Development and Test of an Experimental Hybrid Sounding Rocket

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The UCLA Rocket Project is in its fifth year of design and testing of its custom hybrid rocket engine, which will be integrated into the HyPE 1B2 rocket for UCLA's entry into this year's Intercollegiate Rocket Engineering Competition hosted by the Experimental Sounding Rocket Association (ESRA 8th IREC). The student designed HyPE 1B2 engine combines a new fuel composition of paraffin wax and HTPB with liquid nitrous oxide as the oxidizer. This fuel mix yields a specific impulse of 205 seconds, a thrust of 873 lbf (3885 N), and a burn time of 10.1 seconds. The redesigned HyPE 1B2 engine combined with a new 12.7 ft (3.86 m) long carbon fiber and fiberglass airframe is capable of delivering a 10-pound payload to an altitude of 25,000 feet above ground level. A dual-parachute recovery system along with a normally-open venting solenoid ensures the safe recovery of the rocket approximately six minutes after the rocket reaches apogee.

INTRODUCTION

The UCLA Rocket Project is now in its fifth year of developing and testing a custom hybrid rocket engine called the Hybrid Propulsion Experiment (HyPE). The engine system has been developed with the annual ESRA IREC in mind. The mission is to carry a 10lb payload to an elevation of 25,000ft above ground level for the advanced category. The rocket must also be recovered in a reusable state with the exception of expendables such as propellant and parachute deployment cartridges. Development of the first HyPE engine, called the HyPE 1A, began in the 2008-2009 year with just six active members. The project has now expanded to over 30 participating members with diverse backgrounds including aerospace, mechanical, materials science, and electrical engineering.

This year's rocket is a shorter, lighter, and higher performing version of its predecessor, backed by additional test data and improved component design. Additional research and improvements to avionics, launch infrastructure, manufacturing methods, and tanking procedures have yielded a more robust system. This allows the rocket reach the target apogee as predicted by the NOP 3.2, an Excel calculator developed by the UCLA Rocket Project to estimate the maximum velocity and predict the maximum height of the rocket's trajectory.

AERODYNAMICS AND STRUCTURES

Materials Testing

In order to determine the strength of the materials and adhesives used in the structure, lap shear tests were conducted using carbon fiber and aluminum samples in addition to surveying literature and material property sheets. ASTM testing standards were followed to ensure accurate results. Carbon fiber laminates (CF) and aluminum plates (Al) were cut into 1 by 4 in. (2.54 by 10.16 cm) coupons.

Testing at the UCLA Materials Science and Engineering facility showed maximum bonding strength using the 3M Scotch-Weld DP-420 epoxy. In CF-CF bonding, the adhesive could withstand more than 2200 psi (15.2 MPa) while CF-Al bonding withstood only 880 psi (6.07 MPa). Based on these results and the thrust provided from the engine, a bonding interface of at least 1.5 in. (3.8 cm) was required in bonding the aluminum thrust bulkhead to the rocket body tubes to ensure structural integrity throughout launch.

Airframe

Figure 1 shows the cross section of the HyPE 1B2. The airframe was designed to be the primary thrust structure for the HyPE 1B2 rocket. This eliminates the need for a longeron structures and allowed interior space to be used more efficiently. An aluminum thrust ring transfers the engine load to the airframe while a gravity bulkhead holds the engine within the boattail on the pad. One of the major improvements of the HyPE 1B2 rocket is the elimination of unused space in the rocket. The most significant example of this is the integration of the recovery compartment with the nosecone section. Combined with other aerodynamic design choices, this allowed the nosecone, recovery bay, and engine section to incur drastic length reductions. The total length of the rocket was thus shortened by 2.5ft (0.76m) to 12.7ft (3.86m). Combined with modifications in the engine configuration, the total wet and dry mass of the rocket are 171.7 and 125.2 lbs (77.8 and 56.8 kg) respectively.

The airframe of the rocket houses all of the rocket's subsystems. A minimum airframe diameter of 8 in. (0.2032 m) was required to accommodate the oxidizer tank. Oven-cured pre-impregnated (pre-preg) carbon fiber comprises the majority of the body. Manufacturing methods limited the lengths of the tubes to 24 in. (0.6096 m). These short tubes are then joined together using smaller coupler tubes. The coupler tubes are made of six layers of uni-directional pre-preg, while the main body tubes consisted of a single layer of uni-directional pre-preg and three layers of woven pre-preg carbon fiber.

Drag Analysis

Extensive analysis was performed on various forms of drag to optimize performance of the rocket. Three types of drag were taken into account: skin friction drag, pressure drag, and interference drag. [1,2,3] Skin friction drag was reduced by decreasing the length of the rocket, thereby reducing the total wetted area. Pressure drag, specifically wave and base drag, was reduced by minimizing negative pressure at the aft end of the rocket using a boattail. