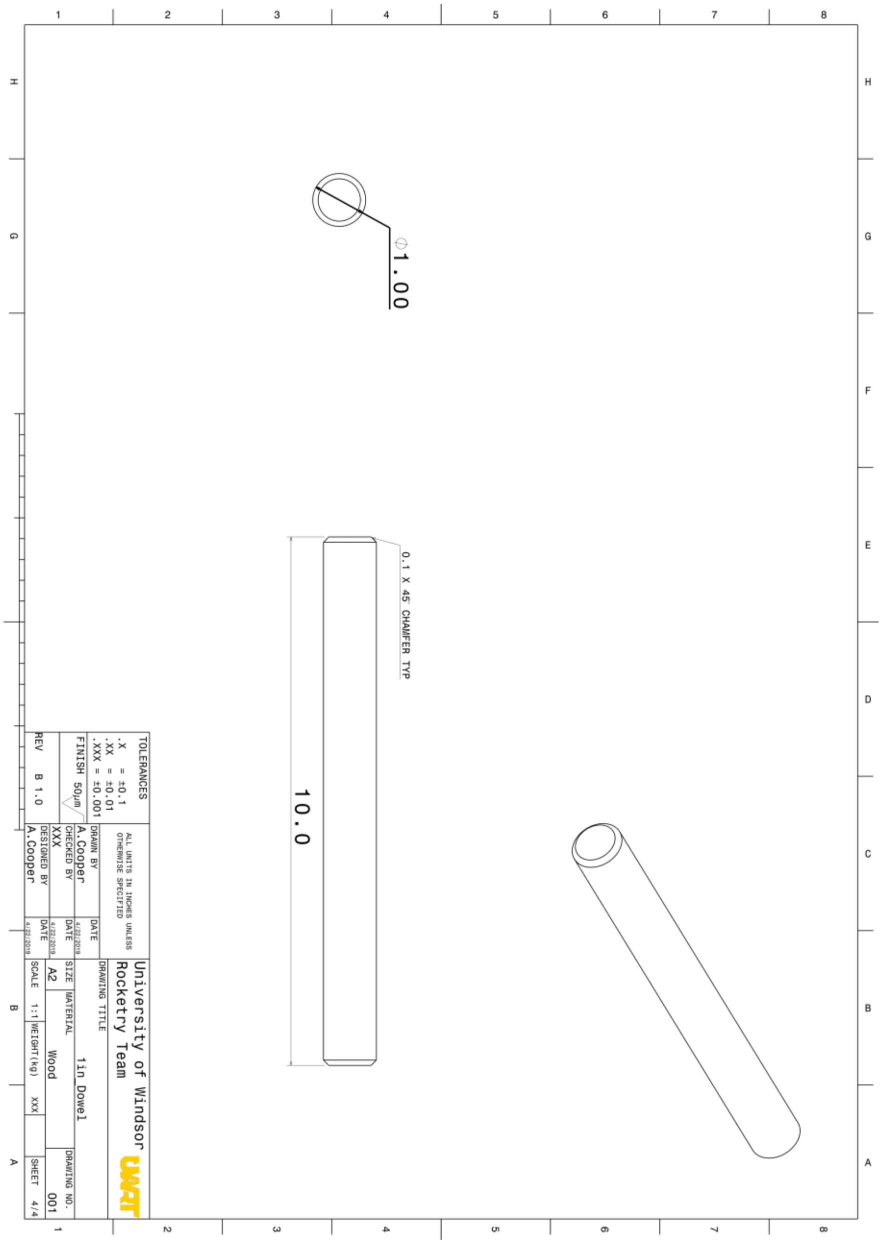

Front view
Scale: 1:1
2
Bottom view
Scale: 1:1
∅5.25
∅0.7
3/4-10 THRU
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
B. CLARKE
CHECKED BY
A. COOPER
DESIGNED BY
B. CLARKE
DATE
University of Windsor Rocketry Team
DRAWING TITLE
AFT TUBE CAP MOLD
SIZE
A2
MATERIAL
ALUMINUM
DRAWING NO.
B-06
SCALE
1:1
WEIGHT(kg)
SHEET
3/3


R2.8
R2.6
R2.0
REF. Length Radius
A 0 1.99
B 0.81 2.24
C 1.63 2.46
D 2.46 2.63
E 2.56 2.54
F 3.54 2.69
G 4.52 2.77
H 5.51 2.8
AA
0.02 AA
9.0
17.5
3.0
2.5
R.04 TYP
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50μm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
D. Odobasic
CHECKED BY
A. Cooper
DESIGNED BY
E. RAAD
University of Windsor Rocketry Team
DRAWING TITLE
Boat Tail Mold
SIZE A2
MATERIAL High Density Foam
SCALE 3:4
WEIGHT(kg) XXX
PART NO. 002
SHEET 1/1

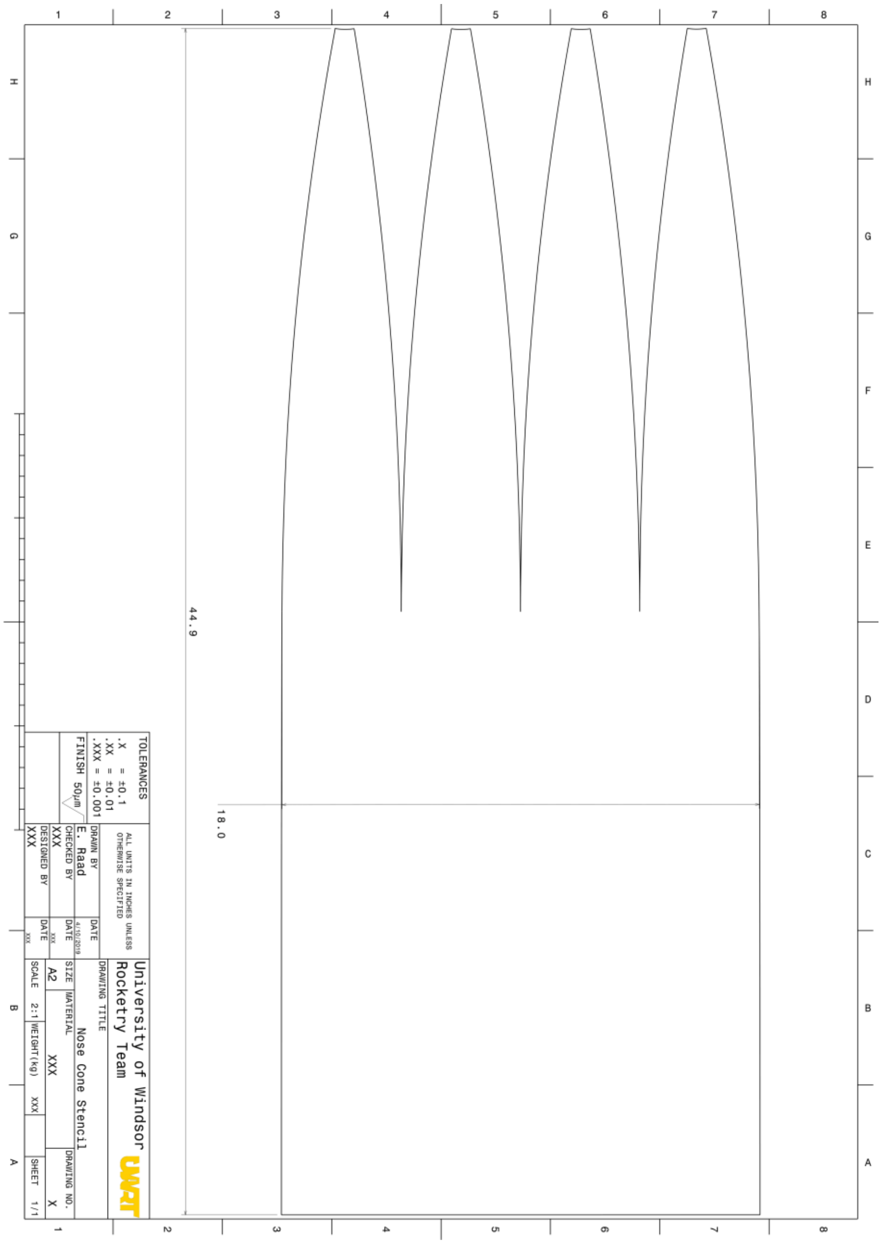

Bill of Material: Nosecone mold assembly
Number | Part Number | Product Description | Quantity | Revision
1 | tangent_ogive_rear | | 1 | B 1.0
2 | tangent_ogive_front | | 1 | B 1.0
3 | 1in_Dowel | | 3 | A 1.0
2
3
1
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
REV A 1.0
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
A.Cooper
DATE
CHECKED BY
XXX
DATE
DESIGNED BY
A.Cooper
DATE
University of Windsor Rocketry Team
DRAWING TITLE
Nosecone mold assembly
SIZE
A2
MATERIAL
Wood
DRAWING NO.
001
SCALE 1:4
WEIGHT(kg) XXX
SHEET 1/4

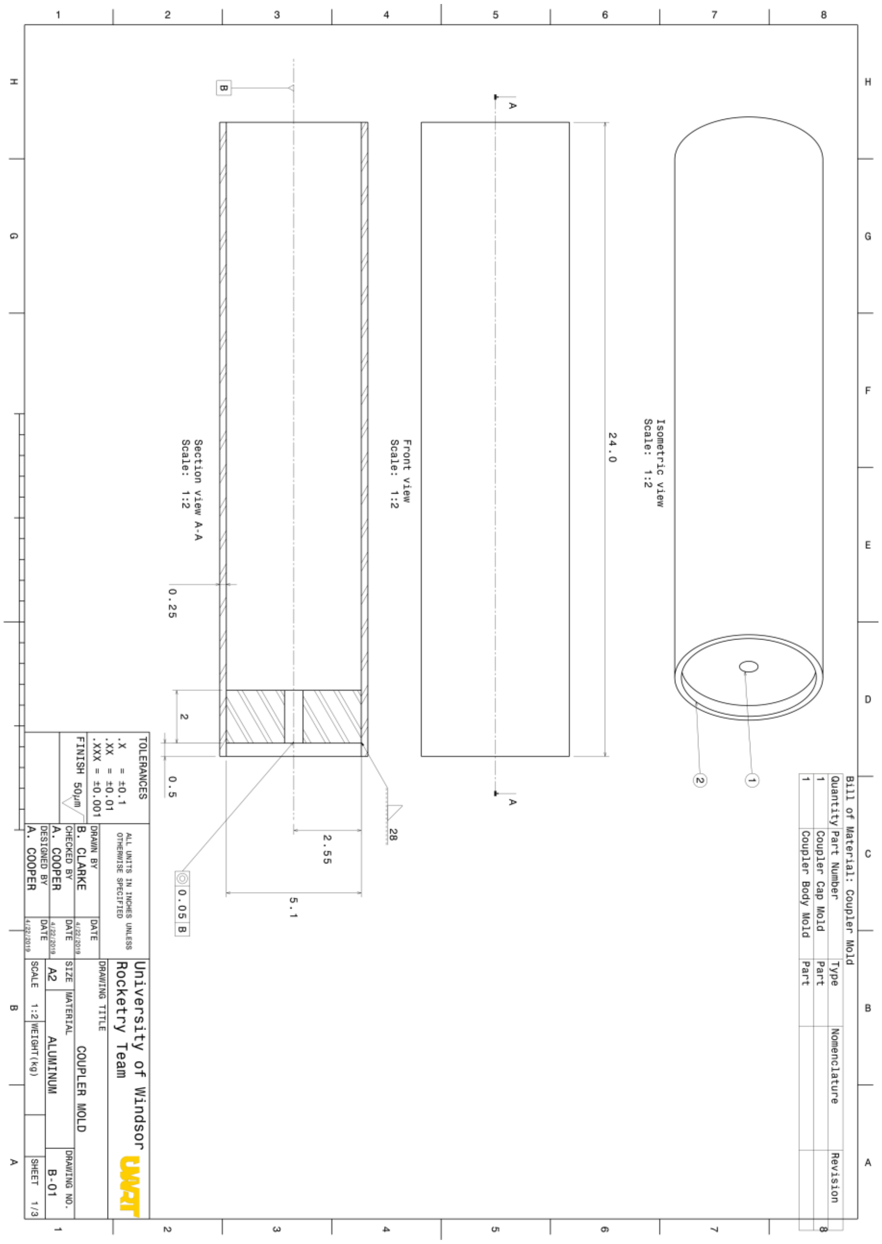

University of Windsor Rocketry Team
DRAWING TITLE
molds nosecone tangent ogive rear
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
A.Cooper
CHECKED BY
XXX
DESIGNED BY
A.Cooper
REV B 1.0
SIZE A2
MATERIAL Wood
SCALE 1:2
WEIGHT(kg) XXX
DRAWING NO. 001
SHEET 2/4
6.0
3.0
24.0
17.0
R 0.2 TYP
0.02 A
5.00
1.27
6.0
3.00
4.73
2.00
3X⌀1.00
5.0
⌀5.75

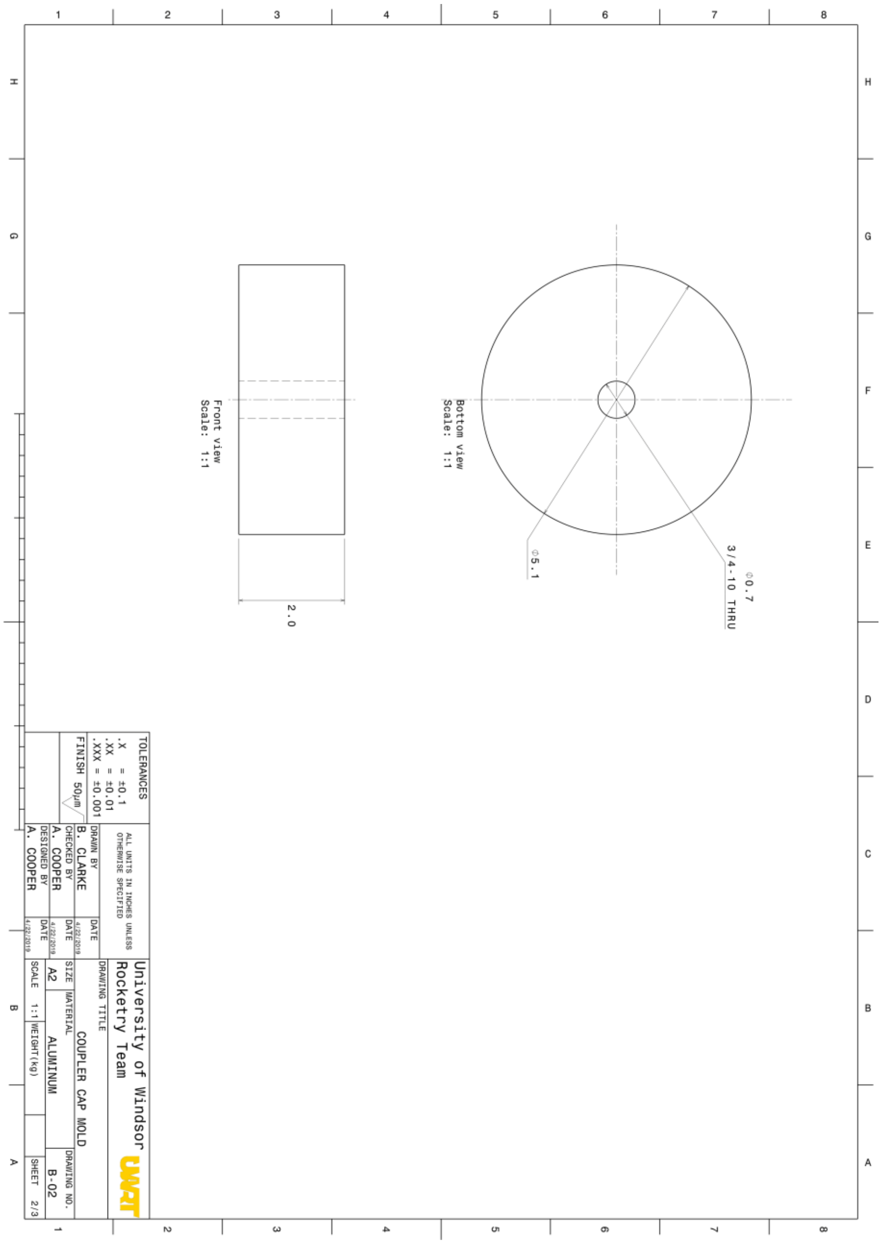

R2.88
R0.46
Rear view
Scale: 1:2
3X ⌀1.00 ↧5.0
EQUALLY SPACED ON A
⌀ 4.0 BC
⌀0.02 AA
AA
0.46
21.97
30.0
2.88
6
H
G
F
E
D
C
B
A
REF. X | Radial Distance (in)
A 21.48 2.85
B 19.02 2.76
C 16.56 2.61
D 14.11 2.4
E 11.66 2.13
F 9.23 1.8
G 6.8 1.41
H 4.38 0.96
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
REV B 1.0
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
A.Cooper
CHECKED BY
XXX
DESIGNED BY
A.Cooper
University of Windsor Rocketry Team
DRAWING TITLE
molds nosecone tangent ogive front
SIZE A2
MATERIAL Wood
DRAWING NO. 001
SCALE 1:2
WEIGHT(kg) XXX
SHEET 3/4



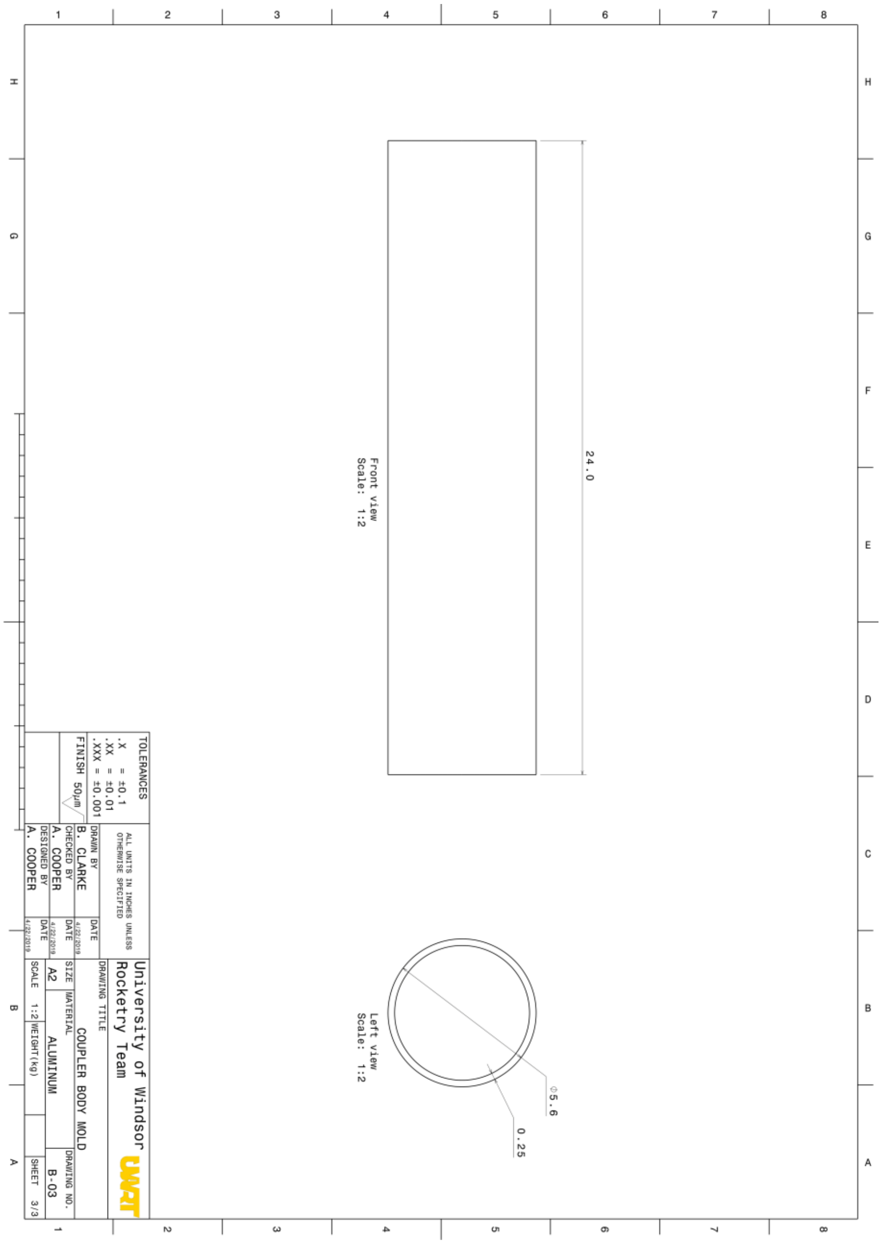
Ø1.00
0.1 X 45 CHAMFER TYP
10.0
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
REV B 1.0
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY A.Cooper
CHECKED BY XXX
DESIGNED BY A.Cooper
University of Windsor Rocketry Team
DRAWING TITLE 1in Dowel
SIZE A2
MATERIAL Wood
SCALE 1:1
WEIGHT(kg) XXX
DRAWING NO. 001
SHEET 4/4


44.9
18.0
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
E. Raad
CHECKED BY
XXX
DESIGNED BY
XXX
DATE
University of Windsor Rocketry Team
DRAWING TITLE
Nose Cone Stencil
SIZE
A2
MATERIAL
XXX
DRAWING NO.
X
SCALE
2:1
WEIGHT(kg)
XXX
SHEET
1/1


Section view A-A
Scale: 1:2
Front view
Scale: 1:2
Isometric view
Scale: 1:2
24.0
0.25
0.5
2
2.55
5.1
28
0.05 B
Bill of Material: Coupler Mold
Quantity Part Number Type Nomenclature Revision
1 Coupler Cap Mold Part
1 Coupler Body Mold Part
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
B. CLARKE
CHECKED BY
A. COOPER
DESIGNED BY
A. COOPER
University of Windsor Rocketry Team
DRAWING TITLE
COUPLER MOLD
SIZE
A2
MATERIAL
ALUMINUM
DRAWING NO.
B-01
SCALE
1:2
WEIGHT(kg)
SHEET 1/3



Front view
Scale: 1:1
2.0
Bottom view
Scale: 1:1
⌀5.1
⌀0.7
3/4-10 THRU
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50µm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
B. CLARKE
DATE
CHECKED BY
A. COOPER
DATE
DESIGNED BY
A. COOPER
DATE
University of Windsor Rocketry Team
DRAWING TITLE
COUPLER CAP MOLD
SIZE
A2
MATERIAL
ALUMINUM
DRAWING NO.
B-02
SCALE
1:1
WEIGHT(kg)
SHEET
2/3


Front view
Scale: 1:2
24.0
Left view
Scale: 1:2
⌀5.6
0.25
TOLERANCES
.X = ±0.1
.XX = ±0.01
.XXX = ±0.001
FINISH 50μm
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
DRAWN BY
B. CLARKE
DATE
4/22/2019
CHECKED BY
A. COOPER
DATE
4/22/2019
DESIGNED BY
A. COOPER
DATE
4/22/2019
University of Windsor
Rocketry Team
DRAWING TITLE
COUPLER BODY MOLD
SIZE
A2
MATERIAL
ALUMINUM
DRAWING NO.
B-03
SCALE
1:2
WEIGHT(kg)
SHEET
3/3

Airfoil CFD Results Appendix

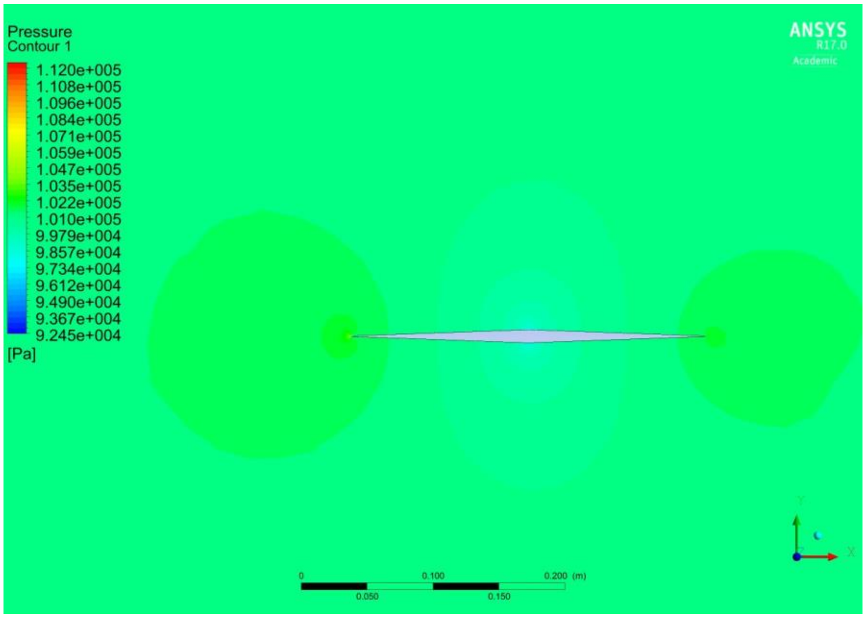


Figure 24. Pressure distribution on diamond airfoil at Mach 0.4

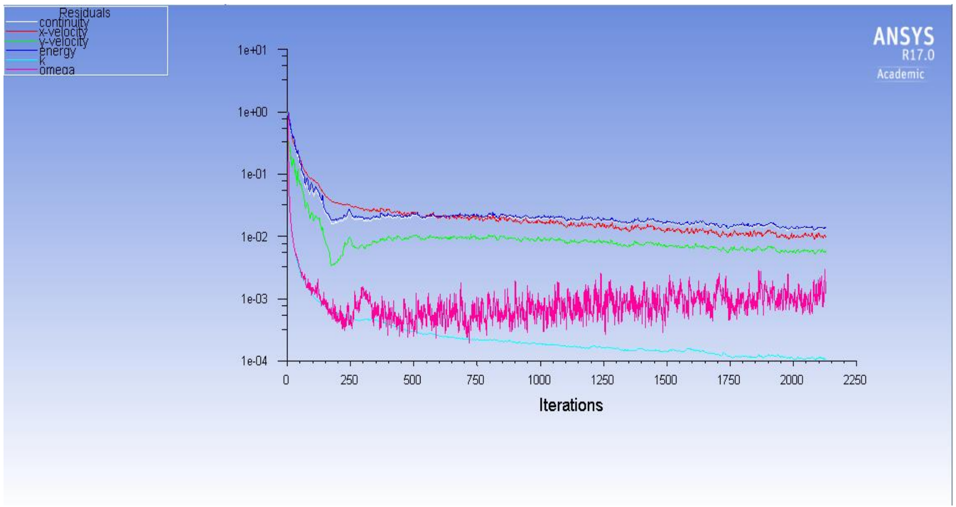


Figure 25. Convergence of Residuals for diamond airfoil at Mach 1.4

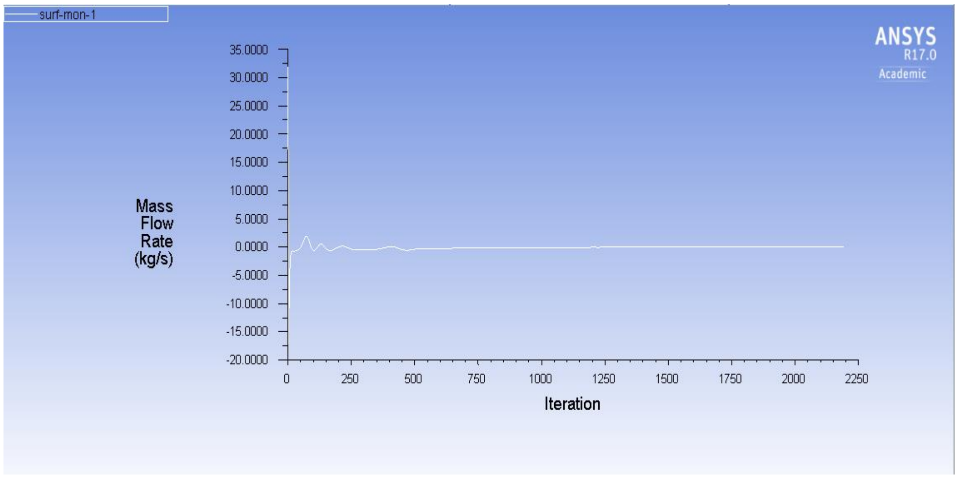


Figure 26. Convergence of Mass Flow rate surface integral for diamond airfoil at Mach 1.4

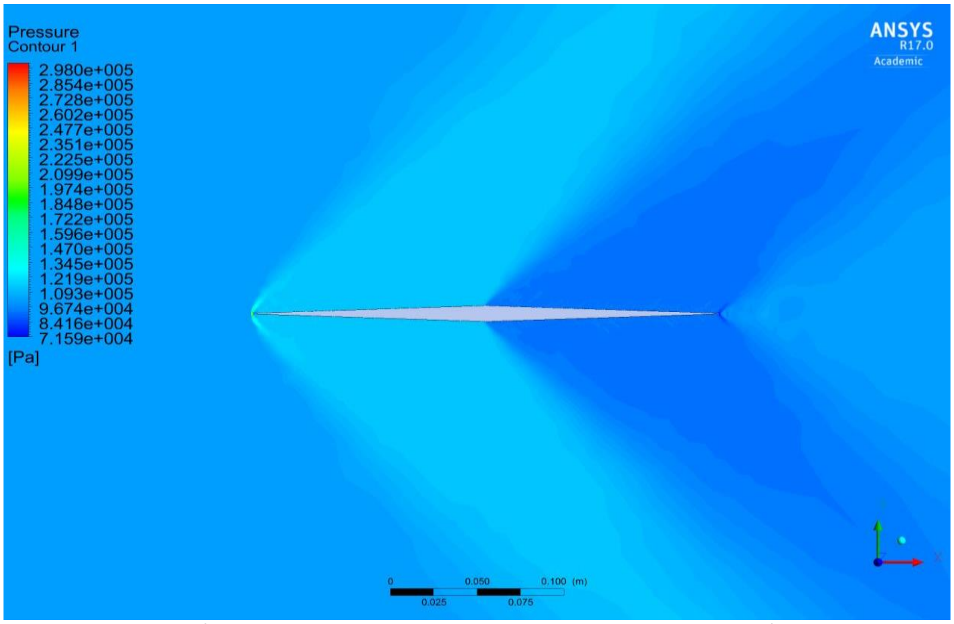


Figure 27. Simulation of Oblique shock and Prandtl-Meyer Expansion Wave on Diamond Airfoil

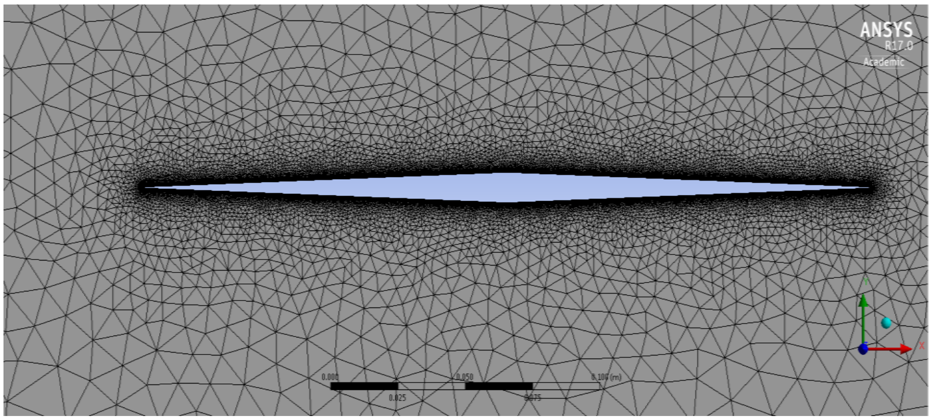


Figure 28. Triangular mesh for diamond airfoil

Details of "Mesh"	
Sizing	
Size Function	Proximity and Curvature
Relevance Center	Fine
Initial Size Seed	Active Assembly
Smoothing	High
Span Angle Center	Fine
Curvature Normal Angle	Default (18.0 °)
Num Cells Across Gap	Default (3)
Proximity Size Function Sources	Faces and Edges
Min Size	Default (1.4738e-003 m)
Proximity Min Size	Default (1.4738e-003 m)
Max Face Size	8.032e-002 m
Max Tet Size	Default (0.294760 m)
Growth Rate	Default (1.20)
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default (7.369e-004 m)
Minimum Edge Length	6.1365e-004 m

Figure 29. Mesh sizing for diamond airfoil

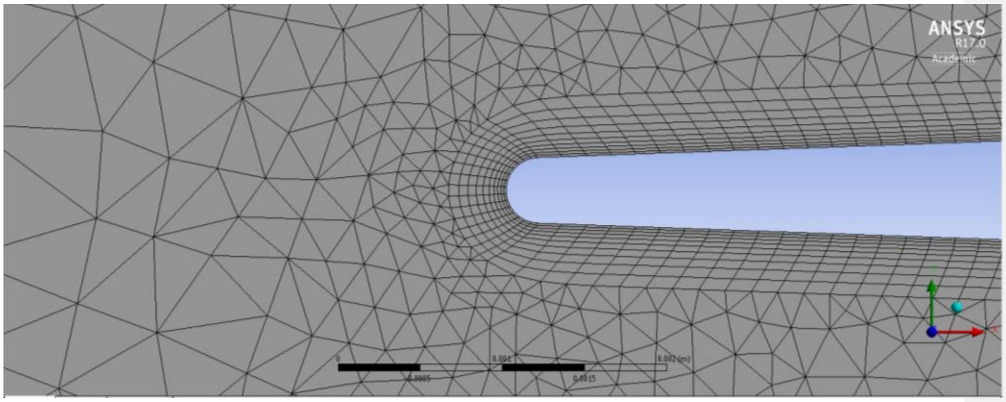


Figure 30. Inflation Layers on diamond airfoil

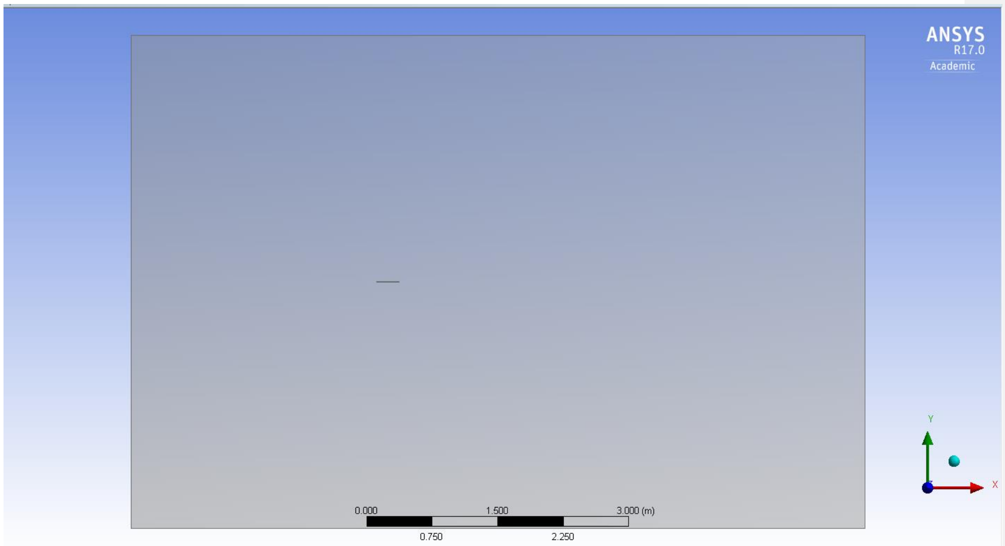


Figure 31. Flow domain setup for diamond airfoil

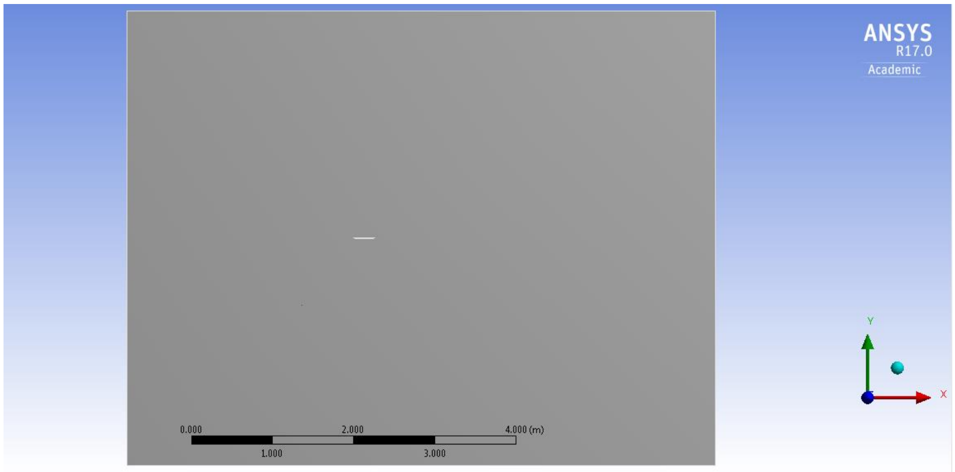


Figure 32. Flow domain setup for biconvex airfoil

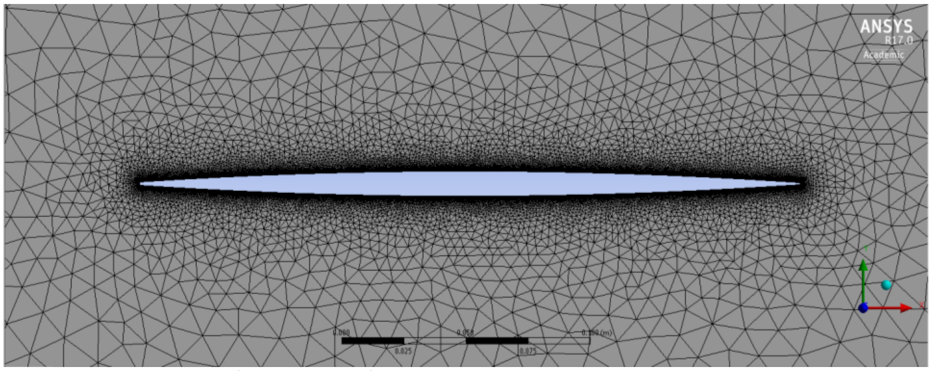


Figure 33. Triangular mesh for Biconvex airfoil

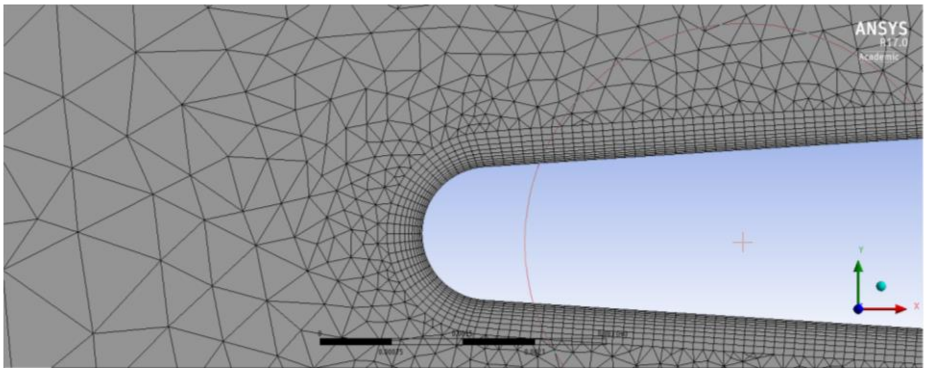


Figure 34. Inflation Layers on Biconvex airfoil

Sizing	
Size Function	Curvature
Relevance Center	Coarse
Initial Size Seed	Active Assembly
Smoothing	Medium
Span Angle Center	Fine
Curvature Normal Angle	Default (18.0 °)
Min Size	Default (4.5722e-003 m)
Max Face Size	8.5722e-002 m
Max Tet Size	Default (0.914430 m)
Growth Rate	Default (1.20)
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default (2.2861e-003 m)
Minimum Edge Length	1.1908e-003 m

Figure 35. Mesh sizing for biconvex airfoil

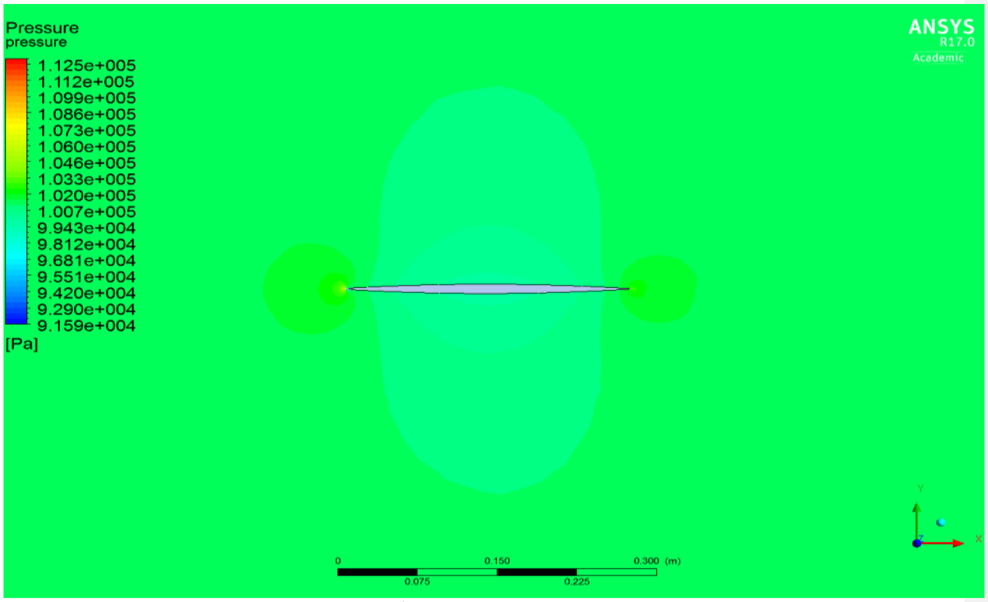


Figure 36. Pressure Distribution on biconvex airfoil at Mach 0.4

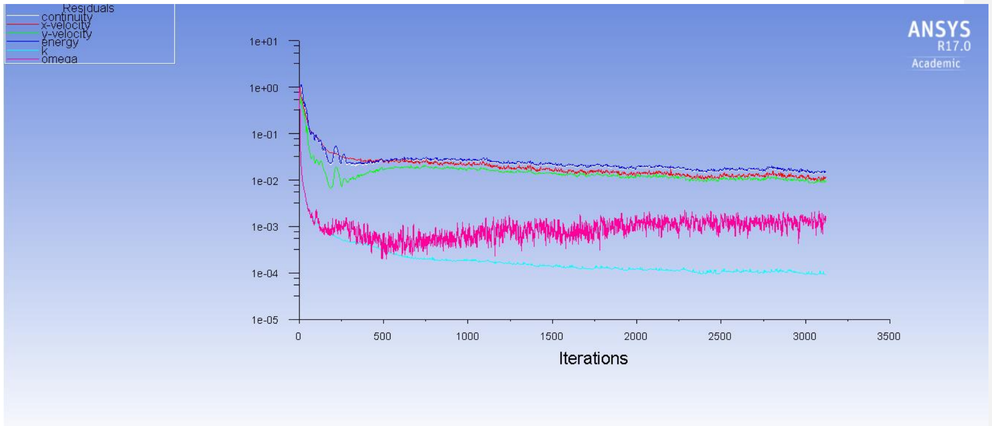


Figure 37. Convergence of Residuals for Biconvex airfoil at Mach 1.4

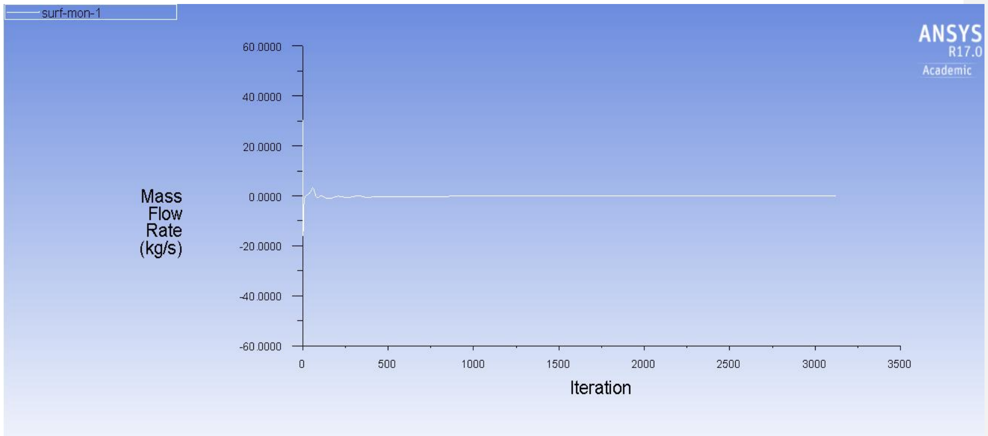


Figure 38. Convergence of Mass Flow rate surface integral for biconvex airfoil at Mach 1.4

