Team 65 Project Technical Report for the 2016 IREC

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The *Vidar III* rocket uses a fully student built nitrous oxide/HTPB hybrid rocket engine, built to compete in the advanced category of IREC 2016, with a target altitude of 10,000' AGL. It is the third iteration of our Vidar hybrid engine design, focusing on the development of a custom valve and injection system. The engine consists of a 7 litre aluminum oxidizer tank with bolted end caps, and a combustion chamber housing the fuel grain and a graphite nozzle. The rocket uses a single bay, dual-deployment recovery system, using CO2 ejection for drogue deployment, and a modified 3-ring release system for main deployment. The avionics system is armed via magnetic switches, and consists of two commercial Raven altimeters, and a BRB 900Mhz GPS transmitter for tracking after descent.

I. Introduction

THE Waterloo Rocketry Team is an undergraduate student design team, representing the University of Waterloo. The team will be competing in the 11th Intercollegiate Rocket Engineering Competition (IREC), hosted by the Experimental Sounding Rocket Association (ESRA) from June 15-19, 2016, in Green River, Utah. The team has developed the *Vidar III* rocket with the goal of becoming the first Canadian team at IREC to launch and recover a self-built hybrid rocket.

II. Propulsion System

A. Engine Design

The engine (Fig. 1) consists of an oxidizer tank and combustion chamber, constructed using 6061-T6 aluminum tubes. Following a monocoque design, the tank and chamber are used as structural skins, eliminating the complexity of building a structural skeleton, and minimizing the diameter. The oxidizer tank is built for a 7 litre maximum capacity and designed operating pressure of 750 psi, with a factor of safety of 3. The tank has been hydrostatically tested to 1.5 times the designed operating pressure. The end caps are custom aluminum bulkheads, which are attached to the tank using a radial bolt pattern. The bulkheads are sealed using redundant O-rings. Nitrous oxide (NOx) fills the tank via a port located on the bottom bulkhead, accessible from the side of the rocket. A check valve inside the tank prevents backflow. A permanently open vent is built into the top bulkhead (Fig. 2), regulating tank pressure, and permitting depressurization of the tank in case of an aborted launch. A dip tube is connected to the vent, restricting the liquid level in the tank. Prior to ignition, the oxidizer is separated from the combustion chamber using a 303 stainless steel piston and O-ring seal (Fig. 3). The piston is kept in place using a combustible pellet on the bottom side, composed of potassium nitrate and epoxy. Upon ignition, the pellet burns away over the course of approximately 30 sec, allowing the piston to displace and open the NOx channel into the combustion chamber. The injector plate, retaining the piston and pellet, is bolted to the bottom bulkhead. Fabricated from 303 stainless steel, the injector plate consists of six 0.116" diameter orifices, to complement the six ports on the fuel grain. The performance of this injector design was deemed adequate following several engine hot-fire tests. A fluid circuit diagram of the feed and venting system can be found in the Appendix.

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Figure 1. Vidar III hybrid rocket engine.

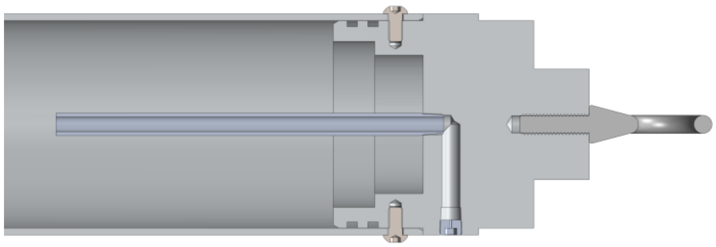

Figure 2. Vented bulkhead.

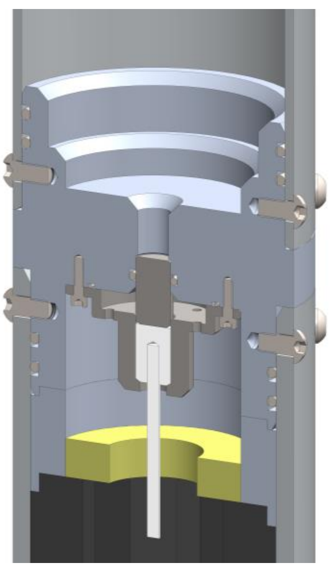

Figure 3. Feed system with custom pyro-valve

The combustion chamber connects directly to the bottom bulkhead on the oxidizer tank using a radial bolt pattern and redundant O-ring seal. The chamber contains the ignition system, fuel grain, and nozzle (Fig. 4). A disk of potassium nitrate and epoxy rests on top of the fuel grain, with strands of nichrome wire woven through the disk. Ignition wiring runs through the chamber and out the nozzle. This ignitable disk serves two purposes: to open the NOx channel from the tank above by burning the pellet, and to vaporize the fuel in anticipation of oxidizer flow. The fuel is casted using 90% HTPB, and 10% UFAL (ultra-fine aluminum powder). The ratios were experimentally determined. HTPB was chosen due to the following advantages: ease of casting, lack of toxicity, and high impact resistance. The addition of aluminum should theoretically increase combustion temperatures due to additional radiative heat transfer, and its effects on engine performance were demonstrated through several engine tests. The finocyl geometry of the fuel was designed to maximize surface area, and to maintain a relatively constant regression rate throughout the burn (Fig. 5). A graphite conical nozzle sits directly under the fuel, featuring a 45^o converging half-angle, 15^o diverging half-angle, 0.869" diameter throat, and 4.7 expansion ratio. It is retained using a flanged steel ring that is attached to the underside of the combustion chamber, using a radial bolt pattern, and sealed in the chamber using redundant O-rings. All interfaces of components in the chamber are lined with an acrylic-latex caulk for a high temperature seal.

Figure 4. Combustion chamber

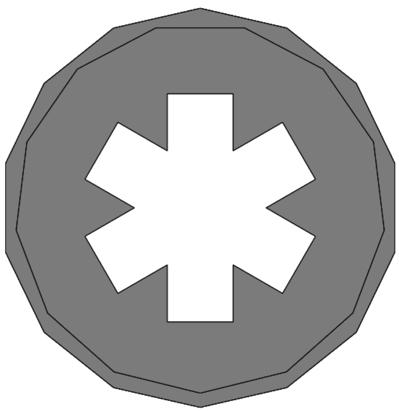

Figure 5. Fuel grain geometry

B. Failure Analysis and Redesign

The previous iteration, *Vidar II*, suffered a catastrophic engine failure in mid-flight at IREC 2015, despite three successful engine hot-fire tests. Around 7 seconds after liftoff, the nozzle exhaust was suddenly cut off, and an explosion was observed between the combustion chamber and oxidizer tank (Fig. 6). The root cause of failure is attributed to the backflow of combustion gases through the feed system, into the oxidizer tank. This is plausible since the tank is mostly vapor NOx at burnout, which readily decomposes with sufficient heat. Analysis of the flight video shows that the exhaust is sharply cut off from the nozzle, supplementing the backflow theory. Additionally, the piston in the recovered injector bulkhead could not be found. Due to the absence of sufficient quantitative data, the exact cause of backflow cannot be determined with certainty. A likely explanation involves sharp chamber pressure changes due to combustion instabilities, creating an undesired pressure difference between the chamber and the tank, pushing the piston through the oxidizer channel, into the tank. Deacceleration of the vehicle, causing slosh, may have been a factor as well.

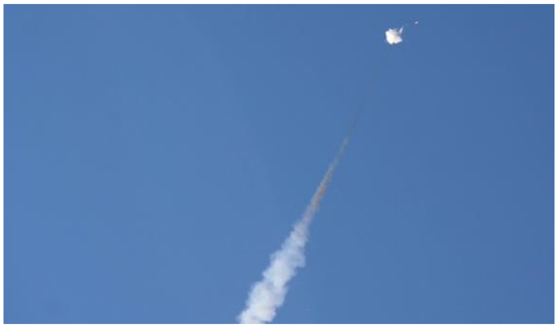

Figure 6. Vidar II flight explosion

The redesign for the *Vidar III* engine is quite conservative due to our lack of understanding regarding backflow, and emphasizes the importance of small, predictable changes during iterative design, rather than large changes that introduce many new variables and unknowns. Figure 7 and 8 show a comparison between the *Vidar II* and *Vidar III* feed systems, machined into the bulkhead. In the redesign, a lip was machined into the oxidizer channel (previously a thru-hole), restraining the piston in case of back pressure. Since the piston is made of a harder material than the bulkhead, it should seize against the lip and seal the oxidizer channel, acting as a check valve, until the chamber pressure drops. Any combustion gases that may pass between the gap should be quenched due to the small flow area and direct contact with a cold bulkhead, cooled from the rapid evaporation of NOx. There should be no significant changes to flow rate since the lip is very small.

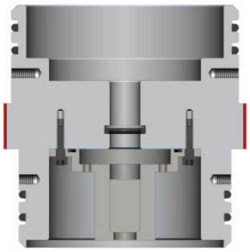

Figure 7. Vidar II feed system

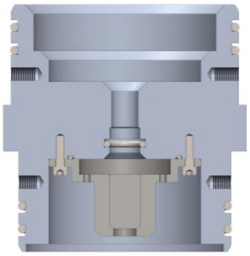

Figure 8. Vidar III feed system

C. Filling Operation

Safety is of utmost priority during a rocket launch. With this in mind, a tank filling mechanism was designed and built to allow for safe disconnect of the fill hose prior to launch. A custom fill adapter (Fig. 9) is connected to a hose, which plugs into a fill port on the bottom bulkhead of the oxidizer tank, using redundant O-rings to seal. The fill adapter is restrained against NOx pressure during filling using loops of fishing wire (Fig. 10). The fill adapter is attached to an arm that is mounted to the launch tower, which retracts using a bungee cord (Fig. 11 and Fig. 12). A spring is placed between the face of the fill adapter and the bulkhead, to assist in its ejection, and confirm tension in the fishing wire. Prior to disconnect, the remaining NOx in the plumbing is vented out of the system. A cutter attached to a long line is pulled, which severs the fishing wire. The adapter ejects itself due to the springs and retractable arm. A fluid circuit diagram of the fill system can be found in the Appendix. The mechanism has been tested 3 times without failure. The cutting mechanism was used at IREC 2015 without failure, or pre-mature disconnect of the fill adapter.

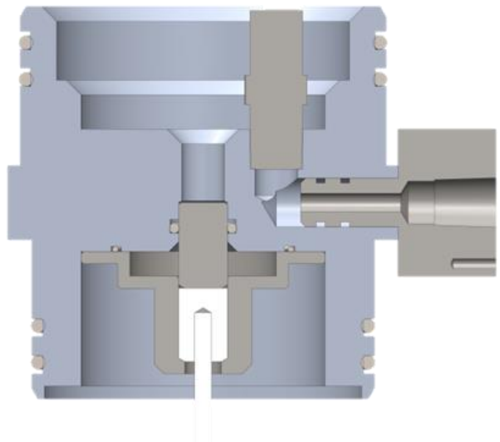

Figure 9. Tank filling mechanism

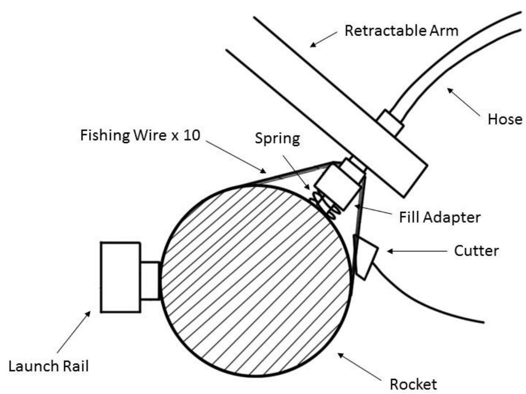

Figure 10. Fill adapter mechanism

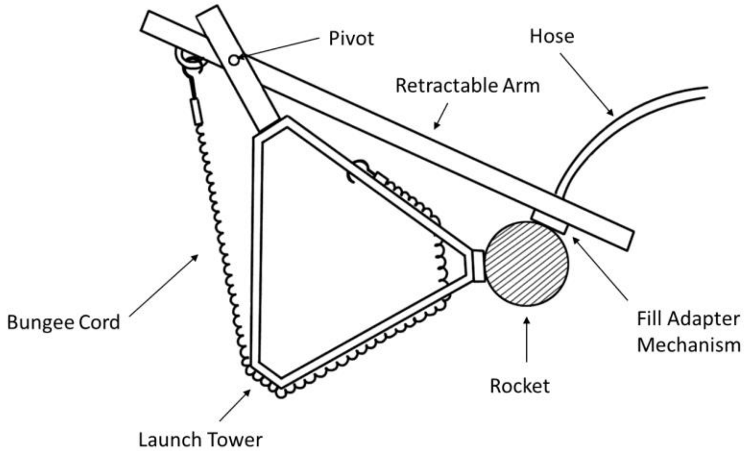

Figure 11. Fill hose retraction mechanism (connected)

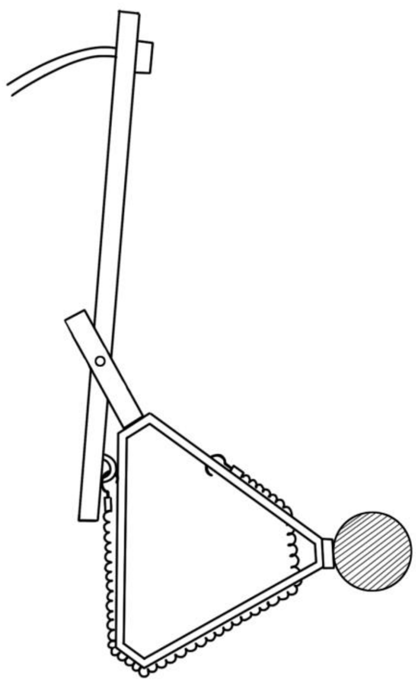

Figure 12. Fill hose retraction mechanism (disconnected)

D. Testing

Aside from the change to the feed system, as described previously, there were no other significant changes made to the engine. As such, hot-fire tests performed for the *Vidar II* rocket are still relevant to this year's project. In total, 3 hot-fire tests were performed for *Vidar II*, and 1 test for *Vidar III*.

Test #1 was a functionality test, performed in an inverted configuration due to the lack of an upright test stand. The oxidizer tank and combustion chamber were kept separate, coupled together by a hose. Observation of the injector plate post-burn revealed partial melting, likely from the ignition disk.

Thanks to our long time sponsor, Stein Industries, an upright test stand constructed and mounted to a concrete slab was used to conduct Test #2 in flight configuration. A spacer was added between the fuel grain and bulkhead, increasing the injector's distance from the ignition disk and fuel, in an attempt to expose the injector to lower temperatures. The engine burn was successful, but unfortunately, the data acquisition system suffered an anomaly at the point of ignition.

Test #3 was conducted in an inverted configuration, with a lower oxidizer volume to decrease the engine impulse needed to reach the target 10,000' altitude. No anomalies were observed.

Test #4 (Fig. 13) used the redesigned feed system, with a thicker injector to prevent partial melting. Unfortunately, it is difficult to replicate the conditions of the *Vidar II* flight without an actual flight test, thus the functionality of the redesign cannot be verified until launch at IREC 2016. Tank pressure, mass, and chamber thrust data were collected from the test (Fig. 14). Mass and pressure data were used to track the CG of the oxidizer throughout the engine burn for ascent stability considerations. No anomalies were observed. Based on Test #4, the *Vidar III* hybrid rocket is expected to output a peak thrust of 460 lbf, with a total impulse of 3120 lbf-sec.

Figure 13. Propulsion test #4

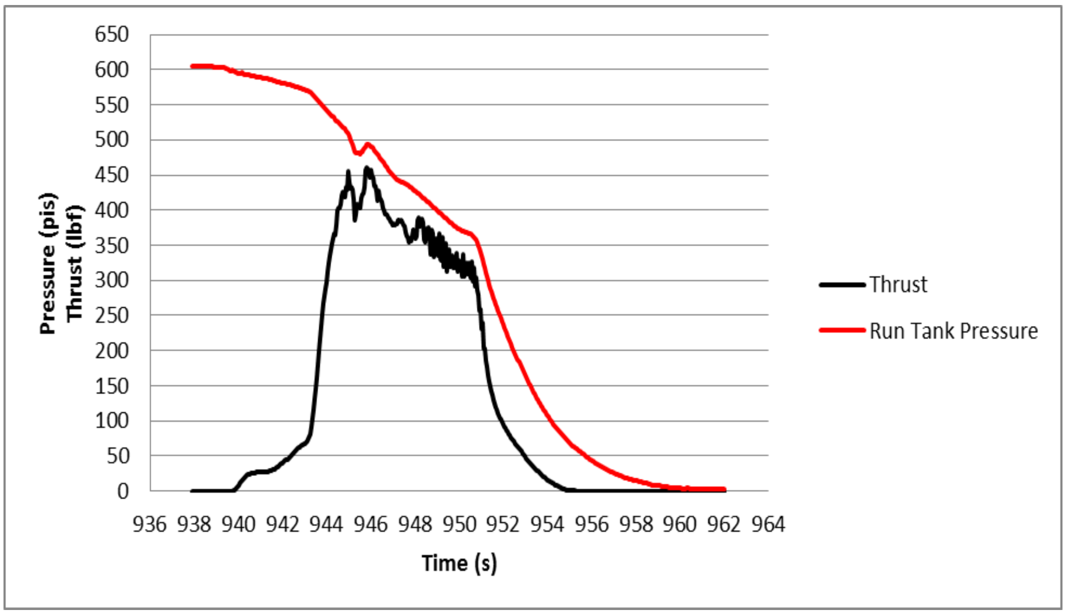

Figure 14. Propulsion test #4 tank pressure and thrust

III. Recovery System

A. System Design and Construction

The recovery system consists of a recovery module, and an avionics module (Fig. 15). The components of each module are housed inside fiberglass airframes, with custom aluminum couplers epoxied to the end. Using a direct aluminum 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.

Figure 15. Recovery system layout

The recovery module employs a single bay to house the drogue and main chutes, sized to achieve appropriate descent speeds as required by the Advanced Category rules. The drogue chute is tethered to the avionics module on one end, and a modified 3-ring release system on the other. Two main chutes are connected to this release system on one end, and the engine on the other (Fig. 16). The recovery module is attached to the engine using a radial bolt pattern.

The avionics module consists of a two commercial Raven altimeters, two 9V power supplies, three magnetic switches, two CO_2 ejection units, and a single BRB 900Mhz GPS transmitter. These components are securely mounted to a rigid sheet aluminum 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.

B. Deployment Events

Upon arming, the altimeters continuously track the rocket's pressure based altitude. Upon detecting the vehicle's descent post-apogee, drogue chute deployment is initiated. 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 acuate a set of pyrotechnically charged wire cutters on the modified 3-ring release system, extracting two main chutes from their deployment bags. The GPS transmitter will ping the location of the avionics module to facilitate location acquisition. See Figure 16 for a diagram of the deployment events.

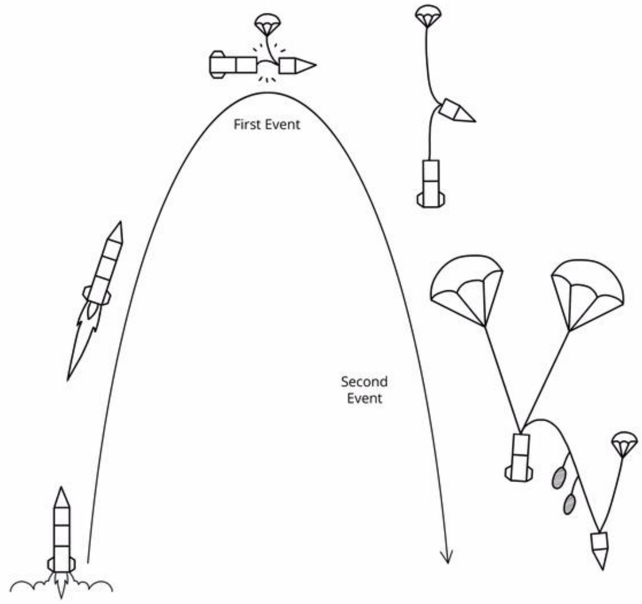

Figure 16. Deployment

IV. Aerodynamics and Flight Simulation

A. Design and Construction

An elliptical nose cone was chosen for the *Vidar III* rocket, since the rocket is expected to stay subsonic for most of the flight. Featuring a 2:1 fineness ratio, the nose cone is manually machined from pine, and layered with epoxy for structural strength (Fig. 17). An aluminum coupler is epoxied to the base for attachment to the avionics module, using a radial bolt pattern. The nose cone has a hollow interior to store a removable 10 lb. steel ballast, serving as our payload for IREC 2016. The tail fins are machined from 6061-T6 aluminum plates, and welded to an aluminum sleeve that is slid over the combustion chamber and fixed using a radial bolt pattern (Fig. 18).

