Vidar III Hybrid Rocket

Team 96 Project Technical Report for the 2017 IREC

Jacob Deery, Nicholas Christopher, Miranda Daly, and Hilbert Li

Waterloo Rocketry Team, Waterloo, Ontario, N2L 3G1, Canada

Vidar III is the Waterloo Rocketry Team's submission in the 10k ft SRAD Hybrid/Liquid and other category of the 2017 IREC. Vidar III contains a SRAD nitrous oxide (NOS) and HTPB hybrid engine, with a unique pyrotechnic valve. The main objective of the Waterloo Rocketry Team is to successfully launch and recover a SRAD hybrid rocket engine. Because of this, Vidar III is not competing in the payload challenge. At the 2016 IREC, Vidar III encountered an ignition failure, and was unable to launch. For this reason, the team has redesigned the ignition system of the engine. Additionally, the injector has been redesigned to mitigate the back-flow of hot combustion gases into the oxidizer tank, which was the cause of the explosion at the 2015 IREC. This year, the team has also implemented a remote fill system which is operational at a distance of 2000 ft.

I. INTRODUCTION

The Waterloo Rocketry Team is an undergraduate student design team, representing the University of Waterloo. The team will be competing in the 1st annual Spaceport America Cup, hosted by the Experimental Sounding Rocket Association (ESRA) from June 20-24, 2017 at Spaceport America, New Mexico. The team has developed the Vidar III rocket with the goal to launch and recover a self-built hybrid rocket.

The team consists of approximately 20 members in Mechanical, Mechatronics, Electrical, Computer, Chemical, Civil and Nanotechnology Engineering programs. The team's stakeholders include the University of Waterloo, as we are representing the University at international competition. The University has supported the team by providing funds, infrastructure and equipment and has been integral to its success. Among the team's stakeholders are also our sponsors who have donated supplies and funds to support the team over the years. In particular, the team has received invaluable support from Dan Steinhaur of Stein Industries, both in the way of sponsorship and technical expertise. Other stakeholders who have provided the team with expert advice are Dr. Andrew J.B. Milne and Adam Trumpour, both who are invested in the team and its success. Finally, the most important team stakeholders are the members themselves. There are over 30 students who have contributed to the project over the years in research, development, design, manufacture and testing in order to bring the project to where it stands today. They have also provided us with background knowledge and researched required to allow future teams to further its development. The success of this rocket would acknowledge the time and effort sacrificed by these students over the years.

The team management strategy involves assigning projects to leads based on members' individual ability and area of expertise. Team members are encouraged to choose to partake in projects they feel will help them to develop themselves from a technical, teamwork and operational perspective. The role of the team lead is to coordinate with the project leads in order to efficiently overcome obstacles and properly allocate resources. The team also places a strong emphasis on consulting advisors when making critical design decisions.

II. SYSTEM ARCHITECTURE OVERVIEW

A cross section of Vidar III is shown in Figure 1. There are four main subsystems of the rocket: the propulsion system, aero-structure, recovery system, and payload. In addition, the ground support equipment for this rocket is a significant portion of the project. The design of the rocket is modular, using aluminium couplers to attach the sections, facilitating modifications of individual subsystems. Vidar III uses a monocoque design, and does not separate the outer airframe from the other subsections of the rocket. This has been done mostly to reduce the complexity and cost of the design.

The engine of Vidar III is a student researched and designed NOS/HTPB hybrid engine with a pyrotechnic valve. The engine is designed to achieve a 10,000 ft apogee. The recovery system consists of a drogue and main parachute, deployed using two commercial altimeters as well as a GPS module for recovery. The payload module contains an 8.8 lb dead weight and a functional payload submodule containing a video camera and accelerometer/gyroscope. Vidar III is not competing in the payload challenge. Almost all of the components of the rocket are machined by team members.

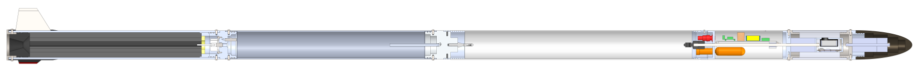


Figure 1: Sectional view of Vidar III

A. Propulsion Subsystems

1. *Combustion Chamber*

The combustion chamber is shown in Figure 2. It is a 1/4" thick, 4" OD aluminium cylinder. Both the top bulkhead and the nozzle are sealed with 2 o-rings. The combustion chamber is insulated with a 1/4" thick ABS tube, and sealed with flame-resistant caulking on the top and bottom ends. The fuel is cast into the ABS tube, and is composed of 90% HTPB and 10% atomized aluminium. The geometry of the grain is shown in Figure 3 and the HTPB/aluminium ratio was chosen based on a series of experimental tests. The grain geometry is achieved by using an investment casting method where styrofoam is used to create a mould, and is dissolved in acetone after the fuel has solidified. The combustion chamber has a factor of safety (FOS) of 4.2, and has been hydro-statically tested to 1.5 times the maximum expected operating pressure.

2. *Nozzle*

The nozzle is machined out of graphite by team members, and therefore is a linear approximation of a bell nozzle. The nozzle can be seen in Figure 2, and its specifications are included in Table 1.

Table 1: Nozzle specifications

	Diameter (inches)	Angle (degrees)
Inlet	2.607	45
Exit	1.890	15
Throat	0.869	N/A

3. *Oxidizer Tank*

The oxidizer tank is shown in Figure 2. It is a 3/16" thick, 4" OD aluminium cylinder. The oxidizer used is nitrous oxide (NOS). The bulkheads on either end of the cylinder act as end caps. They are sealed with 2 o-rings each, and fastened with bolts attached radially. The oxidizer tank has a FOS of 2.5, and has been hydro-statically tested to 2 times maximum expected operating pressure. There is a permanent vent hole on the oxidizer tank in order to ensure that the tank does not over-pressurize due to an increase in temperature after filling. The vent hole is additionally used to vent the tank of NOS in the event of an aborted launch attempt. There is a dip tube attached to the vent hole. 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 gives visual confirmation that that the tank is filled to the desired level. Additionally, a load cell underneath the rocket will sense the mass of oxidizer inside the tank. Using the weight of oxidizer

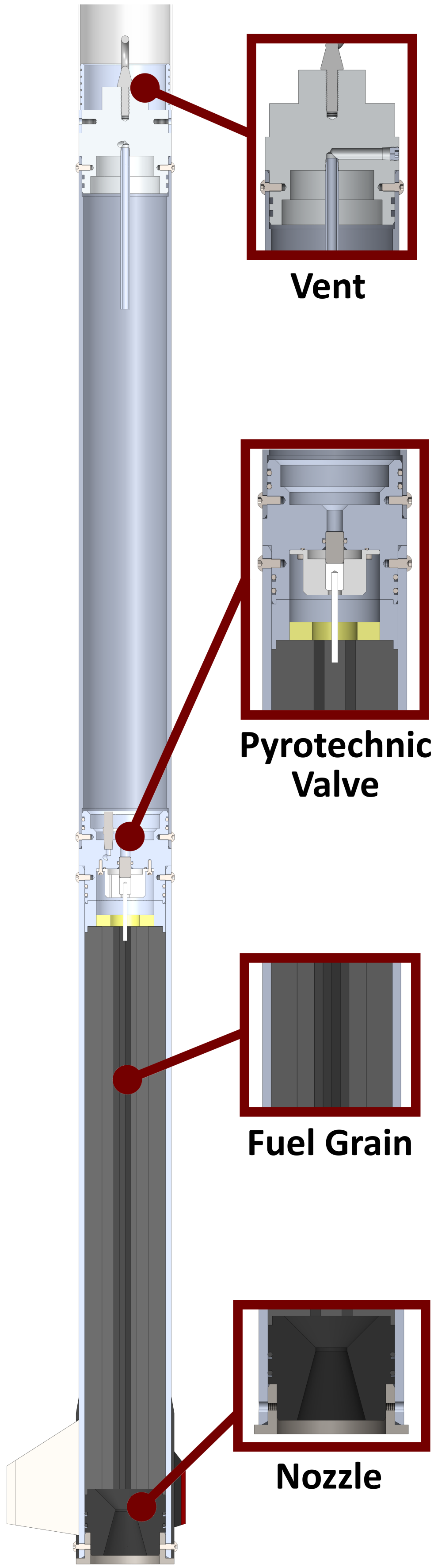


Figure 2: Engine overview. The oxidizer tank sits above the combustion chamber.

Figure 3: Fuel grain cross section

and data from a pressure sensor, the liquid level inside the tank can be approximated. For filling, there is a one-way quick disconnect valve on the bottom bulkhead.

4. Pyrotechnic Valve

The ignition system and valve actuation are coupled, as shown in Figure 4. The channel between the oxidizer tank and the combustion chamber is sealed with a piston and o-ring. When the ignition puck ignites, it simultaneously vaporizes fuel and burns away a pellet which holds the piston in place. Once the pellet has burnt, the pressure on the piston pushes the burnt pellet material into the combustion chamber, and allows the piston to displace past the o-ring, breaking the seal and allowing oxidizer to flow. The piston falls into the channel previously occupied by the pellet. A lip on the oxidizer channel restricts the piston's movement into the oxidizer tank in case of back pressure, acting as a check valve to prevent flow from the chamber to the tank in case of back pressure.

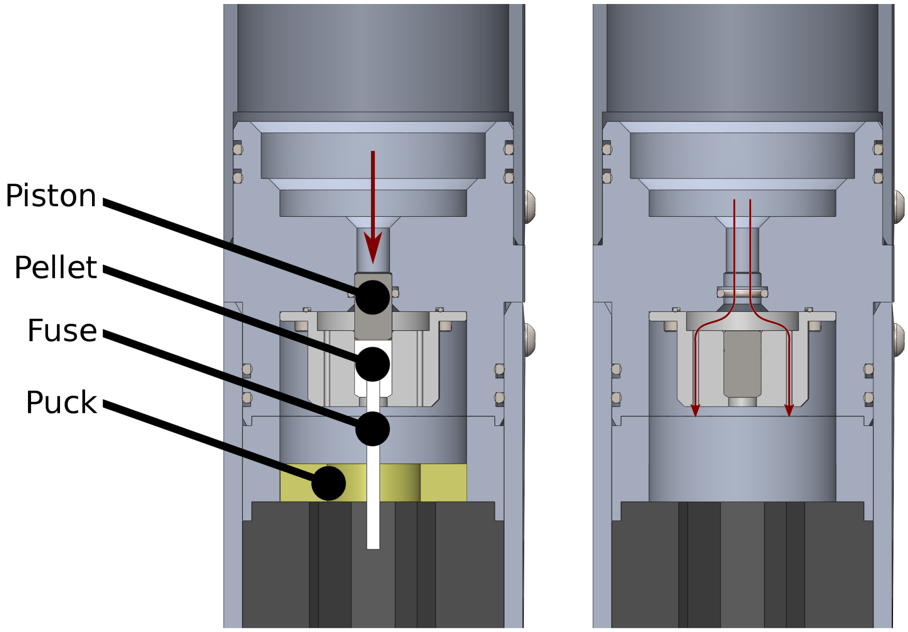


Figure 4: Pyrotechnic Valve. Left: Before ignition. Right: After ignition. Red arrows show the flow of NOS.

5. *Ignition*

The ignition puck, and pellet are composed of 70% potassium nitrate (KNO_3) and 30% epoxy. The fuse consist of a piece of string coated in the same mixture. The use of string facilitates casting and reduces the brittleness of the fuse. The ignition puck is cast with a nichrome coil and all solder joints embedded inside. This is achieved by the lost foam casting (LFC) method, which is a form of investment casting using styrofoam. In previous years, holes were drilled inside the puck, and nichrome was weaved through. Embedding the nichrome inside the puck has the advantage of higher heat transfer to the puck, and less chance of the nichrome connections breaking before ignition due to less variability during installation and less stress on the nichrome during transportation. Through rigorous testing, this method has proven to be significantly more reliable. The nichrome is connected to a 12 V power source, which generates the heat that ignites the puck.

6. *Injector*

To reduce feed-system coupled instabilities, which lead to backflow of combustion gases to the oxidizer tank, the injector of Vidar III was redesigned for the 2017 IREC. The pressure drop across the old injector was determined to be 25%. The new injector pressure drop was tested to be approximately 40%. The aspect ratio of the redesigned injector orifices was increased significantly in the new injector design. This is done to promote vapour formation inside the injector, which chokes the flow of oxidizer across the injector.[1] This redesign has effectively mitigated feed-system coupled combustion instabilities for Vidar III.

B. Aero-structures Subsystems

1. *Airframe*

Vidar III is designed to be modular for ease of assembly. Since the primary objective of the project is to achieve a working engine, optimizing the airframe has not been a priority for the team. The propulsion, recovery, avionics, and payload subsystems are all housed in separate modules, which are connected by aluminium couplers and bulkheads. All of the airframe components are joined using radial bolt circles. For simplicity, Vidar III uses a monocoque design. As there is no outer airframe, the primary airframe structure consists of 6061-T6 aluminium for the engine, fiberglass for the recovery and avionics modules, acrylic for the payload module, and pine wood for the nosecone.

2. *Nosecone*

Since Vidar III is expected to remain subsonic for the entire flight with a simulated maximum velocity of 161 m/s, an elliptical nosecone was chosen (Figure 5). The nosecone measures 4" across at the base and is 8" in length. Pine wood was selected as the nosecone material due to its machinability, low weight, availability, and low cost. The elliptical profile was machined on a lathe from stacked discs of pine, and was then hollowed out to allow integration of the deadweight payload component. The machined nosecone is coated with epoxy for increased strength.

3. *Fins*

The fins for Vidar III were designed to optimize stability margin during launch. The dimensions were chosen and validated through flight simulation using mass and thrust data from static testing. Based on the most recent static test, Vidar III will attain a stability margin of 1.25 cal at launch, increasing to 1.7 cal during boost and remaining at approximately 1.7 cal for the majority of the ascent.

The fins are machined from 6061-T6 aluminium and welded to an aluminium fin can, which is secured to the airframe using a radial bolt circle. Vidar III uses three trapezoidal fins (Figure 6), with a root chord of 5", tip chord of 2.5", and height of 2.3". Each fin has a square cross-section measuring 1/8" in thickness.

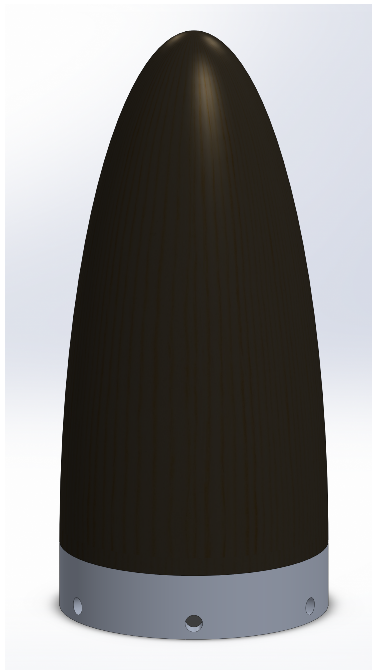


Figure 5: Nosecone.

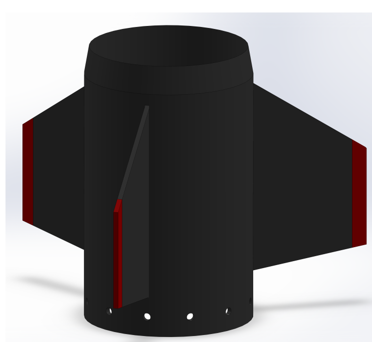


Figure 6: Fin can.

C. Recovery Subsystems

1. System Design and Construction

The recovery system consists of the single bay recovery module and the avionics module. Both modules are contained within fiberglass tubes, which are epoxied to aluminium couplers. Using a direct aluminium connection between modules, rather than a traditional fiberglass connection, allows for extra rigidity against airframe loads during ascent and recovery, as well as ease of fabrication. With the exception of the fiberglass tubes and some avionics hardware, the entire recovery system is student designed and built.

The recovery module houses the drogue and main parachutes, measuring 37.5" and 98" in diameter respectively. The drogue chute is tethered to the avionics module on one end, and a modified 3-ring release system on the other. The main parachute is connected to this release system on one end, and the engine on the other. The recovery module is attached to the engine using a radial bolt pattern.

The avionics module consists of a two commercial Raven altimeters, two 9 V power supplies, three magnetic switches, two CO_2 ejection units, and a single BRB 900 MHz GPS transmitter. These components are securely mounted to a rigid sheet aluminium sled to prevent movement. Each altimeter is wired independently for redundancy, and is armed using a magnetic toggle switch. A separate magnetic switch is used to turn on the GPS. Magnetic switches were chosen over traditional screw switches due to the height of the avionics module above the launch pad; the 4 ft ladder height restriction makes it difficult to access switches within the module. Magnetic switches can be toggled from a distance, without the need for a ladder. Wiring for deployment events are connected through two four pin aviation wire connectors that lead to the recovery bay. These allow the connections to be easily disconnected, providing easy transport and pyrogen safing. The avionics module is attached to the recovery module using shear pins, arranged in a radial bolt pattern that shear upon pressurization with CO_2.

2. Deployment Events

Upon arming, the altimeters continuously track the rocket's pressure-based altitude. Upon detecting the vehicle's descent post-apogee, the drogue chute is deployed. The altimeters actuate the CO_2 ejection units using an e-match, quickly pressurizing the recovery module. This energetically separates the avionics module from the recovery module, simultaneously pulling out a drogue chute to stabilize the rocket's orientation and speed as it continues descent. After the next altitude milestone is reached, the altimeters actuate a set of pyrotechnically charged wire cutters on the modified 3-ring release system, extracting the main chute from its containment bag. The GPS transmitter will ping the location of the avionics module to facilitate location acquisition. See Figure 10 for a diagram of the deployment events.

The initial descent speed of the vehicle is simulated to be 90 m/s after drogue parachute deployment. 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 area of the parachute and thus the size were calculated for a ground hit speed of 8 m/s. Ground testing of the recovery deployment system is performed by programming the Raven altimeters to simulate ascent and descent of the rocket.

D. Payload Subsystems

Vidar III is the first iteration of the Vidar rocket to feature a functional payload. The payload serves two purposes: video capture and vibration data. The payload electronics assembly consists of an MPU-6050 motion tracking device, Arduino Nano microcontroller, 2.4 GHz XBee RF transceiver, and lithium polymer battery. The motion tracking device contains an integrated accelerometer and gyroscope. The x, y, and z acceleration are used to identify low-frequency longitudinal oscillations of the rocket. These oscillations, known as pogo oscillations, result from the interaction of combustion instabilities and the rockets airframe structure, and can only be observed during flight. The gyroscope is used to log rotation rate in the x, y, and z directions. These data are transmitted to launch control for real-time visualization of roll rate, and used post-flight for flight path visualization and flight stability analysis.