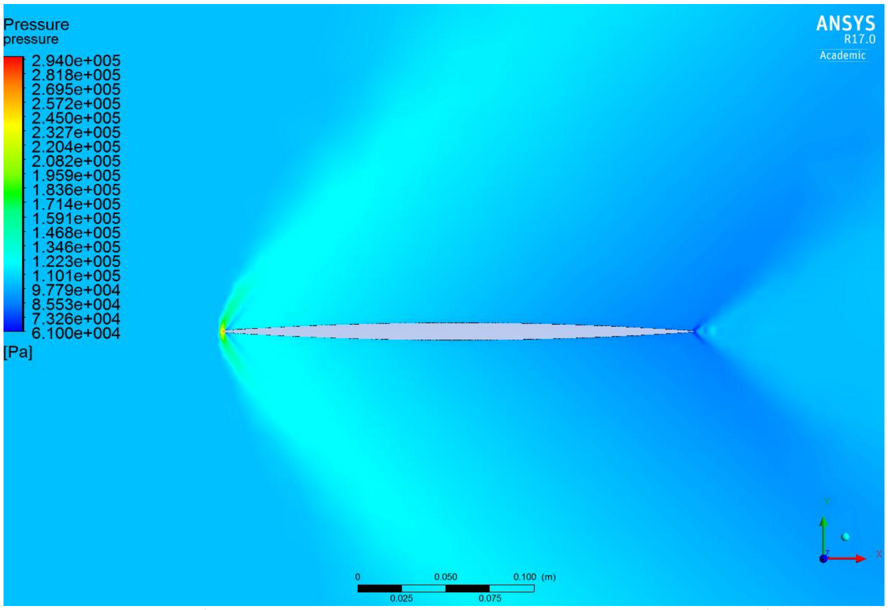


Figure 39. Simulation of Oblique shock and Prandtl-Meyer Expansion Wave on Biconvex airfoil

Nose Cone CFD Results Appendix

Figure 40. Fluid domain for nose cone CFD study

Table 6. Mesh convergence study for nose cone drag

				Drag Coefficient		
nose cone	fineness	mach	max wall y+	pressure	viscous	total
tangent ogive	4	0.45	254	0.001422	0.211652	0.213074
tangent ogive	4	0.45	49	0.002072	0.216030	0.218102
tangent ogive	4	0.45	1	0.002640	0.218392	0.221033

Simulink Descent Model Appendix

The Simulink descent model compares the force of drag to that of gravity at a given speed and altitude. The analog model gives an accurate integration of the acceleration and velocity to determine the changing terminal velocity as the rocket falls from its target apogee. By the use of switches to change the drag force from that of the drogue to the main parachute at the determined altitude the model is able to track the entire descent path. As shown in the model the expected maximum terminal velocity for the drogue and main parachutes descent is 42 and 5.4 m/s, respectively. These speeds are ideal to get the rocket back to ground level quickly and safely.

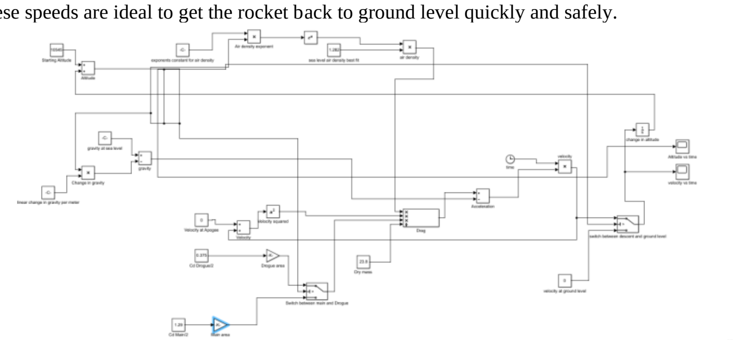


Figure 41. Simulink descent model

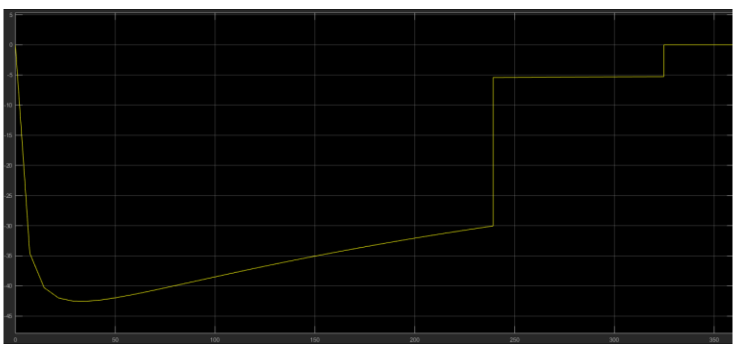


Figure 42. Velocity vs. Time results of descent model

Investigation into Black Powder Alternatives for High Altitude Flights Appendix

A consideration was made to include an airtight cannister to hold the black powder for the drogue deployment. Although this design was never used in the final rocket, the design process is included in the report for completeness.

The drogue ejection canisters are metallic SRAD Pressure vessels. Both of these pressure vessels have been designed and tested with respect to *IREC design, test and evaluation guide 4.2*. The pressure in the drogue ejection canisters is created by the differential pressure from the sealed 1 atm and the lowering atmospheric pressure as the rocket ascends to higher altitudes. The drogue ejection canisters also hold some of the pressure from the combustion of the black powder during the ejection event. In order to ensure a complete combustion a certain percentage of the black powder needs to combust within the canister.

The estimated amount of black powder needed to eject the drogue parachute is 2.25 grams. However, the exact amount of black powder and the pressure required to ensure complete combustion was unknown until testing was completed. Therefore, the ejection canister was designed for 5 grams of black powder and a worst-case scenario of 100% combustion within the drogue ejection canister. It was decided to use aluminum 6061-T6 due to its high strength to weight ratio. As metallic pressure vessels they were designed with a safety factor of 2, *IREC design, test and evaluation guide 4.2.2.* Both drogue ejection canisters are identical and the parts were designed and underwent FEA using CATIA.

The drogue ejection canisters were tested in a vacuum chamber to ensure 100% black powder combustion. The finalized design's relief device was tested by inserting a needle compressed-air adapter into the E-match hole. The hermetic seal of the relief device was broken at 165 kPa, *IREC design, test and evaluation guide 4.2.1*. Therefore, the maximum pressure that this pressure vessel will be expected to endure during pre-launch, flight, and recovery operations is 165 kPa.

The proof pressure test required by, *IREC design, test and evaluation guide 4.2.4.1*, is to be conducted for twice the duration of the device's operation at 1.5 the maximum pressure that this pressure vessel will be expected to endure during pre-launch, flight, and recovery operations. Since the ejection canisters are only in use during ascent, ~40 s and the maximum pressure that these pressure vessels are to be expected to endure during pre-launch, flight, and recovery operations is 165 kPa. The required duration and pressure for the tests are, 80 s, and 247.5 kPa, respectively. It was decided to test the ejection canisters for 2 minutes (120 s) at 275 kPa. Both of the drogue ejection canisters passed their respective proof pressure tests.

Material Testing Appendix

The material testing conducted included tensile and shear testing. These tests were conducted to determine the mechanical properties of the material. They were conducted using plain weave carbon fiber, with the layers being oriented in the same orientation as the previous layer. The tests that were conducted can be seen in the figures below. These graphs show the relationship between the stress and strain of the material in shear when one end is being pulled away while the other is fixed. The test specimens utilized for this test were cut using a water jet cutter at a 10 degree angle from parallel to one of the fiber orientations. It can be observed from the graphs that the results vary. However, they do bear a similarity after the maximum stress is observed, they continue to support a load long after the maximum stress is reached. The implementation of the test is described in detail in NASA-TM-X-73550.

