Shark of the Sky Hybrid Rocket

Team 45 Project Technical Report for the 2019 IREC

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Shark of the Sky (SotS) is a hybrid rocket developed by Waterloo Rocketry for entry in the 30,000 ft apogee with Student Researched & Developed (SRAD) hybrid/liquid propulsion system category at the 2019 Intercollegiate Rocket Engineering Competition. The primary objective of the SotS launch campaign is to attain an apogee greater than 21,000 ft and achieve a non-hazardous descent. Secondary objectives include collection of flight data for future development of flight modelling and estimation capabilities, as well as validation of LoRa radios in the payload module. The SotS launch vehicle is powered by the Kismet engine, a nitrous oxide/hydroxyl-terminated polybutadiene SRAD hybrid engine. Engine control is managed by RocketCAN, a modular and extensible avionics system which also includes subsystems for radio communication, GPS localization, and flight data acquisition. All launch operations are conducted using the Remote Launch Control System, which provides launch control capabilities from a range of over 2,000 ft.

Nomenclature

a	=	Speed of sound
AR	=	Aspect Ratio
c	=	Root chord length
G	=	Shear modulus
P	=	Pressure
t	=	Thickness
λ	=	Fin taper ratio
V_f	=	Flutter velocity

I. Introduction

WATERLOO Rocketry is a student team representing the University of Waterloo, from Waterloo, Ontario, Canada. The team will be competing in the 2019 Intercollegiate Rocket Engineering Competition (IREC) at the 3rd Annual Spaceport America Cup (SAC) with the Shark of the Sky (SotS) rocket, which is entered in the 30,000 ft apogee with Student Researched & Developed (SRAD) hybrid/liquid propulsion system category. The primary mission objective is to launch SotS to an apogee greater than 21,000 ft AGL, followed by successful recovery system operation and a non-hazardous descent.

The team comprises approximately 30 students studying science and engineering at the University of Waterloo. The Team Lead is responsible for overall project management and team direction, including overseeing all technical, administrative, and operational activities necessary to achieve team objectives. Technical projects are led by Project Leads, who are chosen based on past experience, skillset, and interest. Project Leads are responsible for coordinating and managing all aspects related to their projects, leading the design, manufacture, and testing of their systems, and ensuring the successful integration of their project with other vehicle and ground systems. Team members are welcome to work on any projects that interest them, and project teams often have significant overlap and collaboration. Although one team member takes on the role of Safety Captain and is responsible for development and maintenance of safety

[1] All authors are team members of Waterloo Rocketry. Equal contribution; authors ordered alphabetically.

documentation and procedures, safety is the responsibility of every team member and is always the team's highest priority.

Team stakeholders include academic partners, advisors, sponsors, and team members. The team represents the University of Waterloo and owes much to the institutions and resources that the University makes available to student teams. The team's advisors, both from within the University and from industry, are hugely helpful in sharing knowledge and providing insight as the team continues to develop more complex and sophisticated systems. Team sponsors are additional stakeholders, as they have provided significant material and financial support essential for the team's operation. Finally, the team's most important stakeholders are the team members. The primary objective of the team is to provide students with opportunities to engage in hands-on learning through practical engineering challenges. Team growth and continuity is contingent on the team's ability to maintain this atmosphere of learning and collaboration while remaining competitive and improving year-to-year. Many past and present members have dedicated significant time and effort to the team, and continued success is a recognition of this commitment.

II. System Architecture Overview

SotS is a hybrid rocket measuring 217" in length with a primary outer diameter of 6". As an iteration of the UXO series, SotS retains the three primary independent modules: the Kismet engine, the recovery system, and the payload. Unlike UXO, all major avionics systems except for payload and recovery have been consolidated and integrated into the RocketCAN system, distributed throughout the rocket. A sectional view of SotS can be seen in Figure 1.

Figure 1. Sectional view of Shark of the Sky.

The team's objectives for 2019 follow from the team's results at the 2018 IREC with Unexploded Ordnance (UXO). Having attained an apogee of 13,412 ft with UXO, the team is targeting strong performance in the 30,000 ft higher altitude category. As a result, effort was dedicated towards weight saving initiatives and increased engine impulse. Moreover, many of the design decisions made during the development of SotS are motivated by issues encountered during the development, testing, and launch campaign of UXO. In particular, the failure of the UXO recovery system motivated significant changes to the structure of recovery electronics for SotS.

A. Propulsion Subsystems

SotS is powered by an iteration of the Kismet engine, which was first flown on UXO at the 2018 IREC. Modifications over the 2018-2019 design cycle primarily focused on increasing total impulse, thrust, and decreasing the mass of engine components, in order to support efforts to reach 30,000 ft with SotS. Kismet is an SRAD hybrid engine using hydroxyl-terminated polybutadiene (HTPB) as the fuel and nitrous oxide (NOS) as the oxidizer. A sectional view of the engine is shown in Figure 2.

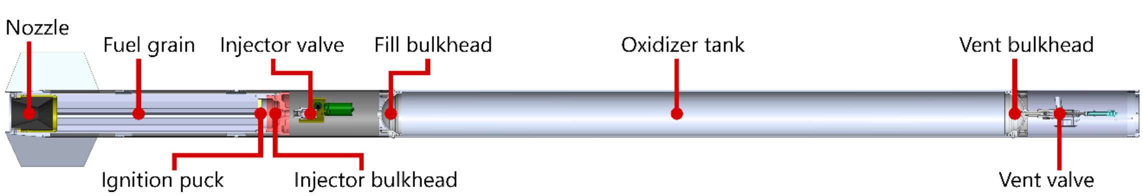


Figure 2. Labelled sectional view of the Kismet engine.

1. *Oxidizer Tank*

The Kismet oxidizer tank has a 6" outer diameter (OD), 3/16" wall thickness, and is 80" long. The tank is 1.7 times the size of last year's tank, in order to store more NOS and achieve a greater total impulse. The tank is sealed on both ends by bulkheads with two Buna-N o-rings. The bulkheads are joined to the tube with twenty-four 1/4"-28 bolts arranged radially, which results in a minimum factor of safety of 2.4 due to bearing failure of the tank, based on a maximum operating pressure of 1000 psi. The system uses autogenous pressurization to feed NOS into the injector through a port at the base.

The primary improvement desired over the previous year's design used on UXO was a reduction in total system weight and an improved accessibility for plumbing components. By far the most important design decision was the move to a hemispherical geometry for the tank bulkheads and a reduction in size of the airframe mounting structure, which resulted in bulkheads 50% lighter than the previous design. This design could be made inherently lighter due to the even distribution of stresses throughout all parts. The lack of sharp corners around which local stress concentrations will form is another major advantage of the design. The airframe was previously attached by a full ring of aluminium, but due to the nature of the bolted connection the material between the mounting points was not necessary to the integrity of the mount and provided only minimal additional stiffness. The full ring was replaced with a set of 6 tabs which hold the airframe sections to the tank. These design selections required more in-depth FEA and the use of a 3-axis CNC mill since the geometry was too complex to machine by hand. However, these tradeoffs were judged to be beneficial towards team learning. The manufactured fill bulkhead can be seen in Figure 3.

Figure 3. Oxidizer tank fill bulkhead.

Both bulkheads were simulated using an axisymmetric model in Ansys Mechanical to validate the safety factor. Each simulation used in excess of 9000 elements with a edge resolution of 150 μm. The simulations were compared against hand calculations done using the thin-walled assumption and showed a minimum safety factor of 2.5 against yielding. Analysis for the fill bulkhead can be seen in Figure 4. Disregarding the stress concentrations on the sharp corners of the drill point, which should not cause issues in the fabricated part, the minimum safety factor is 2.5 right at the center of the fill bulkhead and ~3 for the vent bulkhead, based on a yield strength of 40 ksi. To confirm the results of the simulation and the safety of the system, the entire oxidizer tank assembly was hydrostatically tested to 1500 psi.

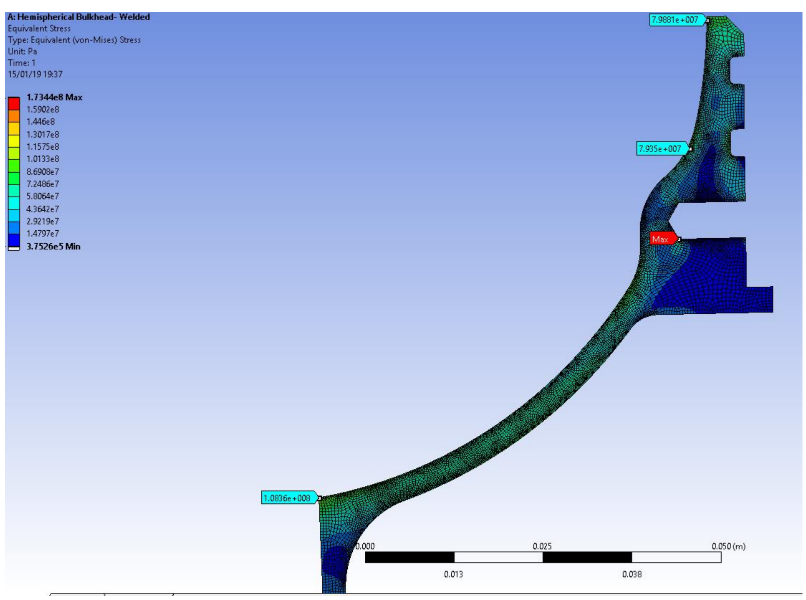


Figure 4. FEA for the oxidizer tank fill bulkhead.

The second major design consideration was the fastening and sealing method. Several options were considered, including a removable flange seal or welding the bulkheads permanently to the tank. Ultimately, a redundant o-ring seal held together by radial bolts was selected as it had already been proven effective on UXO. The weight added by this option was fairly modest and the rounded head screws added only a small amount of drag to the overall rocket. The welded option would have been the lightest but would have been exceptionally complex due to the difficulties of welding a 1000 psi compatible seal from the outside of the tank. Moreover, this method would have required heat treatment of the entire tank assembly to regain the T6 temper of the aluminium in the heat affected zone of the weld.

Another significant change was made to the location of the fill port. On UXO, it was machined into the fill bulkhead; on SotS, a T-fitting below the bulkhead is used. This was done for 2 main reasons:

- At the 2018 IREC, sand and debris was found to have clogged the check valve installed in the tank. This ultimately required total disassembly and re-sanitation of the tank before another launch could be attempted, which is a very labour-intensive procedure. By moving the valve outside of the tank, this component can now be serviced much more easily.
- To allow for the hemispherical design to be feasible, it was crucial that the bulkhead must be continuous with no off-axis holes to avoid large stress concentrations. The inclusion of the secondary fill port and the hemispherical design were thus almost mutually exclusive.

A tradeoff was made on the material selection for the tank. For optimal weight savings it was determined that the high strength 7075 alloy would have been the best choice. However, at the time of purchasing the material it was not possible to source the material for a 7075 tube long enough to form the tank wall. Furthermore, the 102% import tariffs quoted by one supplier on 7075 stock made it financially infeasible for bulkhead fabrication.

The oxidizer tank is separated from the combustion chamber by an SRAD ball valve assembly, known as the injector valve. The injector valve assembly is shown in Figure 5. This assembly has a gearset, which is used in order to align the center of the valve with the center of the rocket, thereby reducing flow losses. The main components (the ball valves and DC motors) are commercial off-the shelf (COTS); however, the assembly coupling the motor to the valve is SRAD. This decision was made due to a lack of COTS solutions that adhere to the space requirements for SotS. The valve assembly was designed for infinite life in fatigue failure. The injector valve is opened after the primary ignition sequence is initiated, to allow flow of oxidizer into the combustion chamber.

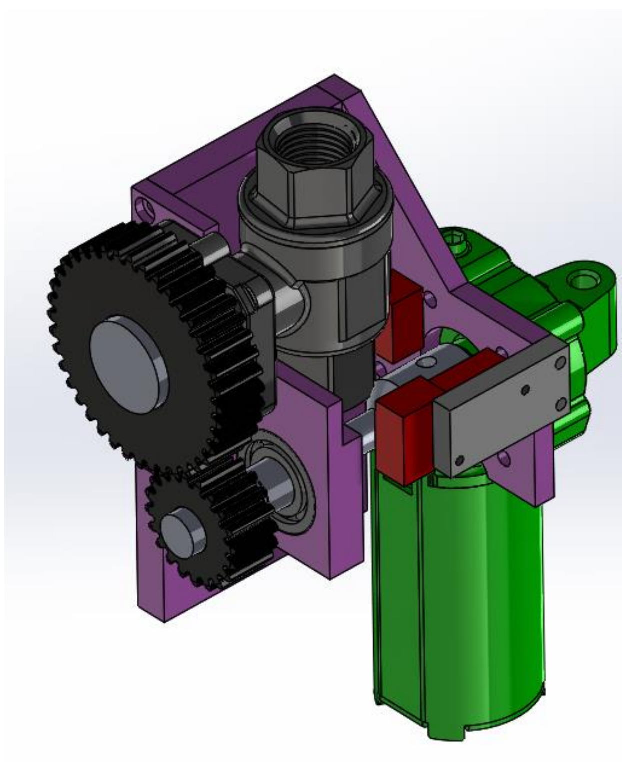


Figure 5. Injector valve assembly.

A second SRAD valve is located at the top of the oxidizer tank, shown in Figure 6. This valve, known as the vent valve, uses a piston mounted on a linear actuator to open or close a channel. This valve is used during filling and venting of the oxidizer tank. During fill procedures, the vent valve remains open, allowing air to escape the oxidizer tank as NOS is loaded. In order to limit the amount of NOS in the oxidizer tank, a dip tube is attached to the vent valve. When the liquid level reaches the bottom of the dip tube, a plume will be visible outside of the rocket indicating that the oxidizer tank is filled with liquid to that line. This provides visual confirmation that that the tank is filled to the desired level. Moreover, the dip tube prevents overfilling of the tank, which could result in dangerously high pressures as the NOS expands in desert temperatures. A COTS rupture disk rated to 1500 psi is mounted to the vent bulkhead as a further safeguard against possible overpressurization. When the tank is full, the vent valve is closed. The valve is reopened to vent the tank of NOS in the event of an aborted launch attempt and is also programmed to automatically open in situations where there are electrical anomalies, such as loss of radio communication, low battery level, or microcontroller failure.

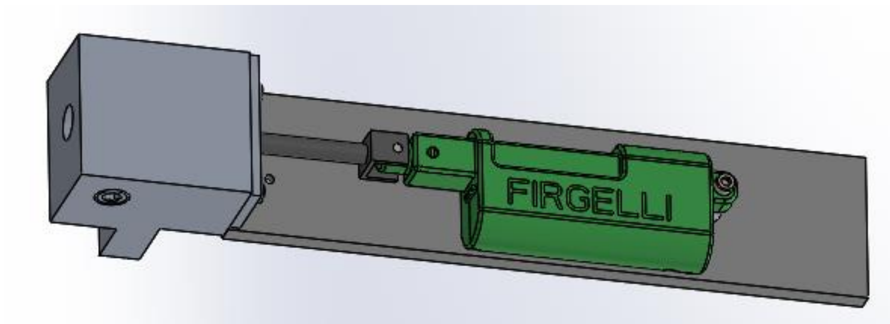


Figure 6. Vent valve.

2. Combustion Chamber

The combustion chamber holds the injector, fuel grain, and nozzle. Once the injector valve opens, the injector sprays the oxidizer through the system. The oxidizer mixes with the fuel as it passes through the system. The propellants combust and exit the nozzle, providing the thrust for the rocket.

The combustion chamber shell is a 1/8" thick, 5" OD cylinder. Both the top bulkhead and the nozzle are sealed with two Buna-N o-rings. The combustion chamber is insulated with a 1/8" thick G11 fiberglass tube and sealed with flame-resistant caulking on the top and bottom ends. The chamber has a limiting FOS of 2.6 in hoop stress, and has been hydrostatically tested to 1.5 times the maximum expected operating pressure of 700 psi. The fuel used in Kismet is a mixture of 90% HTPB and 10% powdered aluminium by mass. The fuel grain has a pseudo-finocyl grain geometry Figure 7, achieved through investment casting. Polystyrene is used to create a mold for the port while the fuel is cast inside the liner and is dissolved in acetone after the fuel has solidified.

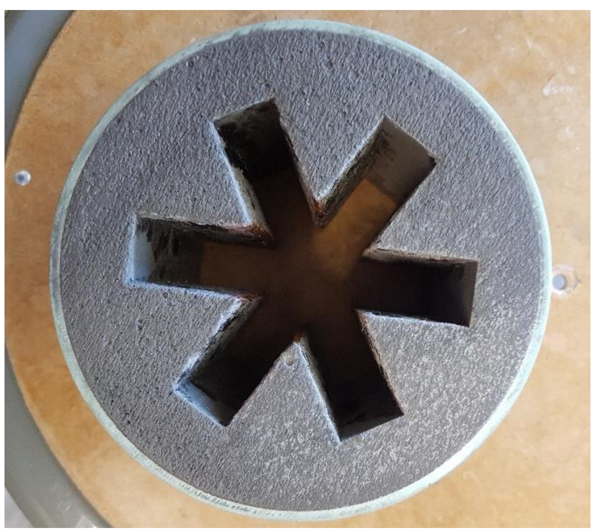


Figure 7. Cross-section of the Kismet fuel grain.

The off-rail velocity of UXO was 75 ft/s [1]. Since the wet mass of SotS is greater than that of UXO, it was important to increase the thrust in order to ensure the off-rail velocity is acceptable. Higher thrust was attained by increasing the mass flow rate of the oxidizer through the injector, which was likewise attained by increasing the number and size of injector ports. This increase in mass flow rate also required a larger throat area for the nozzle. Simulations were conducted to determine the desired mass flow rate of the oxidizer and the corresponding injector parameters. To validate the modifications made to the injector, a series of cold flow tests were conducted by discharging liquid CO_2 through the injector and measuring mass flow rate characteristics.

Due to the larger nozzle area, there is more surface area where heat will enter the graphite. As an approximation of the increase in total heat, the heat transfer rate in the simulation was set to 1.7x its original value, which is approximately the same effect as increasing the surface area of the nozzle by 1.7x. With the previous geometry, this would raise the aluminium temperature enough to anneal the tank. As shown in Figure 8 (left), most of the heat is conducted into the aluminium by direct contact with the graphite nozzle. Since this is a transient problem, it was believed that the aluminium temperature could be reduced by adding a G11 fiberglass liner between the graphite and the aluminium. Since the liner has a very low thermal conductivity relative to the graphite, it delays the process of heat transfer from the graphite to the aluminium. This provides the air outside of the chamber with more time to convect the heat away from the system. However, this also leads to issues with sealing that region. As a result, the liner section requires o-ring grooves machined into it. Figure 8 (right) shows the simulation of the same nozzle heat transfer for the new geometry at the same time. The peak temperature of the aluminium is noticeably lower (115 °C) and is delayed to a much later time (closer to 10 minutes).

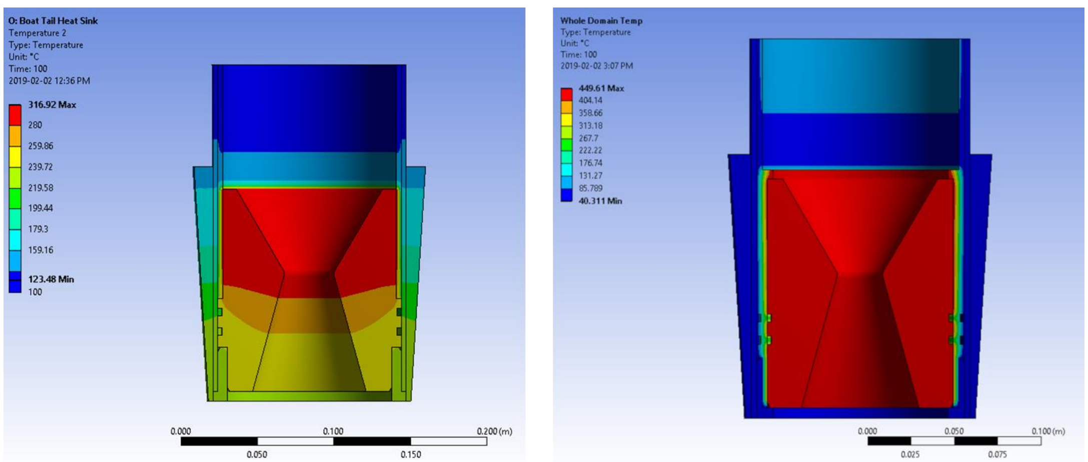


Figure 8. Heat transfer simulations of the nozzle area. Left: previous geometry. Right: modified geometry with liner.

Engine ignition relies on two separate events: heat application via ignition of a puck of solid rocket fuel, and oxidizer flow initiation through opening of the injector valve. The ignition puck is a toroidal disc composed of 70% potassium nitrate (KNO_3) and 30% epoxy, and sits above the fuel grain at the top of the combustion chamber (Figure 9). The puck is cast with two embedded coils of nichrome wire, which connect to wires that exit the chamber through the nozzle. The puck is ignited when current passes through the nichrome coils, causing them to heat up. Once the puck successfully ignites, the nichrome coils break, and the change in current is displayed by the Remote Launch Control System (RLCS). The operator then sends the signal to open the injector valve, which is performed by RocketCAN. Once the valve opens and oxidizer flow begins, thrust ramp of the engine is immediate.

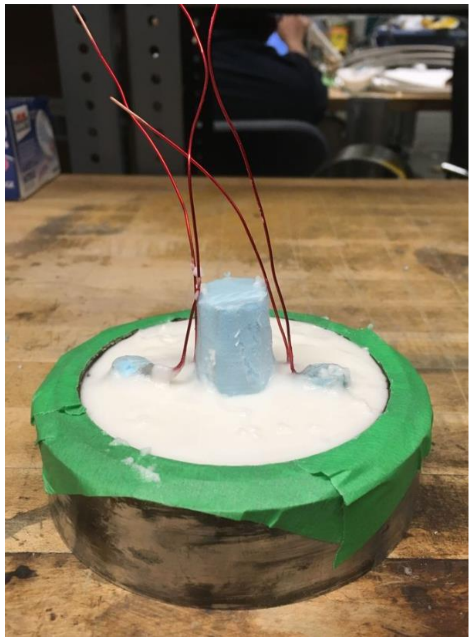


Figure 9. Cast ignition puck.

B. Aero-Structures Subsystems

The fuselage of SOTS is composed primarily of the 80” aluminium oxidizer tank and filament wound fibreglass tubes. These tubes form a “stressed skin” structure in which they serve as the aerodynamic exterior as well as the structural component of the airframe. Additional aero-structures include the nosecone, fins, and RocketCAN fairing.

1. Coupling System

Fastened/adhesively bonded aluminium couplers are used in two locations:

- Between the Payload Bay and Vent Valve sections
- Between the Parachute Bay and Recovery Bulkhead

The two mating couplers are bonded to their respective body tubes using a high shear strength epoxy, and can be assembled or disassembled with the use of 6x ¼”-28 UNF cap screws. The same type of screw is used across the entire rocket airframe to optimize assembly time and to reduce the risk of accidental cross-threading using the wrong fastener.

The decision to manufacture the oxidizer tank bulkheads using CNC allowed for more weight-saving geometry than would have been feasible to machine by hand. This includes the bulkhead coupling tabs, which permit the fibreglass bodytubes to be fastened directly to the bulkheads without the use of an intermediate aluminium coupler, while maintaining a recommended hole-to-edge distance of 4x hole diameter to reduce the risk of destructive fastener shear-out [2]. This connection was tested to failure in an Instron tensile test machine, and the failure load was visually determined to be around 5000 lbf, with the failure mode being a combination of bearing and gradual wedge-type splitting (Figure 10). Using the maximum predicted shock load of 1393.8 lbf at main parachute deployment, the FOS for axial tension loading is 3.59.

Figure 10. Tensile test of fibreglass-aluminium coupling.

2. Nosecone

Due to the possibility of entering the transonic and supersonic regimes, a Von Kármán nosecone with a 4:1 fineness ratio was selected as desirable for the range of speeds attained by SotS throughout flight. The nosecone was manufactured on-campus using the hand lay-up and vacuum bagging technique. Two mold halves made out of MDF were cut on a CNC router to obtain an accurate Von Kármán profile, and the two halves were joined during the layup to form a complete cone shape. To prevent degradation of the material properties of the resin in hot desert temperatures, the nosecone was post-cured at 50 °C for 6 hours, above the average high of 36 °C in White Sands, NM in June.

3. Fin Can

SotS uses a carbon fiber fin can with 3 trapezoidal carbon fiber fins, adhesively bonded to a fibreglass bodytube with an intermediate aluminium coupler. Carbon fiber was chosen for its high specific stiffness, the benefits of which are twofold. Primarily, with stiffer fins, the onset of aeroelastic flutter does not occur in the flight envelope of SotS. Moreover, with lighter fins, the rocket CG is not shifted excessively far backwards, eliminating the need for larger fins with an associated increase in drag. Using Equation 1 [3], the flutter velocity was calculated to be 4687.6 ft/s. At the maximum simulated velocity of 1085.4 ft/s, the resulting FOS is 4.32.

$$V_f = a\sqrt{\frac{G}{\frac{1.337AR^3P(\lambda+1)}{2(AR+2)\left(\frac{t}{c}\right)^3}}} \tag{1}$$

The tube portion of the fin can was fabricated using the hand lay-up and vacuum bagging technique using braided carbon fibre sleeving on an aluminium mandrel, and was also post-cured for maximum resin mechanical properties. The geometry of the fins were cut on a CNC router and bonded to the tube using high shear strength epoxy. A tip-to-tip layup with vacuum bagging was performed to stiffen the tube and to strengthen the root fillets of the fins.

4. RocketCAN Fairing

Due to the introduction of RocketCAN communication between the vent and injector electronics, a routing solution was needed to pass cable from the bottom to the top of the oxidizer tank. An external raceway was selected rather than a tube passing through the oxidizer tank, due to the added complexity associated with modifying the pressurized tank. The cable is secured to the outside of the tank using high-speed aluminium foil tape, and a fibreglass fairing is fastened at the top of the strip of tape to further reduce the risk of peel due to possible wave drag at transonic speeds.

C. Recovery Subsystems

The SotS recovery system can be divided into two electrically independent systems. The parachute recovery subsystem is responsible for initiating parachute deployment, while the tracking and localization subsystem is responsible for recording and communicating the rocket's location in order to facilitate post-flight recovery.

1. Parachute Recovery

The parachute recovery system is housed inside of the nosecone and a fibreglass tube directly underneath. The lower fiberglass tube, the parachute bay, contains the main parachute, main shock cord, drogue shock cord, and other associated lines. The nosecone houses the recovery electronics, drogue attachment, and drogue. The two sections are secured together with an aluminium coupler and secured together by three nylon rivets. These nylon rivets act as shear pins and allow the two sections to separate during deployment.

SotS uses a dual deployment recovery system consisting of a drogue parachute deployed at apogee and a main parachute deployed at 1500' AGL. Deployment of the drogue parachute at apogee was selected in order to minimize the shock loading from the parachute. Drogue deployment is carried out using a carbon dioxide (CO_2) canister-based separation mechanism. A CO_2 canister is mounted into an ejection cylinder that contains a steel cylinder with a sharp point, a small amount of gunpowder, and an electric match. This cylinder is sealed with epoxy, and the electric match is connected to the drogue output terminals of the altimeter. When the altimeter sends the drogue signal, the electric match ignites, causing the gunpowder to detonate and shoot the puncturing cylinder forward into the CO_2 canister. The sharp point of the cylinder punctures the canister, causing it to eject CO_2 into the parachute section. The increasing pressure inside this section applies a force to the bulkheads and nosecone, causing the nylon rivets to shear and separating the sections. As the nosecone and the contained electronics are pushed away from the rocket, an attached line pulls the drogue parachute from the parachute section. The drogue parachute slows descent to a rate of 113 ft/s.

Prior to main parachute deployment, the parachute is secured by a two-ring release mechanism. The release mechanism consists of two interlocking rings secured together by a nylon cord. The cord is secured within a pyrotechnic cutter mechanism. This mechanism is similar to the CO_2 ejection mechanism used for drogue deployment, but uses the pointed cylinder to sever the nylon cord instead of puncture a CO_2 cylinder. Like the drogue ejection mechanism, the pyrotechnic cutter is actuated via electric match; this match is connected to the main output terminals of the altimeter. At 1500 ft AGL, the electric match is detonated, causing the cord to sever and allowing the rings to slip past one another. This allows the main parachute to be pulled from the airframe section by the drag force of the drogue parachute. The main parachute was tested in a wind tunnel at various speeds to determine the drag coefficient. Based on this experimentally determined drag coefficient, the size of the parachute was calculated for a ground hit speed of 30 ft/s. The resulting parachute has a diameter of 75".

SotS uses two COTS altimeters for recovery deployment. Two different altimeters, a PerfectFlite StratoLoggerCF and a Featherweight Raven3, were selected in order to decrease the risk of common mode failures and increase the reliability of the system. Each altimeter is powered by a 9 V battery and armed immediately prior to launch using a magnetic switch actuated from outside of the rocket. Dual redundancy of the deployment system is achieved using two altimeters, two CO_2 ejectors, and two pyrotechnic cutters. Each altimeter is capable of independently triggering each ejector and each cutter, and actuation of one ejector and one cutter is sufficient for deployment. This allows the system to tolerate failure of an altimeter, an ejector, and a cutter, while still resulting in safe recovery.

At the 2018 IREC, with the first flight test of Unexploded Ordnance, the team suffered a failure of the electronics sled that resulted in the main parachute not deploying. It is suspected that this failure was a result of higher than expected shock loading passed through the structure. To mitigate this failure mechanism in SotS, the electronics sled and bulkhead are designed to minimize the shock loading that will pass through them. The drogue parachute is secured by a threaded eyenut to a steel threaded rod which passes through the bulkhead and threads into the tip of the nosecone. This tip is secured with a high lap-shear strength epoxy to absorb the drogue shock load. The electronics sled is not secured to the threaded rod and the bulkhead is only held from one side by the threaded rod. The bottom of the bulkhead has a nut that secures it into the nosecone, where it pushes against and is fastened to a spacer. The spacer is epoxied to the walls of the nosecone to keep the electronics sled in a stable position.

2. Tracking and Localization

The tracking and localization subsystem comprises two parts: an onboard GPS module housed in the nosecone, and the System That Points At The Shark (ST PATS). ST PATS consists of a handheld unit which receives the rocket's location over radio. It uses this location and internal sensors to compute the direction to the rocket. This is then displayed to an LCD in the form of an arrow pointing towards the rocket. An architecture diagram of ST PATS can be seen in Figure 11.

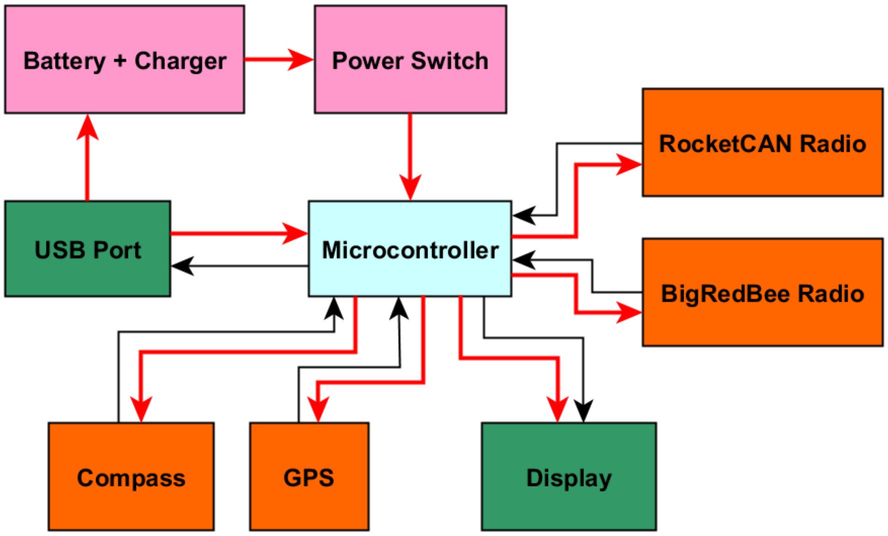


Figure 11. ST PATS architecture. Red lines represent power transfer and black lines indicate data transfer.

ST PATS uses two XBee S3B radios. One communicates with the RocketCAN radio board and receives GPS coordinates reported by the RocketCAN GPS board. The other radio receives coordinates from a COTS BigRedBee GPS board in the nosecone. ST PATS also contains a UART GPS and an I2C compass. These sensors are used to determine the location and heading of the operator, information required in order to display an accurate arrow towards the rocket. An STM32 NUCLEO-144 was selected as the microcontroller. This microcontroller provides an excess of peripherals and processing. As this system is not an avionics system, power consumption was not a major concern, and it was deemed more important to ensure processing power was sufficient. The results of computation are displayed on an LCD. An Adafruit 2.8" TFT breakout was selected as it provides enough resolution to display an arrow along with critical information such as battery voltage and GPS fix, without taking up an excessive amount of space or using excessive power. In addition, the LCD features a touch screen and SD card slot, allowing for possible future functionality extensions.

The entire system is powered off of a 3.7 V 4400 mAh LiPo battery. It was determined that this battery would support over 8 hours of system operation without replacement. A small Adafruit LiPo charger breakout board was selected, as it has pins for USB charging and a power switch while still being low cost. The system is contained in a 3D printed enclosure. A 3D printed enclosure was selected as it allows for any desired mounting geometry and enclosure shape while retaining sufficient strength and virtually zero machining time.

D. Payload Subsystems

The payload for SotS is a 3U CubeSat technology demonstrator. The CubeSat consists of three modules: the Systems Module, Battery Module, and Experiment Module. The modular design will allow the CubeSat to be used for multiple experiments in future competitions by swapping out the Experiment Module. The 2019 IREC payload will only validate the Systems and Battery Modules in the CubeSat, and will not incorporate an experiment. As a result, the Experiment Module will use dead weight as a representative mass for experiment hardware to meet the IREC minimum mass requirements. The total mass of this dead weight will be less than 2.25 lb.

1. Systems Module

The Systems Module provides core functionality for communication and control. It contains a stack of three PCBs: the ARM Board, the Radio Board, and the Power Board. The ARM Board is the core payload computing board, and uses a STM32L496 microcontroller. This microcontroller was selected due to its abundance of computing power and relatively low cost. The ARM board also contains an SD card, USB connector, and CAN-BUS connector, which together make up the CubeSat's electrical interfaces. The Radio Board handles radio communication using LoRa radios, which communicate with a handheld transceiver on the ground. The Power Board handles battery management and power distribution between System and Experiment Modules. A common header is used to connect the boards in the PCB stack, and a cable assembly connects the Systems and Experiment Modules.

2. Battery Module

The Battery Module houses four Hyperion G5 50C 3S 1100 mAh LiPo batteries. These batteries were selected for their high discharge rate, supporting the use of power-demanding experiments in future rockets. The module is mounted independently within the structure, and is designed to allow for the batteries to be easily replaced and swapped out. Cables connect the batteries to the Power Board.

3. Experiment Module

The Experiment Module will be used for experiments in future rockets. The module is designed with two sealed experiment bays: one for active tests and one for a control. Due to the lack of experiment on this rocket, the experiment hardware has been replaced by representative masses. The total added mass will be less than 2.25 lb.

E. Avionics Subsystems

SotS has three primary avionics subsystems: recovery electronics, payload electronics, and RocketCAN. As recovery and payload electronics are described previously in Sections C and D respectively, only RocketCAN is described here.

1. RocketCAN

RocketCAN is the central radio communication, valve control, and sensor logging system onboard the rocket. It integrates with the team's existing Remote Launch Control System (RLCS) to provide remote rocket valve control and status reporting. RocketCAN consists of several single-function boards which communicate over a Controller Area Network (CAN) bus [4]. The RocketCAN bus consists of the lines required by the CAN bus, as well as a 5 V, 12 V, and GND line. The boards present on SotS are:

- Radio: This board contains a radio module which communicates with RLCS, which is in turn controlled by the operators launching the rocket. The radio board communicates with the tower-side part of RLCS, as shown in Figure 12. The radio board relays instructions from the operator to all the other boards on the CAN bus. Additionally, the radio board controls power to the rest of the boards on the bus. This allows the system to save power while the rocket is idle on the launch pad.
- Injector: The injector board is responsible for opening and closing the injector valve.
- Vent: The vent board controls the linear actuator vent valve. The board is designed and programmed in such a way that the vent valve automatically opens if main bus power goes down or if communication with the radio board is lost.
- Logger: This board logs all CAN traffic on the bus for post-launch and recovery analysis.
- Sensor: The sensor board contains an Inertial Measurement Unit (IMU), a barometric pressure sensor, and a magnetometer. It also contains circuitry to interface with an analog pressure transducer and thermistor. All the data read by the sensor board is transmitted over the CAN bus, where it can be used by any board that requires it (such as the logger board).
- GPS: This board reads the rocket's GPS coordinates from a GPS module and transmits them over the CAN bus. These messages are then transmitted to the operators by the radio board.

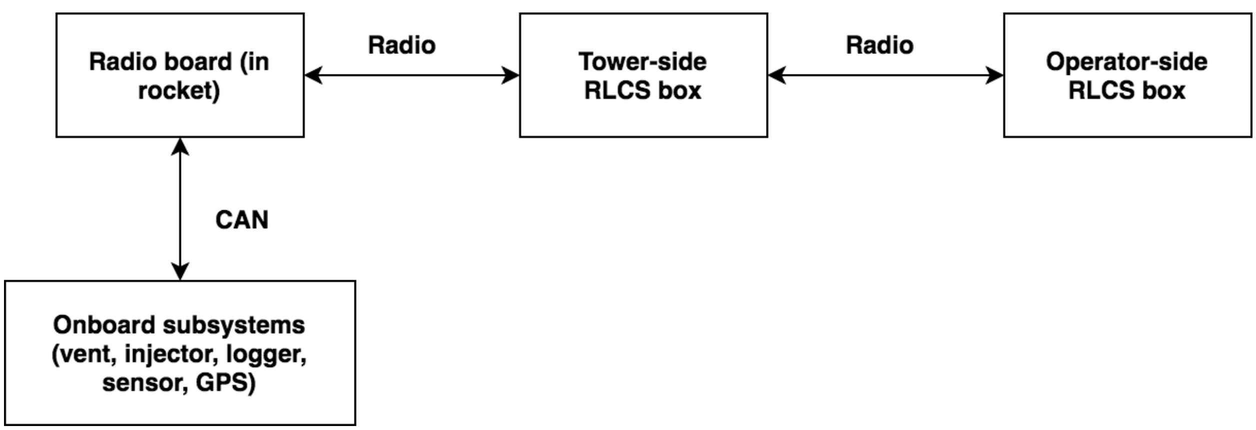


Figure 12. Communication between the rocket and the launch operator.

RocketCAN evolved from the team's Engine Instrumentation system used on UXO [1]. The Engine Instrumentation system consisted of a single monolithic board that communicated with RLCS, actuated the rocket's vent and injector valves, and logged sensor data. Two instances of that board were placed in the rocket - one on the vent section and one in the injector section. This year, that system was modularized in order to improve ease of physical assembly and system integration/extension. Additionally, this configuration also reduces power consumption, reduces system duplication, and improves system debugging.

Splitting up UXO's monolithic boards allows the system to be more easily assembled. Since the Engine Instrumentation boards contained circuitry for radio communication, valve actuation, and sensor logging, the boards were quite large. This made them difficult to fit inside the crowded injector and vent sections of the rocket. This year's individual injector and vent boards are significantly smaller (from 10 in^2 to 5.5 in^2 and 4.17 in^2 respectively), making them easier to accommodate. The other boards can then be placed in parts of the rocket where there is more space available. The radio board and batteries can be placed in an easily accessible location so that they can be hot-swapped during competition, while less critical boards such as the sensor and logger boards can be placed wherever there is space and remain there for the duration of the competition.

The other key advantage of placing all the boards on a bus is that it allows the rocket's electrical systems to be easily extended. A new board can be connected to RocketCAN with minimal additional hardware overhead. This board can then use all the data being transmitted on the bus. For example, a state estimation or aerobraking system would be able to use the existing sensor data on the bus without having to implement its own costly sensor suite. Similarly, any board placed on the bus now has the capability to transmit data back over radio (through the bus) without having to contain its own expensive, power-hungry, and physically large radio module. For SotS, this capability was used to add a GPS module to the system without re-implementing any radio communication or power regulation on that board.

The CAN protocol is very well-suited for use in this system. It supports priority-based multi-master arbitration, which means that at if multiple boards try to use the bus at the same time, the one sending the highest-priority message will automatically be granted use of the bus. All other boards are required to wait until the bus is free again. This is very useful onboard the rocket, because it means that an important message (such as a "valve open" command) will never be ignored in favour of a less important one (such as sensor data). Additionally, any one board on the bus can fail without affecting the integrity of the bus itself. Of course, failure of a critical board will still be problematic. However, if the logger board fails, the rest of the bus will be unaffected and the rocket will still be able to launch. This lowers the risk of non-critical failures causing a total system failure. The CAN protocol also supports very high data rates (up to 1 megabit per second) and has an abundance of inexpensive hardware available. Microcontrollers with CAN modules, stand-alone CAN modules, and CAN transceivers are all widely available, making it simple and inexpensive to add CAN functionality to a subsystem.

A diagram of the system test configuration is shown in Figure 13. The minimum board configuration necessary for launch consists of the radio, vent, and injector boards. This was the configuration that tested first (on a test bench) in order to ensure that the requirements for launch are met. During testing, this configuration was expanded to include a USB to CAN interface board, allowing commands to be sent from and received by a personal computer.

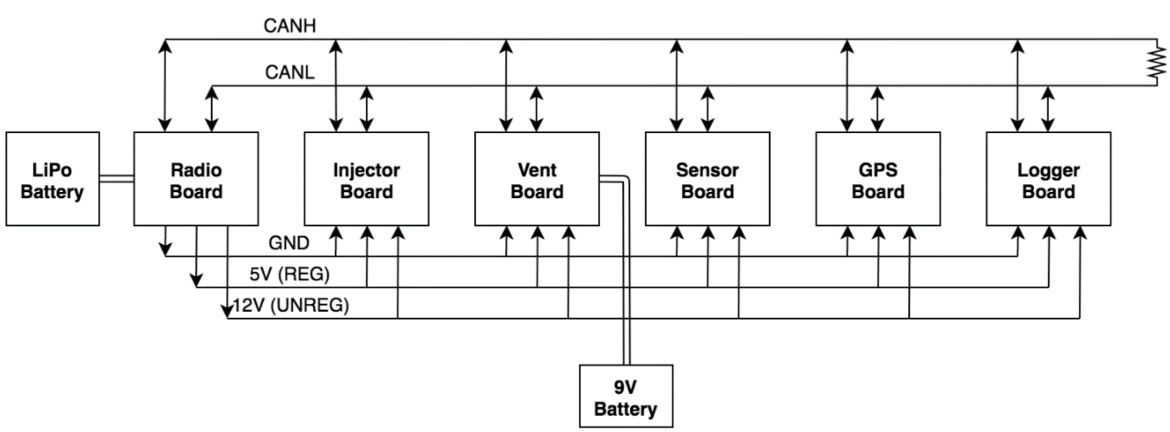


Figure 13. Configuration of subsystem boards inside the rocket. The radio board receives power from a 12V LiPo battery and outputs an unregulated 12V line and a regulated 5V line.

The expected behaviour of the system is that all boards periodically send out their general status. Each board checks for currents and voltages outside their acceptable limits and broadcast any problems. If there is no error, the board broadcasts its status as nominal. This information is sent back to the operator who can then decide how to proceed. The injector and vent boards should also periodically transmit the status of their respective valves (either closed, open, unknown, or illegal). When a valve "open" or "close" command is sent, the appropriate board should open or close that valve. As a safety feature, the vent board should open the valve whenever it does not see CAN traffic from the radio board after a few seconds. The vent valve should also open if the main bus power is cut off. All this behaviour was tested on a test bench.

Additionally, a "Wet Dress Rehearsal" will be conducted in which full propellant loading and off-loading will be performed. The radio, injector, vent, and sensor boards will be present in full flight configuration. Finally, benchtop tests will be performed with all the boards that will be onboard the rocket, including the non-critical boards (sensor, GPS, and logger).

F. Ground Support Equipment Subsystems

The complexity of a hybrid rocket necessitates sophisticated ground support equipment in order to enable safe and efficient launch operations. GSE development makes up a significant portion of the team's activity and requires multiple dedicated members with diverse skillsets. GSE systems can be broadly classified into two categories: the launch tower, and the Remote Launch Control System. Systems that are only used for testing, such as the static engine test DAQ system, are not within the scope of this report.

1. Launch Tower

The launch tower is a modular structure consisting of five sections of steel lattice mounted on a base of square steel tubing. When fully erected at an angle of 5° from vertical, the tower reaches a total height of 39 ft. The launch tower provides support for the 1515 aluminium extrusion launch rail, which guides the rocket during the first few seconds of unstable flight. The tower also acts as a mounting structure for other GSE subsystems, including RLCS components.

In order to raise the launch tower to a vertical position, a gin pole assembly is used (Figure 14). The gin pole is a steel arm that is mounted to the base of the tower, perpendicular to the tower axis. A steel cable runs from the end of the gin pole to a cross member midway up the tower, and a separate steel cable runs from the end of the gin pole to a motorized winch away from the tower. When the winch is powered, force is transmitted through tension in the steel cables to the cross member on the tower; this results in a moment about the tower base, causing it to rotate upwards. Once upright, the tower is secured with three guy-wires to ensure that any unexpected forces do not cause it to tip.

Figure 14. Raising the launch tower to a vertical position.

The launch tower additionally provides mounting features for the remote disconnect mechanism. Due to the nature of hybrid fill operations, it is necessary that a mechanism exist to disconnect the fill line from the engine prior to launch. This is accomplished using a spring-loaded system secured with quick connect fittings. The female quick connect fitting, attached to the end of the fill hose, is mounted to an aluminium arm that pivots around a bracket mounted to the tower; the other end of this arm is connected to two tension springs. During fill, the female fitting is connected to the male quick connect fitting on the rocket. The release mechanism consists of a linear actuator under the control of RLCS, a bracket inserted between the male and female quick connect fittings, and a mounting structure to secure the linear actuator to the arm. Once fill has concluded, the linear actuator retracts to pull the bracket, which also pulls the collar on the female fitting, allowing the fittings to disconnect. Pulled by the tension springs, the fill arm pivots away from the rocket and pulls the fill hose from the fill port.

2. Remote Launch Control System

The Remote Launch Control System is the system that controls all electrical components involved in propellant loading and other preflight actions required to launch the rocket. It allows the launch operations team to conduct launch procedures from a safe distance without placing any human operators in danger. The primary objective of RLCS is to allow the launch system to be operated at a minimum distance of 2,000 ft from the launch tower. Once RLCS takes control of the launch operations, no intervention should be required (in any possible error state) that requires a human to approach the system. In the event of total failure, the system must safe all engine and fill systems so that personnel can approach the rocket without placing themselves in any danger.

RLCS controls the following actuators necessary for fill and engine start:

- The Remote Fill Valve, which controls the entry of NOS into the fill system
- The Line Vent Valve, which opens the fill system to atmosphere in order to vent NOS
- The linear actuator that triggers the remote disconnect mechanism
- Two nichrome coils inside the engine ignition puck
- The Injector Valve, which controls the flow of NOS into the combustion chamber
- The Tank Vent Valve, which allows the oxidizer tank to be vented of NOS

Moreover, RLCS must use sensors to collect the following data, and report that data back to the operator:

- The current state of all valves (open/closed)
- The amount of current flowing through each nichrome coil inside the ignition puck
- The current mass of the rocket, loaded on the rail
- The pressure of oxidizer in the rocket's oxidizer tank
- The pressure of oxidizer in the fill lines
- The pressure of oxidizer in the supply lines

RLCS is composed of two parts: the client-side module and the tower-side module. The client-side module provides an operator interface with switches for actuator control and an LCD for displaying system data. The towerside module controls all actuators necessary to launch the rocket. In addition to controlling the actuators, the towerside communicates with RocketCAN for control of engine actuators and DAQ. Both modules communicate over a pair of XBee Pro S3B transceivers, both using half dipole antennas with a gain of 3 dBi. The tower-side module communicates with RocketCAN using an XBee Pro S2C transceivers with small whip antennas. The S3B transceivers operate at 900 MHz while the S2C transceivers communicate at 2.4 GHz.

The client-side module LCD, radio transceiver, and switches all connect to an Arduino Mega which runs the core system logic. All switches are connected in series with a key switch to allow the system to be disabled whenever personnel are nearby the rocket. The ignition switch is in series with a momentary pushbutton to remove any possible danger of a switch being left in the the "fire" position when the system is first started. The client-side also uses a custom power regulation board. This board is a switching regulator which drops the 11.1 V supply from the battery to 5 V, which can be used by the microcontroller.

The tower-side module controls external actuators through relay boards, which are customed designed PCBs that feature a DPDT relay, for changing direction of valves or swapping between ignition circuits, and an SPST relay, for interrupting current to the actuator when it is set to off. The boards also feature current sensors on all actuator outputs, and logic level shifting for the limit switch signals coming off of the valve, dropping the signal from 12 V to 5 V, which the microcontroller can read. The batteries in this module are fused to prevent a fire in the event of a short circuit.

RLCS is powered by several 2200 mAh LiPo batteries designed for use in RC cars. These batteries were selected due to their low cost, size, and very high energy density. Because of their low cost, the team was able to purchase enough replacements to have a spare for every battery in the system, which relieves the problem of long charge times.

III. Mission Concept of Operations Overview

The SotS CONOPS can be divided into seven phases, as seen in .

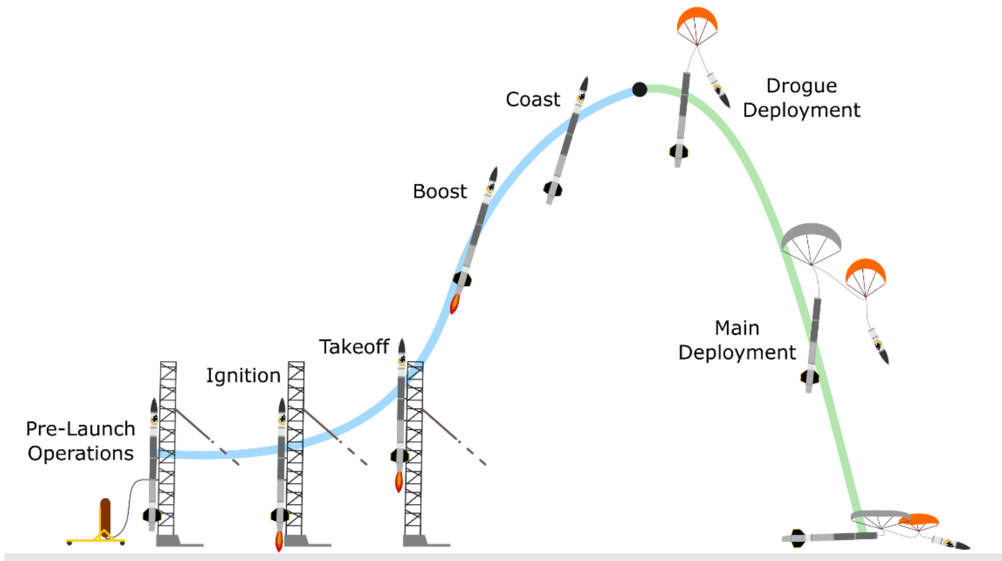


Figure 15. SotS nominal flight CONOPS.

The Pre-Launch Operations Phase begins when the launch tower is raised to the vertical position and the launch operations team begins final launch preparations. This phase encompasses recovery system arming, oxidizer fill procedures, and fill arm disconnect. During this phase, RLCS is expected to operate nominally and provide continuous feedback of oxidizer pressure and rocket mass. This phase ends when the fill arm is disconnected and permission is given to proceed to ignition.

The Ignition Phase encompasses ignition procedures of the Kismet engine. It begins when the ignition signal is sent to the primary ignition puck. The puck must ignite successfully. Once puck ignition is confirmed, the injector valve is opened. This phase ends when Kismet ignites and SotS begins to move.

The Takeoff Phase begins at first vehicle motion. SotS begins accelerating along the launch rail and departs the rail with a velocity of 97 ft/s and a static stability margin of 2.1 cal.

The Boost Phase begins once SotS departs the launch rail. The engine continues burning for approximately 20 seconds, accelerating the rocket to approximately 1085 ft/s and climbing to an altitude of approximately 15,000 ft. At burnout, the stability margin of the rocket is approximately 6 cal.

The Glide Phase begins following burnout and lasts for the remainder of the ascent. As the engine is no longer producing thrust, the rocket begins to decelerate. SotS reaches an apogee of 24,300 ft at 23 seconds after burnout and 43 seconds after engine ignition. The peak stability margin reached during this phase is 6.0 cal.

The Drogue Recovery Phase begins at apogee. The recovery altimeters detect that the apogee has been reached, and trigger the first deployment event. The parachute section is pressurized with CO_2, causing the nylon rivets to shear and detach the recovery electronics section at the mating coupler. The drogue parachute is pulled out by the force of the deployment event, and inflates, slowing descent rate to 113 ft/s. The main parachute remains restrained by the two-ring release mechanism.

The Main Recovery Phase begins when SotS descends to 1500 ft AGL. The recovery altimeters detect that the preset altitude has been reached, and trigger the second deployment event. The pyrotechnic cutters are actuated, severing the strap retaining the main parachute release mechanism. This allows the drag force on the drogue to pull the main parachute out of the airframe. As the main parachute inflates, it slows descent speed to 30 ft/s. This phase concludes once SotS has landed.

IV. Conclusions and Lessons Learned

Testing and simulation of SotS has been successful, and suggests that launch at the 2019 IREC will attain an apogee of 24,300 ft, while RocketCAN and the payload LoRa radios will function successfully. As the team's primary objective is to provide learning experiences to team members, the development of SotS brought with it many lessons, both related to team management and technical development.

A. Team Management

As the team continues to grow in size and take on increasingly ambitious projects, effective project management becomes more important and more challenging. Due to the sheer amount of work conducted by the team, it is not feasible for the Team Lead to manage technical projects at a low level. Continuing the trend that began with Vidar III in 2016-2017, the role of the Team Lead has increasingly shifted to that of a project manager and, to a lesser extent, systems integrator. The team's main project management strategy (weekly meetings) was deemed inadequate due to the need to discuss projects in greater detail than could be covered in a brief all-hands meeting. Therefore, two additional strategies were explored: task tracking and project management using Basecamp, and weekly meetings for individual project teams.

The use of Basecamp to track ongoing tasks and their completion was successful, especially at the beginning of the design cycle; however, as the year progressed, the team noticed a tendency for projects to stop updating Basecamp and instead independently discuss and communicate ongoing work. Although this can be successful in the short term, in the long term it makes it difficult to track overall project progress and determine whether a project is on schedule. As a result, the team experienced difficulties staying on schedule throughout the year.

Likewise, the introduction of weekly project meetings was successful. Initially adopted for the electrical project team, meetings were later introduced for the payload team. These proved very useful for allowing project teams to regularly sync up and ensure they were internally on schedule, while being able to discuss their project in detail. Due to the University of Waterloo engineering co-op system, multiple project leads spent large portions of the development cycle on co-op work terms, often outside of Waterloo or even outside of Canada. Without any way to be physically present in the team's workspace to ensure their project was progressing, these meetings became very valuable in allowing off-stream project leads to communicate with their proxies in Waterloo.

The primary role of the Team Lead as Project Manager rather than Chief Engineer, while necessary, resulted in additional difficulties. Without one person responsible for system integration and overall technical development, integration responsibilities were divided between Project Leads and overall system architecture decisions were made through discussion and consensus. Although this promoted internal communication and collaboration, it could occasionally lead to disconnects between project teams if integration concerns were not noticed or addressed by either Project Lead. As an example, the physical integration of RocketCAN into the rocket was delayed due to a failure to design mounting for the boards until late in the cycle. While this was identified as an outstanding task weeks prior, each project team was focused on internal system functionality, and as such no one was assigned to complete the integration task. This has been identified as an issue over the past few years, arising naturally from the team's rapid growth and the changing role of team leadership. In the future, the team will consider assigning individual team members to form a systems integration team, in order to ensure that dedicated team members take responsibility for integration concerns rather than leaving them as last-minute tasks.

The team's heavy focus on outreach and recruitment continues to be incredibly beneficial. During 2018-2019, new members took on primary responsibility for several critical projects, including ST PATS and the RocketCAN fairing. It is critical for the continuity and stability of the team that new members be recruited every year and involved with technical projects immediately, and as always, the team's new recruits have demonstrated considerable work ethic and commitment.

B. Technical Development

This year, the team took on several projects that involved new processes or unfamiliar systems. In particular, SotS is the first rocket of the team's modern era to use student-designed composite fins; all fins in previous years have been aluminium. In developing the design and fabrication process for the fins, the team was careful to consult literature and advisors in order to ensure the benefits and limitations of the new design were well understood.

Although many systems underwent significant changes from their original designs in UXO, the team was always careful to keep the philosophy of iteration in mind. Systems were improved where possible and kept unchanged where necessary; changes were only made if there was a significant and noticeable advantage to the new design. By keeping working systems and processes in place where possible, such as with the launch tower, fuel casting process, and Remote Launch Control System, the team was able to limit the number of independent variables that needed to be considered and tested while still developing a more sophisticated rocket.

System Weights, Measure, and Performance Data Appendix

Vehicle Parameter	Measurement
Airframe Length (inches):	215
Airframe Diameter (inches):	6.0
Fin-span (inches):	17.5
Vehicle weight (pounds):	104.2
Propellent weight (pounds):	58
Payload weight (pounds):	8.8
Liftoff weight (pounds):	171
Number of stages:	1
Strap-on Booster Cluster:	No
Propulsion Type:	Hybrid
Propulsion Manufacturer:	Student-built
Kinetic Energy Dart:	No

Predicted Flight Data	Measurement
Launch Rail:	Team-Provided
Rail Length (feet):	36
Liftoff Thrust-Weight Ratio:	7
Launch Rail Departure Velocity (feet/second):	97
Minimum Static Margin During Boost (cal):	2.1
Maximum Acceleration (g):	6.5
Maximum Velocity (feet/second):	1,085
Target Apogee (feet AGL):	30,000
Predicted Apogee (feet AGL):	24,300

Date	Type	Description	Status	Comments
11-11-18	Ground	Static fire test	Successful	Test of new post-combustor
3-31-19	Ground	Static fire test	Successful	Validation of new injector and nozzle and longer oxidizer tank
5-25-19	Ground	Wet dress rehearsal	TBD	Propellant loading/offloading; test of launch operations
5-31-19	Ground	Recovery deployment test	TBD	Ground test of CO_2 and pyrotechnic cutter mechanisms

The oxidizer tank was hydrostatically tested to 1500 psi for 2 hours. As the maximum expected operating pressure of the tank is 1000 psi, this corresponds to a hydrostatic test at a FOS of 1.5 times the maximum operating pressure. The maximum operational time of the oxidizer tank was identified as 1 hour, which is the amount of time it would take to vent the oxidizer if the launch attempt had to be aborted. For this reason, the tank was hydrostatically tested for 2 hours, which is equal to twice the maximum operational time.

A hydrostatic test was performed on the combustion chamber to 1050 psi (FOS of 2.1) for 2 minutes. Since the tank is not able to be hydrostatically tested with the nozzle in place, an end cap was made to sit in the nozzle's position and seal the tank. During engine testing, the measured pressure drop across the injector was 50%; therefore, the maximum operating pressure of the combustion chamber was determined to be 500 psi. The combustion chamber is in operation for less than 1 minute, during the engine burn, so the tank was hydrostatically tested for 5 minutes, which is equal to five times the maximum operational time.

Two static fire tests of the Kismet engine were conducted during the 2018-2019 design cycle. In both cases, the test was conducted with the combustion chamber in an inverted configuration and mounted on a cantilever load cell. Measurements of thrust, oxidizer pressure, combustion chamber pressure, and oxidizer tank mass were recorded throughout the test.

Static Fire 3 of Kismet was conducted on 11 November, 2019. The purpose of this test was to evaluate the impact of a post-combustor on engine efficiency. Therefore, only one change was made to nominal configuration: 6 inches of fuel were bored out of the nozzle end of the fuel grain/liner assembly. It was hypothesized that this change would increase the efficiency of the engine. The results of SF3 are shown in Figure 16.

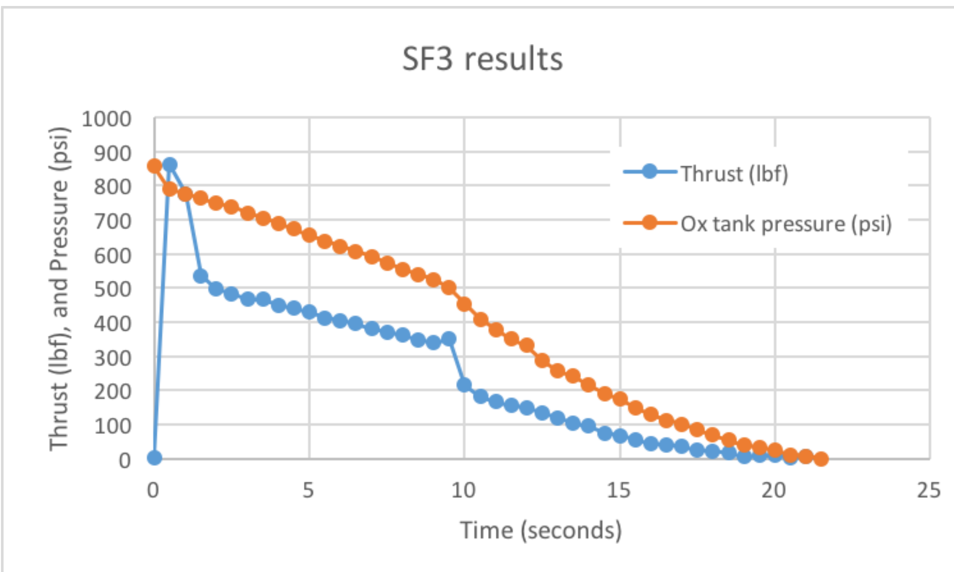


Figure 16. SF3 results.

The total impulse resulting from SF3 was 23,350 N s, which is a slight increase compared to the 22,040 N s of SF2 (conducted during 2017-2018). As this small change would not be sufficient to reach an apogee of over 21,000 ft, the team elected not to pursue postcombustor development, and focus instead on modifications to the injector, nozzle, and oxidizer tank.

Static Fire 4 of Kismet was conducted on 31 March, 2019. This test was intended to validate the major changes made to Kismet over the 2018-2019 year:

- Lengthening of the oxidizer tank to 80"
- Modification of the nozzle and injector to achieve a higher thrust
- Use of G11 as a liner for the nozzle to reduce heat transfer to the aluminium combustion chamber

Aside from the changes made to the engine, the test setup remained unchanged. The results of SF4 are shown in Figure 17.

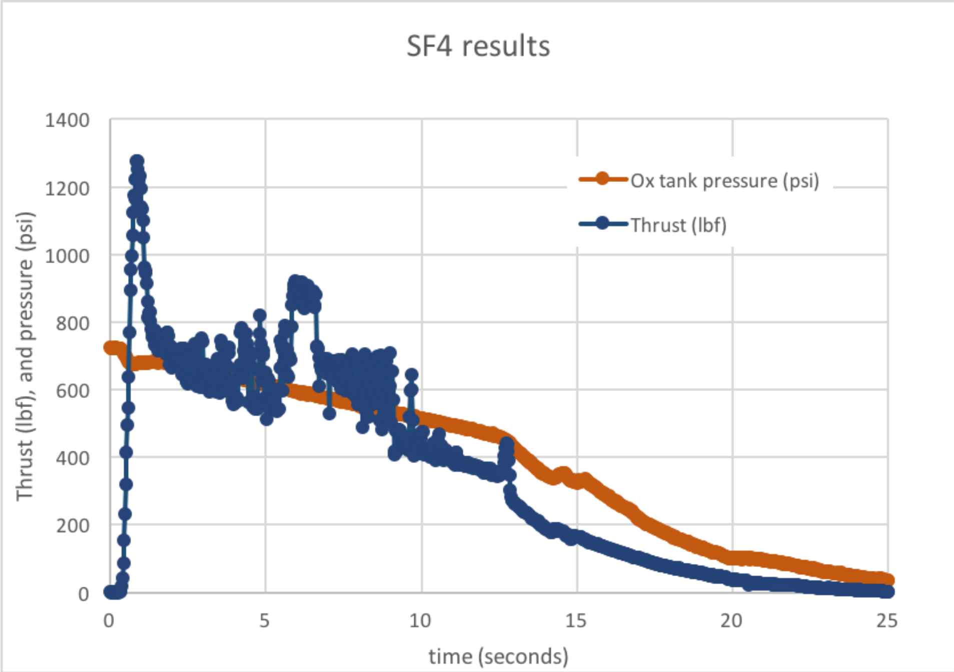


Figure 17. SF4 results.

The total impulse resulting from SF4 was 38,000 N s. Although the temperature of the combustion chamber rose higher than anticipated, hydrostatic testing after the static fire indicated that the chamber still retained adequate strength; as such, the use of G11 was considered a success. Flight simulation using the data taken from this engine test indicated that SotS would reach an altitude of over 21,000 ft; therefore, the engine modifications were deemed successful and no further static fire tests were conducted.

A fluid circuit diagram for Kismet in flight configuration can be seen in Figure 18.

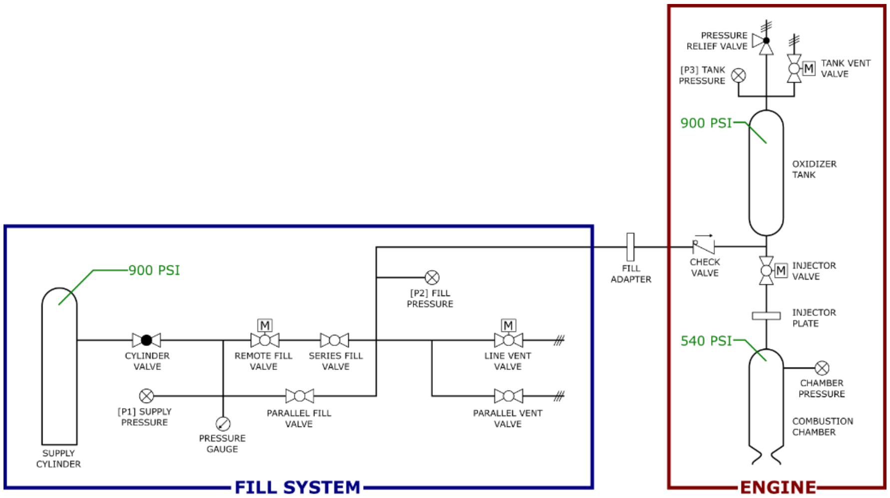


Figure 18. Kismet fluid circuit diagram.

Ground tests of the recovery mechanisms were performed on June 4, 2018, in UXO recovery configuration. The recovery module was assembled, complete with pyrotechnics and parachutes, and laid out horizontally. The Raven altimeter was programmed through Featherweight software to simulate an ascent, apogee, and descent. At 5 s after simulated apogee, the CO_2 canisters were punctured, separating the avionics module from the recovery module. At a simulated altitude of 1500 ft AGL, the pyrotechnic cutters were actuated, allowing the three-ring release to deploy. The drogue chute was pulled from the recovery module, pulling the main parachute from the fiberglass tube and thus verifying successful pyrotechnic actuation. A full deployment test in SotS configuration is planned for May 30, 2019.

The controller used for the recovery system are commercial Featherweight Raven3 and PerfectFlite StratoLoggerCF altimeters. These units are used in parallel to control recovery deployment mechanisms. The two controllers use independent circuits with separate power supplies and switches (Figure 19). Each controller is capable of actuating both CO_2 canisters and both pyrotechnic line cutters even if the other controller fails.

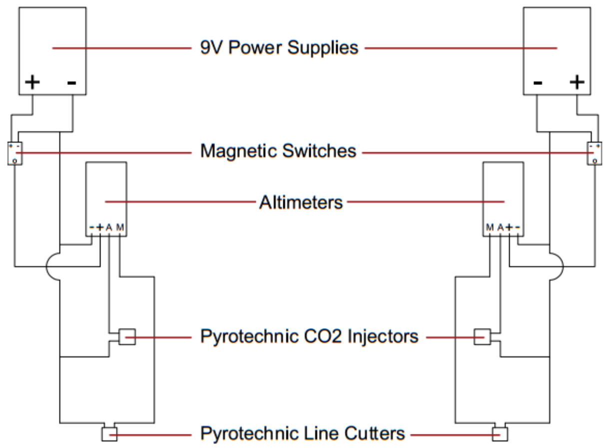


Figure 19. Recovery electronics schematic.

Hazard Analysis Appendix

Kismet uses nitrous oxide as a liquid oxidizer. Among the commonly used hybrid oxidizers, NOS is usually regarded as the safest. However, NOS is a general anesthetic and can be dangerous to personnel if inhaled. Moreover, evaporating NOS can result in significant low temperatures, potentially causing frostbite or other injury. It is therefore of the utmost importance that personnel not come into contact with liquid or gaseous oxidizer. To mitigate the dangers posed by NOS, the team takes significant precautions whenever oxidizer must be handled. Nitrous oxide is stored in the team's workspace, kept in the original supply cylinders. These cylinders are stored upright and chained to mounts on the wall. They are never removed from these mounts unless required for a test fire or for weighing. Supply cylinders are secured to a wheeled cart using chains for localized transportation between storage and the team's static test location. The team does not transport NOS to remote test locations.

As the cylinders used by the team are non-siphoning, they must be inverted in order to decant liquid NOS. For this purpose, the team has designed a tank inversion fixture, made from welded steel tube. The NOS supply cylinder is moved from the wheeled transport cart, laid horizontally in a frame on the tank inverter, and secured using a steel bracket and a ratchet strap. Once the cylinder is secured, the frame is lifted, rotating the cylinder 90° to invert it. The frame is secured using two locking pins. Any personnel that will be near NOS supply lines during fill procedure are required to wear Personal Protective Equipment (PPE). For NOS, this includes safety glasses, face shields, and shop coats to protect any exposed skin. In addition, any personnel operating valves for NOS are required to wear cold-resistant gloves. As HTPB is non-toxic, no special procedures or equipment are required for handling Kismet's solid fuel. However, during the fuel casting process, the presence of aluminium powder requires precautions. Aluminium is kept in an ammunition box, which is only opened after the required safety criteria are met. Fuel casting is always performed in a well-ventilated area, and personnel are required to wear safety glasses, respirators, and gloves. In addition, a Class D fire extinguisher is always present, in order to extinguish any fires resulting from accidental ignition of aluminium powder.

The pyrotechnic materials used in the ignition and recovery subsystems also require precautions to be taken. Gunpowder and KNO_3 are both stored in separate ammunition boxes to prevent accidental spills or exposure. As gunpowder is not absorbed through the skin, gloves are not necessary. However, personnel are required to wear safety glasses and thoroughly wash their hands after handling gunpowder. KNO_3, used in the ignition puck, fuse, and pellet, requires personnel to wear safety glasses, gloves, and respirators, and can only be used if a fire extinguisher is present.

Due to the danger inherent in firing a rocket engine, the team takes significant precautions during static tests. Prior to beginning fill procedure, a perimeter around the test location is established and secured, to prevent others from accidentally coming too close to the engine. Additionally, a blast shield is placed around the combustion chamber in case of accidental explosion. All personnel witnessing the test are required to remain a safe distance away and to wear safety glasses and industrial hearing protection.

Risk Assessment Appendix

Waterloo Rocketry	Shark of the Sky	18-May-19		
Failure Mode	**Possible Causes**	**Risk of Mishap and Rationale**	**Mitigation Approach**	**Risk of Injury after Mitigation**
Pre-Launch Operations				
Rocket ignites during launch preparations, causing injury to surrounding personnel	Premature activation of ignition circuit	Low; solid rocket fuel requires presence of liquid oxidizer to ignite.	Ignition circuit requires activation of an emergency stop, manual depression of ignition button for several seconds, and independent actuation of injector valve.	Low
			Rocket and power supply are not connected to the ignition circuit until immediately prior to fill.	
Rocket falls from launch rail during launch preparations, causing injury to surrounding personnel	Stopping mechanism fails to support the weight of the rocket	Low; rail stops are rated for >200 lb load compared to rocket weight of approximately 140 lb. Rail buttons are not load-bearing.	Tower is raised with rocket on top, with the tower structure and gin pole supporting the rocket during erection.	Low
	Rail buttons rip out of bulkhead		Launch rail is kept level to avoid stress on rail buttons.	
			All personnel involved in launch tower erection are to wear hard hats.	
Recovery system deploys during launch preparations, causing injury to surrounding personnel	E-matches fire prematurely	Low; carbon dioxide canisters only rupture under significant force from the puncturing cylinder.	Avionics are only to be armed using magnetic switches once final assembly and launch preparations are complete.	Low
	Carbon dioxide canisters are ruptured			
Nitrous oxide escapes from the supply plumbing during fill procedure, causing freezing of body parts, unconsciousness, or other bodily harm	Leaks in valves, fittings, or hoses	Low; all plumbing components have been tested without failure and have adequate factors of safety. Check valve is rated to well over expected operating pressure.	Visually inspect all plumbing components during assembly.	Low
	Premature activation of remote disconnect system		Remote disconnect system requires power supply connection and activation of arming switch.	
	Failure of oxidizer tank check valve		During remote fill procedure, all personnel are to remain well away from supply plumbing. Manual fill procedure (if necessary) is to be performed by only two technicians clothed in appropriate PPE.	
	Fill line does not adequately depressurize upon disconnect		Personnel are to remain well away from fill line following disconnect and prior to launch.	
Explosion of oxidizer tank during fill procedure with blast or flying debris causing injury	Overpressurization due to clogging of the vent	Low; burst disk provides pressure relief.	Cover all open ends of plumbing during assembly, only uncovering before launch.	Low
	Oxidizer tank fails to hold normal operating pressure		Oxidizer tank is designed to rupture laterally instead of radially, minimizing flying debris.	
			Oxidizer tank is pressure tested to 1.5x expected maximum operating pressure.	
Rocket ignites during fill procedure, causing injury to nearby personnel	Premature activation of ignition circuit	Low; ignition circuit is designed to minimize the possibility of accidental ignition.	All personnel are to remain well away from the rocket during fill procedure.	Low
			Ignition circuit requires activation of a key switch and an emergency stop button prior to arming.	
			Ignition circuit is not armed until launch personnel receive	

			confirmation from range safety personnel.	
Operators are no longer able to control the valves onboard the rocket.	Radio contact loss between RLCS operator and rocket.	Low - medium (depends on line of sight)	Vent section: radio board is programmed to open the vent valve if it is unable to re-establish radio contact. Injector: do nothing. Leaving the valve in its current state is the safest action.	Low
	CAN module failure on radio or valve boards.	Low. This failure mode has not been observed in 5 months of development.	Vent: open vent valve if no CAN traffic is observed for 1 second (it should usually observe hundreds of messages per second). Injector: do nothing. Leaving the valve in its current state is the safest action.	
	Microcontroller failure on radio/valve boards.	Low. All connections are terminated properly to avoid potential intermittent shorts, etc.	Vent: board is designed so that the valve and control sections have separate power sources. If the microcontroller goes down (and leaves the control lines floating), the board is hardwired to open the valve.	
	Main battery runs out and bus goes down	Low. The bus is powered by a 2200 mAh LiPo battery. The bus (other than radio board) is off for most of the day, minimizing quiescent current draw. While the bus is off, the battery should last around 50 hours.		
Vent valve closes and cannot be opened again	Vent valve battery has run out	Low. The linear actuator does not draw any current at steady state, and it is only actuated a few times during the day.	If a launch abort is required, open injector valve very slightly. If this fails, allow oxidizer tank to overpressurize and rupture burst disk.	Low
			The vent board continuously measures its battery voltage and is programmed to open the valve if the battery is low	
Ignition Phase				
Rocket does not ignite when command is given ("hang fire"), but does ignite when team approaches to troubleshoot	Primary igniter is activated, but gives no visual or electrical confirmation	Low; rocket ignition relies on continuous delivery of current over several seconds. Primary igniter produces a great deal of smoke for visual confirmation of successful ignition. Fuel will only ignite in the presence of NOS.	LCD on RLCS indicates that ignition circuit is active; personnel are not to approach the rocket during this time.	Low
	Electrical ignition signal is delayed		All ignition control systems are to be disarmed prior to approach by launch personnel.	
			Personnel are not to approach the rocket if the oxidizer tank contains NOS.	
Takeoff Phase				
Rocket deviates from nominal flight path at takeoff and	Failure of launch tower components	Low; simulated off-the-rail velocity is 97	Thoroughly inspect all launch tower components before assembly	Low

comes into contact with personnel at high speeds	Unexpectedly low off-the-rail velocity resulting in low stability	ft/s, resulting in acceptable stability	Direct launch tower away from the campsite.	
Explosion of combustion chamber or oxidizer tank during engine burn with blast or flying debris causing injury	Backflow of gases from the combustion chamber into the oxidizer tank	Medium; engine has not been tested in flight or static tested in Spaceport America New Mexico weather conditions. Backflow, nozzle clogging, or fuel grain inhomogeneity have not been observed during static test fires. Engine components are designed with high factor of safety.	Injector has been designed for 50% pressure drop to minimize the chances of backflow.	Low
	Clogging of the nozzle due to bundled ignition wires		Use minimal, thin, ignition wires.	
	Fuel grain inhomogeneity, causing breach of ABS tubing or clogging of nozzle		Adhere to fuel casting procedure and visually inspect fuel grain prior to assembly.	
	Failure of hex bolts used to connect bulkheads, oxidizer tank, and combustion chamber		All personnel should remain well away from the launch pad during launch procedures.	
			Oxidizer tank and combustion chamber are designed to rupture laterally instead of radially, minimizing flying debris.	
Boost Phase				
Explosion of combustion chamber or oxidizer tank during engine burn with blast or flying debris causing injury	*Identical to entry in Takeoff Phase*			
Rocket deviates from nominal flight path during engine burn and comes into contact with personnel at high speeds	Unexpectedly high winds	Low; simulated rocket flight with high winds did not experience significant deviation.	Design fins to maintain a stability margin of between 2.1-6 cal throughout flight.	Low
	Damaged tail fins		Ensure the tail fins are unobstructed during ascent on the tower.	
			Ensure all participants are aware of the launch and can take cover if necessary	
Coast Phase				
Rocket deviates from nominal flight path during engine burn and comes into contact with personnel at high speeds	*Identical to entry in Boost Phase*			
Drogue Recovery Phase				
Drogue chute fails to deploy, rocket comes in contact with personnel	Failure of altimeters	Low; altimeters are commercial components, and two are used for redundancy.	Ground test all decoupling systems prior to launch.	Low
	Insufficient pressure in the recovery bay to break shear bolts		Ensure all participants are aware of the rocket’s position and are able to avoid it if necessary.	
Main parachute deploys at or near apogee, rocket drifts	E-matches fire unintentionally	Low; avionics have been thoroughly tested in a vacuum	Ground test all decoupling systems prior to launch.	Low

into unexpected area	2-ring system breaks under load when the drogue is deployed	chamber, 2 ring system is rated to well above expected stress	Check rings for signs of wear prior to launch.	
Main Recovery Phase				
Main chute fails to fully deploy, rocket comes in contact with personnel	Failure of altimeters	Medium; line tangling has not been tested, outcome is uncertain.	Ground test all decoupling systems prior to launch.	Low
	2-ring system fails to decouple the avionics bay and booster, main chute does not deploy		Use a commercial pyrotechnic cutter to decouple the 2-ring system	
	Drogue chute lines tangle with main chute lines		Ensure all participants are aware of the rocket's position and are able to avoid it if necessary.	
Rocket airframe separates into multiple assemblies, components come into contact with personnel	Failure of recovery lines, resulting in component freefall not slowed by main parachutes	Low; all recovery lines used are designed for use with parachutes	Ensure all participants are aware of the rocket's position and are able to avoid it if necessary.	Low

Assembly, Preflight, and Launch Checklists Appendix

The following pages contain checklists for assembly, preflight setup, and launch operations.

Sanitation Procedures

Equipment and Materials

- Hand tools for component disassembly
- Screwdrivers
- Tweezers
- Cups
- Small, clean trays
- Toothbrush for small components
- Larger pipe brush for oxidizer tank
- Deionized water
- Simple Green cleaning solution
- Ziploc bags (both large and small)
- Clean plastic cups (for cleaning solution and water)
- Aluminium foil
- PPE equipment as noted above
- Hose and component plugs/caps
- Table cover (plastic or parchment sheet to prevent dust)
- Paper towel
- Sieve
- Storage Box lined with plastic drop sheet (for storage of cleaned components)

Cleaning Procedure by Component Type

Oxidizer Tank
1. Rinse loose dirt/dust off of outside and inside of oxidizer tank using tap water.
2. Prepare 1/3 to 1/2 bucket of diluted cleaning solution, as per manufacturer instructions.
3. Using pipe brush and bucket of Simple Green cleaning solution placed inside the sink, scrub the inside of the oxidizer tank for 15 minutes. Be mindful of even coverage and use a cup or similar to frequently coat the inside of the tank with cleaning solution.
4. Rinse the tank, bucket, and brush thoroughly with tap water for at least 5 minutes. The tank should receive the most care.
5. Use a small quantity of deionized water to rinse the inside of the oxidizer tank.
6. After previous step (rinsing with deionized water), the inside of the tank should NOT contact any other material (i.e. paper towel). Shake the tank to remove excess water.
7. Dry interior of tank with compressed air.
8. Place covering on either end of the oxidizer tank and the hose (ie Ziploc bag or similar), and secure using rubber bands or similar.
9. Store tank in a safe location.
10. Attach label to the tank indicating date/time of cleaning, and by whom.

Hoses
1. Remove residual Teflon tape or other debris from hose ends.
2. Prepare 1 cup of Simple Green cleaning solution.
3. Pour cleaning solution through hose, catching at the other end with another cup.
4. Repeat three times.
5. Repeat step 3 with deionized water until the water is clear when exiting the hose.
6. Use compressed air to flush hose of excess water for 5 minutes.
7. Cap/plug hose ends, label hose (date/time cleaned and by whom), and store safely.

Valves
1. Rinse away loose surface dust/dirt using tap water.
2. Prepare roughly a cup’s worth of cleaning solution as per manufacturer instructions.
3. Disassemble valve with reference to the manufacturer specifications, being careful to document reassembly

instructions and to not lose components.
4. Clean each component thoroughly using a toothbrush and cleaning solution.
5. Rinse components in tap water using a sieve.
6. Rinse components in a small quantity of deionized water.
7. Dry components with compressed air.
8. Reassemble component.
9. Cover open ports on component with aluminium foil.
10. Place component in Ziploc bag. Label (date/time cleaned and by whom), and store safely.

Fittings and Miscellaneous small components
1. Rinse away loose surface dust/dirt using tap water.
2. Prepare roughly a cup's worth of cleaning solution as per manufacturer instructions.
3. Clean each component thoroughly using a toothbrush and cleaning solution.
4. Rinse components in tap water using a sieve.
5. Rinse components in a small quantity of distilled water.
6. Dry components with compressed air.
7. Wrap components with aluminium foil.
8. Place component in Ziploc bag. Label (date/time cleaned and by whom), and store safely.

Sensors / Gauges
1. Ensure that the sensor can be cleaned using the materials prescribed (sensor dependent). Modify following procedure accordingly.
2. Prepare roughly a cup's worth of cleaning solution as per manufacturer instructions.
3. Rinse away loose surface dust/dirt using tap water.
4. Clean each component thoroughly using a toothbrush and cleaning solution.
5. Rinse components in tap water using a sieve.
6. Rinse components in a small quantity of deionized water.
7. Cover open ports on component with aluminium foil.
8. Place component in Ziploc bag. Label (date/time cleaned and by whom), and store safely.

Bulkheads
1. Rinse away loose surface dust/dirt using tap water.
2. Prepare roughly a cup's worth of cleaning solution as per manufacturer instructions.
3. Clean each component thoroughly using a toothbrush (or other appropriate tool) and cleaning solution.
4. Rinse components in tap water.
5. Rinse components in a small quantity of deionized water.
6. Use compressed air to remove large water droplets.
7. Wrap component with aluminium foil.
8. Place component in Ziploc bag. Label (date/time cleaned and by whom), and store safely.

<u>Combustion Chamber Assembly</u>

Note o-ring sizes: 242 between nozzle and liner, 246 between liner and aluminium chamber

1. Ensure injector bulkhead and inside of injector are sanitized.
2. Align fuel grain to injector ports. (at least align one star corner to one injector port)
3. Align bulkhead holes on injector bulkhead to retaining ring holes to help the alignment in the previous step.
4. Mark alignment using a sharpie.
5. Make sure the nozzle is cleaned (using a toothbrush), and all the old o-rings are removed.
6. Install o-rings on the nozzle (size: 236) with o-ring lubricant.
7. Place a layer of tape above the o-rings to prevent contact with caulking. Ensure that the tape does not contact the o-rings.
8. Place nozzle on retaining ring.
9. Apply high temperature caulking on female lip of fuel grain.
10. Use a popsicle stick to evenly spread the caulking.
11. Add a little caulking on the male end of the nozzle.

12. Use a popsicle stick to evenly spread the caulking.
13. Put nozzle liner on nozzle
14. Add a little caulking on the end of the nozzle liner.
15. Use a popsicle stick to evenly spread the caulking.
16. Join fuel grain and the nozzle together.
17. Clean excess caulking using paper towel.
18. Ensure the caulking didn't get over the O-ring.
19. Align combustion chamber to the retaining ring.
20. Put fin can on the bottom of combustion chamber. Do not screw it in!
21. Take off the tape on the nozzle o-rings.
22. Slide the combustion chamber and fin can onto the fuel grain assembly.
23. Make sure no component of fuel grain assembly rotates.
24. Rotate the fin can until the bolt hole for rail button and the pre-marked fill port location are 90 degrees apart clockwise.
25. Screw the fin can in using Eleven ¼"-28 (long ones) and a ¼"-28 (super long one) with rail button.
26. Ensure that the rail button is between two fins.
27. Install the break link adapter onto the retaining ring. Ensure the break link adapter is mounted opposite the rail button.
28. Join the end of ignition wiring to a thin tube using masking tape.
29. Pass this tube through the fuel grain and nozzle while making sure not to damage the nozzle.
30. ENSURE that you do not pull on the ignition wiring.
31. Get two pieces of wooden 2x4 to support the engine so as to not compress the ignition wiring under the weight of the engine.
32. Apply caulking to the male end of the fuel grain.
33. Use a popsicle stick to evenly spread the caulking.
34. Apply caulking to the female end of the spacer.
35. Use a popsicle stick to evenly spread the caulking.
36. Press the spacer onto the fuel grain.
37. Check continuity on both ignition cables to ensure good assembly.
38. Slide the fiberglass sleeve on the injector bulkhead.
39. Install combustion chamber external o-rings (size: 236) onto injector bulkhead with o-ring lubricant.
40. Apply caulking to the male end of the spacer.
41. Use a popsicle stick to evenly spread the caulking.
42. Apply caulking to the female end of the injector bulkhead.
43. Use a popsicle stick to evenly spread the caulking.
44. Make sure the alignment between injector bulkhead and combustion chamber is correct.
45. Ensure to use the correct (longer) O-ring fillers
46. Insert oxidizer tank assembly onto the engine assembly.
47. Check if any of the O-rings ruptured during installation through the bolt holes.
48. Fasten with twelve ¼"-28 screws (short ones)
49. Check if the O-ring fillers ruptured after installation.
50. Check continuity on both ignition cables to ensure good assembly.
51. Strain relief the ignition cables by using masking tape to connect it to the outside of the engine.
52. Close the nozzle end of the engine using a ziploc bag and masking tape.
53. Short the igniters to ensure they do not accidentally ignite during transport.

Oxidizer Tank Assembly

Notes:

- Use gloves for installation to avoid contamination
- Apply PTFE tape to all pipe fittings

Procedure:

1. Sanitize everything that will contact oxidizer (ref. Sanitation Procedure)
2. Inspect all components for damage. Dents, digs, or deep scratches larger than 1cm should be noted and evaluated more closely for impact to seal quality. Note that extrusion marks on the tank do not apply.

3. Record the dip tube length and insert it on vent bulkhead
4. Install o-rings on both bulkheads using o-ring lube
5. Place bolt hole plugs into one end of tank, secure and check for any plugs protruding inside the tank.
6. Slide bottom fill bulkhead into place, ensuring the holes align while inserting
7. Remove plugs and bolt fill bulkhead into place, tightening all 12 ¼-28 fasteners in a star pattern and checking for ripped o-rings. DO NOT OVERTIGHTEN to avoid stripping the threads.
8. Place bolt hole plugs into holes on the top side of the tank, secure and check for any plugs protruding inside the tank.
9. Slide vent bulkhead into place, ensuring the holes align.
10. Remove plugs and bolt vent bulkhead into place, tightening all 12 ¼-28 fasteners in a star pattern and checking for ripped o-rings. DO NOT OVERTIGHTEN to avoid stripping the threads.
11. Cap both ends of the tank if not immediately assembled to injector and vent valves.

<u>Recovery System Setup Procedures</u>

Inspection

1. Ensure all components are undamaged
2. Ensure that all pyrotechnics and batteries are disconnected and shorted before starting

Wiring

1. Ensure that all pyrotechnics and batteries are disconnected and shorted before wiring
2. Check that all circuit components are properly mounted to the sled with proper spacers, screws, and nuts
3. Ensure all switches are in the energized position
4. Check continuity between batteries and altimeters
5. Turn all switches to the non-energized position
6. Check batteries for full capacity (nominal 9 V)
7. Install batteries correctly in battery holders

CO2 System Installation

1. Ensure all ejection device wires and batteries are disconnected from the electronics bay before proceeding
2. Ensure the two CO2 ejection devices are installed into the bulkhead
3. Install two 38 gram CO2 cylinders into the ejection devices, using two washers to ensure CO2 vent holes are unobstructed. Use Teflon tape on the threads of the CO2 cylinder when connecting

GPS System

1. Ensure GPS battery is fully charged
2. Ensure GPS is functional after connecting battery
3. Turn GPS system off by waving magnet over the magnetic switch

Sled Installation

1. Ensure all wires are tucked away to prevent pinching during installation
2. Ensure the CO2 cylinders are installed into the CO2 ejection device
3. Ensure that the batteries are installed in the battery holder
4. Slide the sled onto the central threaded rod
5. Connect the altimeters to the circular connectors using the screw terminals
6. Check continuity between recovery bay connector pins and altimeter

CO2 Ejector Setup

1. Place igniter and wires inside igniter cylinder and center igniter in cylinder using tissue paper
2. Place epoxy on igniter wires so that when the igniters are pulled, the wires do not pull out of the igniter cylinder
3. Ensure igniter is placed so that it is flush with the rim of the cylinder that touches the puncturing cylinder
4. Place aluminium foil on the working surface
5. Place a separate piece of aluminium foil on the working surface for holding and pouring the gunpowder
6. Place avionics assembly on the first aluminium sheet with the injector body opening upwards such that the entire body is grounded

7. Place O-ring on puncturing cylinder and lightly lubricate with spray silicone lubricant making sure to wipe off excess lubricant
8. Place puncturing cylinder in injector body
9. Fill puncturing cylinder to the rim with FFFF gunpowder
10. Ensure igniter leads remain shorted
11. Place O-ring on igniter cylinder and lubricate
12. Place igniter cylinder on top of puncturing cylinder and push down until igniter cylinder is flush with injector body
13. Ensure gunpowder vent holes are clear of obstructions and cover lightly with masking tape
14. Run igniter wires through body cap and screw cap on tightly
15. Check for movement of the igniter wires
16. If moving, take apart and reseat igniter so that it is seated firmly in place

Pyrotechnic Cutter Setup

1. Slide an O-Ring into the bottom of the cutter to act as a bumper for the piston
2. Insert recovery dual ring rope through the hole of the cutter
3. Trim excess rope
4. Insert shearing piston
5. Insert black powder
6. Insert E-match
7. Install o-rings to act as seal
8. Slide hex screw over E-match leads and screw into cutter

Parachute Section Assembly

1. Ensure that all recovery lines are free and not tangled
2. Ensure that the 9 V batteries are disconnected
3. Fold the main parachute, gore by gore, in an accordion-style pattern
4. Fold the main parachute vertically in half
5. Roll the main parachute from the top towards the main parachute lines
6. Pack the rolled parachute into the parachute bag so that the main parachute lines extend from one of the open corners
7. Secure the main parachute lines over the parachute bag cover using the elastics
8. Use the carabiner to connect the main parachute line to the main coupling line
9. Connect the two-ring release mechanism and secure using the dual ring rope
10. Secure the pyrotechnic line cutters to the primary recovery line using electrical tape
11. Connect the pyrotechnic leads to the connectors on the primary recovery line
12. Secure the drogue parachute line to the base of the avionics module
13. Pack the parachute bag into the recovery module and push it towards the engine end
14. Fasten the eyebolt to the top of the vent bulkhead with a lock washer and Loctite
15. Wrap a fireproof cloth around the pyrotechnic line cutters to protect main parachute and recovery lines from the black powder burn
16. Apply a thick layer of grease to the coupler at the base of the recovery tube and a thin layer of grease on the payload bulkhead
17. Insert the payload bulkhead into the recovery module
18. Secure the payload bulkhead to the recovery module coupler using 6x 1/4"-28 (1/2") screws
19. Connect the circular connector from the primary recovery line to the avionics module
20. Pack the drogue parachute and the remaining recovery lines into the recovery module
21. Confirm that the altimeters are off
22. Make all appropriate electrical connections at the avionics terminals
23. Insert the 9V batteries into their mounts
24. Slide the avionics module over the threaded rod into the nosecone
25. Secure the avionics bulkhead to the bulkhead spacer
26. Tighten the eyenut on the threaded rod below the avionics bulkhead
27. Wrap a fireproof cloth around the igniter cylinders to protect recovery lines and parachutes from the black powder burn
28. Apply a layer of grease to the avionics and recovery couplers

29. Place the avionics module coupler over the recovery module coupler
30. Secure the avionics and recovery modules together with shear pins

Launch Tower Operations

Assembly Checks

1. Ensure all ¼" cable clamps are torqued to 4 ¾ lbs.ft (57 lbs.in) minimum
2. Ensure all 3/16" cable clamps are torqued to 3 ¾ lbs.ft (45 lbs.in) minimum
3. Ensure that there are a minimum of 2 threads sticking sticking out the end of the turnbuckles
4. Ensure that cable assemblies are at least the lengths specified in the "Gin Pole Mechanism Drawings"
5. Ensure that the "Connecting Wire ASY" and "Puller Wire ASY" are assembled onto the long gin pole. A section of the "Puller Wire ASY" will not be connected to the winch; this is what should be on the gin pole
6. Have the hand drill set on low speed. Max rpm on low speed is 600 rpm, which is also the rpm rating of the winch
7. Ensure there is sufficient lubrication on winch gears

Launch Pad Installation Procedure

Estimated time: 10 min
Technicians Required: 2

Tools Required:
- Sledgehammer
- Strike plate
- Level measurement device

Procedure
1. Identify a fairly flat piece of land, unobstructed by plants
2. Place the launch pad on the ground. If the ground is soft, place several 2x4's underneath the pad, evenly spaced
3. Level the launch pad by adding/removing ground as required. Max of 2deg tilt is acceptable
4. Drive stakes through each corner of the launch pad legs, leaving about 1"-2" sticking out

Gin Pole Installation

Estimated Time: 1 min
Technicians Required: 3

Tools Required
- Adjustable wrench/ratchet wrench x2
- Long Gin Pole section

Procedure
1. Ensure the pad is rotated to "tower vertical" position
2. Disassemble the bolt and nut on the Short Gin Pole (already installed on the pad)
3. Slide the Long Gin Pole onto the Short Gin Pole
4. Use the bolt and nut to fasten the sections together, and tighten with wrenches

Ground Anchor Installation

Estimated Time: 25 (5 min per anchor). Time is reduced with more technicians and hammers
Technicians Required: 1 (per sledgehammer)

Tools Required
- Sledgehammer

- Short stake
- Medium stake
- Long stake
- Strike plate
- Measuring tape (at least 22')
- 5x ground anchors

PPE
- Safety glasses (per sledgehammer)

Procedure
1. Locate a point 18' away from the pivot point of the launch tower. Line up this point with the gin pole (installed on the tower)
2. Use the short stake, strike plate, and sledgehammer to drive two anchors vertically down at this location. Switch to the medium, then long stake when there is insufficient length of rod
3. Leave 2" of cable sticking out of the ground, close enough that they can be routed to attach at a single point
4. Pull on the cable to lock the anchor in the ground
5. Locate three points 16' away from the pivot point of the launch tower, in the geometry shown in "Guy Wire Schematic"
6. Drive at one anchor at each point.

Winch Installation

Estimated Time: 30 sec
Technicians Required: 1

Procedure
1. Ensure the cable on the winch is fully retracted
2. Snap the carabiner on the winch frame to the both ground anchors. Ensure the winch cable is facing the pad
3. Ensure the carabiner is twist locked
4. Extend the winch cable until it reaches the "Puller Wire ASY", which is installed on the gin pole
5. Snap the carabiner from the "Puller Wire ASY" onto the winch cable
6. Ensure the carabiner is twist locked

Tower Installation Procedure

Estimated Time: 30 min
Technicians Required: 3

Tools Required
- Hand drill with ⅝" socket and adapter
- Winch handle

PPE
- Gloves x1 pair (for holding the wire on the winch)

Procedure
1. Locate the turnbuckle on the "Connecting Wire ASY" closest to the gin pole. Leave 2 inches of threads sticking out either end
2. Place technician #1 at the winch. This technician should have the hand drill/handle
3. Place technician #2 between the winch and the gin pole. This technician should hold the winch wire with gloves
4. Place technician #3 at the pad, holding the gin pole
5. Unwind the winch, and rotate the gin pole until it hits the launch pad
6. Technician #1: Use the hand drill/winch to unwind the winch cable
7. Technician #2: Keep tension on the winch cable

8. Technician #3: Rotate the gin pole to keep tension on the wire
9. Install the tower (see "Tower Assembly Procedure") onto the launch pad
10. Install any other GSE required for the tower before it is lifted
11. Snap the carabiner from the "Connecting Wire Assembly" to the "Cable Mount Assembly" on the tower
12. Tighten the turnbuckle on the connecting wire assembly to prevent slack

Tower Raising Procedure

Estimated Time: 2 min (based on test)
Technicians Required: 6

Tools Required

- Hand drill with ⅝" socket and adapter for the socket
- Winch handle
- Wooden rod (for adjusting wire)

PPE

- Gloves x4 pairs (for handling the wire)
- Hard hat x2
- Safety glasses x7

Procedure

1. Place technicians #1 to #2 at each guy wire, pulling with the tower rotation direction. Gloves should be worn
2. Place technician #3 at the guy wire, pulling against the tower rotation direction. Gloves should be worn
3. Place technician #4 and #5 at the launch pad. Hard hats should be worn
4. Place technician #6 and #7 at the winch. Technician #6 should have the hand drill. Technician #7 should have gloves and the wooden rod
5. Ensure there are no people under the tower
6. Lift the tower
    a. Technicians #1 to #2: Keep light tension on the guy wires to prevent the tower from swaying side to side. Walk towards the ground anchors. Do not wrap the wire around your back. If the tower falls, you will be dragged along with it. Keep the wire in front of you. Hold it and the turnbuckle with two hands
    b. Technician #3: Hold the wire, do not pull
    c. Technician #4 and #5: Keep your hands on the rocket and watch for any hoses/wires. Make sure they are secure
    d. Technician #6: Use the hand drill/handle to wind the wire on the winch
    e. Technician #7: Use the wooden rod to correct the fleet angle on the winch, ensuring the wire is winding neatly
7. Observe the tower as it approaches the vertical position
    a. Technicians #1 to #3: Hook your turnbuckle into the ground anchors if possible
    b. Technicians #4 and #5: Get ready to support the tower as it lands
    c. Technician #6: Slow down
    d. Technician #7: Keep correcting the fleet angle
8. The tower is vertical
    a. Technicians #1 and #2: Tighten your turnbuckles.
    b. Technician #3: Tighten your turnbuckle.
    c. Technician #6: Remove your drill/handle from the winch. Install the locking bracket on the gin pole. Then, locate the turnbuckle on the end of the gin pole (part of the "Connecting Wire Assembly") and loosen it. Bring the cable to the launch pad and secure it there, away from the rocket and surrounding systems
    d. Technician #4, #5, #7: You are on standby.

Shark of the Sky Hybrid Rocket
2019 IREC

Launch Operations Procedures

Compiled on 2019-05-20

Background and Reference

Contents

This document contains two nominal procedures:

- **N1**, *Final Setup and Pre-Launch Checks*, comprises the final checks and tests performed on the Remote Launch Control System (RLCS) prior to rocket launch, as well as avionics systems arming.
- **N2**, *Fill and Launch Operations*, comprises steps for oxidizer fill and rocket launch.

Additionally, this document contains five abort procedures:

- **A1**, *Abort Procedure - Leak At Supply Plumbing*, is used if a plumbing leak is detected when the supply cylinder is initially opened.
- **A2**, *Abort Procedure - Low Supply Pressure*, is used if the oxidizer pressure is below the acceptable limit for launch.
- **A3**, *Abort Procedure - High Supply Pressure*, is used if the oxidizer pressure is above the acceptable limit for launch.
- **A4**, *Abort Procedure - Leak At Fill Plumbing*, is used if a plumbing leak is detected during manual fill leak checks.
- **A5**, *Abort Procedure - Remote Disconnect or Ignition Failure*, is used if the remote disconnect or ignition systems fail, necessitating a full vent of the oxidizer tank.
- **A**γ, *Abort Procedure - Voice Contact Loss*, is used if the operators at the launch site lose the ability to communicate with the operators at launch control.

Personnel Required

The launch operations team consists of four personnel:

1 ☐ The **Operations Director [OPS]** is stationed at Launch Control. **OPS** directs operations procedures and communicates with the other launch personnel.

2 ☐ The **Control System Operator [CONTROL]** is stationed at Launch Control and is responsible for operation of RLCS, including remote fill, disconnect, and ignition.

3 ☐ The **Primary Fill Operator [PRIMARY]** is initially stationed at the Launch Tower and carries out all tasks occurring at the Launch Tower. **PRIMARY** engages the remote disconnect system, arms the vehicle recovery deployment system, connects the ignition wires to the rocket, and operates all manual valves during the manual portion of fill.

4 ☐ The **Secondary Fill Operator [SECONDARY]** is the backup for **PRIMARY**, and communicates with **OPS**. If **PRIMARY** becomes incapacitated, **SECONDARY** is responsible for removing them from danger.

Sign-Off

To be completed by all test personnel after reading and familiarization with procedures

1 ☐ **Operations Director [OPS]** ________________ ________________

2 ☐ **Control System Operator [CONTROL]** ________________ ________________

3 ☐ **Primary Fill Operator [PRIMARY]** ________________ ________________

4 ☐ **Secondary Fill Operator [SECONDARY]** ________________ ________________

[N1] Final Setup and Pre-Launch Checks

Prior to Start

1 ☐ Ensure that the following procedures are complete:

2 ☐ Rocket Assembly procedure

3 ☐ RLCS Setup procedure

4 ☐ Launch Tower Setup procedure

5 ☐ Ensure that all personnel as defined above are available and have completed the sign-off.

6 ☐ Ensure that the following personnel have walkie-talkies and communication is functional:

7 ☐ **OPS**

8 ☐ **CONTROL**

9 ☐ **PRIMARY**

10 ☐ **SECONDARY**

11 ☐ Ensure that **OPS** is in possession of the system control key.

12 ☐ Ensure that the client-side RLCS box is powered off.

13 ☐ Ensure that the locations of Launch Control, Launch Tower, and the Minimum Safe Distance are clearly defined.

Launch Control	Launch Tower	Minimum Safe Distance

Nominal Procedure

1 ☐ **PRIMARY**: Confirm that the following valves are initially closed:

2 ☐ Cylinder Valve

3 ☐ Remote Fill Valve

4 ☐ Parallel Fill Valve

5 ☐ Series Fill Valve

6 ☐ Line Vent Valve

7 ☐ Parallel Vent Valve

8 ☐ **PRIMARY**: Confirm that the ignition connectors are disconnected from the rocket.

9 ☐ **CONTROL**: Power on the client-side RLCS box.

10 ☐ **CONTROL** and **SECONDARY**: Confirm that the following actuators fail to move:

11 ☐ Remote Fill Valve

12 ☐ Line Vent Valve
13 ☐ Remote Disconnect
14 ☐ Injector Valve

15 ☐ **SECONDARY**: Confirm that the voltage across the ignition connectors is 0 V.

16 ☐ **OPS**: Give the system control key to **CONTROL**.

17 ☐ **CONTROL**: Confirm that all actuator controls are in the off state:

18 ☐ Remote Fill Valve
19 ☐ Line Vent Valve
20 ☐ Remote Disconnect
21 ☐ Tank Vent Valve
22 ☐ Primary Ignition
23 ☐ Secondary Ignition
24 ☐ Injector Valve

25 ☐ **CONTROL**: Engage the key switch and enable actuators.

26 ☐ **CONTROL** and **SECONDARY**: Confirm that all actuators actuate as intended:

27 ☐ Remote Fill Valve
28 ☐ Line Vent Valve
29 ☐ Remote Disconnect
30 ☐ Tank Vent Valve
31 ☐ Injector Valve

32 ☐ **CONTROL** and **SECONDARY**: Confirm that the ignition voltage is 12 V when the ignition button is fired:

33 ☐ Primary Ignition
34 ☐ Secondary Ignition

35 ☐ **CONTROL**: Confirm that all DAQ readings are displaying appropriately.

36 ☐ **OPS**: Record the resting DAQ values:

[M] Dry Mass (lbs)	[P1] Supply Pressure (psi)	[P2] Fill Line Pressure (psi)	[P3] Oxidizer Tank Pressure (psi)

37 ☐ **CONTROL**: Remove the system control key and give it to **OPS**.

38 ☐ **PRIMARY**: Arm the payload using the transponder.

39 ☐ **PRIMARY**: Arm recovery avionics using the magnetic switches

40 ☐ **PRIMARY**: Arm remote disconnect by connecting the springs, fill adapter, and strap.

41 ☐ **PRIMARY**: Connect the ignition connectors to the rocket.

[N2] Fill and Launch Operations

Prior to Start

1 ☐ Ensure that the following procedure is complete:

2 ☐ **N1**, *Final Setup and Pre-Launch Checks*

3 ☐ Ensure that all personnel are available and have completed the sign-off.

4 ☐ Ensure that the following personnel have walkie-talkies and communication is functional:

5 ☐ **OPS**

6 ☐ **CONTROL**

7 ☐ **PRIMARY**

8 ☐ **SECONDARY**

9 ☐ Ensure that **PRIMARY** and **SECONDARY** are wearing face shields and have no exposed skin.

10 ☐ Ensure that **PRIMARY** is wearing thermal gloves.

11 ☐ Ensure that **OPS** is in possession of the system control key.

Nominal Procedure

1 ☐ **SECONDARY**: Confirm that no personnel other than **PRIMARY** and **SECONDARY** are within the Minimum Safe Distance.

2 ☐ **OPS**: Confirm that the actuator key switch is disabled and that only **OPS** is in possession of the system control key.

3 ☐ **OPS**: Confirm that the Range Safety Officer and Launch Control Officer have given clearance to proceed with fill procedures.

4 ☐ **CONTROL**: Confirm that the RLCS client-side box is on and displaying DAQ information.

5 ☐ **PRIMARY**: Confirm that the following valves are initially closed:

6 ☐ Cylinder Valve

7 ☐ Remote Fill Valve

8 ☐ Parallel Fill Valve

9 ☐ Series Fill Valve

10 ☐ Line Vent Valve

11 ☐ Parallel Vent Valve

12 ☐ **OPS**: Confirm that the Tank Vent Valve is initially open.

13 ☐ **OPS**: Confirm that the Pressure Relief Valve is initially closed.

14 ☐ **OPS**: Confirm that the Injector Valve is initially closed.

15 ☐ **PRIMARY**: Slowly open the Cylinder Valve through $\frac{3}{4}$ of a turn.

- If leaks are observed:

16 ☐ **OPS**: Proceed to procedure A1.

17 ☐ **PRIMARY**: Communicate the supply line pressure as visible on the Pressure Gauge.

- If the supply line pressure is below 800 psi:

18 ☐ **OPS**: Proceed to procedure **A2**.

- If the supply line pressure exceeds 1000 psi:

19 ☐ **OPS**: Proceed to procedure **A3**.