The static margin of any rocket will change over the duration of the engine burn. In a solid rocket, the CG of the vehicle will shift towards the nose, since the motor loses mass over the duration of the burn. However, in a hybrid rocket, the depletion of oxidizer in the tank may cause the vehicle CG to shift tailwards for a short period of time. To verify the mass distribution of the vehicle and design the fins for an adequate ascent stability, the CG of the propellents was calculated over the duration of an engine burn using mass and pressure data from Test #4.

Implementing this prediction using OpenRocket flight simulation software, the fins were designed to achieve a 1.6 caliber stability off-rail.

Figure 17. Nose cone

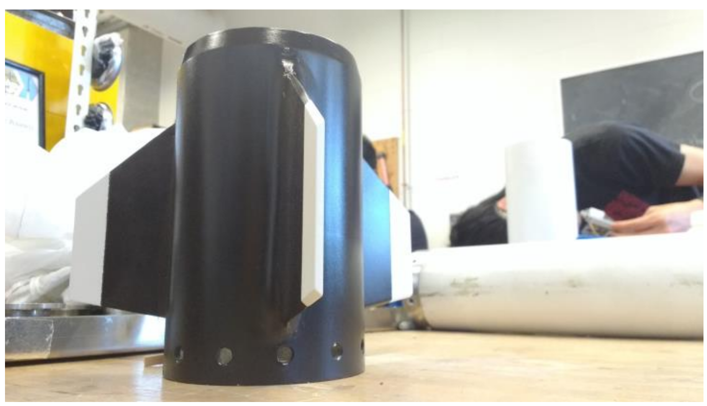

Figure 18. Slip-on fin can

B. Flight Simulation

The flight of *Vidar III* was simulated in OpenRocket (Fig. 19), using average weather data from Green River during the month of June 2015 as the input conditions. The simulation predicts an apogee of 18,000’, which is much higher than the target of 10,000’; however, given the somewhat unpredictable nature of a rocket flight, the actual vehicle apogee is expected to be much lower than the simulation output. Using the team’s custom 32’ launch rail, the rocket is expected to achieve a 88 ft/s off-rail speed, with a 1.6 caliber static margin. The rocket has a dry mass of 52 lbs, and a wet mass of 65 lbs.