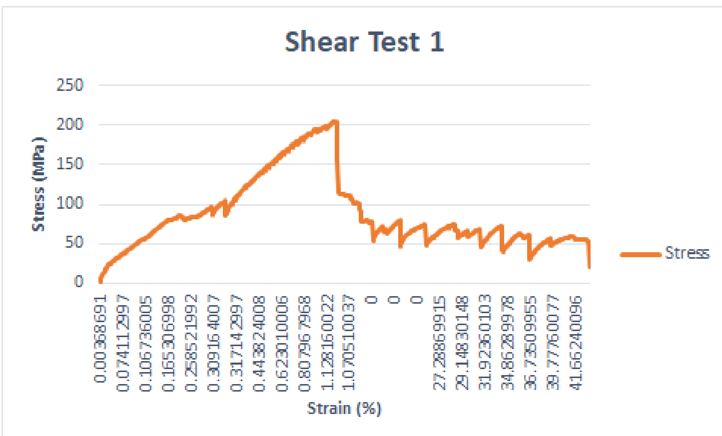


Figure 43. Stress-Strain Shear Test #1

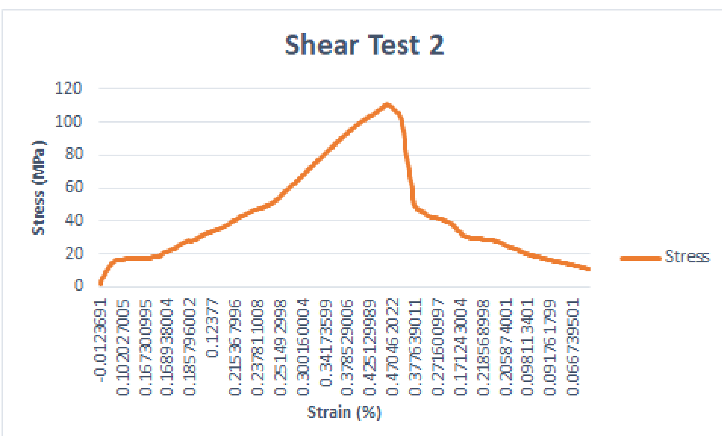


Figure 44. Stress-Strain Shear Test #2

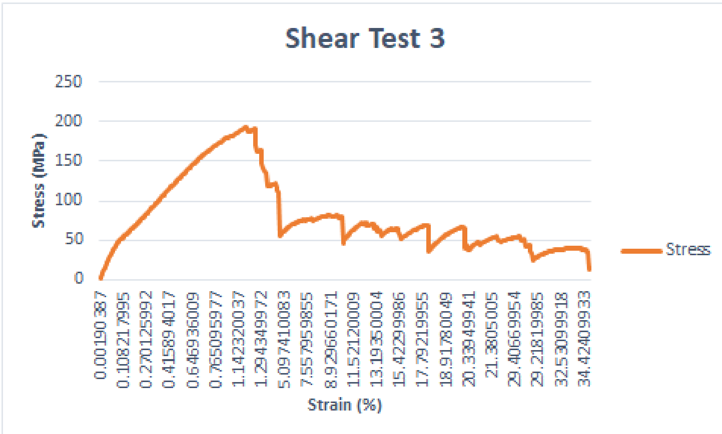


Figure 45. Stress-Strain Shear Test #3

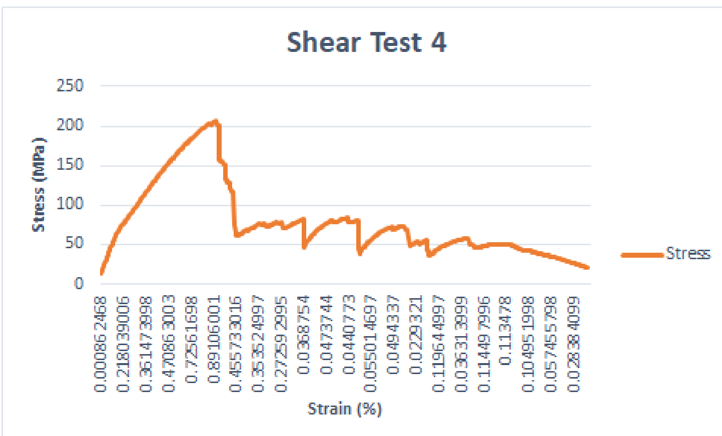


Figure 46. Stress-Strain Shear Test #4

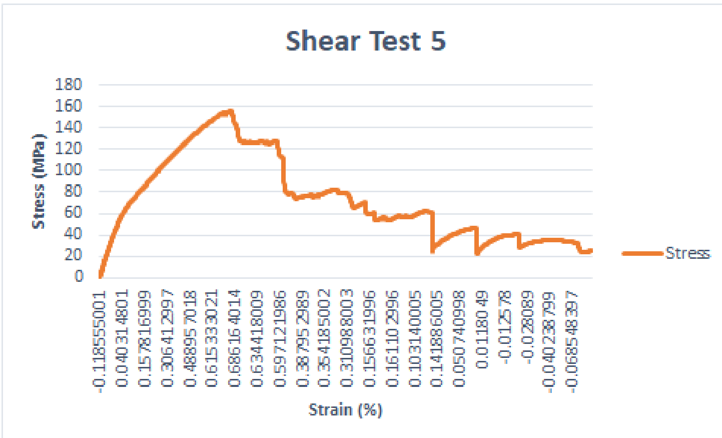


Figure 47. Stress-Strain Shear Test #5

The tensile test was performed with test specimens prepared to the ASTM D3039 specifications. The specimens were made in a sheet, then cut using a water jet cutter. This was done to keep the size of materials as consistent as possible. The specimens were cut so that their axis was parallel to one of the fiber orientations. The results from these tests can be observed in the figures below. It can be observed from the graphs that the stress increases almost linearly, then the samples begin yielding, the stress decreases, then continues to increase until fracture.