In addition to the electronics assembly, the payload features a GoPro HERO3+. This camera is set to record throughout launch, ascent, and recovery for video documentation of the mission. The GoPro is held in place using a 3D printed mount, and the electronics assembly and GoPro are both secured to an aluminium frame. In order to meet the minimum payload mass requirements, the electronics assembly and GoPro are supplemented with 8.81 lb of steel. The payload is built to PocketQube dimensions of 2P.

The majority of the payload is housed in the payload module, which consists of an acrylic tube connected by aluminium couplers to the nosecone and avionics module. Acrylic was used to allow the GoPro to record video. Due to length, the payload deadweight extends into the nosecone, and is secured with a threaded rod. The integrated payload assembly can be seen in Figure 7.

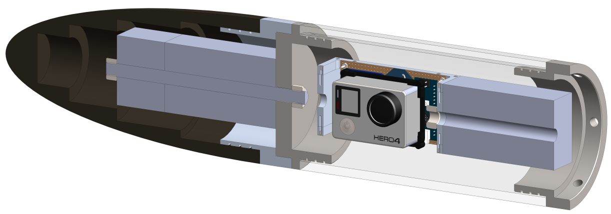


Figure 7: Sectional view of the payload module

E. Ground Support Systems

1. Remote Fill/Disconnect System

For the 2017 IREC, the team is introducing a remote fill/disconnect system in order to decrease risk to personnel and improve the speed of fill procedure. The remote fill subsystem replaces the manual fill and vent valves with automated electric ball valves, which are remotely controlled by launch personnel. For redundancy, the manual valves are left in parallel with the automated valves. If the remote fill procedure fails, the manual fill procedure is executed. A fluid circuit diagram of the Vidar III engine and fill system can be found in the Appendix.

The remote disconnect subsystem Figure 8 allows launch personnel to disconnect the NOS fill line from the fill port at a safe operating range. When connected to the oxidizer tank, the fill line is secured to the disconnect arm, which pivots at a mount bolted to the launch tower. During fill, the end of the disconnect arm is held by a bungee cord under tension, and the arm is prevented from moving by straps secured with a modified 3-ring release mechanism. After the conclusion of fill procedure, a linear actuator is used to pull a pin, disengaging the 3-ring release and allowing the bungee cord to pull the disconnect arm. As the arm pivots, the fill adapter on the fill line is disconnected from the fill port, and the fill line is pulled away from the rocket.

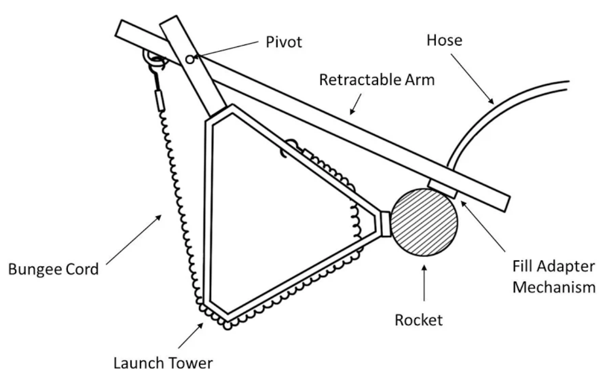


Figure 8: Fill disconnect mechanism

2. *Remote Launch Control System*

Due to the mandated maximum operating range of 2000 ft, the team has developed an electronic system for remote control of fill, disconnect, data acquisition (DAQ), and ignition procedures. Instead of wiring the ignition, remote fill/disconnect, and DAQ control boxes directly to actuators and instrumentation, the control boxes are connected to the remote launch control system (RLCS) interface box. Communication between the interface box and the receiving box at the launch tower is performed wirelessly through 900 MHz XBee RF transceivers, with a range of over 5 km. Two Arduino Unos are used to interface between the transceivers, DAQ sensors, and control circuits.

As part of the DAQ system, load cell data, for measuring NOS mass, and pressure sensor data, for measuring NOS pressure, are logged at 1 Hz during fill procedure, and transmitted via radio. Fill data is output on a display to allow launch personnel to monitor NOS mass and pressure during fill procedure. The remote fill, remote disconnect, and remote ignition subsystems use control boxes connected to the RLCS interface box, but are otherwise unchanged. All control signals are sent via RF transceiver, resulting in the actuation of relays at the launch tower and fill lines.

3. *Launch Tower*

The team's launch tower consists of five sections of steel lattice, and reaches a total height of 39' when fully erected. The team also uses an 8020 extruded aluminium launch rail measuring 36' in length. The rail is secured to the tower using bolts, and the tower is kept upright using both a base made from rectangular aluminium tubing and three guy wires that are anchored into the ground with stakes. The launch tower supports the launch rail, including the rocket, and provides mounting points for the remote disconnect arm, remote disconnect linear actuator, load cell, and break link mount.

4. *Break Link*

The break link mechanism is installed during launch preparations, and prevents the rocket from leaving the launch pad until a threshold thrust has been reached. This mechanism was introduced to ensure that Vidar III would attain a suitable takeoff velocity for off-rail stability. Based on tensile testing of the mechanism, and flight simulation using a modified thrust curve, the mechanism will release at a net thrust of 96 lbf, resulting in an off-rail velocity of 106.3 ft/s.

The break link adapter is connected to the base of the fin can, and consists of an aluminium block with a hole through which a shear pin is passed (Figure 9). This pin secures to a cable, which mounts to a mounting point on the launch tower base. The cable is placed under tension by use of a turnbuckle. Once the engine exceeds the threshold thrust, the shear pin breaks, allowing the rocket to proceed to takeoff.

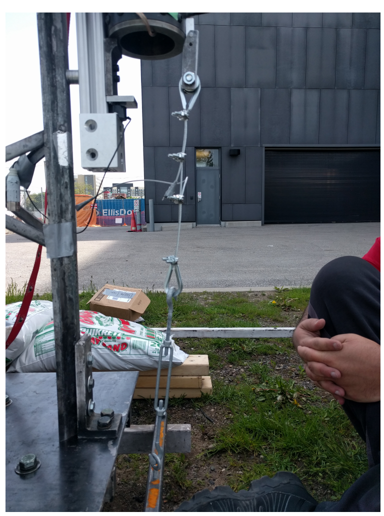


Figure 9: Break link mechanism

III. MISSION CONCEPT OF OPERATIONS OVERVIEW

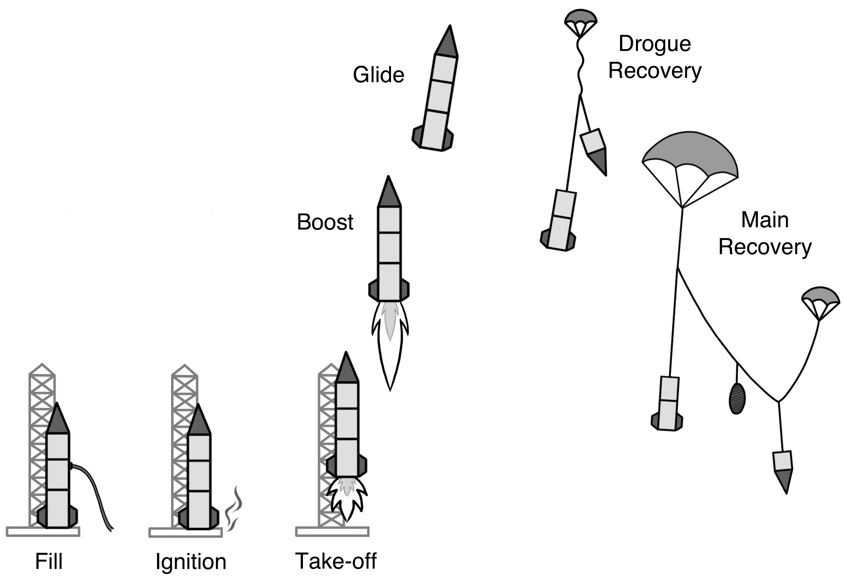


Figure 10: Vidar III mission phases for the 2017 IREC

The Concept of Operations Overview contains numerical data taken from a simulation of Vidar III based on the most recent engine test. It is notable that the engine has since been modified slightly to target an apogee of 10,000 ft. Therefore, the altitude, speed and burn time data is not what is expected of Vidar III in its current state.

A. Fill Phase

In order to enter into the fill phase, all prerequisite assembly and setup procedures must be complete. The fill phase begins when the supply valve on the NOS supply cylinder is opened and nitrous oxide at 750 psi begins to enter the supply lines. The fill valve is opened, allowing liquid NOS to fill the oxidizer tank. Once the launch tower load cell reading plateaus and the NOS pressure has reached the acceptable cutoff as defined in the operations checklist, the fill valve is closed and the vent valve is opened, venting the remaining NOS from the fill lines. Following vent, the remote disconnect system is activated, and the fill line is disconnected from the oxidizer tank.

B. Ignition Phase

The ignition phase begins after remote disconnect is complete and the team has obtained clearance to proceed with launch procedures. The ignition key switch is activated and the emergency stop is released, arming the system. After ensuring that it is still safe to proceed, the ignition button is depressed and held down, closing the ignition circuit and allowing current to flow to the nichrome coil igniter. Within 5 seconds, the igniter begins burning, and visible signs of smoke are seen from the nozzle. At this point, the ignition button is released. After approximately 10 more seconds, the pyrotechnic valve is opened and NOS flow begins, resulting in ignition of the solid fuel grain and initial thrust. The ignition phase is concluded after the rocket reaches the threshold thrust of 100 lbf plus the weight of the rocket and the break link breaks, allowing the rocket to begin takeoff.

C. Takeoff Phase

At first motion, the rocket enters takeoff phase. The rocket begins accelerating and ascending the launch rail. As the rocket leaves the launch rail, it reaches a velocity of 106 ft/s and attains a stability margin of 1.25 cal.

D. Boost Phase

The boost phase begins once the rocket departs the launch rail. The engine continues burning for approximately 7 seconds, accelerating the rocket to approximately 500 ft/s and climbing to an altitude of approximately 3000 ft. At burnout, the stability margin of the rocket is approximately 1.7 cal.

E. Glide Phase

Following burnout, the rocket enters the glide phase for the remainder of its ascent. As the engine is no longer producing thrust, the rocket begins to decelerate. The rocket reaches an apogee of 5700 ft at 13 seconds after burnout and 23 seconds after engine ignition. Over this phase, except for immediately prior to apogee, the rocket maintains a stability margin between 1.0 and 1.8 cal.

F. Drogue Recovery Phase

Once the rocket reaches apogee, the Raven altimeters send an ignition signal to the pyrotechnic disconnect mechanism. The CO_2 canisters in the recovery module are punctured and the airframe separates between the recovery and avionics modules. The drogue parachute deploys and opens, holding the rocket to a descent speed of approximately 90 ft/s. At this point, the main parachute remains undeployed, secured by the modified three-ring release mechanism.

G. Main Recovery Phase

The main recovery phase begins when the rocket reaches an altitude of 1500 ft AGL during descent. The Raven altimeters send a second signal, activating the pyrotechnic line cutters. Once these lines have been cut, the three-ring release disengages, allowing the drogue parachute to pull the main parachute out of the recovery bay. As it inflates, the main parachute slows the rocket to its final velocity of 28 ft/s. This phase, and the mission, ends when the rocket hits the ground.

IV. CONCLUSIONS AND LESSONS LEARNED

A. Team Management

In the past year, the team has grown significantly in size to accommodate a wider range of projects and develop a wider range of abilities. In particular, the team has shifted from a team composed primarily of Mechanical Engineers to one that includes more members in Electrical and Mechatronics Engineering. It was learned through this growth that a strategy where the team lead is the expert on every subject is not sustainable. It is not realistic for the team lead to be involved heavily in the technical details of every single project. This was learned as the number of projects increased and as more projects incorporated electrical design. A good example of this is the development of the Remote Launch Control System.

The team management strategy has shifted to one where the team leads focus is to understand the roadblocks and drivers for all projects, understanding enough about their technical challenges and integration with other systems so that systems come together to complete the project in a timely matter. While the management still holds some amount of technical expertise, project leads are trusted to have extensive knowledge of their respective projects. With dedicated experts, the team lead is able to focus moreso on making sure projects are overcoming obstacles as they arise and ensuring resources are being properly allocated. This new strategy freed up personnel to allow for the development of a functional payload for this iteration of the rocket, which has not been attempted by the team thus far. It also allowed projects like the Remote Launch Control System to develop more efficiently than similar projects in the past due to a dedicated project team.

As the team moves forward from year to year, senior members leave, and junior members gradually take their place. To ensure that knowledge is successfully transferred to the new generation, the team employs several strategies. Most often, junior members will shadow senior members when working on projects. Hands-on skills, like machining, are best taught through practice, so junior members have lots of opportunities to fabricate and test components for the vehicle. The team also promotes extensive documentation throughout any project, so members can review each stage of the development process and learn from its successes and failures. Lastly, the team keeps a virtual library of resources that were discovered during the design stages, so that junior members can trace the basis of decisions back to credible information.

B. Technical Development

The most important objective for this team has always been to successfully launch and recover a student researched and developed hybrid rocket engine. The failure of the ignition system in 2016 reiterated for the team that the most important thing is to develop a working engine. Complicating the design at this stage is not desirable and can be done in future years once this primary objective is achieved. Any added complexity that risks the primary objective should be avoided until the team can obtain proof of concept. This is especially important due the rarity of launch opportunities for the team. This philosophy drove the two biggest projects of the term: the ignition redevelopment and injector redesign. These were identified as critical projects due to the failure of Vidar II in 2015 and Vidar III in 2016.

The injector redevelopment project taught the team about how to approach technical design. It is understood that not every design needs to be approached with a brand new creative solution. There are often sources that have already addressed problems faced as part of the project. These available solutions can provide critical insight and a good baseline about how to begin approaching a problem. It is also understood that all technical challenges will come with their own levels of uncertainty, making empirical data crucial for validation. The injector needed to be unique for Vidar III, but based on research into injector design and preventing combustion instability, it was determined that achieving choked flow was desired for the team's design and as a result the aspect ratio of the holes in our injector was increased. This design was then validated with several cold flow and hot fire tests to confirm the validity of the design.

The development cycle of this rocket also has helped the team to understand the inconsistency that comes along with hybrid rocket design. The importance of changing as few variables as possible when performing tests became well understood as part of the testing and validation stages of the ignition system and of the injector. This applies to variation between tests, but also to variation from desired launch configuration and conditions. It is of the utmost importance that test conditions are as close to launch conditions as can be achieved and that variations between tests must be well documented and minimized wherever possible.

Appendix

A. SYSTEM WEIGHTS, MEASURES, AND PERFORMANCE DATA APPENDIX

All pertinent system weights, measures, and performance data can be found in the 3rd Progress Update, summarized below.

Table 2: Overall Rocket Parameters

	Measurement	Additional Comments (Optional)
Length (inches):	128.5	
Max Diameter (inches):	4.25	
Vehicle weight (pounds):	42.1	* Payload not included in vehicle weight
Liftoff weight (pounds):	63.1	
Number of stages:	1	* Not including Kinetic Energy Dart
Strap-on Booster Cluster:	No	
Propulsion Type:	Hybrid	
Propulsion Manufacturer:	Student-built	
Kinetic Energy Dart:	No	

- Propulsion System Information
  - Single-stage propulsion system: SRAD Hybrid, 7 pounds of nitrous oxide and 2.2 pounds of HTPB/aluminium, M Class, 5575 Ns
  - Total impulse of all motors: 5575 Ns

Table 3: Predicted Flight Data and Analysis

	Measurement	Additional Comments (Optional)
Launch Rail:	Team-Provided	
Rail Length (feet):	32	
Liftoff Thrust-Weight Ratio:	6.2	At rail departure
Launch Rail Departure Velocity (feet/second):	106.3	
Minimum Static Margin During Boost:	1.24	*Between rail departure and burnout
Maximum Acceleration (G):	5.1	
Maximum Velocity (feet/second):	528.2	
Target Apogee (feet AGL):	10000	
Predicted Apogee Altitude (feet AGL):	5689	Based on last Static Test Fire: see Other Pertinent Information

- Payload Information
  - Steel ballast (approximate mass 4 kg)
  - Functional payload submodule: GoPro HERO3+ for video capture, accelerometer/gyroscope, XBee radio transceiver

Table 4: Recovery Information

Payload Recovery Method:	Parachute	
1st Stage Recovery:		Additional Comments
Type:	Parachute	
Primary Initiation Sensor:	Barometer	
Secondary Initiation Sensor:	Barometer	
Deployment energy Source:	Compressed Gas	
2nd Stage Recovery:		Additional Comments
Type:	Parachute	
Primary Initiation Sensor:	Barometer	
Secondary Initiation Sensor:	Barometer	
Deployment energy Source:	Black Powder	Used to actuate pyrotechnic line cutter

Table 5: Planned Tests

Date	Type	Description	Status	Comments
11-26-16	Ground	Static hot-fire test, inverted	Minor Issues	Oxidizer pressure low due to low ambient temperature. Successful upstream injector and chamber pressure measurements
1-21-17	Ground	Static hot-fire test, inverted	Successful	Used water bath to increase oxidizer temperature. Successful upstream injector pressure measurement. Unsuccessful chamber pressure measurement
2-11-17	Ground	Cold flow test	Successful	
2-25-17	Ground	Cold flow test	Successful	
3-18-17	Ground	Cold flow test/ignition	Successful	
3-26-17	Ground	Static hot-fire test, inverted	Successful	Using smaller oxidizer tank and new injector
5-20-17	Ground	Recovery deployment test	Minor Issues	System is unchanged from last year. Previous tests are still valid
5-28-17	Ground	Remote fill test	TBD	Testing the use of actuated valves to fill with oxidizer
6-1-17	Ground	Recovery deployment test	TBD	

- Other Pertinent Information
  - The data contained in "Predicted Flight Data and Analysis" is based off of a simulated flight of the rocket, using data from the last Static Test Fire of the engine. Following this test, we have increased the volume of liquid oxidizer in an attempt to raise the apogee of the rocket closer to the target of 10,000 ft.

B. PROJECT TEST REPORTS APPENDIX

Throughout the 2016-2017 year, ground tests were performed on all critical subsystems of Vidar III. Due to Canadian aerospace regulations, no in-flight testing could be performed. In total, two recovery system tests, three Static Test Fires of the Vidar III engine, and two pressure vessel tests were conducted.

1. Recovery Systems Testing

A ground test of the recovery system was performed on June 1, 2016. The recovery and avionics modules were assembled, complete with pyrotechnics and parachutes, and the connected modules were laid out horizontally. The Raven altimeters were programmed through Featherweight software to simulate an ascent, apogee, and descent. At 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 modified three-ring release to deploy. The drogue chute was pulled away from the recovery module, pulling the main parachute from the fiberglass tube and thus verifying successful pyrotechnic actuation. A further test was performed on May 19, 2017, confirming that both the CO_2 canisters and pyrotechnic cutters were functional.

2. Dual Redundancy of Recovery System Electronics

The controller used for the recovery system is a commercial Featherweight Raven altimeter. Two of these units are used in parallel to control recovery deployment mechanisms. The two controllers use independent circuits with separate power supplies and switches. Each controller is capable of actuating both CO_2 canisters and both pyrotechnic line cutters in the event that the other controller fails. The dual avionics circuits can be seen in Figure 11.

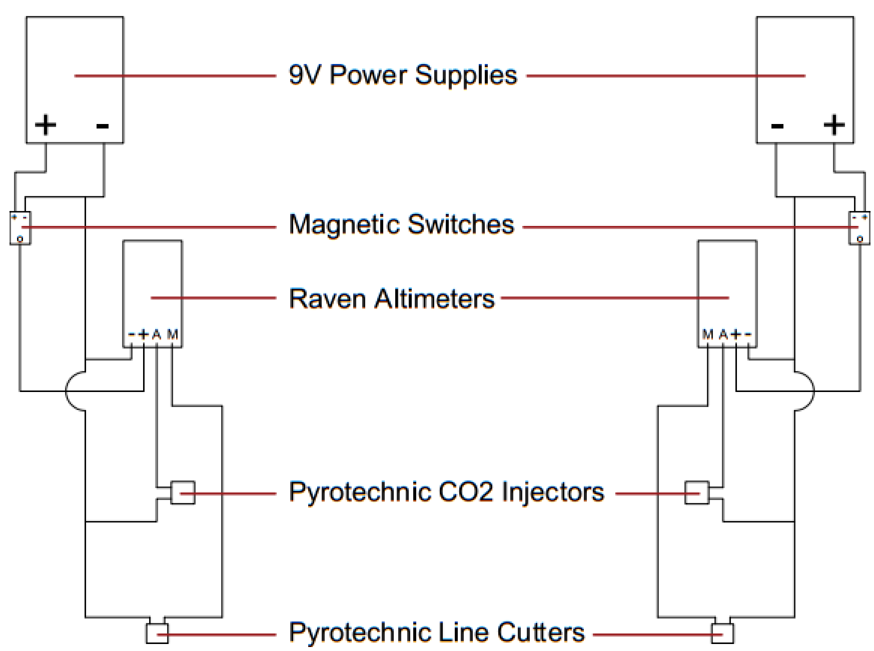


Figure 11: Electrical schematic of recovery electronics

3. SRAD Propulsion Systems Testing

During the 2016-2017 cycle, the team conducted three propulsion tests of the Vidar III hybrid rocket engine. All three tests were performed as static tests, with the combustion chamber inverted and separated from the oxidizer tank.

i. Static Test Fire 5

Static Test Fire 5 was conducted on November 26, 2016, with three objectives:

- Verify the functionality of the ignition straw system
- Acquire pressure data from the engine to investigate the injector design and confirm the theory for cause of the 2015 failure
- Familiarize new members with engine test procedures

For STF 5, the team used an upgraded data acquisition (DAQ) system to record oxidizer tank pressure, pre-injector pressure, combustion chamber pressure, thrust, and oxidizer tank mass. The data from STF 5 can be seen in Figure 12.

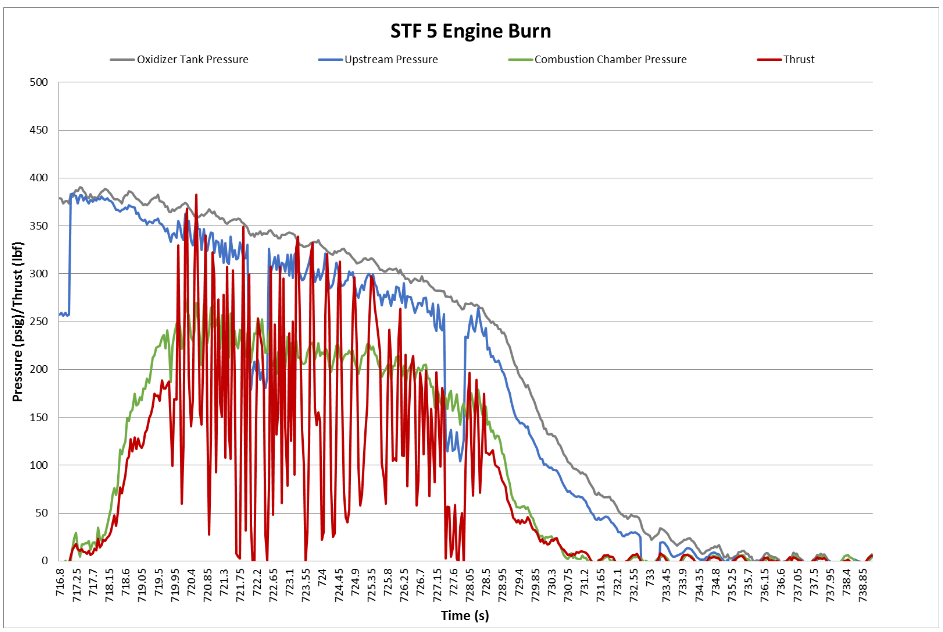


Figure 12: Static Test Fire 5 Engine Burn

Although the ignition straw system functioned as expected, meeting the first objective, the burn appeared visually unstable, which is confirmed by the test data. This was attributed to a failure of the oxidizer heating system, preventing the NOS from reaching acceptable pressure levels prior to ignition. As a result of this unstable burn, the engine achieved a low peak thrust. Additionally, melting of the injector stem and partial burn-through of the ABS tube were identified during disassembly of the engine. Due to this instability, the test data was deemed unusable for evaluation of the injector. Despite the success of the ignition straw system, it was abandoned after this test in favour of the more robust LFC system.

ii. Static Test Fire 6

Static Test Fire 6 was conducted on January 21, 2017, with three objectives:

- Verify the functionality of the lost foam casting ignition system

- Acquire pressure data from the engine to investigate the injector design and confirm the theory for cause of the 2015 failure
- Prove that desirable engine operating conditions are achievable at low ambient temperatures

Due to the low oxidizer pressure attained during STF 5, modifications were made to the tank heating system in order to avoid an unstable burn. This test was conducted with the new LFC igniter instead of the ignition straw system used for STF 5. The plumbing and DAQ systems remained unchanged from STF 5.

The LFC igniter functioned nominally, providing visible indication of ignition approximately 5 seconds after the electrical signal was given. As observed visually and confirmed by the test data (Figure 13), the engine burn was significantly more stable than in STF 5. The modified tank heating system was considered a success, and the data was used to evaluate the characteristics of the old injector.

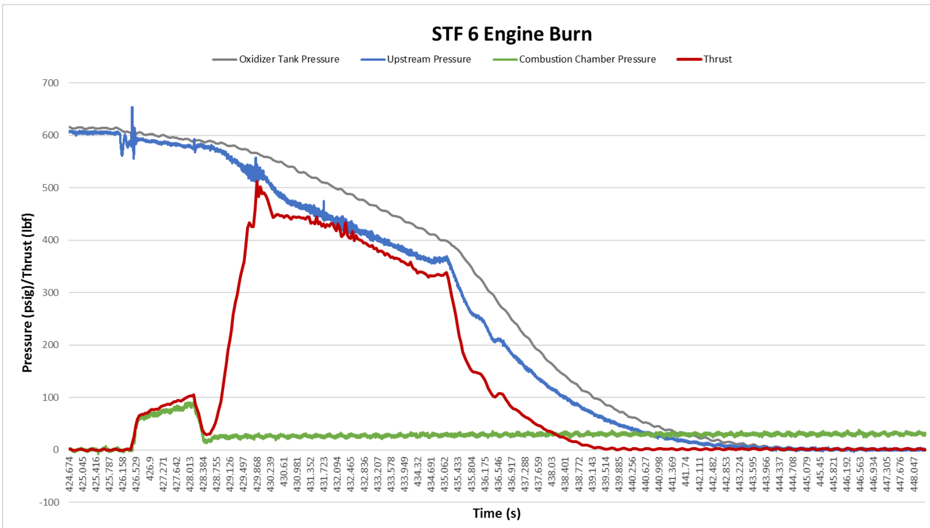


Figure 13: Static Test Fire 6 Engine Burn

iii. Static Test Fire 7

Static Test Fire 7 was conducted on March 26, 2017, with three objectives:

- Demonstrate that the engine is capable of reaching desired thrust levels with the redesigned injector
- Verify that the redesigned injector reduces combustion instabilities
- Demonstrate that the thrust curve obtained with a smaller oxidizer tank results in desired apogee and off-the-rail velocity
- Verify that sufficient fuel remains at burnout to prevent damage to the combustion chamber
- Observe timing of the pyrotechnic valve
- Obtain mass data from the oxidizer tank for flight stability analysis

Between STF 6 and STF 7, several changes were made to the oxidizer tank and feed system. Primarily, the old injector was replaced with the redesign injector. Additionally, in order to reduce the simulated apogee of the rocket closer to the target of 10,000 ft, the oxidizer tank was shortened and the length of the dip tube was increased. This resulted in a decrease in effective liquid NOS volume of 41%.

As a direct result of the NOS decrease, the burn time was significantly shortened. However, due to the rate of NOS discharge from the vent hole, the oxidizer tank did not reach as high a pressure as the 650 psi of STF 6. The lower NOS pressure, in combination with the higher pressure drop of the redesigned injector, resulted in a lower combustion chamber pressure and thus a lower peak thrust (Figure 14).

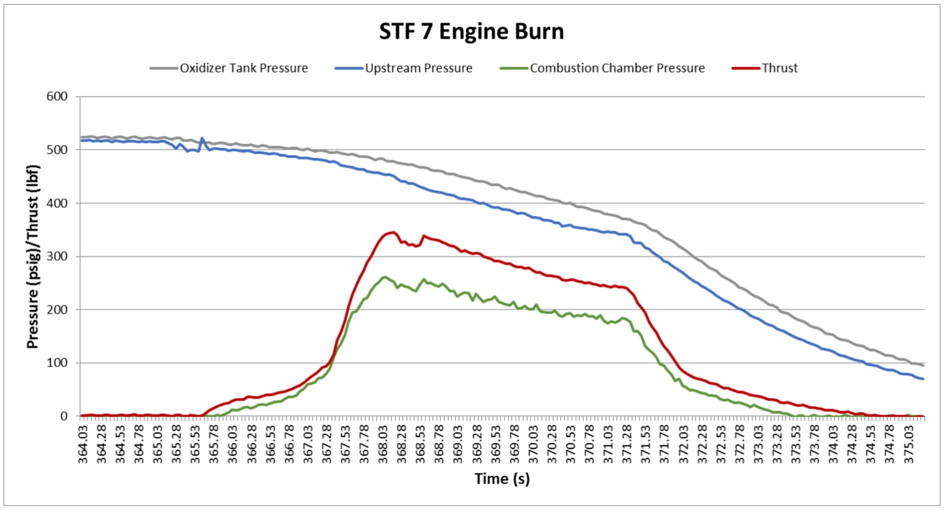


Figure 14: Static Test Fire 7 Engine Burn

The objectives of STF 7 were partially met. Analysis of pressure data indicated that combustion instabilities were mitigated, and the burn was visibly significantly more stable. Additionally, no burn-through of the ABS tube was observed, and the combustion chamber remained shielded from damage. The pyrotechnic valve opened as expected, allowing full oxidizer flow after combustion of the ignition pellet. Although the lower thrust attained during this test resulted in an apogee of only 5,700 ft, well below the target altitude of 10,000 ft, the mass and thrust data indicate that the burn would have achieved sufficient off-the-rail velocity for stability during the ascent. Based on the results of STF 7, the team elected not to conduct further propulsion system testing, deeming the system flight-ready.

iv. Fluid Circuit Diagram

A fluid circuit diagram for the Vidar III engine and fill system, in flight configuration, can be seen in Figure 15.

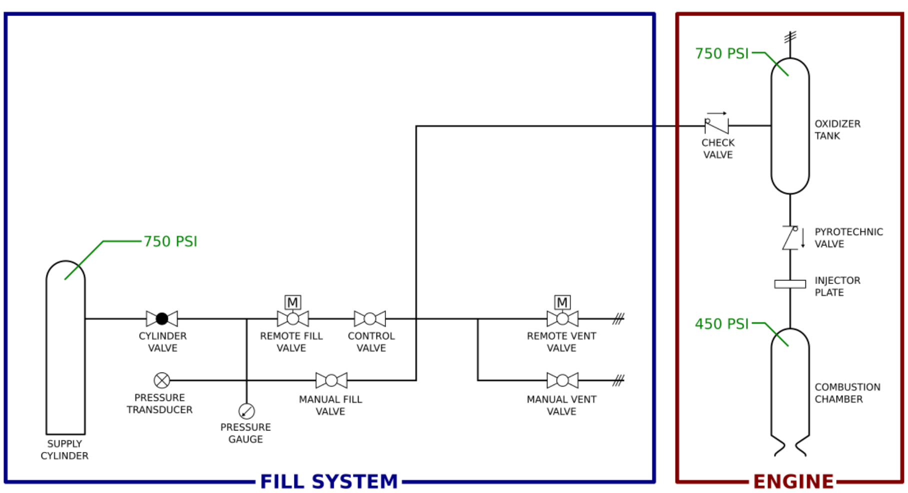


Figure 15: Fluid circuit diagram for the Vidar III engine and fill system. Nominal NOS pressures are in green.

During the 2016-2017 year, Static Test Fires were not conducted in flight configuration, but rather in an inverted configuration with the oxidizer tank and combustion chamber separated. Moreover, additional pressure transducers were used for data acquisition purposes. A fluid circuit diagram for this setup can be seen in Figure 16

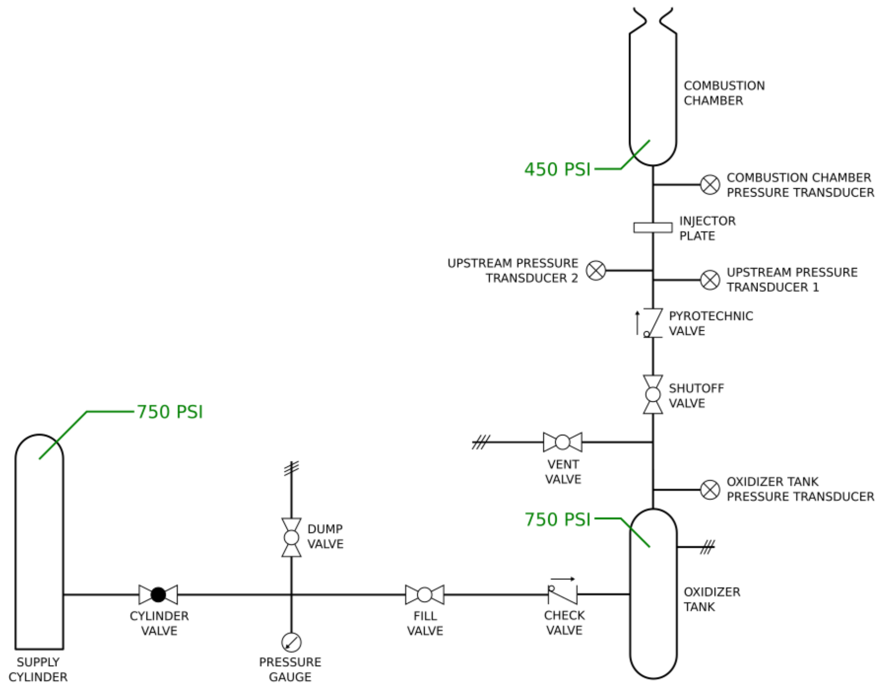


Figure 16: Fluid circuit diagram for Static Test Fires of the Vidar III engine and fill system. Nominal NOS pressures are in green.

4. SRAD Pressure Vessel Testing

After replacing the original oxidizer tank with the current, shorter tank, the team performed a hydrostatic test on the tank. The tank was assembled with bulkheads on both ends and pressurized to 1500 psi, 2 times higher than the expected maximum operating pressure of 750 psi.

A hydrostatic test was additionally performed on the combustion chamber. The chamber was sealed at both ends and filled with water. Given that the maximum operating pressure of the oxidizer tank is 750 psi, and the injector was designed for a 40% pressure drop, the maximum expected operating pressure of the chamber is 450 psi. The chamber was pressurized to 1000 psi, 2.22 times the expected maximum.

C. HAZARD ANALYSIS APPENDIX

The oxidizer used for Vidar III is nitrous oxide (NOS). Among the commonly used hybrid oxidizers, NOS is usually regarded as the safest. However, NOS has two characteristics that make it hazardous to personnel – it is used as a general anesthetic, and it is stored at low temperatures that can cause frostbite if it comes into contact with skin. 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 workbay, 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 teams 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 degrees 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. 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 temperature resistant gloves.

Due to the potency of NOS as an oxidizer, the team ensures that all components that will come into contact with NOS are fully sanitized. This includes the oxidizer tank, bulkheads, and all fill system hoses, valves, and fittings. Components are sanitized using a commercial cleaning solution and rinsed with deionized water, before being dried with compressed air. Sanitation procedures are conducted before each static test of the engine or launch attempt of the rocket.

As HTPB is non-toxic, no special procedures or equipment are required for handling Vidar III's solid fuel. During the fuel casting process, the presence of aluminium powder requires significant safety precautions. Aluminium powder is stored 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 that may result from accidental ignition of aluminium powder.

The pyrotechnic materials used in the ignition and avionics subsystems also require precautions to be taken. Gunpowder and potassium nitrate (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 inherent danger 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 pedestrians from coming too close to the engine. Additionally, two blast shields are erected to protect all personnel involved. The first steel blast shield is placed around the combustion chamber in case of accidental explosion, while the second is placed a distance away from the engine and used for cover by the primary and secondary technicians during testing. All personnel witnessing the test are required to remain a safe distance away and to wear safety glasses and industrial hearing protection.

D. RISK ASSESSMENT APPENDIX

Failure modes of the Vidar III rocket, assessments of risk, and mitigation strategies can be found in Table 6.

Table 6: Risk Assessment for the Vidar III rocket

Waterloo Rocketry Team	Vidar III	26-May-17		
Failure Mode	**Possible Causes**	**Risk of Mishap and Rationale**	**Mitigation Approach**	**Risk of Injury after Mitigation**
Assembly & Launch Preparations				
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 a key switch, emergency stop, and manual depression of ignition button for several seconds.	Low
			Rocket and power supply are not connected to the ignition circuit until immediately prior to fill phase, as per operations procedure.	
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 recovery bullet. Raven altimeter is a commercial electronic device, unlikely to activate prematurely.	Avionics are only to be armed using magnetic switches once final assembly and launch preparations are complete.	Low
	Carbon dioxide canisters are ruptured		All personnel are to remain well away from the rocket after the avionics system has been armed.	
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 70 lb. Rail buttons are not load-bearing.	Tower is raised with rocket on top, with the tower structure and launch personnel 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.	

Failure Mode	**Possible Causes**	**Risk of Mishap and Rationale**	**Mitigation Approach**	**Risk of Injury after Mitigation**
Fill Phase				
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; permanent vent hole provides pressure relief. Clogging of the vent can be identified through absence of visible and audible venting.	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

Failure Mode	Possible Causes	Risk of Mishap and Rationale	Mitigation Approach	Risk of Injury after Mitigation
			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.	
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 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.	LEDs in the ignition box indicate that an ignition signal is currently being sent; 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.	
Takeoff Phase				
Rocket deviates from nominal flight path at takeoff and comes into contact with personnel at high speeds	Failure of launch tower components	Low; simulated off-the-rail velocity is 106 ft/s, resulting in acceptable stability.	Thoroughly inspect all launch tower components before assembly.	Low
	Unexpectedly low off-the-rail velocity resulting in low stability		Implement a break link system to hold the rocket in place until a threshold thrust level is reached.	
			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	Injector has been designed for 40% pressure drop to minimize the chances of backflow.	Low

Failure Mode	Possible Causes	Risk of Mishap and Rationale	Mitigation Approach	Risk of Injury after Mitigation
	Clogging of the nozzle due to bundled ignition wires	inhomogeneity have not been observed during static test fires. Engine components are designed with high factor of safety.	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.	
	Failure of O-ring seal		Oxidizer tank and combustion chamber are designed to rupture laterally instead of radially, minimizing flying debris.	
			Two O-rings are used for redundancy.	
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 1.2-1.8 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.	

Failure Mode	**Possible Causes**	**Risk of Mishap and Rationale**	**Mitigation Approach**	**Risk of Injury after Mitigation**
Glide 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 Raven altimeters	Low; Raven altimeter is a commercial component, 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 rockets position and are able to avoid it if necessary.	
Main parachute deploys at or near apogee, rocket or payload drifts to highway(s)	E-matches fire unintentionally	Low; avionics have been thoroughly tested in a vacuum chamber, 2-ring system is rated to well above expected stress	Ground test all decoupling systems prior to launch.	Low
	2-ring system breaks under load when the drogue is deployed		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 Raven 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 rockets 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 rockets position and are able to avoid it if necessary.	Low

E. ASSEMBLY, PREFLIGHT, AND LAUNCH CHECKLISTS APPENDIX

1. *Engine Assembly Checklist*

- ☐ Oxidizer Tank Assembly
  - ☐ Injector Bulkhead
    - ☐ Make sure the injector bulkhead is sanitized, all the openings are sealed, and all the old o-rings are removed
    - ☐ Prepare the pellet fuse assembly by epoxying the fuse to the pellet. Ensure that the epoxy layer is thin and the connection is rigid
    - ☐ Ensure you are wearing gloves when working with any components of the oxidizer tank
    - ☐ Make sure the vent bulkhead is sanitized, all the openings are sealed, and all the old o-rings are removed
    - ☐ Install the 3" dip tube
    - ☐ Remove the rubber plug to install vent plug. Ensure the Teflon is not too thick or too wide. Extra thickness of Teflon tape will lead to improper installation, and extra width of Teflon tape can block the vent hole from the inside
    - ☐ Seal the vent plug with aluminium foil and masking tape
    - ☐ Install oxidizer tank external o-rings (size: 238) with o-ring lubricant
    - ☐ Align the vent bulkhead to the fill port. Make sure the vent hole is on the opposite direction as the fill port
    - ☐ Ensure to use the correct (shorter) O-ring fillers
    - ☐ Insert vent bulkhead in the oxidizer tank
    - ☐ Check if any of the O-rings ruptured during installation through the bolt holes. If so, remove vent bulkhead, replace O-rings, and reinstall bulkhead
    - ☐ Fasten with twelve 1/4"-28 (1/2") screws
    - ☐ Install check valve on the other side of the injector bulkhead. Ensure that it is in proper orientation by observing the flow direction arrow on the side of the check valve. This should be pointing up towards the oxidizer tank after installation
    - ☐ Install piston o-ring (size: 112) with o-ring lubricant
    - ☐ Install piston. Make sure the piston is installed in the proper orientation, with the more heavily chamfered/dented side facing towards the oxidizer tank
    - ☐ Install injector o-ring (size: 031) with o-ring lubricant
    - ☐ Place pellet inside injector with the fuse sticking out of the central hole
    - ☐ Cap the injector on the piston and bolt it down using six 6-32 screws
  - ☐ Use a plug to seal the fill port
  - ☐ Install oxidizer tank external o-rings (size: 238) with o-ring lubricant
  - ☐ Make sure oxidizer tank is sanitized
  - ☐ Ensure to use the correct (shorter) O-ring fillers
  - ☐ Insert injector bulkhead to the oxidizer tank
  - ☐ Check whether any of the O-rings ruptured during installation through the bolt holes
  - ☐ Check if the O-ring fillers ruptured after installation
  - ☐ Fasten with twelve 1/4"-28 (1/2") screws
- ☐ Combustion Chamber Assembly
  - ☐ Align fuel grain to injector ports (align one star corner to one injector port)
  - ☐ Align bulkhead holes on injector bulkhead to retaining ring holes to help the alignment in the previous step
  - ☐ Mark alignment using a permanent marker

☐ Make sure the nozzle is cleaned (using a toothbrush), and all the old o-rings are removed.
☐ Install o-rings on the nozzle (size: 236) with o-ring lubricant
☐ Wrap o-rings in a thin layer of painters tape to keep it clean
☐ Place nozzle on retaining ring
☐ Apply high temperature caulking on female lip of fuel grain
☐ Use a popsicle stick to evenly spread the caulking
☐ Add a little caulking on the male end of the nozzle
☐ Use a popsicle stick to evenly spread the caulking
☐ Join fuel grain and the nozzle together
☐ Clean excess caulking using paper towel
☐ Ensure the caulking did not spread on to the o-rings
☐ Align combustion chamber to the retaining ring
☐ Place fin can on the bottom of combustion chamber, but do not fasten
☐ Take off the tape on the nozzle o-rings
☐ Slide the combustion chamber and fin can onto the fuel grain assembly
☐ Make sure no component of the fuel grain assembly rotates
☐ Rotate the fin can until the bolt hole for rail button and the pre-marked fill port location are 90 degrees apart clockwise.
☐ Screw the fin can in using ten 1/4"-28 (5/8") screws and a 1/4"-28 (1") screw with rail button
☐ Ensure that the rail button is between two fins
☐ Install the break link adapter onto the retaining ring using a 1/4"-28 (1.5") screw
☐ Join the end of ignition wiring to a thin tube using masking tape
☐ Pass this tube through the fuel grain and nozzle while making sure not to damage the nozzle
☐ Support the engine so that the ignition wires are not pinched underneath the retaining ring
☐ Apply caulking to the male end of the fuel grain
☐ Use a popsicle stick to evenly spread the caulking
☐ Apply caulking to the female end of the spacer
☐ Use a popsicle stick to evenly spread the caulking
☐ Press the spacer onto the fuel grain
☐ Check continuity on both ignition cables to ensure good assembly
☐ Slide the fiberglass sleeve on the injector bulkhead
☐ Install combustion chamber external o-rings (size: 236) onto injector bulkhead with o-ring lubricant
☐ Apply caulking to the male end of the spacer
☐ Use a popsicle stick to evenly spread the caulking
☐ Apply caulking to the female end of the injector bulkhead
☐ Use a popsicle stick to evenly spread the caulking
☐ Make sure the alignment between injector bulkhead and combustion chamber is correct
☐ Ensure to use the correct (longer) O-ring fillers
☐ Insert oxidizer tank assembly onto the combustion chamber assembly
☐ Check if any of the O-rings ruptured during installation through the bolt holes. If so, remove vent bulkhead, replace O-rings, and reinstall bulkhead
☐ Fasten with twelve 1/4"-28 (1/2") screws
☐ Check continuity on both ignition cables to ensure good assembly
☐ Strain relief the ignition cables by using masking tape to connect it to the outside of the engine
☐ Close the nozzle end of the engine using a plastic bag and masking tape
☐ Short the ends of the ignition wires

2. Avionics and Recovery Assembly Checklist

- ☐ Pre-Inspection
  - ☐ Ensure all bulkheads, fiberglass and electronics sled is undamaged
  - ☐ Ensure that all pyrotechnics and batteries are disconnected and shorted before starting
- ☐ Electrical Checks
  - ☐ Ensure that all pyrotechnics and batteries are disconnected and shorted before wiring
  - ☐ Check that all circuit components are properly mounted to the sled with proper spacers, screws and nuts.
  - ☐ Ensure all switches are in the energized position
  - ☐ Check continuity between batteries and the Raven
  - ☐ Check continuity between recovery bay connector pins and the Raven
  - ☐ Turn all switches to the non-energized position
  - ☐ Check nine volt battery for full capacity (nominal 9V)
  - ☐ End of procedure
- ☐ CO_2 System Installation
  - ☐ Ensure all ejection device wires and batteries are disconnected from the electronics bay before proceeding
  - ☐ Ensure the two CO_2 ejection devices are installed into the bulkhead
  - ☐ Install two 38 gram CO_2 cylinders into the ejection devices using two washers to ensure CO_2 vent holes are unobstructed. Do not forget to use teflon tape on the threads of the CO_2 cylinder
  - ☐ End of procedure
- ☐ GPS System
  - ☐ Ensure GPS battery is fully charged Ensure GPS is functional after connecting battery
  - ☐ Turn GPS system off by waving magnet over the magnetic switch
  - ☐ End of procedure
- ☐ Sled Installation
  - ☐ Ensure all wires are tucked away to prevent pinching during installation
  - ☐ Ensure the CO_2 cylinders are installed into the CO_2 ejection device
  - ☐ Ensure that the batteries are installed in the battery holder
  - ☐ Install fiberglass onto upper bulkhead
  - ☐ Line up the sled rod guide with the center rod
  - ☐ Insert sled into fiberglass slowly checking for obstructions to installation
  - ☐ Ensure sled is fully inserted and lower bulkhead is fully seated on fiberglass
  - ☐ Place rubber washer and aluminium sleeve over the remaining center rod
  - ☐ Screw eyebolt onto center rod until snug with washer
  - ☐ End of procedure
- ☐ CO_2 Ejector Setup
  - ☐ Place igniter and wires inside igniter cylinder and center igniter in cylinder using tissue paper
  - ☐ Place epoxy on igniter wires so that when the igniters are pulled, the wires do not pull out of the igniter cylinder

- ☐ Ensure igniter is placed so that it is flush with the rim of the cylinder that touches the puncturing cylinder
- ☐ Place aluminium foil on the working surface
- ☐ Place a separate piece of aluminium foil on the working surface for holding and pouring the gunpowder
- ☐ Place avionics assembly on the first aluminium sheet with the injector body opening upwards such that the entire body is grounded
- ☐ Place O-ring on puncturing cylinder and lightly lubricate with spray silicone lubricant making sure to wipe off excess lubricant
- ☐ Place puncturing cylinder in injector body
- ☐ Fill puncturing cylinder to the rim with gunpowder
- ☐ Ensure igniter leads remain shorted
- ☐ Place O-ring on igniter cylinder and lubricate
- ☐ Place igniter cylinder on top of puncturing cylinder and push down until igniter cylinder is flush with injector body
- ☐ Ensure gunpowder vent holes are clear of obstructions
- ☐ Run igniter wires through body cap and screw cap on tightly
- ☐ Check for movement of the igniter wires
- ☐ If moving, take apart and reseat igniter so that it is seated firmly in place
- ☐ End of procedure

☐ Pyrotechnic Line Cutter Setup

- ☐ Slide an O-Ring into the bottom of the pyrotechnic line cutter to act as a bumper for the piston
- ☐ Insert recovery dual ring rope through the hole of the pyrotechnic line cutter
- ☐ Trim excess rope
- ☐ Insert shearing piston
- ☐ Insert black powder or Pyrodex (0.1mL of Pyrodex is recommended)
- ☐ Insert E-match
- ☐ Place o-rings on E-match along with screw cap to create a seal
- ☐ Slide hex screw over E-match leads and screw into pyrotechnic line cutter
- ☐ End of procedure

☐ Recovery Module Assembly

- ☐ Ensure that all recovery lines are free and not tangled
- ☐ Ensure that the 9V batteries are disconnected
- ☐ Fold the main parachute, gore by gore, in an accordion-style pattern
- ☐ Fold the main parachute vertically in half
- ☐ Roll the main parachute from the top towards the main parachute lines
- ☐ Pack the rolled parachute into the parachute bag so that the main parachute lines extend from one of the open corners
- ☐ Secure the main parachute lines over the parachute bag cover using the elastics
- ☐ Use the carabiner to connect the main parachute line to the main coupling line
- ☐ Connect the modified three-ring release mechanism and secure using the dual ring rope
- ☐ Secure the pyrotechnic line cutters to the primary recovery line using electrical tape
- ☐ Connect the pyrotechnic leads to the connectors on the primary recovery line

- ☐ Secure the drogue parachute line to the base of the avionics module
- ☐ Pack the parachute bag into the recovery module and push it towards the engine end
- ☐ Fasten the eyebolt to the top of the vent bulkhead
- ☐ Wrap a fireproof cloth around the pyrotechnic line cutters to protect main parachute and recovery lines from the black powder burn
- ☐ Apply a thick layer of grease to the coupler at the base of the recovery tube and a thin layer of grease on the velt bulkhead
- ☐ Insert the vent bulkhead into the recovery module
- ☐ Secure the vent bulkhead to the recovery module coupler using 6x 1/4"-28 (1/2") screws
- ☐ Connect the 4 pin connector from the primary recovery line to the avionics module
- ☐ Pack the drogue parachute and the remaining recovery lines into the recovery module
- ☐ Confirm that the Raven altimeters are off
- ☐ Make all appropriate electrical connections at the avionics terminals
- ☐ Wrap a fireproof cloth around the igniter cylinders to protect recovery lines and parachutes from the black powder burn
- ☐ Apply a layer of grease to the avionics and recovery couplers
- ☐ Place the avionics module coupler over the recovery module coupler
- ☐ Secure the avionics and recovery modules together with shear pins
- ☐ Insert the 9V batteries into their mounts
- ☐ End of procedure

3. Payload Assembly Checklist

- ☐ Place the battery in the battery mount
- ☐ Place the electronics board over the battery mount and secure in place using 4 1/16" screws
- ☐ Connect the battery to the female JST-PH connector on the electronics board
- ☐ Place the GoPro camera in the back half of the GoPro mount and place the other half of the mount over the front of the camera
- ☐ Secure the GoPro mount into the frame using 4 1/16" screws
- ☐ Turn the GoPro camera to standby mode with WiFi enabled
- ☐ Thread a 3/8" locknut onto one end of the threaded rod.
- ☐ Push the threaded rod through the hole in the top coupler of the payload shroud, such that the locknut is inside the shroud
- ☐ Place a 3.5" and a 1.5" steel block on the threaded rod, and thread a 3/8 locknut on the other side
- ☐ Tighten the nut, securing the blocks in place
- ☐ Place the nose cone over the steel blocks and secure in place using 1/4-28 screws
- ☐ Place the 3.5" steel block on the threaded rod protruding from the top of the avionics bay
- ☐ Place the payload on the threaded rod
- ☐ Secure the payload by threading a 3/8" locknut onto the threaded rod
- ☐ Connect a lock nut to 3/8" threaded rod, and pass the threaded rod through the top coupler of the acrylic section

- ☐ Place the 3.5” and 1.5” steel block on the threaded rod and secure it with a nut
- ☐ Place the nose cone over the blocks and secure it to the top coupler using 1/4-28 screws
- ☐ Place the nose cone assembly over the payload
- ☐ Secure the nose cone assembly to the avionics coupler using 6x 1/4-28 screws

4. Launch Tower Setup Checklist

- ☐ Tower Base Assembly
  - ☐ Bolt side rods to centre rods of tower base
  - ☐ Place tower base on wooden supports
  - ☐ Secure base and supports with 4 stakes
  - ☐ Align launch pad so that it is tilted away from base camp by 5° from the horizontal
  - ☐ Install 3 guy wire anchorages and 1 winch anchorage
  - ☐ Hook winch onto winch anchorage
- ☐ Tower Assembly
  - ☐ Connect bottom tower segment to base
  - ☐ Set out wooden supports
  - ☐ Connect remaining 4 tower segments
  - ☐ Install and connect 4 launch rail segments
  - ☐ Check that all tower bolts are tightened
  - ☐ Attach 3 guy wires and winch wire to tower
  - ☐ Attach turnbuckles to guy wires
- ☐ Load Cell Installation
  - ☐ Install fixed and sliding supports on launch rail
  - ☐ Ensure that load cell is mounted to fixed support
  - ☐ Install load cell shield
- ☐ Rocket Installation
  - ☐ Ensure 2 launch lugs are installed on the rocket
  - ☐ Slide rocket onto rail
  - ☐ Ensure ignition wires are not damaged
  - ☐ Fill Disconnect Arm Installation
  - ☐ Install L-brackets on tower
  - ☐ Install arm between brackets
- ☐ Pre-Erection Checklist
  - ☐ Items to inspect:
    - ☐ All wooden supports are in place
    - ☐ Guy wires are firmly attached to the tower
    - ☐ Anchors are secure in the ground
    - ☐ Ratchet puller is operational
    - ☐ Launch pad is stable, no signs of damage on structural components