20 ☐ **CONTROL**: Confirm that the supply line pressure as read by **PRIMARY** agrees with the supply line pressure [P1] measured by the DAQ system.

21 ☐ **OPS**: Record the resting rocket dry mass and supply pressure:

[M] Dry Mass (lbs)	[P1] Supply Pressure (psi)

22 ☐ **PRIMARY**: Open the Series Fill Valve.

23 ☐ **PRIMARY** and **SECONDARY**: Retreat 100 ft from the fill system.

24 ☐ **OPS**: Give the system control key to **CONTROL**.

25 ☐ **CONTROL**: Confirm the following valves are closed:

26 ☐ Remote Fill Valve
27 ☐ Remote Vent Valve
28 ☐ Tank Vent Valve

29 ☐ **CONTROL**: Engage the key switch and enable actuators.

30 ☐ **CONTROL**: Open and close the Tank Vent Valve, ensuring that the limit switch reading updates accordingly.

31 ☐ **CONTROL**: Open the Remote Fill Valve.

32 ☐ **CONTROL**: Confirm the following pressures are increasing:

33 ☐ [P2] Fill line pressure
34 ☐ [P3] Oxidizer tank pressure

35 ☐ **CONTROL**: Close the Remote Fill Valve.

36 ☐ **CONTROL**: Confirm the following pressures are stable:

37 ☐ [P2] Fill line pressure
38 ☐ [P3] Oxidizer tank pressure

- If the pressures are decreasing:

39 ☐ **OPS**: Proceed to procedure **A4**.

40 ☐ **CONTROL**: Open the Remote Vent Valve.

41 ☐ **CONTROL**: Open the Tank Vent Valve.

42 ☐ **CONTROL**: Confirm the following pressures are atmospheric:

- 43 ☐ [P2] Fill line pressure
- 44 ☐ [P3] Oxidizer tank pressure

45 ☐ **CONTROL**: Disengage the key switch and disable actuators

46 ☐ **PRIMARY** and **SECONDARY**: Retreat to the Minimum Safe Distance.

47 ☐ **SECONDARY**: Confirm that **PRIMARY** and **SECONDARY** are at the Minimum Safe Distance.

48 ☐ **PAUSE POINT**

49 ☐ **CONTROL**: Confirm that all actuator controls are in the off state:

- 50 ☐ Remote Fill Valve
- 51 ☐ Line Vent Valve
- 52 ☐ Remote Disconnect
- 53 ☐ Tank Vent Valve
- 54 ☐ Primary Ignition
- 55 ☐ Secondary Ignition
- 56 ☐ Injector Valve

57 ☐ **CONTROL**: Engage the key switch and enable actuators.

58 ☐ **CONTROL**: Open the Tank Vent Valve.

59 ☐ **CONTROL**: Open the Remote Fill Valve.

60 ☐ **CONTROL**: Monitor the RLCS display for rocket mass and oxidizer tank pressure.

61 ☐ **OPS**: Proceed only when the following is true:

- 62 ☐ Rocket mass [M] plateaus
- 63 ☐ Oxidizer tank pressure [P3] is within the acceptable limits

64 ☐ **CONTROL**: Close the Tank Vent Valve.

65 ☐ **CONTROL**: Close the Remote Fill Valve.

66 ☐ **CONTROL**: Open the Remote Vent Valve.

67 ☐ **CONTROL**: Confirm that the fill line pressure [P2] is atmospheric.

68 ☐ **CONTROL**: Actuate Remote Disconnect.

- If Remote Disconnect fails to actuate:
  - 69 ☐ **OPS**: Proceed to procedure **A5**.

70 ☐ **PAUSE POINT**

71 ☐ **OPS**: Perform pre-launch checks:

- 72 ☐ Request clearance for launch from the Launch Control Officer.
- 73 ☐ Confirm that all members are aware of launch.

74 ☐ **PRIMARY**: Perform engine startup procedure:

- 75 ☐ Arm the Primary Ignition switch.
- 76 ☐ Hold down the Fire button until the Primary current reading drops to 0 A.
  - In the event of a failed ignition (current drop not observed within 1 minute):

77 ☐ **PRIMARY**: Disarm the Primary Ignition switch.
78 ☐ **PRIMARY**: Arm the Secondary Ignition switch.
79 ☐ **OPS**: Revisit ignition procedure.

- In the event of a second failed ignition (current drop not observed within 1 minute):

80 ☐ **PRIMARY**: Disarm the Secondary Ignition switch.
81 ☐ **OPS**: Proceed to procedure **A5**.

82 ☐ **PRIMARY**: Start the engine by opening the Injector Valve.

83 ☐ **ALL**: Observe the rocket during takeoff, ascent, and recovery:

84 ☐ First vehicle motion
85 ☐ Launch rail departure
86 ☐ Engine burnout
87 ☐ Payload deployment
88 ☐ Drogue parachute deployment
89 ☐ Main parachute deployment
90 ☐ Approximate recovery area/direction

91 ☐ **CONTROL**: Disarm RLCS:

92 ☐ Disable actuator control by removing the system control key.
93 ☐ Give the system control key to **OPS**.

94 ☐ **OPS**: Confirm that RLCS is disarmed and **OPS** is in possession of the system control key.

95 ☐ **OPS**: Proceed only when clearance is received from the Launch Control Officer to approach the Launch Tower.

96 ☐ **PRIMARY** and **SECONDARY**: Approach the Launch Tower.

97 ☐ **PRIMARY**: Close the Cylinder Valve.

98 ☐ **PRIMARY**: Open the Parallel Vent Valve.

99 ☐ **PRIMARY**: Slowly open the Parallel Fill Valve.

100 ☐ **PRIMARY** and **SECONDARY**: Retreat 20 ft from the fill system.

101 ☐ **OPS**: Give the master key to **CONTROL**

102 ☐ **CONTROL**: Engage the key switch and enable actuators.

103 ☐ **CONTROL**: Open the Remote Fill Valve.

104 ☐ **CONTROL**: Confirm that the supply line pressure [P1] is atmospheric.

105 ☐ **PRIMARY**: Disconnect the supply line from the supply cylinder.

106 ☐ **PRIMARY**: Replace the cap on the nitrous oxide supply cylinder.

107 ☐ **OPS**: Proceed with teardown and disassembly.

Abort Procedures

[A1] Abort Procedure - Leak At Supply Plumbing

1 ☐ **PRIMARY**: Close the Cylinder Valve.

2 ☐ **PRIMARY**: Slowly open the Parallel Vent Valve.

3 ☐ **PRIMARY**: Slowly open the Parallel Fill Valve.

4 ☐ **CONTROL**: Confirm the following pressures are atmospheric:

5 ☐ [P1] Supply pressure

6 ☐ [P2] Fill line pressure

7 ☐ **PRIMARY**: Disarm the system:

8 ☐ Disconnect the ignition leads from the rocket.

9 ☐ Detatch the torsion springs from the disconnect mechanism.

10 ☐ Disarm the recovery electronics system using the magnetic switches.

11 ☐ Disarm the payload using the transponder.

12 ☐ Disconnect the fill line from the supply cylinder.

13 ☐ Replace the cap on the nitrous oxide supply cylinder.

14 ☐ **OPS**: Revisit plumbing setup.

[A2] Abort Procedure - Low Supply Pressure

1 ☐ **PRIMARY**: Close the Cylinder Valve.

2 ☐ **PRIMARY**: Slowly open the Parallel Vent Valve.

3 ☐ **PRIMARY**: Slowly open the Parallel Fill Valve.

4 ☐ **CONTROL**: Confirm the following pressures are atmospheric:

5 ☐ [P1] Supply pressure

6 ☐ [P2] Fill line pressure

7 ☐ **PRIMARY**: Allow the supply cylinder to warm up.

8 ☐ **OPS**: Revisit **N1**.

[A3] Abort Procedure - High Supply Pressure

1 ☐ **PRIMARY**: Close the Cylinder Valve.

2 ☐ **PRIMARY**: Slowly open the Parallel Vent Valve.

3 ☐ **PRIMARY**: Slowly open the Parallel Fill Valve.

4 ☐ **CONTROL**: Confirm the following pressures are atmospheric:

5 ☐ [P1] Supply pressure

6 ☐ [P2] Fill line pressure

7 ☐ **PRIMARY**: Disarm the system:

8 ☐ Disconnect the ignition leads from the rocket.
9 ☐ Detatch the torsion springs from the disconnect mechanism.
10 ☐ Disarm the recovery electronics system using the magnetic switches.
11 ☐ Disarm the payload using the transponder.
12 ☐ Disconnect the fill line from the supply cylinder.
13 ☐ Replace the cap on the nitrous oxide supply cylinder.

14 ☐ **OPS**: Revisit cylinder cooling methods.

[A4] Abort Procedure - Leak At Fill Plumbing

1 ☐ **CONTROL**: Close the Remote Fill Valve.

2 ☐ **CONTROL**: Open the Tank Vent Valve.

3 ☐ **CONTROL**: Open the Remote Vent Valve.

4 ☐ **CONTROL**: Confirm the following pressures are atmospheric:

5 ☐ P2: Fill line pressure
6 ☐ P3: Rocket Tank pressure

7 ☐ **PRIMARY** and **SECONDARY**: Return to plumbing setup

8 ☐ **PRIMARY**: Close the Cylinder Valve.

9 ☐ **PRIMARY**: Slowly open the Parallel Vent Valve.

10 ☐ **PRIMARY**: Slowly open the Parallel Fill Valve.

11 ☐ **CONTROL**: Confirm the following pressures are atmospheric:

12 ☐ [P1] Supply pressure
13 ☐ [P2] Fill line pressure

14 ☐ **PRIMARY**: Disarm the system:

15 ☐ Disconnect the ignition leads from the rocket.
16 ☐ Detatch the torsion springs from the disconnect mechanism.
17 ☐ Disarm the recovery electronics system using the magnetic switches.
18 ☐ Disarm the payload using the transponder.
19 ☐ Disconnect the fill line from the supply cylinder.
20 ☐ Replace the cap on the nitrous oxide supply cylinder.

21 ☐ **OPS**: Revisit plumbing setup.

[A5] Abort Procedure - Remote Disconnect or Ignition Failure

1 ☐ **CONTROL**: Open the Tank Vent Valve.

2 ☐ **CONTROL**: Monitor the RLCS display for rocket mass and oxidizer tank pressure as the oxidizer tank vents.

3 ☐ **OPS**: Proceed only when the following is true:

4 ☐ Rocket mass is equal to the pre-launch recorded mass
5 ☐ Oxidizer tank pressure [P3] is atmospheric

6 ☐ The Launch Control Officer has given clearance to approach the Launch Tower.

7 ☐ **PRIMARY** and **SECONDARY**: Approach the Launch Tower.

8 ☐ **PRIMARY**: Close the Cylinder Valve.

9 ☐ **PRIMARY**: Open the Parallel Vent Valve.

10 ☐ **PRIMARY**: Slowly open the Parallel Fill Valve.

11 ☐ **PRIMARY** and **SECONDARY**: Retreat 20 ft from the fill system.

12 ☐ **OPS**: Give the system control key to **CONTROL**

13 ☐ **CONTROL**: Engage the system control switch and enable actuators.

14 ☐ **CONTROL**: Open the Remote Fill Valve.

15 ☐ **CONTROL**: Confirm the following pressures are atmospheric:

16 ☐ [P1] Supply pressure
17 ☐ [P2] Fill line pressure

18 ☐ **PRIMARY**: Disarm the system:

19 ☐ Disconnect the ignition leads from the rocket.
20 ☐ Detatch the torsion springs from the disconnect mechanism.
21 ☐ Disarm the recovery electronics system using the magnetic switches.
22 ☐ Disarm the payload using the transponder.
23 ☐ Disconnect the fill line from the supply cylinder.
24 ☐ Replace the cap on the nitrous oxide supply cylinder.

25 ☐ **OPS**: Proceed with teardown and disassembly.

[Aγ] Abort Procedure - Voice Contact Loss - For Launch Control Operators

1 ☐ **CONTROL**: Remove the system control key from the client side box.

2 ☐ **OPS**: Attempt to regain communication with the operators at the pad:

3 ☐ Send "**OPS** to **SECONDARY**, **OPS** to **SECONDARY**, **SECONDARY** please come in".
- If contact is restored:
  4 ☐ Return to normal operations.

5 ☐ Check batteries in radio.
6 ☐ Check that radio is set to the proper channel.
7 ☐ Check that radio volume is high enough.
8 ☐ Wait 30 seconds, then send message again.
- If contact is restored:
  9 ☐ Return to normal operations.

10 ☐ **OPS**: Wait 30 seconds.

11 ☐ **OPS**: Send "**OPS** to **SECONDARY**, **OPS** to **SECONDARY**, going to full abort. Say again, going to full abort."

12 ☐ **OPS**: Inform the ESRA official that launch operations will be aborted.

13 ☐ **OPS**: Wait for operators to return from pad.

14 ☐ **OPS**: Proceed with teardown and disassembly.

[Aγ] Abort Procedure - Voice Contact Loss - For Launch Pad Operators

1 ☐ **SECONDARY**: Attempt to regain communication with the operators at launch control:

- 2 ☐ Send "**SECONDARY** to **OPS**, **SECONDARY** to **OPS**, **OPS** please come in".
  - If contact is restored:
    - 3 ☐ Return to normal operations.
- 4 ☐ Check batteries in radio.
- 5 ☐ Check that radio is set to the proper channel.
- 6 ☐ Check that radio volume is high enough.
- 7 ☐ Wait 30 seconds, then send message again.
  - If contact is restored:
    - 8 ☐ Return to normal operations.

9 ☐ **SECONDARY** and **PRIMARY**: Approach the rocket, listening for hisses coming from fill system

10 ☐ **PRIMARY**: Close the cylinder valve.

11 ☐ **PRIMARY**: Slowly open the Parallel Vent Valve.

12 ☐ **PRIMARY**: Slowly open the Parallel Fill Valve.

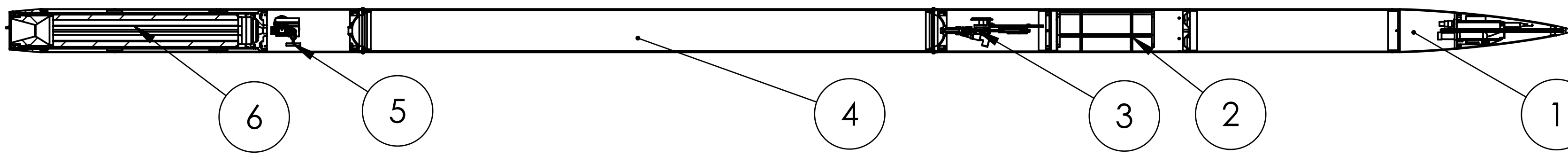
13 ☐ **SECONDARY** and **PRIMARY**: Return to launch control.

Engineering Drawings Appendix

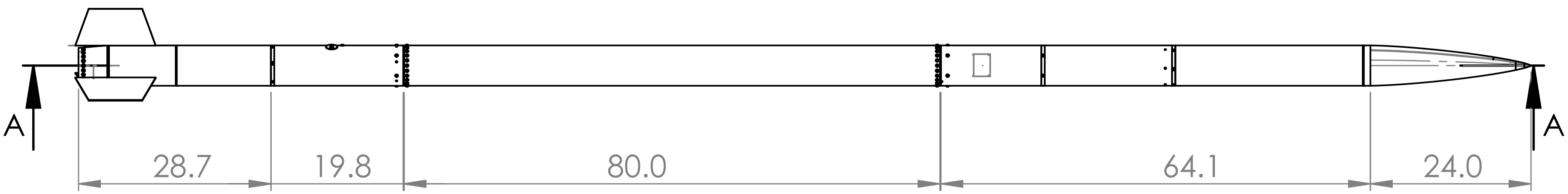
The following pages contain engineering drawings of significant SotS components and assemblies.

REVISION HISTORY

REV	DESCRIPTION	DATE	AUTHOR
XX	XXXXXXXXXXXXXX	XXX XX/XXXX	X.X



SECTION A-A



ITEM NO.	PART
1	NOSE CONE
2	PAYLOAD SECTION
3	VENT VALVE
4	OXIDIZER TANK
5	INJECTOR VALVE
6	COMBUSTION CHAMBER

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
REMOVE BURRS AND SHARP EDGES

TOLERANCES:
LINEAR: ±0.15 mm
ANGULAR: ±1°

WATERLOO ROCKETRY

	NAME	DATE
DRAWN		

MATERIAL:

FINISH:

WEIGHT: GRAMS

DESCRIPTION: SOTS- TOP ASSY

SIZE: A | DRAWING NUMBER: | REVISION:

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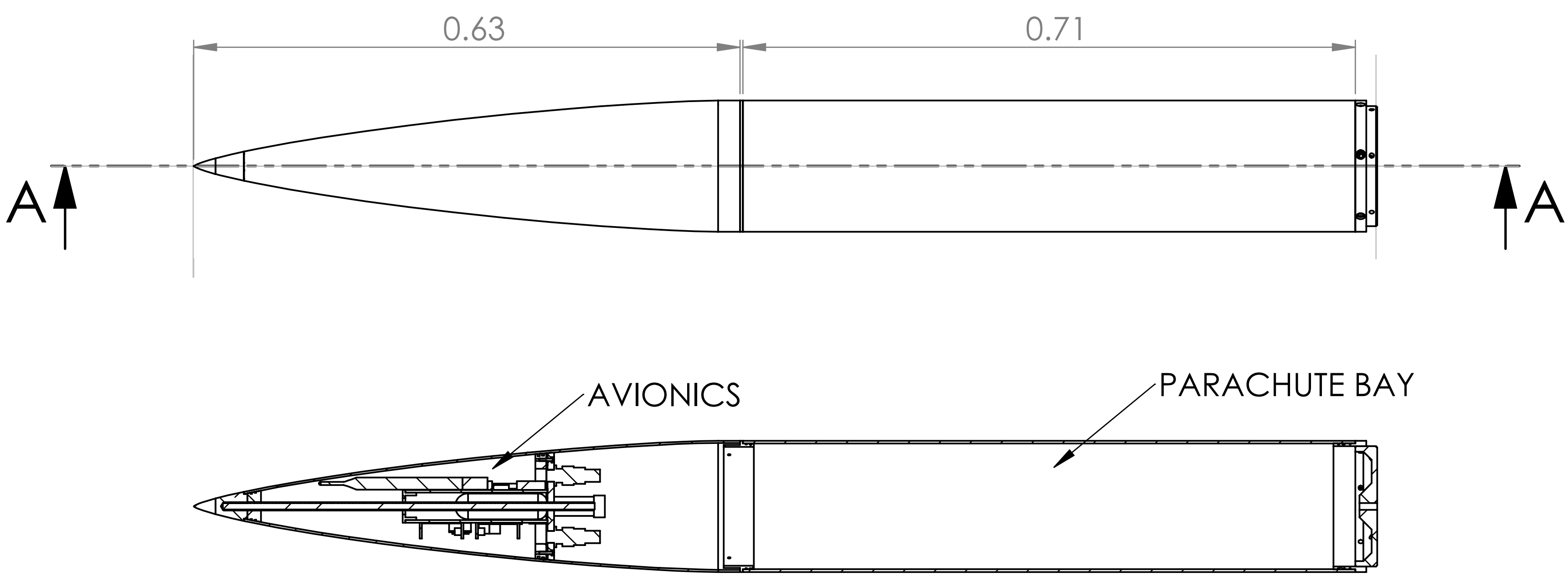


SECTION A-A

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
REMOVE BURRS AND SHARP EDGES
TOLERANCES:
LINEAR: 2 DECIMALS: ±0.010"
3 DECIMALS: ±0.005"
ANGULAR: ±1°

WATERLOO ROCKETRY

	NAME	DATE
DRAWN		

MATERIAL:

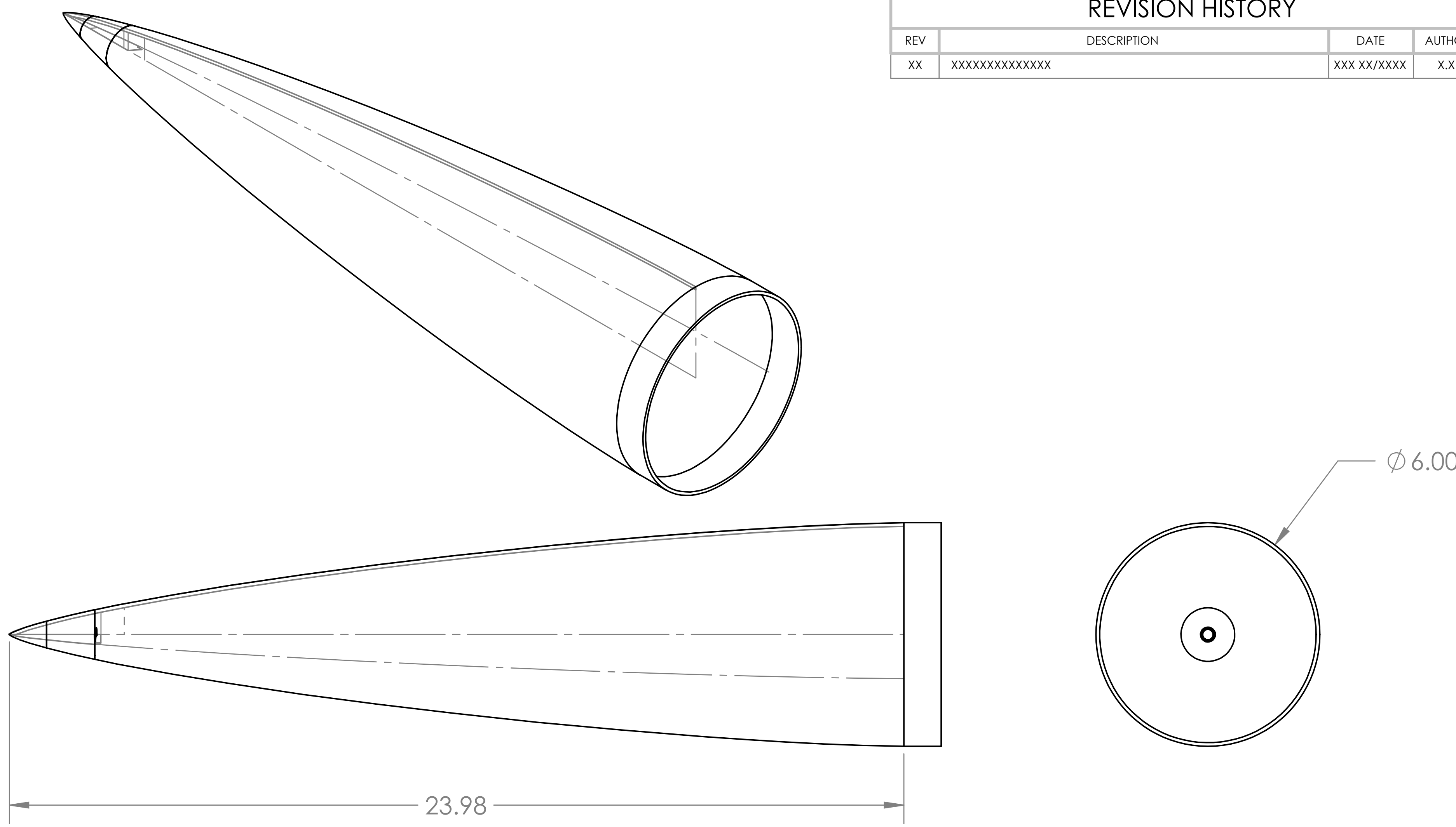
FINISH:

WEIGHT: LBS

DESCRIPTION: SOTS - RECOVERY

SIZE: A | DRAWING NUMBER: | REVISION:

SCALE: 1:8 | DO NOT SCALE DRAWING | SHEET 1 OF 1



REVISION HISTORY

REV	DESCRIPTION	DATE	AUTHOR
XX	XXXXXXXXXXXXXX	XXX XX/XXXX	X.X

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
REMOVE BURRS AND SHARP EDGES
TOLERANCES:
LINEAR: 2 DECIMALS: ±0.010"
3 DECIMALS: ±0.005"
ANGULAR: ±1°

WATERLOO ROCKETRY

	NAME	DATE
DRAWN		

MATERIAL:

FINISH:

WEIGHT: LBS

DESCRIPTION:

SOTS - NOSE CONE

SIZE: A

DRAWING NUMBER:

REVISION

SCALE: 1:4 | DO NOT SCALE DRAWING | SHEET 1 OF 1

REVISION HISTORY

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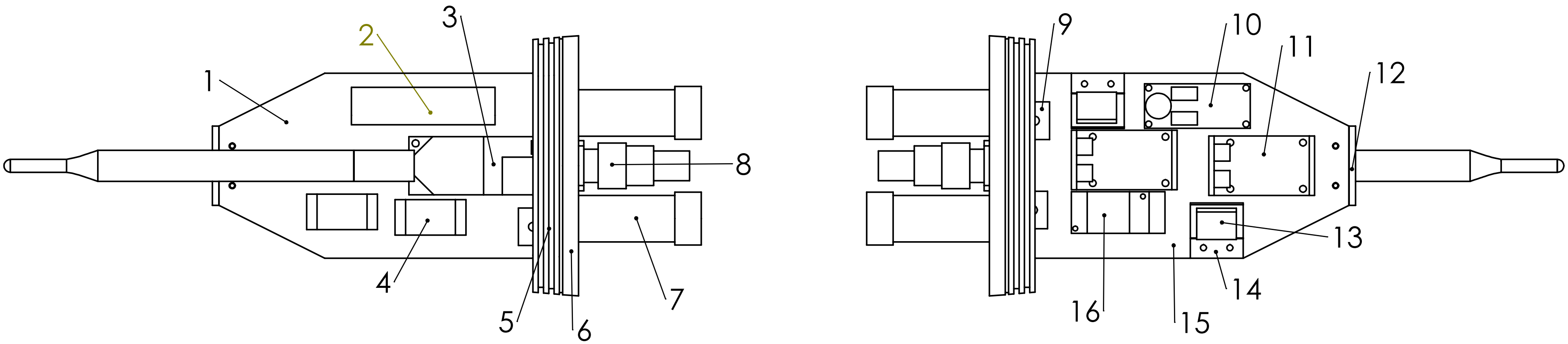


Item No	Qty	Description
1	1	GPS SLED
2	1	GPS BATTERY MOUNT
3	1	GPS
4	2	BUZZER
5	1	BULKHEAD SPACER
6	1	AVIONICS BULKHEAD
7	2	CO2 EJECTORS
8	2	CIRCULAR CONNECTOR
9	4	L - BRACKETS
10	1	STRATOLOGGER
11	2	9 VOLT BATTERY MOUNT
12	1	PI - BRACKET
13	2	MAGNETIC SWITCH
14	2	MAGNETIC SWITCH BRACKET
15	1	ALTIMETER SLED
16	1	RAVEN

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
REMOVE BURRS AND SHARP EDGES
TOLERANCES:
LINEAR: 2 DECIMALS: ±0.010"
3 DECIMALS: ±0.005"
ANGULAR: ±1°

WATERLOO ROCKETRY

	NAME	DATE
DRAWN		

MATERIAL:

FINISH:

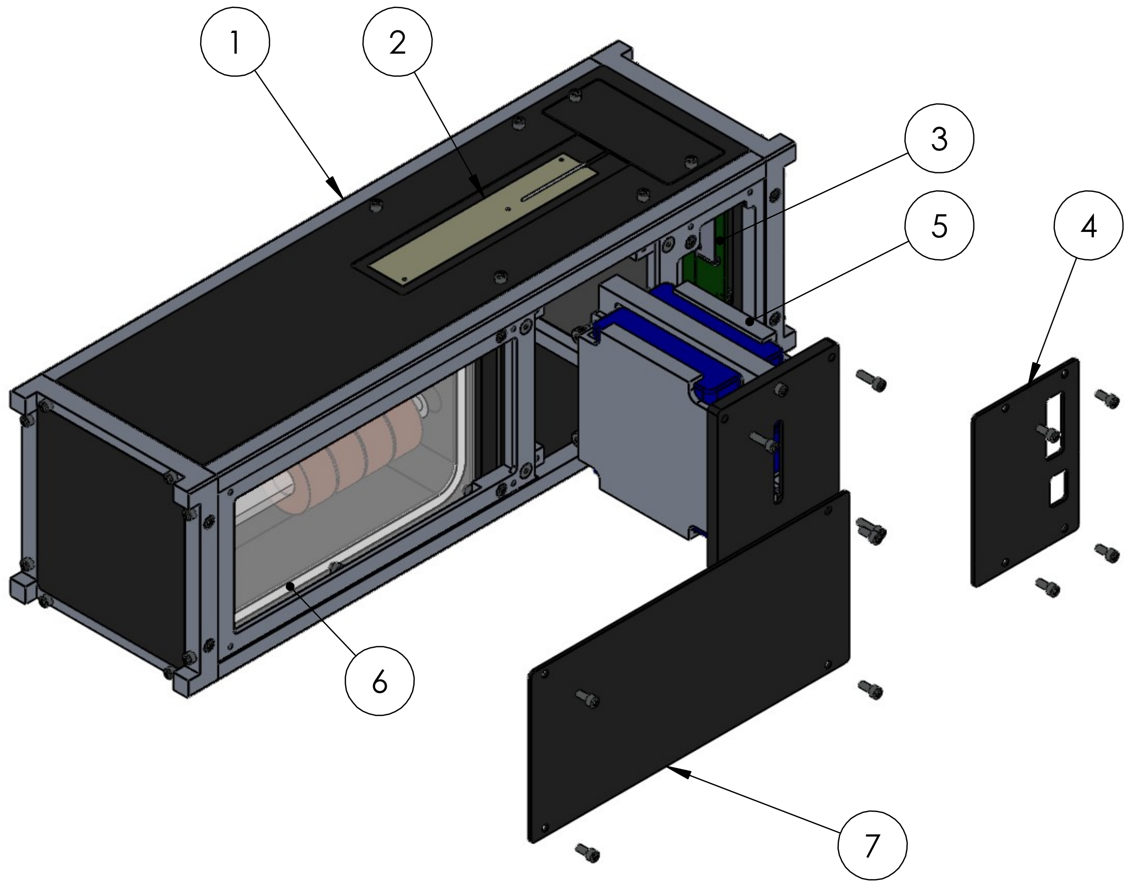
WEIGHT: LBS

DESCRIPTION:
SOTS - RECOVERY AVIONICS

SIZE: A
DRAWING NUMBER:
REVISION

SCALE: 1:3
DO NOT SCALE DRAWING
SHEET 1 OF 1

REVISION HISTORY			
REV	DESCRIPTION	DATE	AUTHOR
00	INITIAL RELEASE	MAY 18/2019	J.R



ITEM NO.	DESCRIPTION	QTY.
1	STRUCTURE	1
2	ANTENNA ASSEMBLY	2
3	SYSTEMS MODULE	1
4	SYSTEMS COVER PANEL	1
5	BATTERY MODULE	1
6	EXPERIMENT MODULE	1
7	EXPERIMENT COVER PANEL	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
REMOVE BURRS AND SHARP EDGES

TOLERANCES:
LINEAR: ±0.15 mm
ANGULAR: ±1°

WATERLOO ROCKETRY

	NAME	DATE
DRAWN	J.ROBINSON	MAY 18/2019

MATERIAL:

FINISH:

WEIGHT: GRAMS

DESCRIPTION: MAPLE-CUBESAT

SIZE: A

DRAWING NUMBER: 19-PA-017

REVISION: 00

SCALE: 1:3 | DO NOT SCALE DRAWING | SHEET 1 OF 1

6 5 4 3 2 1

D C B A

REVISION HISTORY

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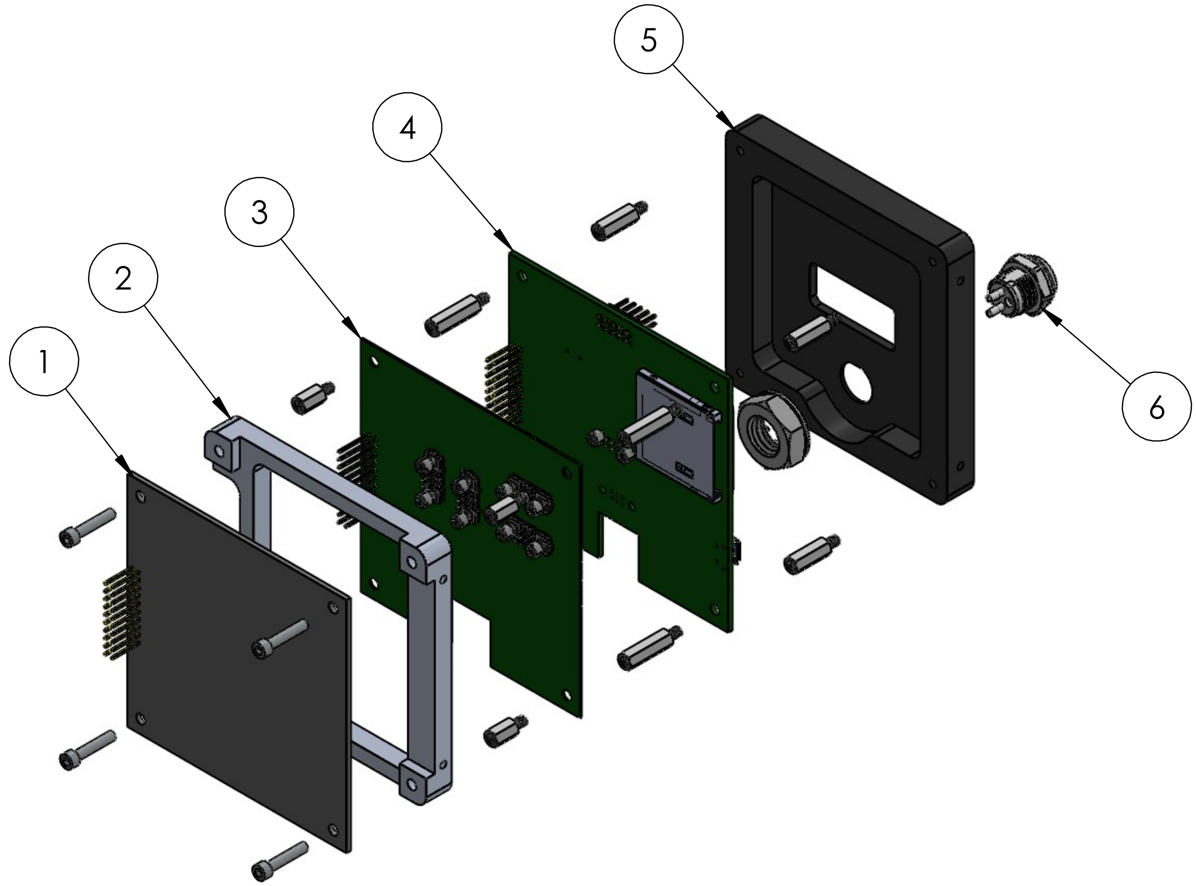

ITEM NO.	DESCRIPTION	QTY.
1	BATTERY BOARD	1
2	BATTERY PCB MOUNT	1
3	RADIO BOARD	1
4	ARM BOARD	1
5	SYSTEMS MODULE END FACE	1
6	KEYSWITCH	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
REMOVE BURRS AND SHARP EDGES

TOLERANCES:
LINEAR: ±0.15 mm
ANGULAR: ±1°

WATERLOO ROCKETRY

	NAME	DATE
DRAWN	J.ROBINSON	MAY 19/2019

MATERIAL:

FINISH:

WEIGHT: GRAMS

DESCRIPTION: SYSTEMS MODULE

SIZE: A

DRAWING NUMBER: 19-PA-018

REVISION: 00

SCALE: 1:2

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SHEET 1 OF 1

REVISION HISTORY			
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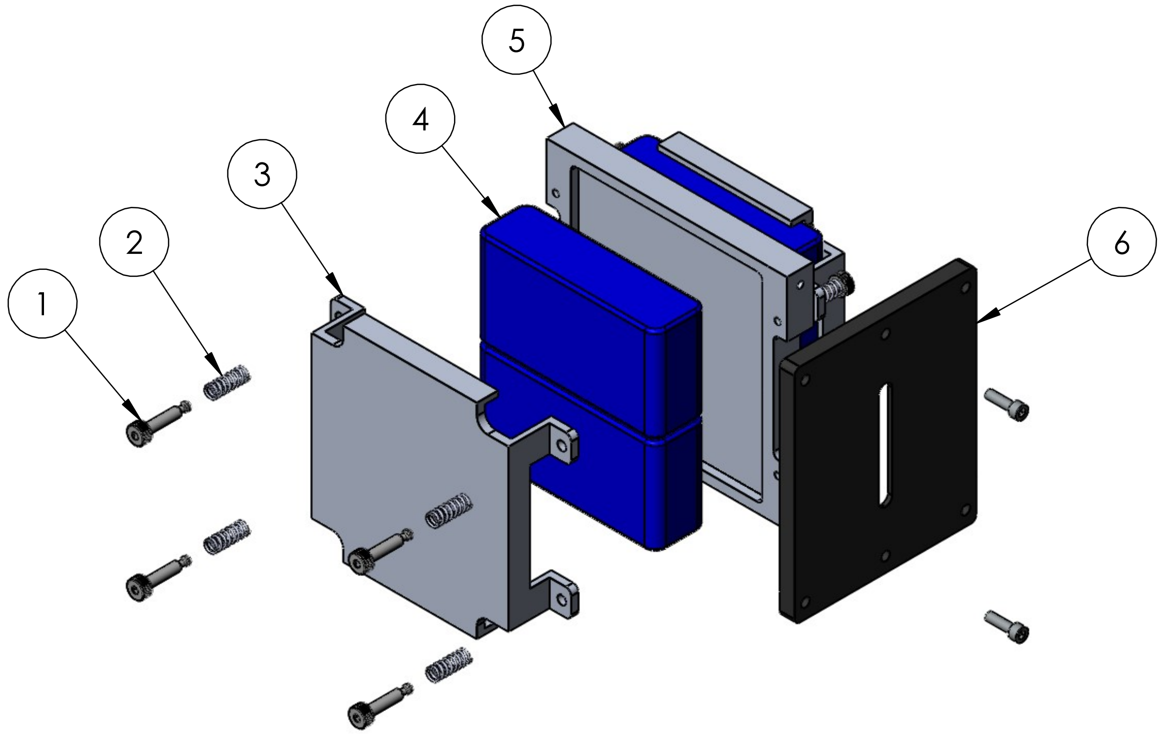

ITEM NO.	DESCRIPTION	QTY.
1	SHOULDER SCREW	8
2	COMPRESSION SPRING	8
3	BATTERY COVER PLATE	2
4	HYPERION 1100 mAh BATTERY	4
5	BATTERY MOUNTING PLATE	1
6	BATTERY FRONT MOUNTING PLATE	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
REMOVE BURRS AND SHARP EDGES

TOLERANCES:
LINEAR: ±0.15 mm
ANGULAR: ±1°

WATERLOO ROCKETRY

	NAME	DATE
DRAWN	J.ROBINSON	MAY 19/2019

MATERIAL:

FINISH:

WEIGHT: 614.69 GRAMS

DESCRIPTION: BATTERY MODULE

SIZE: A

DRAWING NUMBER: 19-PA-019

REVISION: 00

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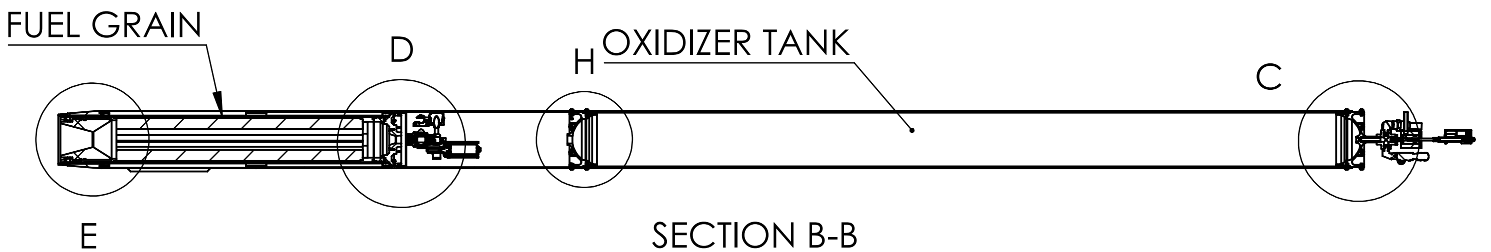
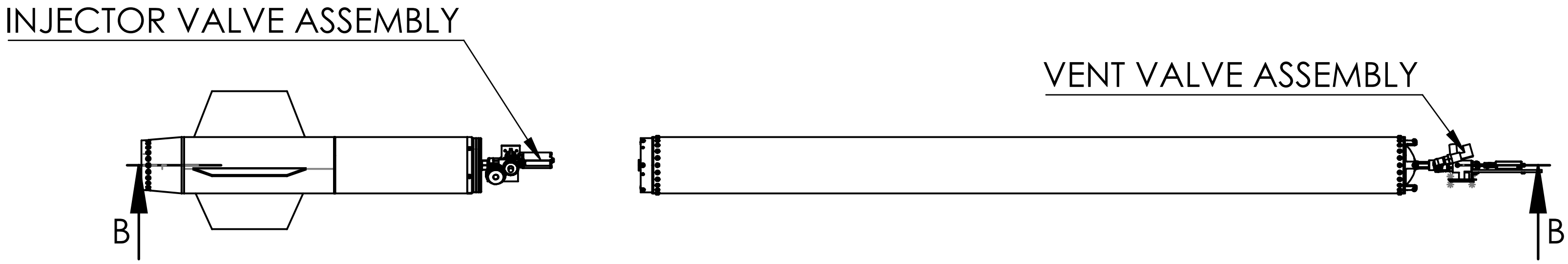
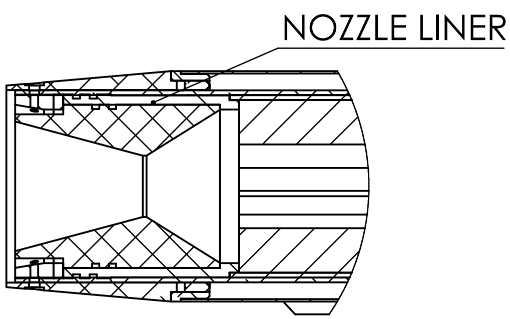
DO NOT SCALE DRAWING

SHEET 1 OF 1

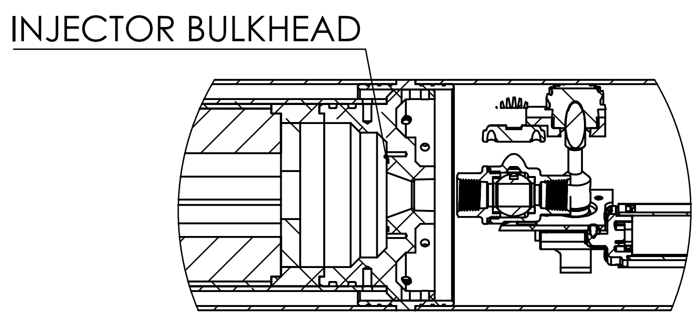


SECTION B-B
SCALE 1 : 20

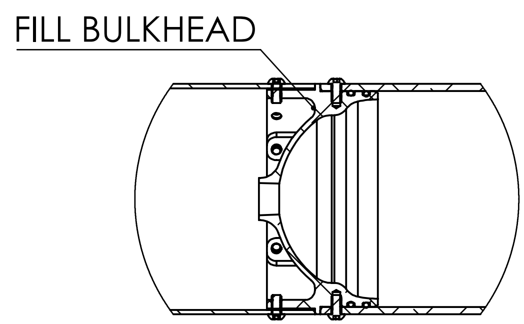




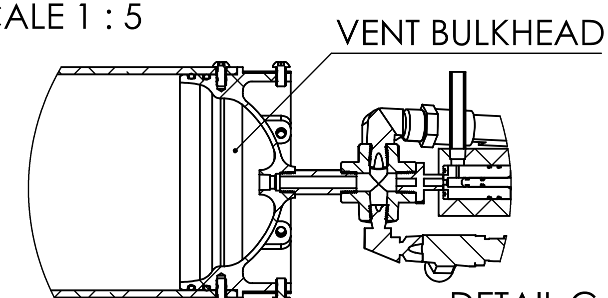
DETAIL E
NOZZLE
SCALE 1 : 5



DETAIL D
SCALE 1 : 5



DETAIL H
SCALE 1 : 5



DETAIL C
SCALE 1 : 5

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
REMOVE BURRS AND SHARP EDGES

TOLERANCES:
LINEAR: ±0.15 mm
ANGULAR: ±1°

WATERLOO ROCKETRY

	NAME	DATE
DRAWN		

MATERIAL:

FINISH:

WEIGHT: GRAMS

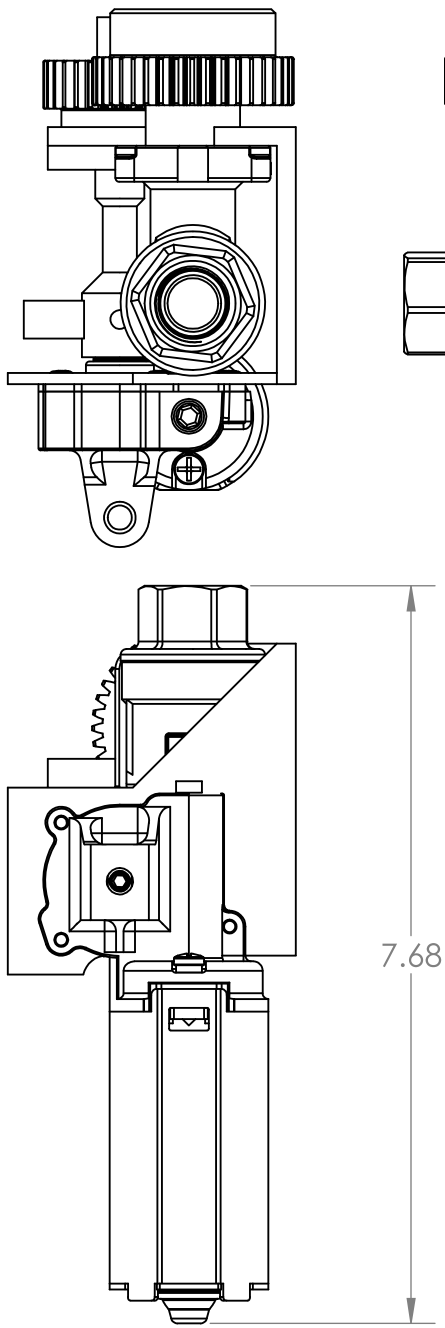
DESCRIPTION:
OX TANK AND CC

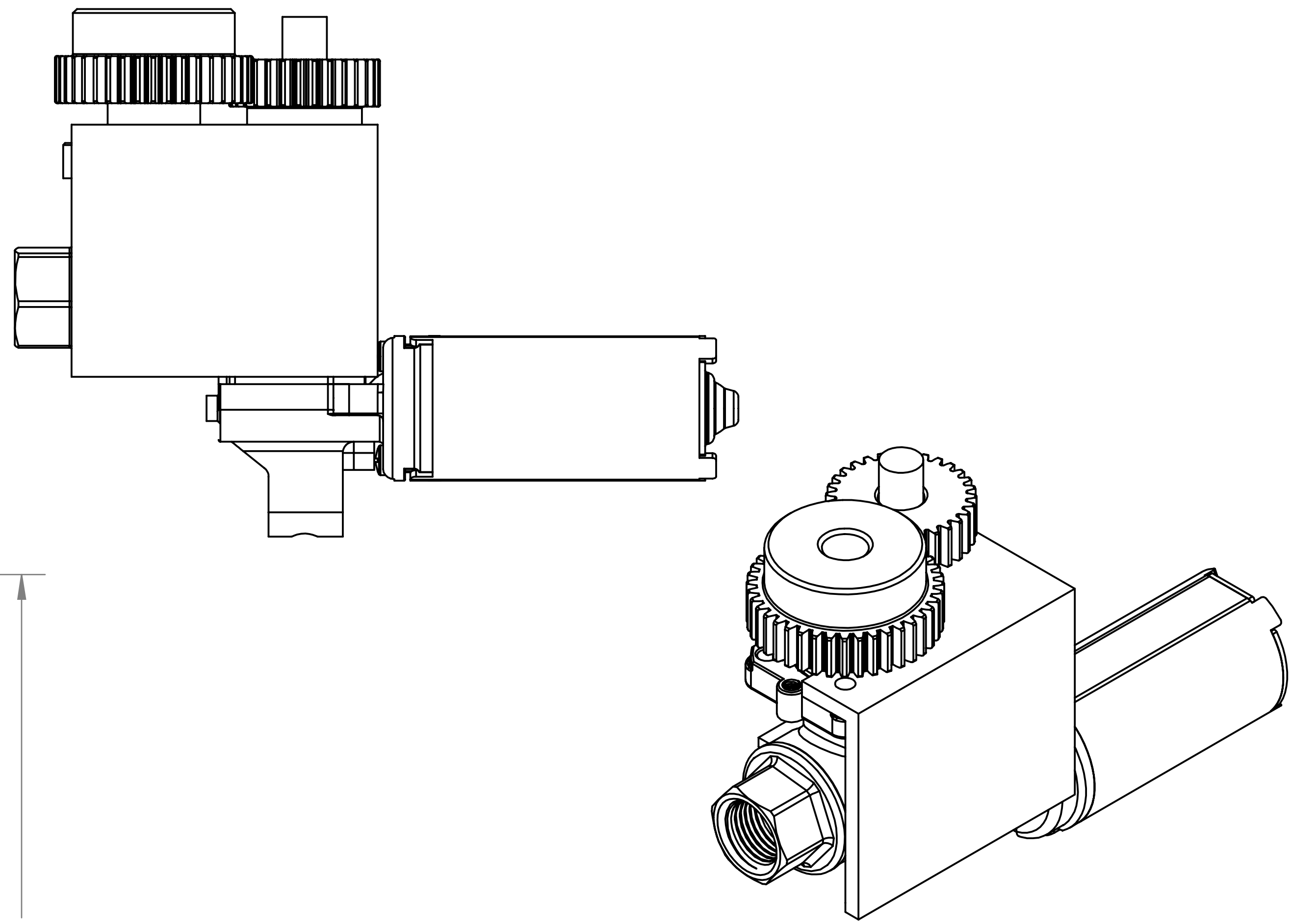
SIZE	DRAWING NUMBER:	REVISION
A		

SCALE: 1:15	DO NOT SCALE DRAWING	SHEET 2 OF 2

REVISION HISTORY

REV	DESCRIPTION	DATE	AUTHOR
XX	XXXXXXXXXXXXXX	XXX XX/XXXX	X.X





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
REMOVE BURRS AND SHARP EDGES
TOLERANCES:
LINEAR: 2 DECIMALS: ±0.010"
3 DECIMALS: ±0.005"
ANGULAR: ±1°

	NAME	DATE
DRAWN		

MATERIAL:

FINISH:

WEIGHT: LBS

WATERLOO ROCKETRY

DESCRIPTION:

SOTS - INJECTOR VALVE

SIZE: A

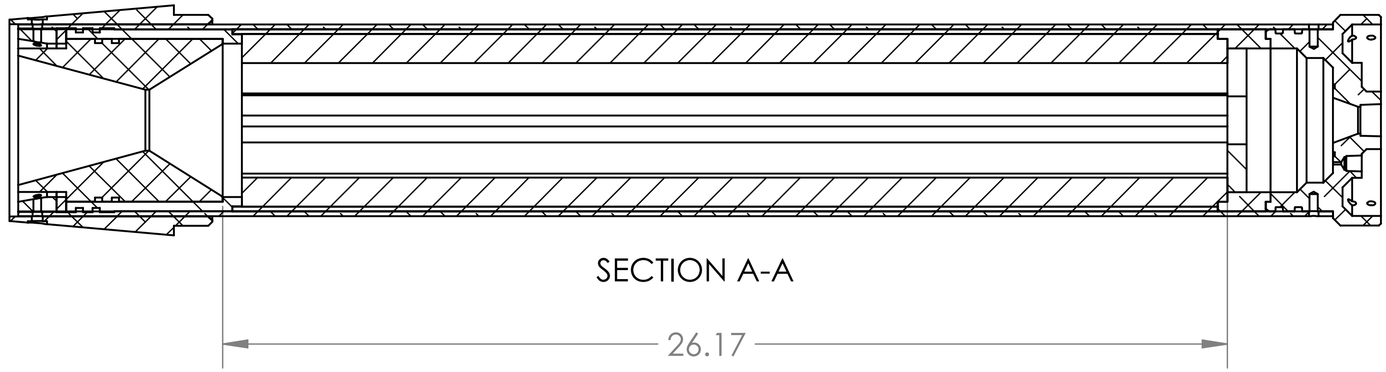
DRAWING NUMBER:

REVISION

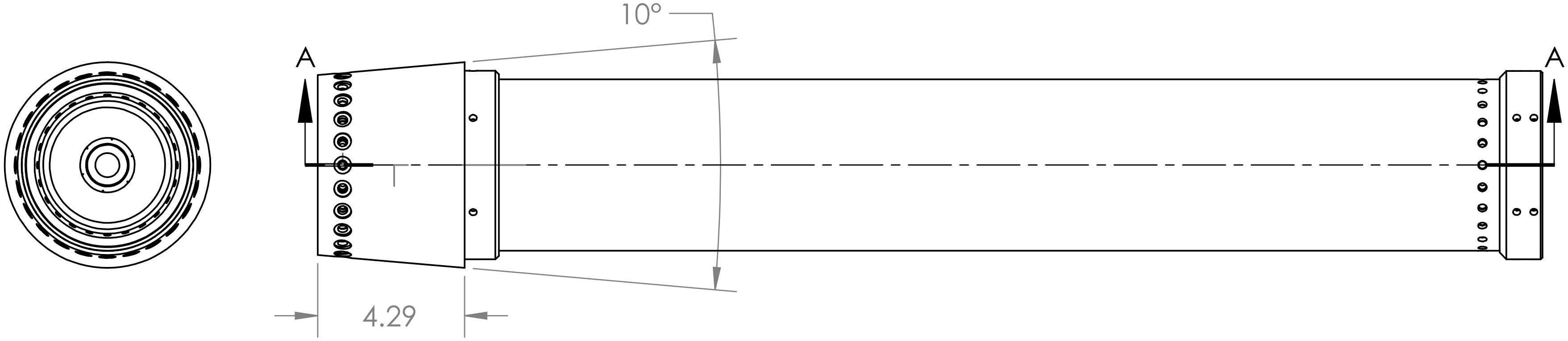
SCALE: 1:2 | DO NOT SCALE DRAWING | SHEET 1 OF 1

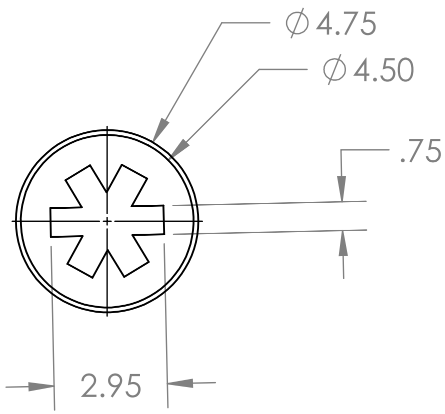
REVISION HISTORY

REV	DESCRIPTION	DATE	AUTHOR
XX	XXXXXXXXXXXXXX	XXX XX/XXXX	X.X



SECTION A-A





FUEL GRAIN

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES REMOVE BURRS AND SHARP EDGES TOLERANCES: LINEAR: 2 DECIMALS: ±0.010" 3 DECIMALS: ±0.005" ANGULAR: ±1°	WATERLOO ROCKETRY

	NAME	DATE
DRAWN		

MATERIAL:

FINISH:

WEIGHT: LBS

DESCRIPTION: SOTS - COMBUSTION CHAMBER

SIZE	DRAWING NUMBER:	REVISION
A		

SCALE: 1:5	DO NOT SCALE DRAWING	SHEET 1 OF 1

REVISION HISTORY

REV	DESCRIPTION	DATE	AUTHOR
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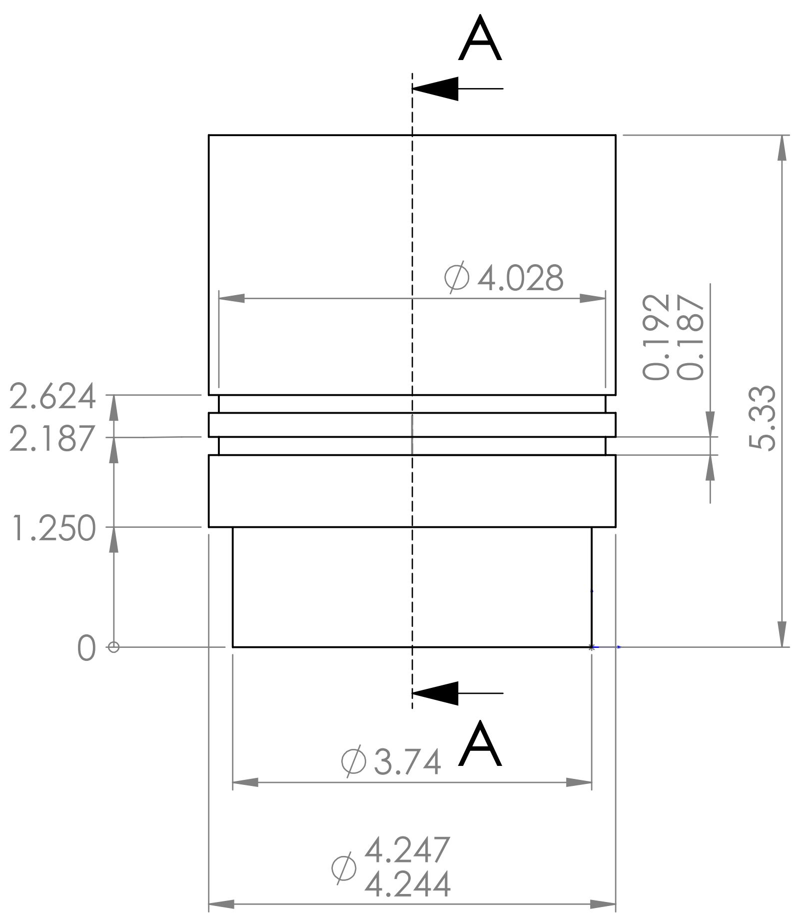
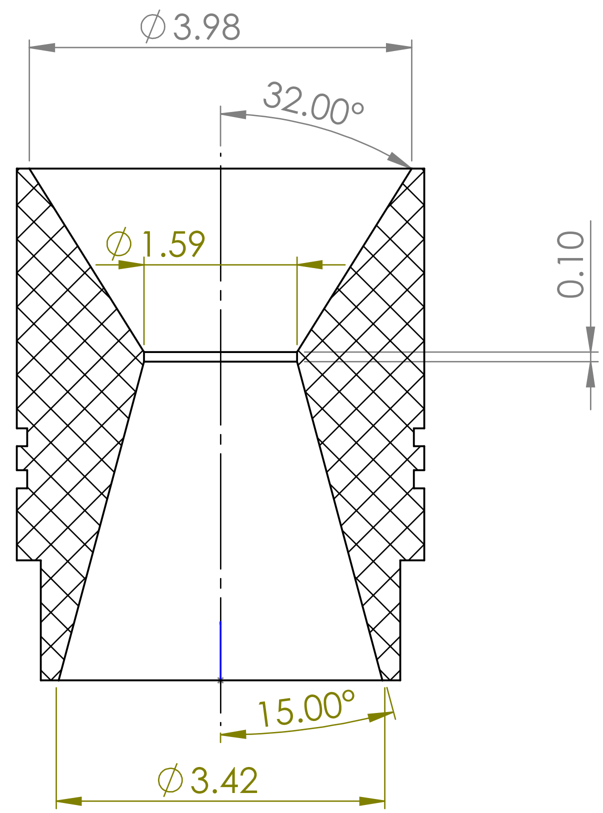




SECTION A-A

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
REMOVE BURRS AND SHARP EDGES
TOLERANCES:
LINEAR: 2 DECIMALS: ±0.010"
3 DECIMALS: ±0.005"
ANGULAR: ±1°

WATERLOO ROCKETRY

	NAME	DATE
DRAWN		

MATERIAL:

FINISH:

WEIGHT: LBS

DESCRIPTION: SOTS- NOZZLE

SIZE: A

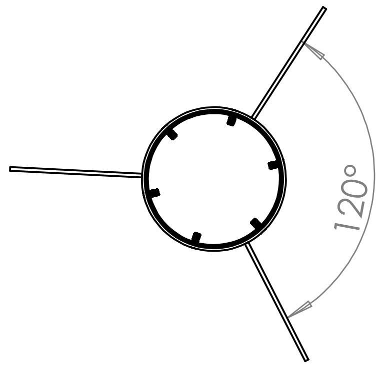
DRAWING NUMBER:

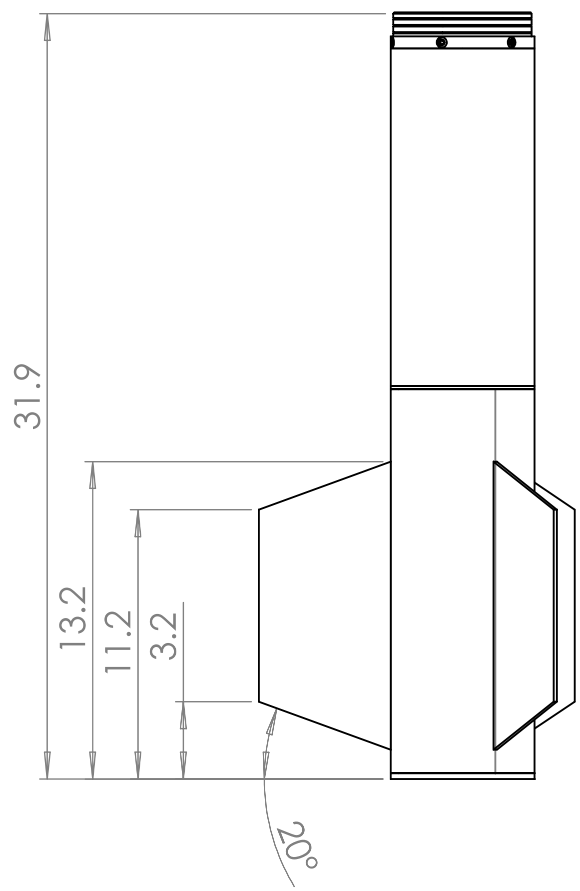
REVISION

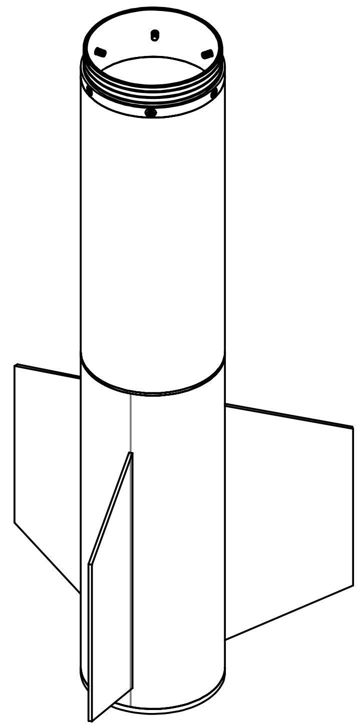
SCALE: 1:2 | DO NOT SCALE DRAWING | SHEET 1 OF 1

REVISION HISTORY

REV	DESCRIPTION	DATE	AUTHOR
XX	XXXXXXXXXXXXXX	XXX XX/XXXX	X.X







UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
REMOVE BURRS AND SHARP EDGES
TOLERANCES:
LINEAR: 2 DECIMALS: ±0.010"
3 DECIMALS: ±0.005"
ANGULAR: ±1°

WATERLOO ROCKETRY

	NAME	DATE
DRAWN		

MATERIAL:

FINISH:

WEIGHT: LBS

DESCRIPTION: SOTS- FIN BODY

SIZE: A

DRAWING NUMBER:

REVISION

SCALE: 1:8

DO NOT SCALE DRAWING

SHEET 1 OF 1

Acknowledgments

The team would like to thank our advisors, who have provided invaluable advice and guidance throughout our development. Specifically, we would like to thank Dr. Andrew J.B. Milne, Dan Steinhaur, Adam Trumpour, Dr. Jean-Pierre Hickey, and Andy Phillips. We would also like to acknowledge the contributions of all of our sponsors. Without their support, we would not be able to continue providing valuable learning opportunities for our team members. In particular, Stein Industries has made and continues to make significant investments in our team's success. Stein Industries and Dan Steinhaur deserve special acknowledgement for the many years of support that they have provided to our team. Finally, the team wishes to thank all of the team alumni who have paved the way for the current team members. The team owes much to the dedication of past members.

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[1] N. Christopher, T. Cojocar, J. Deery, M. Daly, C. Farrow, D. Jiang, S. Kong, H. Li, R. Liu, E. Ma, M. Marczak, A. Mihaila, A. Morrison, D. Ng, A. Paul, V. Rajkumar and E. Yang, "Unexploded Ordnance Hybrid Rocket: Team 38 Project Report for the 2018 IREC," in *Proceedings of the 2018 Spaceport America Cup Conference*, Las Cruces, 2018.

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[4] Robert Bosch GmbH, "CAN Specification 2.0," Stuttgart, 1991.