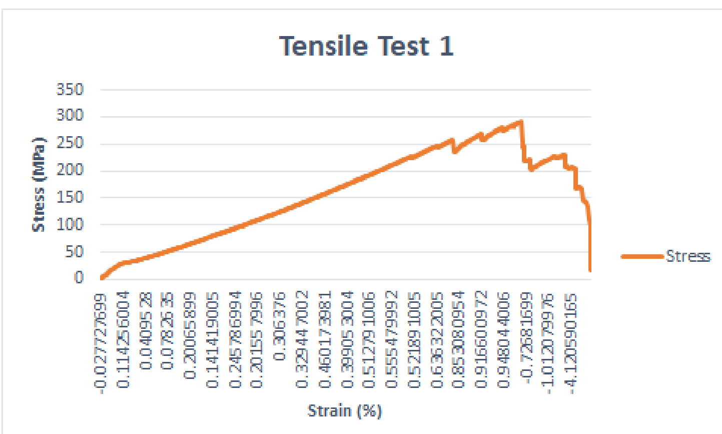


Figure 48. Stress-Strain Tensile Test #1

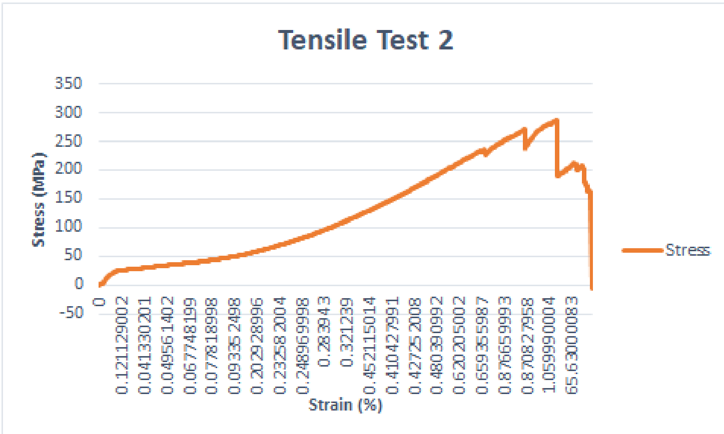


Figure 49. Stress-Strain Tensile Test #2

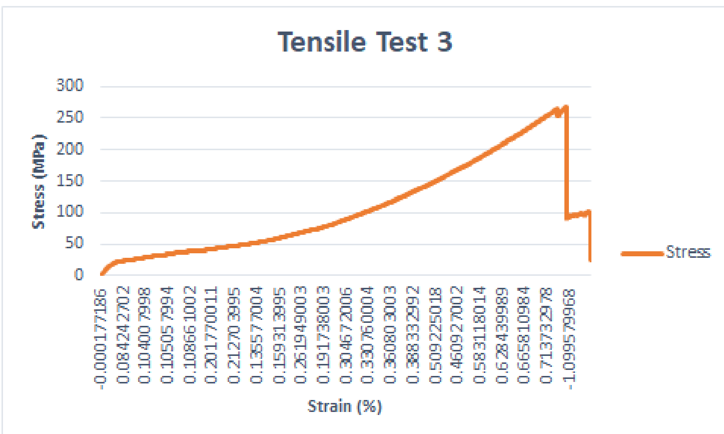


Figure 50. Stress-Strain Tensile Test #3

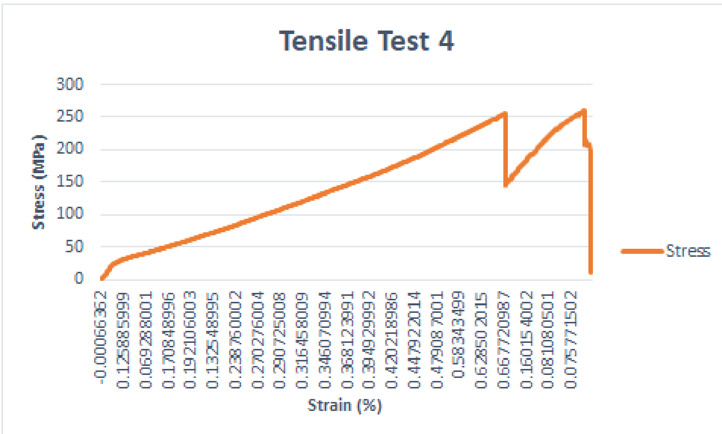


Figure 51. Stress-Strain Tensile Test #4

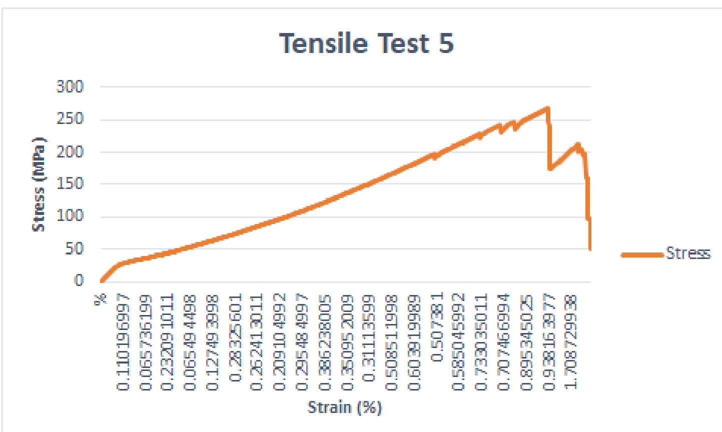


Figure 52. Stress-Strain Tensile Test #5

Fin Construction Process Appendix

Alternative inexpensive methods of construction were also considered, but they were less successful due to the small thickness of the fin. First, a fin was constructed by CNC'ing a flat plate of carbon fiber, shown in Fig. 53 and Fig. 54. This broke the fibers, and the resultant fin was too weak. The construction of a male mold through additive layer manufacturing was attempted, but the printer did not capture the diamond profile correctly. This attempt is shown in Fig. 55 and Fig. 56. Next, a male mold made from a foam cutter was constructed, but the foam was too fragile to use for laying composites. The aluminum stencils used to cut the foam are shown in Fig. 57 and the foam core is shown in Fig. 58.

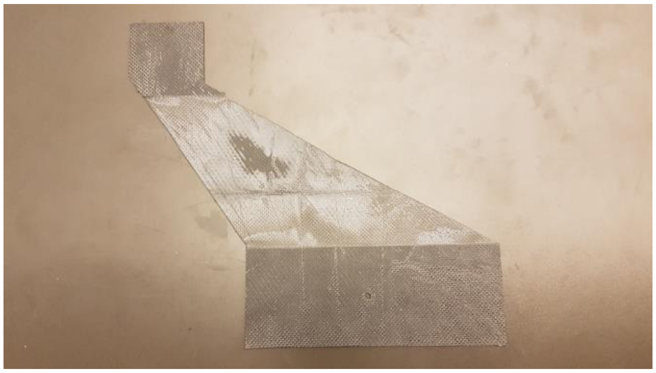


Figure 53. Carbon fiber fin machined in the CNC, top view

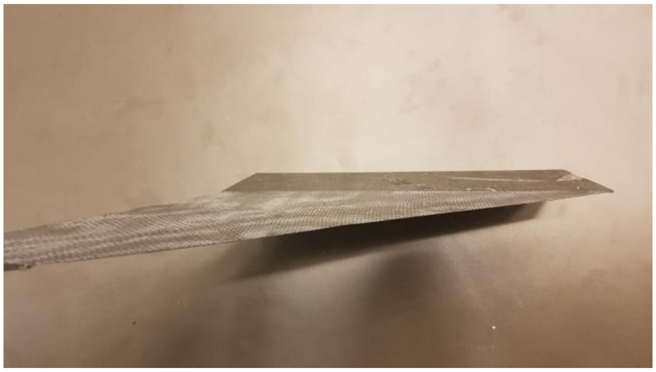


Figure 54. Carbon fiber fin machined in the CNC, side view

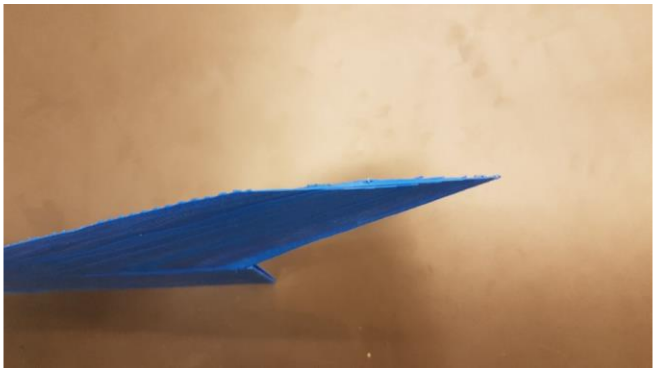


Figure 55. 3D printed fin, side view

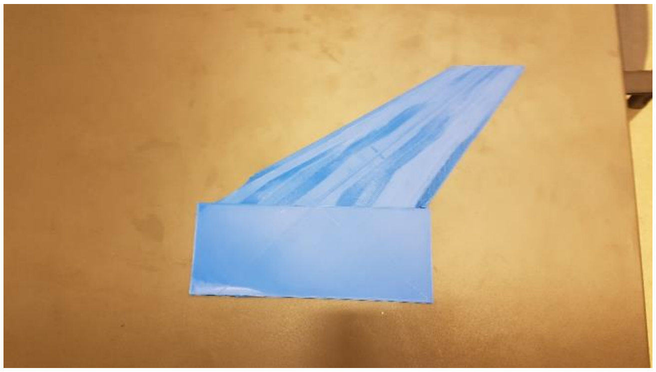


Figure 56. 3D printed view, top view

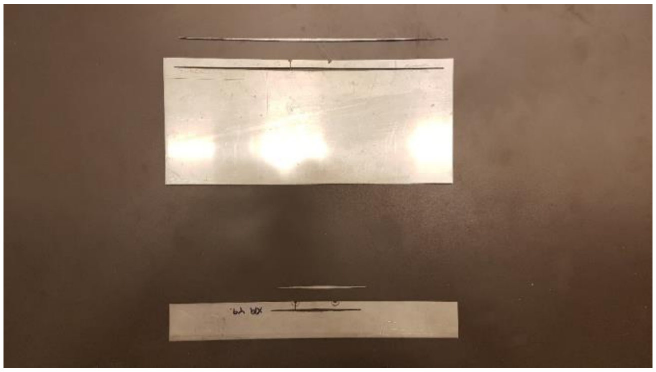


Figure 57. Aluminium stencils

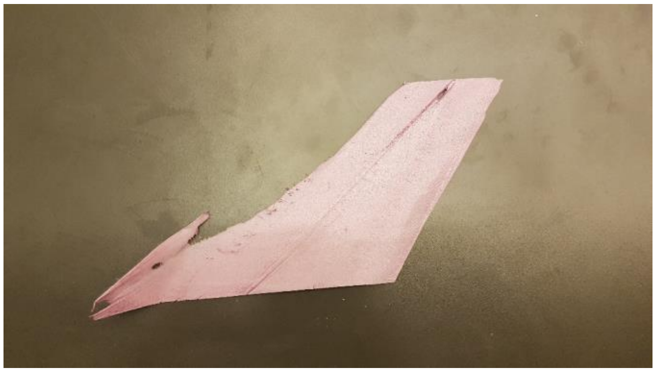


Figure 58. Foam fin core

Acknowledgments

The team would like to thank Bill, Bruce, Kevin, Dean, Dave, Matt, and Jerome for all their help in the machine shop. Almost every component of the rocket passed under their eyes or hands at some point of the project.

To Dr. Defoe, the team's advisor, who always there to provide his insight to what the team was working on. He always made sure we were on the right track.

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To Jay, Norm, Chris, all of whom are high powered rocketry enthusiasts. They have been great with aiding the team with advice with regards to manufacturing and logistics of the test launch.

To SAE Formula, who always let us borrow their tools.

The team would like to thank GC Painting, Ventra Plastics, AP Plasman, Windsor Mold Group, Windsor Engineering Society, University of Windsor Student Life Enhancement Fund, and University of Windsor Alumni Association for their generous donations.

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