- ☐ Launch pad base has been assembled properly according to the document Launch Pad Assembly Guide
- ☐ Items to have on hand:
  - ☐ Launch pad bolts to fix the pad to the base structure once the tower is erect
  - ☐ Wrench and/or ratchets to tighten bolts
  - ☐ Hard hats
  - ☐ Work gloves
  - ☐ Caution tape
- ☐ People to notify:
  - ☐ Competition organizers
  - ☐ All team members
- ☐ Installation Environment Conditions:
  - ☐ Ensure guy wires are untangled on the ground and do not pose as a tripping hazard
  - ☐ Ensure there are no other tripping hazards present
- ☐ Personnel positions:
  - ☐ Lifting team of 5 people
  - ☐ 1 coordinator
  - ☐ 1 team member supporting rocket
  - ☐ 1 winch operator
  - ☐ 3 team members at guy wire ends
  - ☐ 1 team member to remove wooden frames

☐ Raising Procedure

- ☐ Lift tower to 30° and connect winch to winch cable
- ☐ Raise tower to 5° from vertical by winch
- ☐ Hook guy wires onto anchorages and hand-tighten turnbuckles
- ☐ Bolt top and bottom plates of launch pad
- ☐ Tension all guy wires with wrench
- ☐ Unhook winch cable from winch
- ☐ Tie caution tape onto each guy wire

☐ Pre-Lowering Checklist

- ☐ Items to inspect:
  - ☐ Ratchet puller is operational
  - ☐ Launch pad is stable, no signs of damage on structural components
- ☐ Items to have on hand:
  - ☐ Wrench and/or ratchets to loosen bolts
  - ☐ Hard hats
  - ☐ Work gloves
- ☐ People to notify:
  - ☐ Competition organizers
  - ☐ All team members
- ☐ Installation Environment Conditions:
  - ☐ Ensure there are no tripping hazards present
- ☐ Personnel positions:
  - ☐ Lifting team of 5 people

- ☐ 1 coordinator
- ☐ 1 team member supporting rocket
- ☐ 1 winch operator
- ☐ 3 team members at guy wire ends
- ☐ 1 team member to set up wooden frames

☐ Lowering Procedure

- ☐ Have lifting team ready to support the tower
- ☐ Connect winch to winch cable
- ☐ Tension winch cable
- ☐ De-tension guy wires
- ☐ Unhook guy wires from anchorages
- ☐ Lower tower by de-tensioning winch cable
- ☐ Disconnect winch when tower is at approximately 30° from the horizontal
- ☐ Lower tower onto wood frames
- ☐ Secure guy wires by coiling

☐ Clean-Up Procedure

- ☐ Slide rocket off launch rail
- ☐ Remove launch rail from tower
- ☐ Disconnect tower segments
- ☐ Disconnect side rods from tower base
- ☐ Pull out stakes securing launch pad
- ☐ Remove anchorages from ground
- ☐ Pack away all components

5. *Final Setup Checklist*

☐ Fill Line Setup

- ☐ Ensure that the plumbing setup agrees with the P&ID shown in Figure 17
- ☐ Ensure NPT to JIC adapter is connected to fill line
- ☐ Run fill hose through fill arm
- ☐ Secure fill hose on arm extension with zip ties
- ☐ Place run adapter mount and ring release on fill hose
- ☐ Remove aluminium foil from fill hose and fill adapter
- ☐ Connect hose and adapter
- ☐ Ensure fill adapter hole is still covered in aluminium foil
- ☐ Secure adapter mount to fill arm with steel zip ties

☐ Fill Disconnect Setup

- ☐ Remove aluminium foil from fill adapter
- ☐ Install o-rings and spring on adapter
- ☐ Secure adapter to rocket with ring release
- ☐ Ensure o-rings did not tear when inserted into rocket

☐ Break Link Setup

- ☐ Ensure break link is installed on retaining ring
- ☐ Connect break link adapter with nylon bolt
- ☐ Connect break link cable to turnbuckle
- ☐ Tighten turnbuckle to remove slack

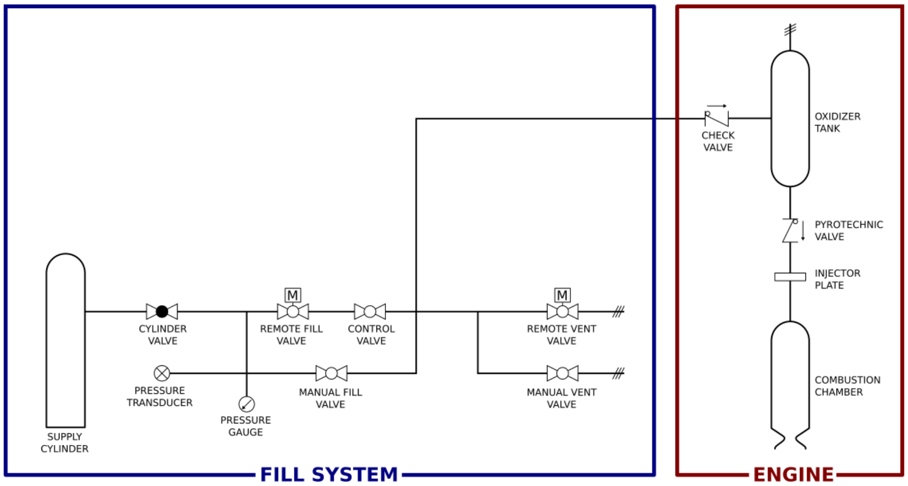


Figure 17: P&ID for the Vidar III engine and fill system

6. *Pre-Fill and Launch Checklist*

- ☐ Ensure that the ignition wires are not connected to the rocket
- ☐ Ensure that all other setup procedures are complete
- ☐ Ensure that four technicians are available before proceeding:
  - ☐ The Primary Technician operates the remote fill/disconnect client-side interface and is equipped with a walkie-talkie.
  - ☐ The Secondary Technician is located at the launch tower and is equipped with a walkie-talkie. The Secondary Technician reads the procedure to the Tertiary Technician and over the walkie-talkie to the Primary Technician, and oversees all electrical assembly procedures and checks at the launch tower.
  - ☐ The Tertiary Technician performs all electrical assembly procedures and checks at the launch tower.
  - ☐ The Quaternary Technician is located at launch control and operates the master key switch and ignition control interface, as well as monitoring the GPS receiver.
- ☐ Ensure that the ignition wires are not connected to the rocket
- ☐ Ensure that the master key switch is disabled and that only the Secondary Technician and Quaternary Technician are in possession of master keys
- ☐ The Tertiary Technician will make the following connections:
  - ☐ Connect the RLCS receiving box to the ignition relay box using the four-pin connector
  - ☐ Connect the RLCS receiving box to the remote fill relay box using the Cat 5 cable connector
  - ☐ Connect the remote DAQ cables to the corresponding DAQ screw terminals in the RLCS receiving box
- ☐ The Tertiary Technician will perform the following electrical checks:
  - ☐ Ensure that the ignition wires are not connected to the rocket
  - ☐ Ensure that all tower-side system batteries are disconnected
  - ☐ Ensure that the voltage of all tower-side system batteries is at least 11 V
    - ☐ Ignition battery

    - ☐ Remote fill battery
    - ☐ Communication battery
  - ☐ Ensure that the following connections are continuous:
    - ☐ Primary LFC coil
    - ☐ Secondary LFC coil
  - ☐ Ensure that the remote disconnect linear actuator is not connected to the remote fill relay box
- ☐ Ensure that the ignition wires are not connected to the rocket
- ☐ Ensure that the master key switch is disabled
- ☐ Connect all tower-side system batteries
- ☐ Ensure that none of the remote fill switches, remote disconnect switch, or remote ignition switches result in relay actuation while the master key switch is disabled
- ☐ Enable radio communication by activating the master key switch
- ☐ The Primary and Tertiary Technicians will perform the following control system checks:
  - ☐ Ensure that the remote fill switches actuate the Remote Fill Valve and Remote Vent Valve in both directions
  - ☐ Ensure that the remote disconnect switch results in a voltage of 12 V across the remote disconnect linear actuator terminals
- ☐ Return the Remote Fill Valve and Remote Vent Valve to the closed position
- ☐ The Tertiary and Quaternary Technicians will perform a check of the ignition system:
  - ☐ Ensure that the ignition wires are not connected to the rocket
  - ☐ Press the ignition button and ensure that neither ignition relay fires
  - ☐ Release the ignition emergency stop
  - ☐ Set the ignition system to primary
  - ☐ Press the ignition button and ensure that the primary ignition relay fires and the voltage across the primary terminals is 12 V
  - ☐ Set the ignition system to secondary
  - ☐ Press the ignition button and ensure that the secondary ignition relay fires and the voltage across the primary terminals is 12 V
- ☐ The Primary and Tertiary Technicians will perform a check of the remote data acquisition system:
  - ☐ Ensure that the LCD on the remote fill control box is displaying mass and pressure data
  - ☐ Ensure that the mass reading changes when the rocket is pushed down onto the load cell with moderate force
- ☐ Record the resting mass and resting pressure of the remote data acquisition system
- ☐ Disable radio communication by disabling the master key switch
- ☐ The Quaternary Technician will give the master key to an IREC official and confirm via walkie-talkie that they are no longer in possession of the master key
- ☐ Ensure that the ignition wires are not connected to the rocket
- ☐ Arm and test the payload
  - ☐ Actuate the payload magnetic switch using the magnetic rod
  - ☐ Open the payload interface program and ensure that the payload transceiver is communicating

    - ☐ Run the diagnostic tool to ensure all functions are working
- ☐ The Secondary and Tertiary Technicians will be equipped with face shields for the remainder of the procedure
- ☐ Set up the disconnect bungee cord
    - ☐ Connect the disconnect bungee cord to the U-bolt
    - ☐ Loop the disconnect bungee cord around the launch tower
    - ☐ Connect the disconnect bungee cord to the cross member on the opposite side of the launch tower
- ☐ Actuate the three magnetic switches in the avionics module using the magnetic rod and listen for high and low buzzer confirmation
- ☐ The Quaternary Technician will confirm that the GPS tracking pings are being received
- ☐ Connect the ignition wires to the rocket using the quick connectors
- ☐ End of procedure

7. *Rocket Launch and Recovery Checklist*

- ☐ Filling Procedure
    - ☐ Ensure that all setup and check procedures are complete
    - ☐ Turn on cameras
    - ☐ Have only 4 members available before proceeding
        - ☐ Primary Technician operates the remote fill/disconnect client-side interface
        - ☐ Secondary Technician reads checklists and procedures, opens the supply valve, and operates the client-side ignition box
        - ☐ Tertiary Technician acts as a backup for the Secondary Technician while opening the Cylinder Valve
        - ☐ Quaternary Technician stands a safe distance from the vent, observing the system using binoculars
    - ☐ Secondary Technician and Tertiary Technician must be fully covered to protect against evaporating NOS
        - ☐ Thermal gloves
        - ☐ Face shields
        - ☐ Safety goggles
    - ☐ If at any point in the procedure any member becomes injured, assist if it is safe, and retreat from the hazard
    - ☐ Secondary and Tertiary Technicians verify that all valves are initially closed
    - ☐ Secondary Technician slowly opens Cylinder Valve
        - ☐ If leaks are observed, slowly close Cylinder Valve
        - ☐ Open Manual Vent Valve until the system is fully depressurized
    - ☐ Secondary Technician will check the supply tank pressure on the pressure gauge
        - ☐ Insufficient pressure $<$ 700 psi
    - ☐ Secondary Technician slowly opens Control Valve
        - ☐ If leaks are observed, slowly close Cylinder Valve
        - ☐ Open Manual Vent Valve until the system is fully depressurized
    - ☐ Secondary and Tertiary Technicians safely jog towards launch control
    - ☐ Ensure no personnel are near the launch pad

- ☐ Communicate with competition judges to get clearance for fill
- ☐ Actuate key switch
- ☐ Open Remote Fill Valve
  - ☐ Quaternary Technician confirms that valve actuates
  - ☐ Monitor the LCD for NOS pressure and mass
  - ☐ Quaternary Technician observes the system for plume and/or leaks
- ☐ When pressure is nominal and mass plateaus:
  - ☐ Minimum pressure: 700 psi
- ☐ If nominal pressure/mass are not met, proceed to Abort Procedure
- ☐ If nominal pressure/mass are met:
- ☐ Close Remote Fill Valve
  - ☐ Quaternary Technician confirms that valve actuates
- ☐ Open Remote Vent Valve
  - ☐ Quaternary Technician confirms that valve actuates and/or observes vent plume
- ☐ Actuate Remote Disconnect
  - ☐ Quaternary Technician confirms that fill arm disconnects and nothing is connected to the rocket
  - ☐ If the rocket is not fully disconnected, proceed to Abort Procedure
- ☐ End of Procedure

☐ Pre-Ignition Checks

- ☐ Check that the GPS pings are being received.
- ☐ Check that the range is clear, launch is go from Range Safety Officer
- ☐ No aircraft in area
- ☐ No signs of vehicle disturbance (dust, etc)
- ☐ No personnel in area
- ☐ End of Procedure

☐ Abort

- ☐ Call "ABORT" over radio and inform RSO and competition judges of abort protocol
- ☐ Close Remote Fill Valve
  - ☐ Quarternary Technician confirms that valve actuates
- ☐ Open Remote Vent Valve
  - ☐ Quarternary Technician confirms that valve actuates and/or witnesses plume
- ☐ Wait for 60 minutes to depressurize the tank
  - ☐ Quarternary Technician will report when plume disappears
- ☐ End of Procedure

☐ Ignition

- ☐ Check that all members are aware of launch
- ☐ Ensure only the Secondary Technician has control of the ignition
- ☐ Pull out E-stop
- ☐ Hold down ignition button until black smoke is observed
- ☐ In case of apparently failed ignition (no smoke observed for at least 1 minute), wait for 60 minutes to depressurize the tank

    - ☐ Quaternary Technician will report when plume disappears
  - ☐ End of Procedure

- ☐ Flight
  - ☐ All members are to observe launch and look for the following:
    - ☐ Plume exiting engine
    - ☐ Leaks
    - ☐ Straight flight
    - ☐ Parachute deployment (drogue chute is orange, main chute is white)
    - ☐ Approximate recovery and booster landing area

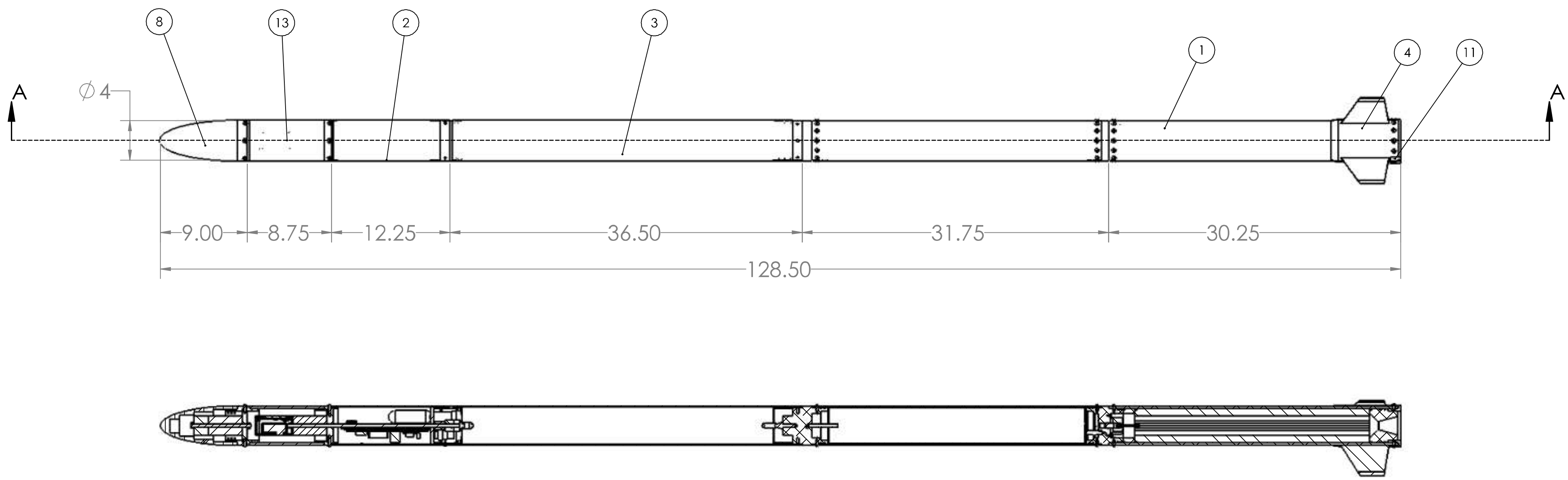
- ☐ Recovery
  - ☐ Check the following:
    - ☐ Permission has been given for recovery from the Range Safety Officer
    - ☐ Range is safe
    - ☐ Weather is clear
  - ☐ PPE:
    - ☐ Hardhat
    - ☐ Safety Goggles
    - ☐ Gloves
    - ☐ Sunscreen
    - ☐ Hats
  - ☐ Equipment:
    - ☐ Sunglasses
    - ☐ At least two bottles of water for each member
    - ☐ Compass
    - ☐ GPS devices(s)
    - ☐ Whistle/Air horn
    - ☐ Snacks
    - ☐ First Aid Kit
    - ☐ Walkie Talkies
  - ☐ One truck driver should remain with the truck in case of medical emergency
  - ☐ Throughout the search, all members will look out for launches at the launch site and avoid potential wreckage.
  - ☐ 4-5 members will form a line perpendicular to the direction in which the rocket was last observed
  - ☐ Members will be spaced out approximately 20 m away from each other at all times. Must be able to maintain visual contact
  - ☐ Members will sweep a reasonable recovery area in a straight line, and repeat until the entire area is covered
  - ☐ If a component is spotted, communicate over radio. All members will gather at the component
  - ☐ Do not disturb the component. Mark down the location, and take pictures before retrieval
  - ☐ End of Procedure

F. ENGINEERING DRAWINGS APPENDIX

This appendix contains engineering drawings for significant SRAD subsystems of the Vidar III rocket.

ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	1	17_00_A_PYROIS ENGINE_01	
2	1	17_06_A_AVIONICS ASSEMBLY_01	
3	1	16_10_A_RECOVERY MODULE_01	
4	1	15_09_FIN CAN_A_01	
5	17	SBHCSCREW 0.25-28x0.625-HX-N	
6	3	SBHCSCREW 0.125-44x0.4375-HX-N	
7	6	SBHCSCREW 0.25-28x0.75-HX-N	
8	1	16_11_A_NOSE CONE_01	
9	2	16_03_C_RAIL BUTTON_01	
10	1	16_03_C_RAIL BUTTON WASHER_01	
11	1	17_04_C_BREAK LINK ADAPTER_01	
12	1	HX-SHCS 0.25-28x1.125x1.125-N	
13	1	PAYLOAD ASSEMBLY	

VIDAR III ROCKET



SECTION A-A
SCALE 1 : 8

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF THE WATERLOO ROCKETRY TEAM. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF THE WATERLOO ROCKETRY TEAM IS PROHIBITED.