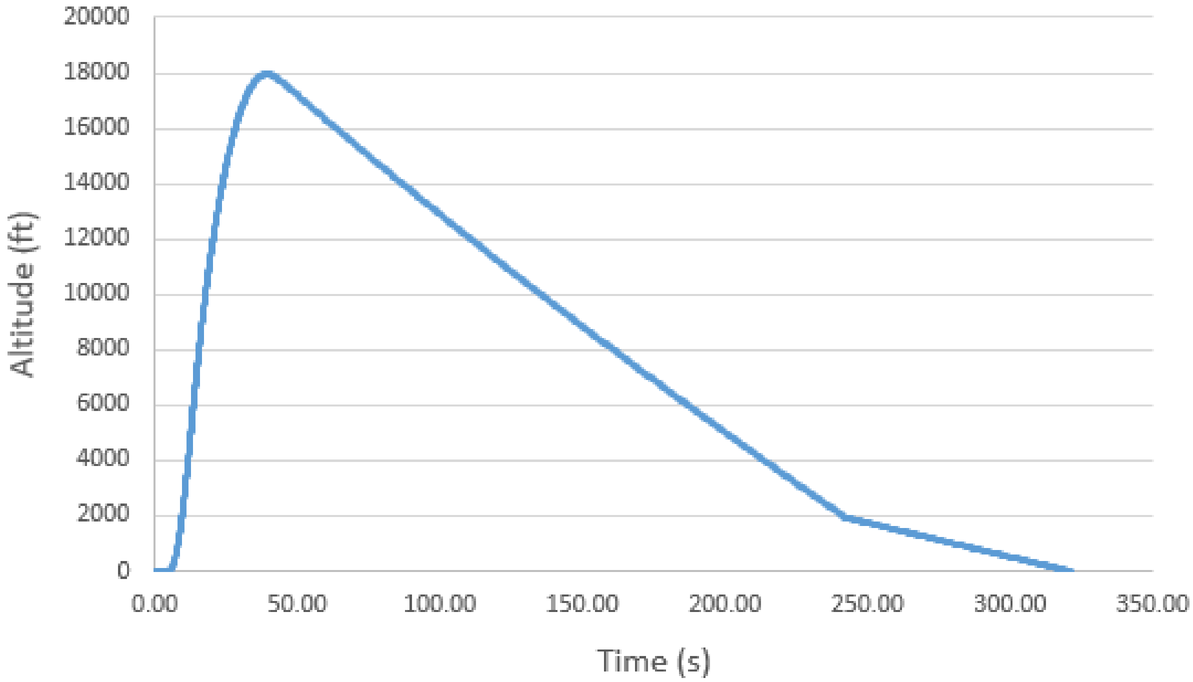

Figure 19. Predicted altitude vs time

V. Conclusion

A hybrid rocket engine, using nitrous-oxide and HTPB as propellants, has been designed, built, and tested by the Waterloo Rocketry Team. A preliminary design used at IREC 2015 by *Vidar II* has proven its ability to achieve liftoff of the launch vehicle. The objective of the 2016 *Vidar III* rocket project is to launch and fly a redesigned hybrid rocket without destruction of the vehicle, and achieve a non-hazardous recovery on descent. The 2016 launch will use a distanced fill disconnect system for increased safety. The rocket has been designed to achieve a suitable off-rail speed and static margin for adequate ascent stability. The recovery system has been designed to achieve a non-hazardous descent of all vehicle components, implementing redundant avionics for safety.

Appendix

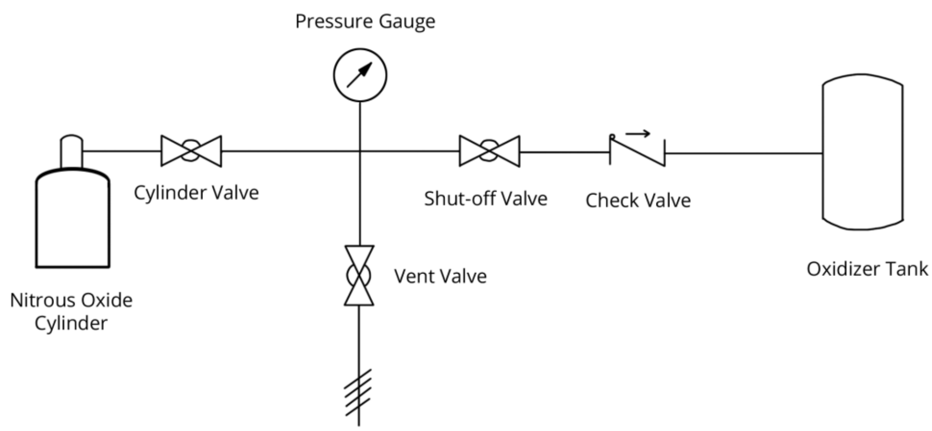

Figure 20. Tanking fluid circuit diagram

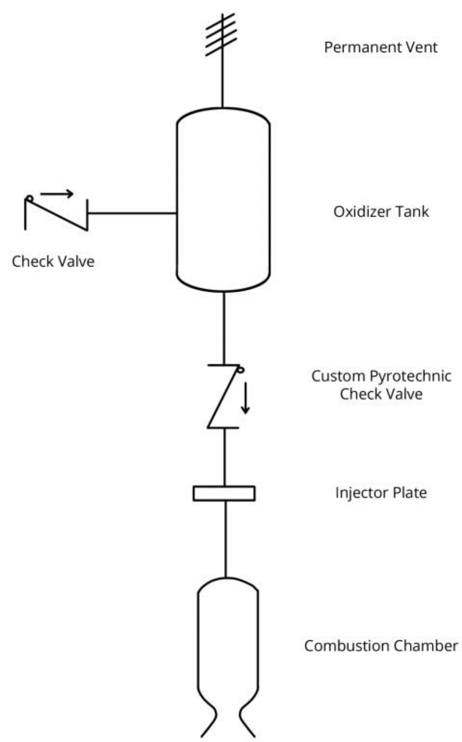

Figure 21. Engine feed system fluid circuit diagram

Acknowledgments

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References

[1]Newlands, R., “Hybrid safety,” Aspirespace technical papers, 2015.