QUANTITY	#	UNLESS OTHERWISE SPECIFIED:		NAME	DATE	**WATERLOO ROCKETRY TEAM**
PROJECT	00_ROCKET	DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± 1/32 ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ±0.015 THREE PLACE DECIMAL ±0.005	DRAWN	HL	17-05-25	TITLE: VIDAR III ROCKET
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			ENG APPR.			
			MFG APPR.	INITIAL	YY-MM-DD	
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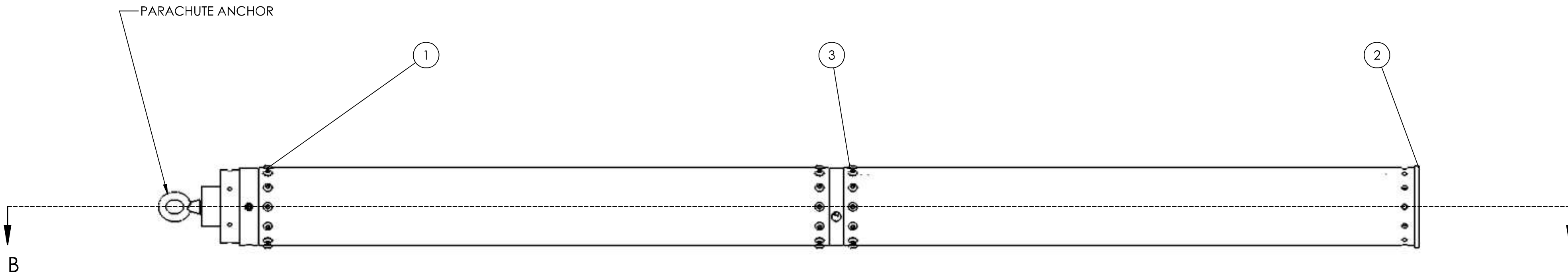
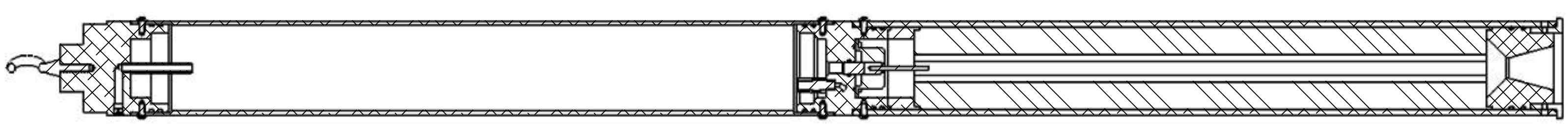
		MATERIAL MATERIAL	COMMENTS:			SIZE A DWG. NO. REV 01
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:16 WEIGHT:65 lbs WET SHEET 1 OF 13

ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	1	17_01_A_OXIDIZER TANK_01	
2	1	16_04_A_COMBUSTION CHAMBER_02	
3	12	SBHCSCREW 0.25-28x0.5-HX-N	

VIDAR III HYBRID ROCKET ENGINE





SECTION B-B
SCALE 1 : 4

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			ENG APPR.		
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		MATERIAL MATERIAL	Q.A.		
NEXT ASSY	USED ON	FINISH	COMMENTS:		
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WATERLOO ROCKETRY TEAM

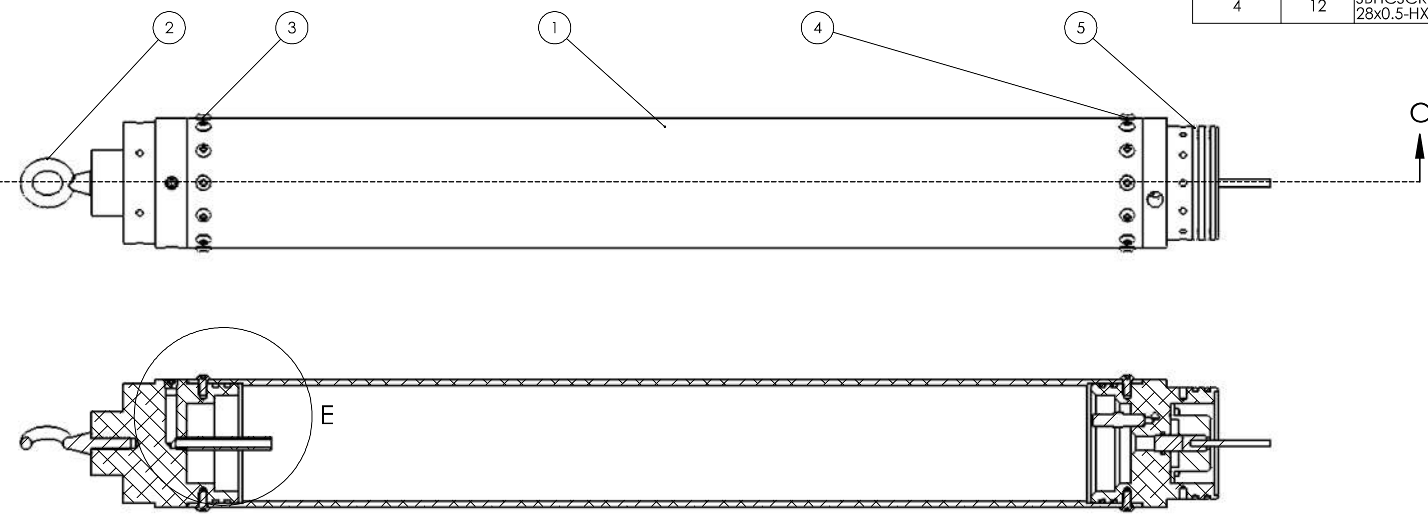
TITLE: VIDAR III ROCKET

SIZE A | DWG. NO. | REV 01

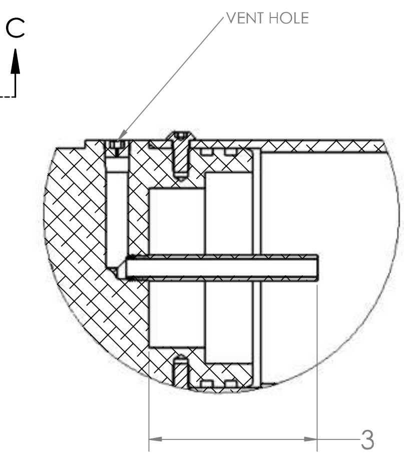
SCALE: 1:20 WEIGHT:65 lbs WET SHEET 2 OF 13

OXIDIZER TANK

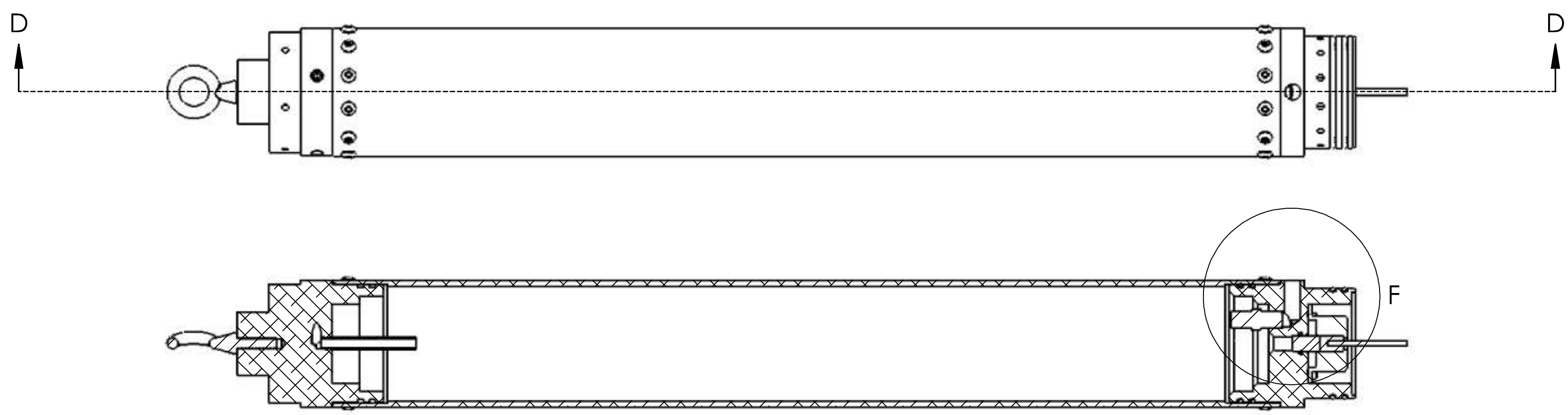
ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	1	17_01_C_OXIDIZER TANK_02	
2	1	17_01_A_VENT BULKHEAD_01	
3	12	socket button head cap screw_ai	
4	12	SBHCSCREW 0.25-28x0.5-HX-N	



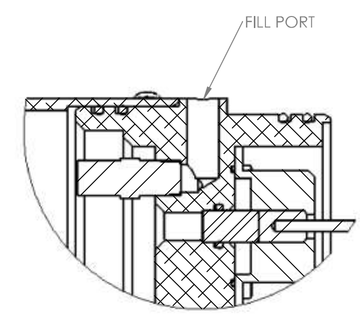
SECTION C-C
SCALE 1 : 3



DETAIL E
SCALE 2 : 3



SECTION D-D
SCALE 1 : 3



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SCALE 2 : 3

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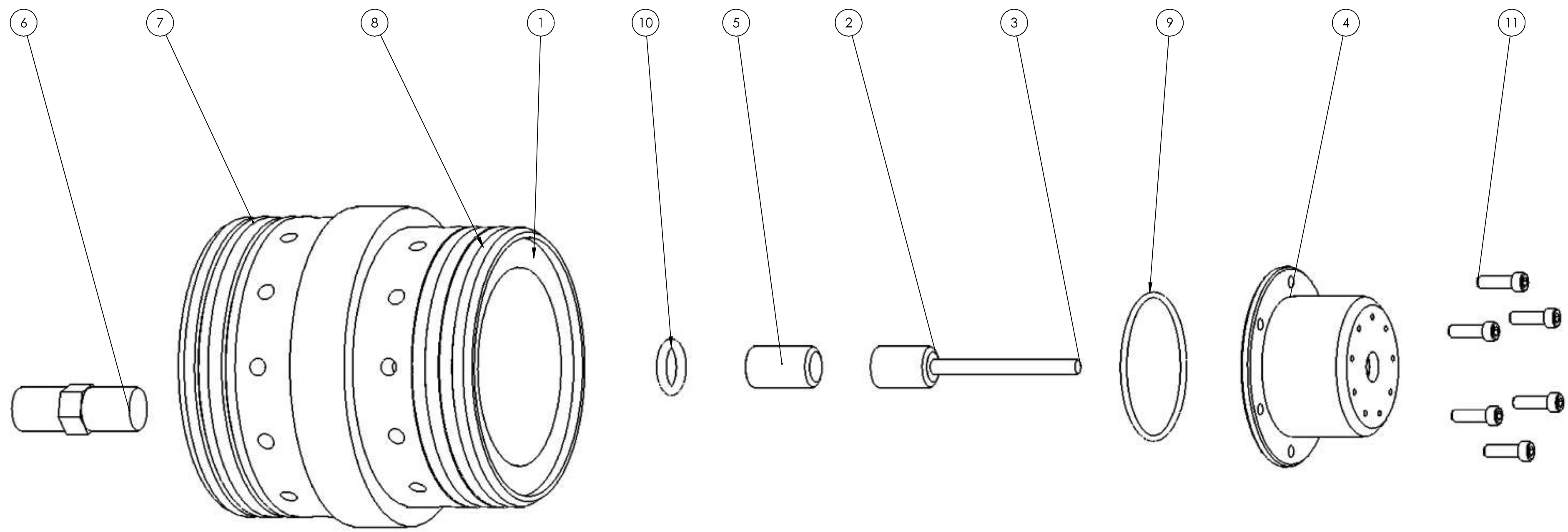
PROJECT	00_ROCKET	DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/32 ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.015 THREE PLACE DECIMAL ±0.005	DRAWN	HL	17-05-25	TITLE:
			CHECKED	INITIAL	YY-MM-DD	VIDAR III ROCKET
			ENG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	MFG APPR.	INITIAL	YY-MM-DD	
		MATERIAL MATERIAL	Q.A.			SIZE A DWG. NO. REV 01
NEXT ASSY	USED ON	FINISH	COMMENTS:			
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:20 WEIGHT:65 lbs WET SHEET 3 OF 13

ITEM NO.	Default/ QTY.	DESCRIPTION	MATERIAL
1	1	16_03_C_INJECTOR BULKHEAD_02	6061-T6 ALUMINIUM
2	1	16_01_C_IGNITION PELLET_02	POTASSIUM NITRATE + EPOXY
3	1	16_01_C_FUSE_02	POTASSIUM NITRATE + EPOXY + HTPB
4	1	17_01_C_INJECTOR PLATE_01	303 STAINLESS STEEL
5	1	16_01_C_PISTON_02	303 STAINLESS STEEL
6	1	16_03_C_CHECK VALVE_01	316 STAINLESS STEEL
7	2	o-rings ai	
8	2	o-rings ai	
9	1	o-rings ai	
10	1	o-rings ai	
11	6	HX-SHCS 0.138-32x0.5x0.5-N	

PYROTECHNIC VALVE ASSEMBLY



QUANTITY	#	UNLESS OTHERWISE SPECIFIED:		NAME	DATE
PROJECT	00_ROCKET	DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± 1/32 ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ±0.015 THREE PLACE DECIMAL ±0.005	DRAWN	HL	17-05-25
			CHECKED	INITIAL	YY-MM-DD
			ENG APPR.		
			MFG APPR.	INITIAL	YY-MM-DD
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

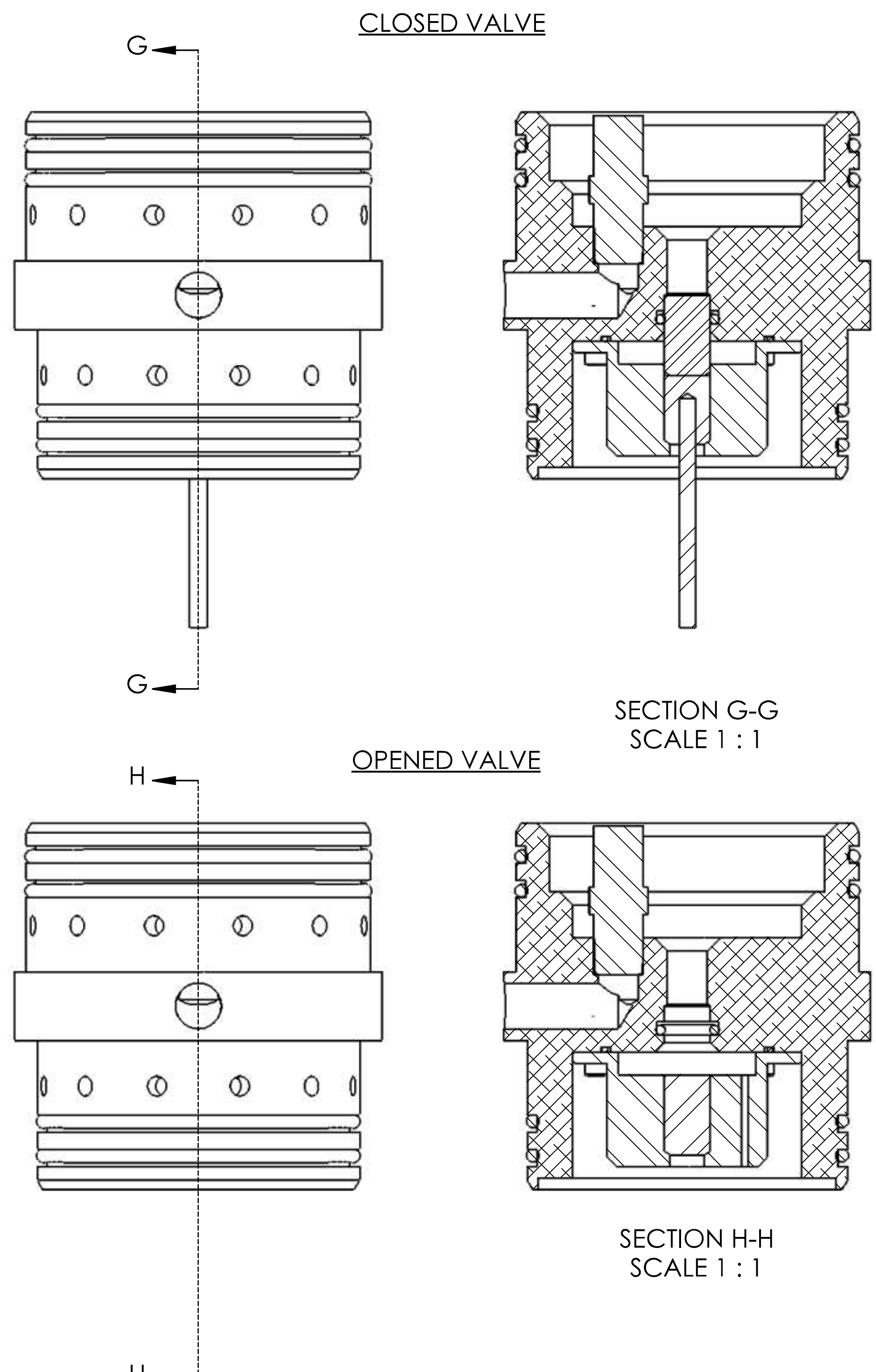
WATERLOO ROCKETRY TEAM

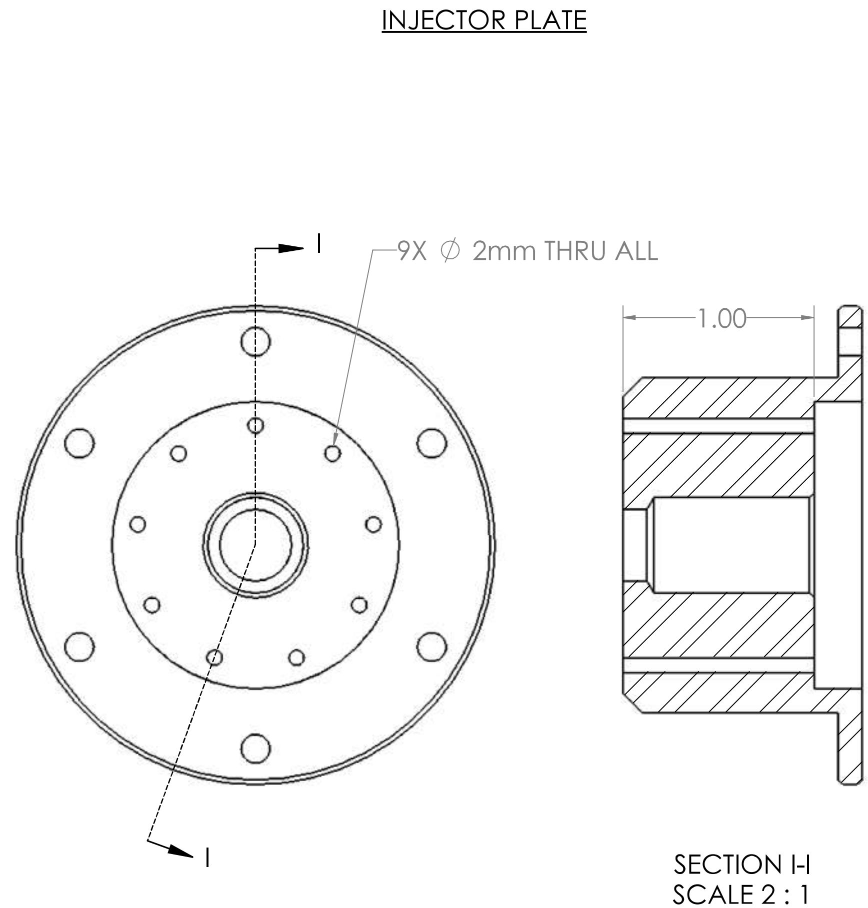
TITLE:

VIDAR III ROCKET

SIZE **A** DWG. NO. REV 01

SCALE: 1:2 WEIGHT:65 lbs WET SHEET 4 OF 13





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QUANTITY	#
PROJECT	00_ROCKET
NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/32
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.015
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HL	17-05-25
CHECKED	INITIAL	YY-MM-DD
ENG APPR.		
MFG APPR.	INITIAL	YY-MM-DD
Q.A.		
COMMENTS:		

WATERLOO ROCKETRY TEAM

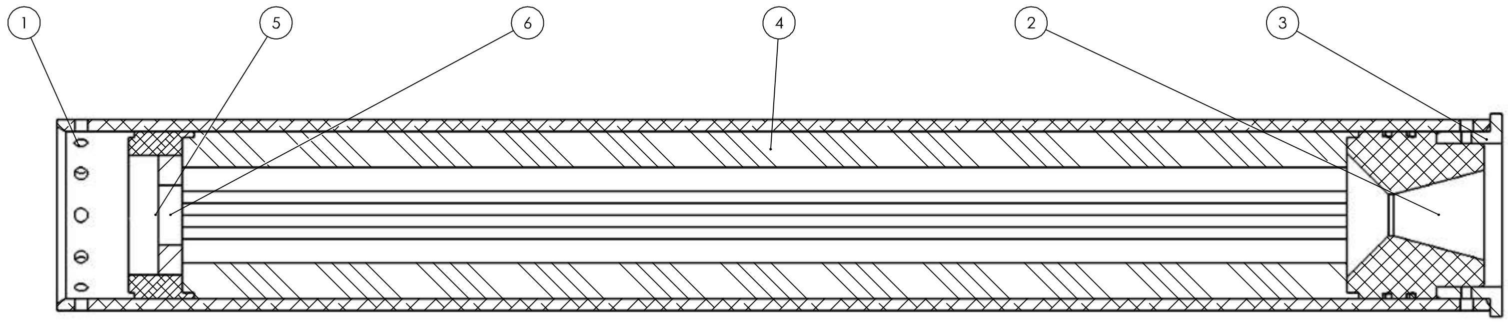
TITLE:
VIDAR III ROCKET

SIZE A | DWG. NO. | REV 01

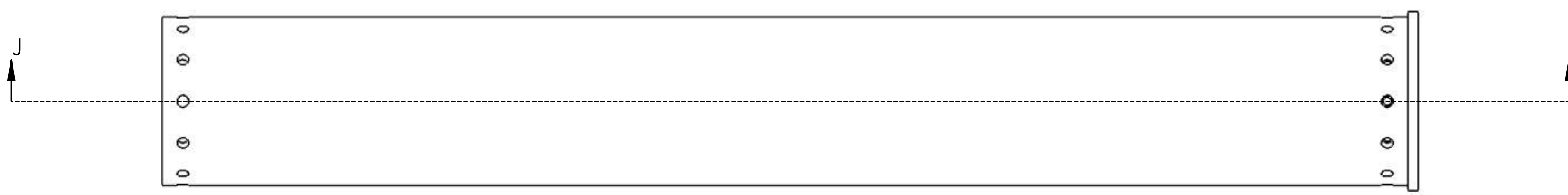
SCALE: 1:4 | WEIGHT:65 lbs WET | SHEET 5 OF 13

ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	1	16_04_C_COMBUSTION CHAMBER_02	6061-T6 ALUMINIUM
2	1	17_02_A_NOZZLE_01	GRAPHITE
3	1	16_05_C_NOZZLE RETAINER_01	MILD STEEL
4	1	16_04_C_FUEL GRAIN_02	90% HTPB, 10% UFAL
5	1	15_04_C_SPACER_03	
6	1	16_04_C_IGNITION PUCK_03	POTASSIUM NITRATE + EPOXY

COMBUSTION CHAMBER



SECTION J-J
SCALE 1 : 2



QUANTITY	#	UNLESS OTHERWISE SPECIFIED:		NAME	DATE	WATERLOO ROCKETRY TEAM
PROJECT	00_ROCKET	DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± 1/32 ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ±0.015 THREE PLACE DECIMAL ±0.005	DRAWN	HL	17-05-25	TITLE: VIDAR III ROCKET
			CHECKED	INITIAL	YY-MM-DD	
			ENG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	MFG APPR.	INITIAL	YY-MM-DD	
		MATERIAL MATERIAL	Q.A.			SIZE A DWG. NO. REV 01
NEXT ASSY	USED ON	FINISH	COMMENTS:			
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:4 WEIGHT:65 lbs WET SHEET 6 OF 13

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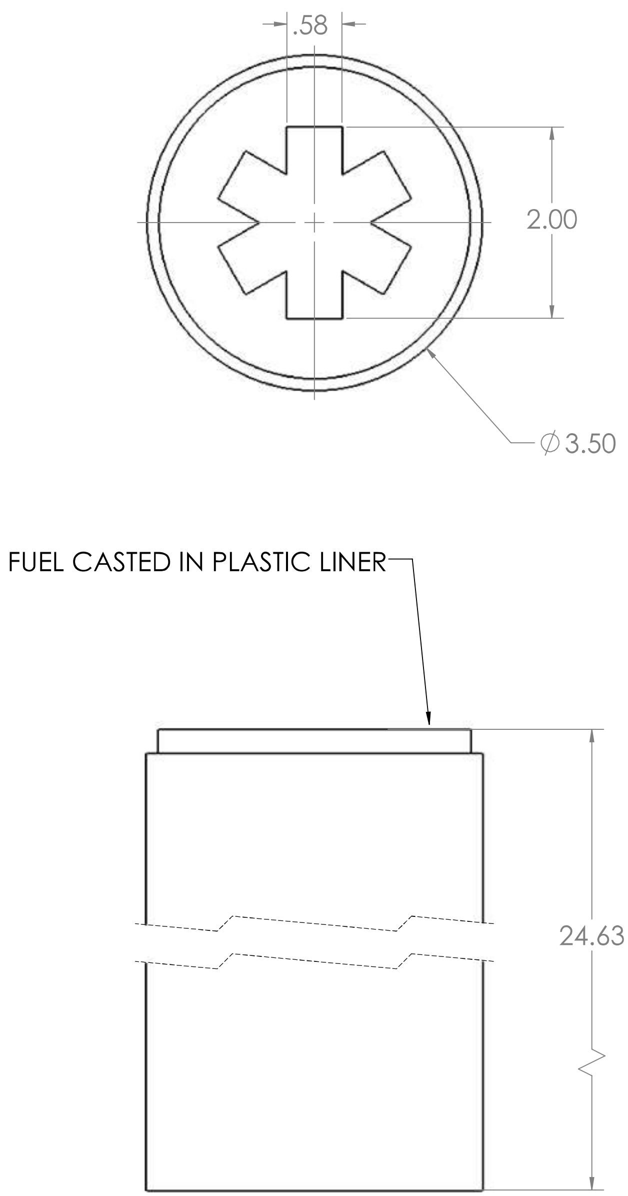
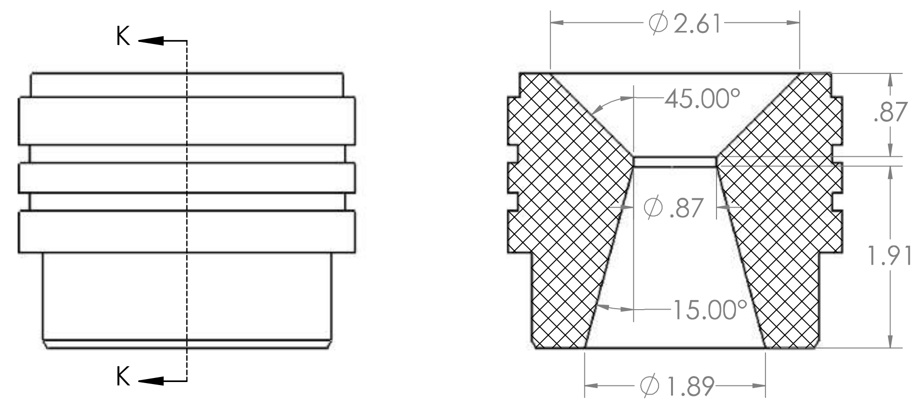
FUEL GRAIN



NOZZLE



SECTION K-K
SCALE 1 : 1

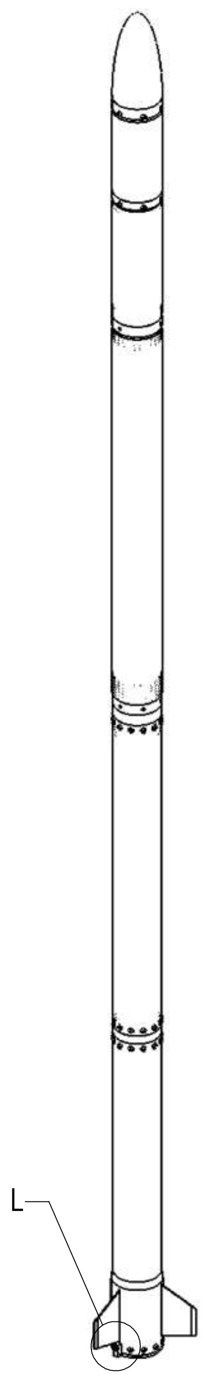
QUANTITY	#	UNLESS OTHERWISE SPECIFIED:		NAME	DATE
PROJECT	00_ROCKET	DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/32 ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.015 THREE PLACE DECIMAL ±0.005	DRAWN	HL	17-05-25
			CHECKED	INITIAL	YY-MM-DD
			ENG APPR.		
			MFG APPR.	INITIAL	YY-MM-DD
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

WATERLOO ROCKETRY TEAM

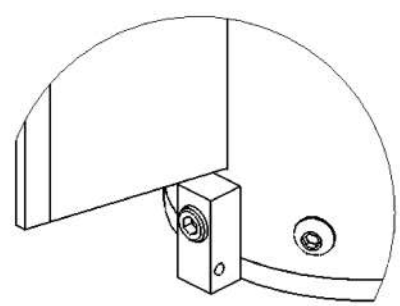
TITLE:

VIDAR III ROCKET

SIZE	DWG. NO.	REV
A		01
SCALE: 1:4	WEIGHT:65 lbs WET	SHEET 7 OF 13

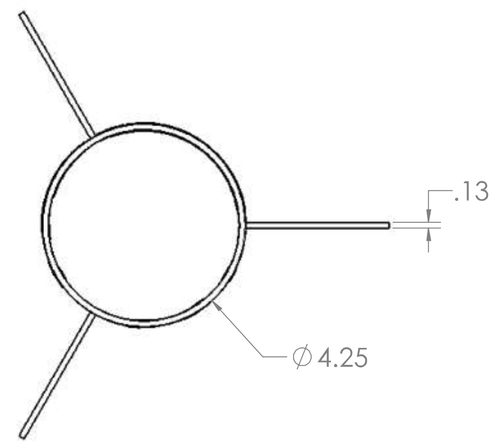


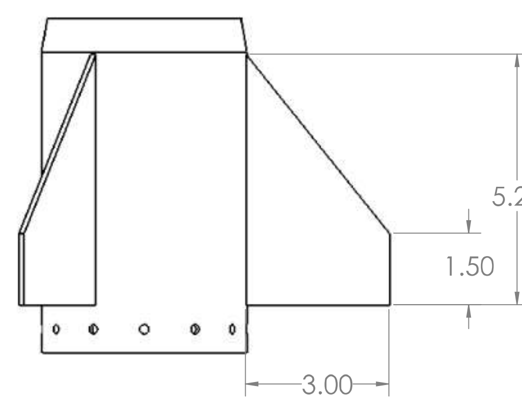
BREAK LINK ADAPTER



DETAIL L
SCALE 1 : 1

FIN CAN





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PROJECT	00_ROCKET	DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/32 ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.015 THREE PLACE DECIMAL ±0.005	DRAWN	HL	17-05-25
			CHECKED	INITIAL	YY-MM-DD
			ENG APPR.		
			MFG APPR.	INITIAL	YY-MM-DD
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

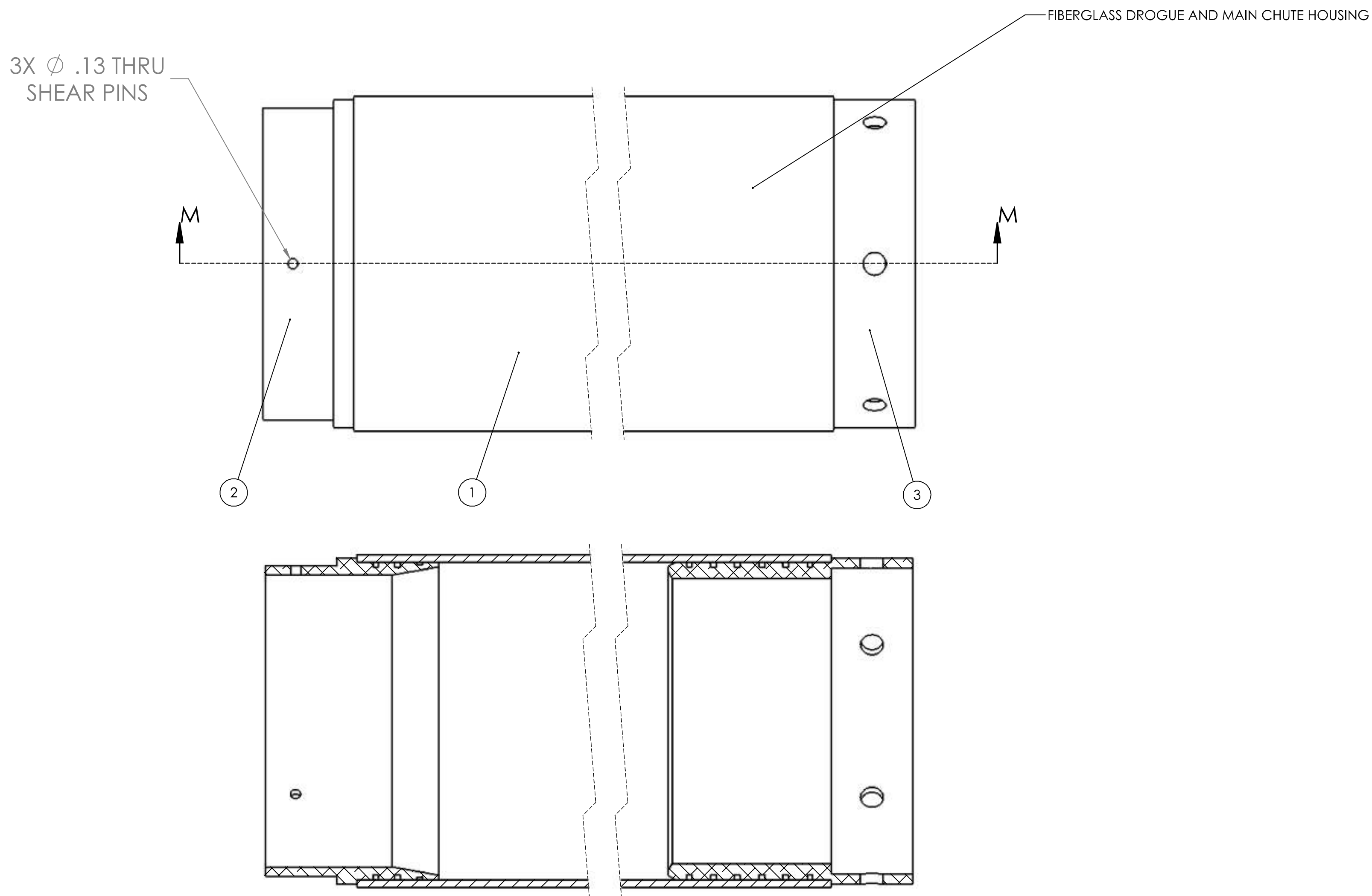
WATERLOO ROCKETRY TEAM
TITLE:
VIDAR III ROCKET

SIZE A | DWG. NO. | REV 01

SCALE: 1:2 | WEIGHT:65 lbs WET | SHEET 8 OF 13

ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	1	16_10_C_RECOVERY BAY_01	FIBERGLASS
2	1	16_09_C_COUPLER 4_03	6061-T6 AL
3	1	16_09_C_COUPLER 5_04	6061-T6 AL

RECOVERY MODULE



SECTION M-M
SCALE 1 : 1

QUANTITY	#	
PROJECT	00_ROCKET	
NEXT ASSY	USED ON	
APPLICATION		

UNLESS OTHERWISE SPECIFIED:
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FRACTIONAL± 1/32
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±0.015
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HL	17-05-25
CHECKED	INITIAL	YY-MM-DD
ENG APPR.		
MFG APPR.	INITIAL	YY-MM-DD
Q.A.		
COMMENTS:		

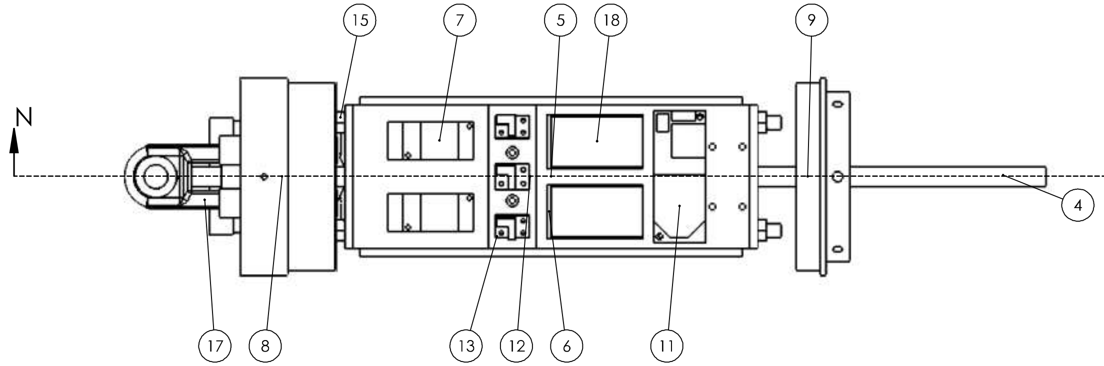
WATERLOO ROCKETRY TEAM

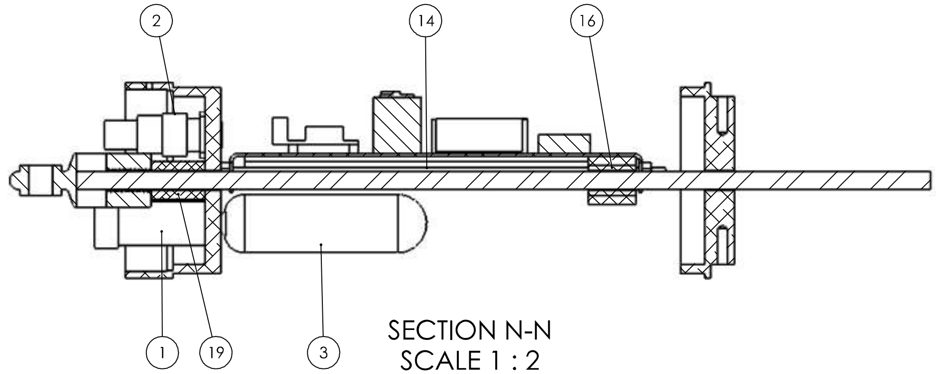
TITLE:
VIDAR III ROCKET

SIZE A | DWG. NO. | REV 01

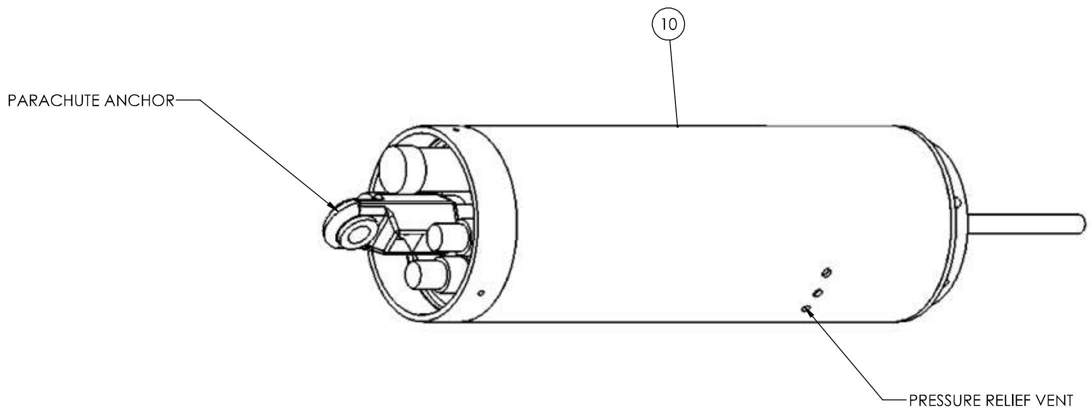
SCALE: 1:8 | WEIGHT:65 lbs WET | SHEET 9 OF 13

AVIONICS MODUE





SECTION N-N
SCALE 1 : 2



ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	2	16_09_C_CO2 MOUNT_01	
2	2	16_09_C_CIRCULAR HIGH RELIABILITY CONNECTOR_01	
3	2	16_09_C_CO2 CYLINDER_01	
4	1	17_06_C_0.375-16 THREADED ROD_01	
5	1	16_09_C_AVIONICS SLED_02 (2016_Jun_04 Rev Update_HTong)	
6	2	16_09_C_SNAP IN BATTERY HOLDER 9V_01	
7	2	16_09_C_RAVEN_01	
8	1	16_09_C_COUPLER 3_02	
9	1	16_09_C_COUPLER 2_03	
10	1	16_09_C_AVIONICS BAY_01	
11	1	16_09_C_GPS MODULE_1	
12	1	16_09_C_MAGNETIC SWITCH SPACER_01	
13	3	16_09_C_MAGNETIC SWITCH_01	
14	2	16_09_C_0.25-20 THREADED ROD_01	
15	6	MSHXNUT 0.250-20-S-N	
16	1	16_09_A_BEARING BLOCK ASSM_01	
17	1	29995T72	
18	2	16_09_C_9V BATTERY_01	
19	1	16_09_C_EYENUT SPACER_01	

QUANTITY	#
PROJECT	00_ROCKET
NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
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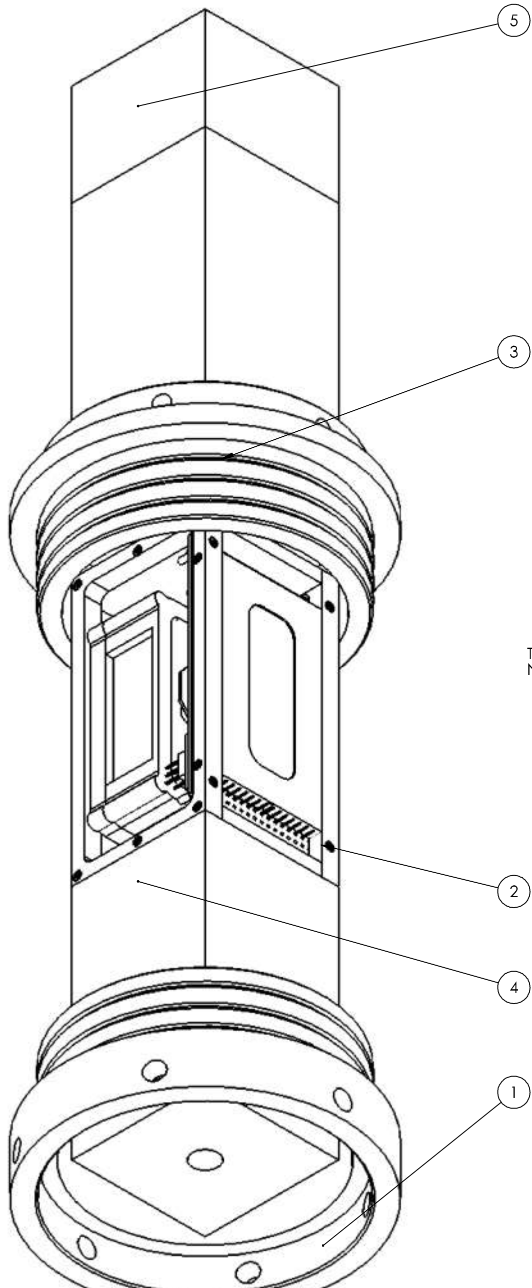
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HL	17-05-25
CHECKED	INITIAL	YY-MM-DD
ENG APPR.		
MFG APPR.	INITIAL	YY-MM-DD
Q.A.		
COMMENTS:		

WATERLOO ROCKETRY TEAM
TITLE:
VIDAR III ROCKET
SIZE A DWG. NO. REV 01
SCALE: 1:4 WEIGHT:65 lbs WET SHEET 10 OF 13

PAYLOAD MODULE

ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	1	EXTENSION COUPLER BOTTOM	
2	1	Functional Payload Assembly	
3	1	EXTENSION COUPLER TOP	
4	2	3.5in deadweight	
5	1	1.5in deadweight	
6	2	HNUT 0.3750-16-D-N	
7	1	threaded rod 2	
8	1	Acrylic Coupler	



TRANSPARENT ACRYLIC CASING
NOT SHOWN

QUANTITY	#	UNLESS OTHERWISE SPECIFIED:		NAME	DATE
PROJECT	00_ROCKET	DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/32 ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.015 THREE PLACE DECIMAL ±0.005	DRAWN	HL	17-05-25
			CHECKED	INITIAL	YY-MM-DD
			ENG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	MFG APPR.	INITIAL	YY-MM-DD
		MATERIAL MATERIAL	Q.A.		
NEXT ASSY	USED ON	FINISH	COMMENTS:		
APPLICATION		DO NOT SCALE DRAWING			

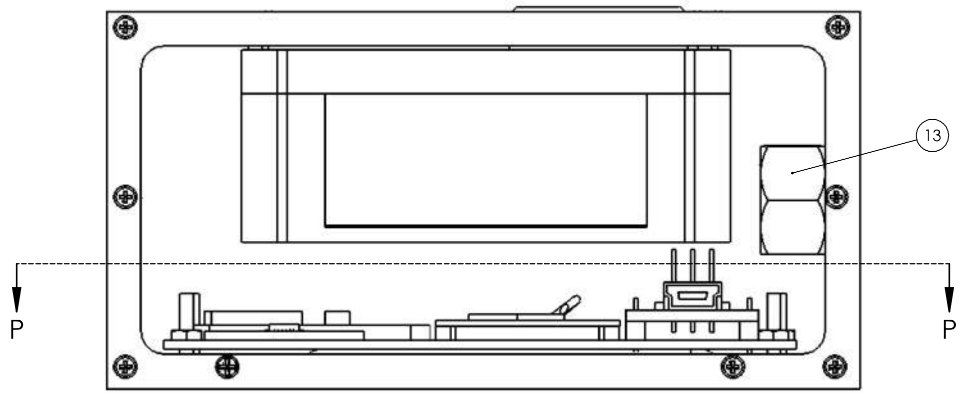
WATERLOO ROCKETRY TEAM

TITLE: VIDAR III ROCKET

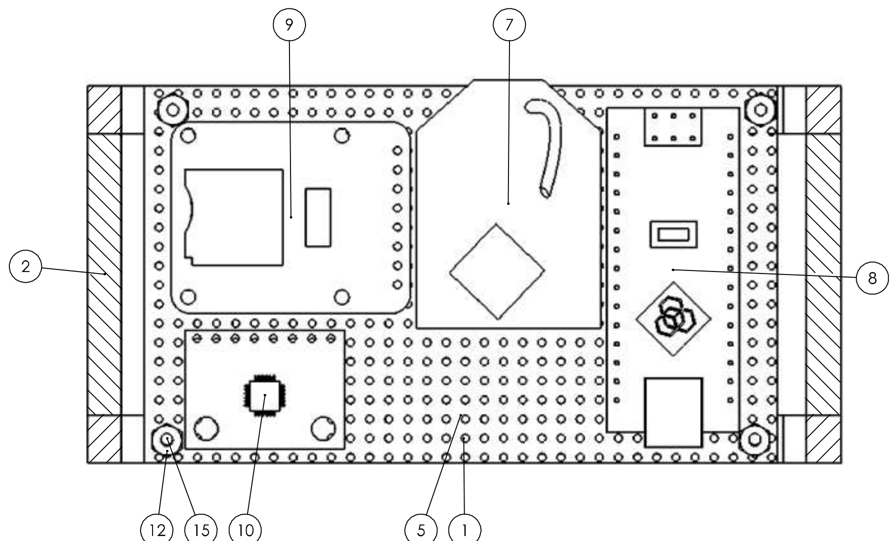
SIZE **A** DWG. NO. REV 01

SCALE: 1:2 WEIGHT:65 lbs WET SHEET 11 OF 13

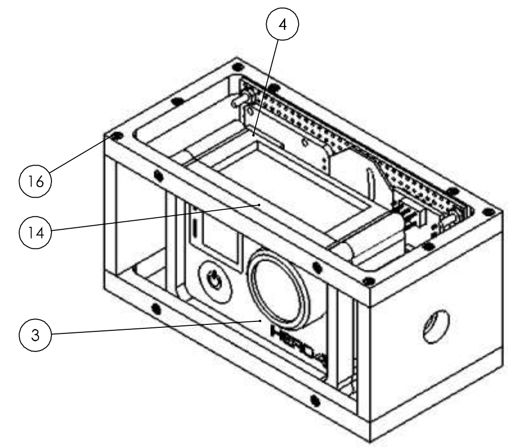
FUNCTIONAL PAYLOAD ASSEMBLY



ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	2	Aluminum side	
2	2	Aluminum End	
3	1	Part1	
4	1	GoPro Mount	
5	1	Vero Board 1	
6	1	Lipo Battery	
7	1	xbeePro900	
8	1	Arduino Nano	
9	1	SD Card Board	
10	1	MPU 6050 IMU	
11	1	Battery Holder	
12	4	MSHXNUT 0.060-80-S-N	
13	1	HNUT 0.3750-16-D-N	
14	1	Go Pro Secondary Cover	
15	11	flat head 100 screw_ai	
16	12	flat head 100 screw_ai	
17	1	flat head screw_ai	



SECTION P-P
SCALE 2 : 1



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QUANTITY	#
PROJECT	00_ROCKET
NEXT ASSY	USED ON
APPLICATION	

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INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HL	17-05-25
CHECKED	INITIAL	YY-MM-DD
ENG APPR.		
MFG APPR.	INITIAL	YY-MM-DD
Q.A.		
COMMENTS:		

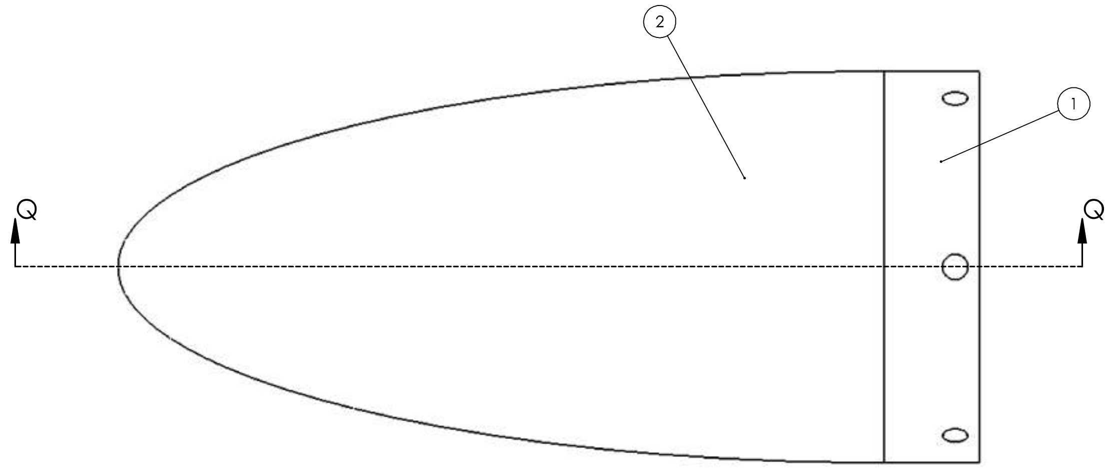
WATERLOO ROCKETRY TEAM
TITLE:
VIDAR III ROCKET

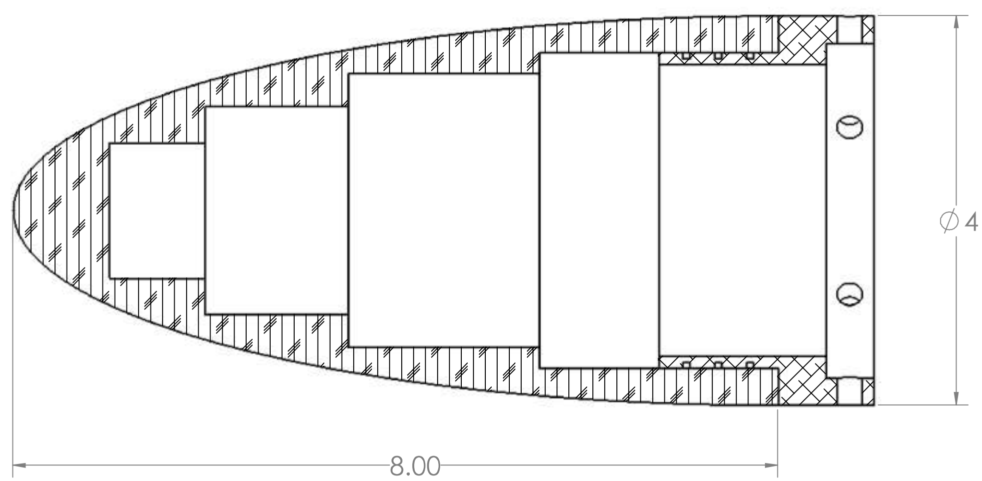
SIZE A | DWG. NO. | REV 01

SCALE: 1:1 | WEIGHT:65 lbs WET | SHEET 12 OF 13

ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	1	16_09_C_COUPLER 1_01	6061-T6 AL
2	1	16_11_C_ELLIPTICAL NOSE_01	PINE

NOSE CONE





SECTION Q-Q
SCALE 1 : 1

QUANTITY	#	UNLESS OTHERWISE SPECIFIED:		NAME	DATE	WATERLOO ROCKETRY TEAM
PROJECT	00_ROCKET	DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/32 ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ±0.015 THREE PLACE DECIMAL ±0.005	DRAWN	HL	17-05-25	TITLE: VIDAR III ROCKET
			CHECKED	INITIAL	YY-MM-DD	
			ENG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	MFG APPR.	INITIAL	YY-MM-DD	
		MATERIAL MATERIAL	Q.A.			SIZE A DWG. NO. REV 01
NEXT ASSY	USED ON	FINISH	COMMENTS:			
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT:65 lbs WET SHEET 13 OF 13

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Acknowledgments

Thank you to the various members of the Waterloo Rocketry Team who provided Standard Operating Procedures, models and drawings used in this report. A sincere thank you also goes to our advisors Dan Steinhaur, Dr. Andrew J.B. Milne and Adam Trumpour for providing us invaluable expertise at all stages in our development.

The success of this team would not be possible without the continued support of the University of Waterloo and all of our sponsors. Your aid over the years is greatly appreciated.

References

[1]Benjamin S. Waxman, "An Investigation of Injectors for use with high Vapor Pressure Propellants with applications to Hybrid Rockets", Ph.D. dissertation, Dept. of Aeronautics and Astronautics, Stanford University, Stanford, California, June 2014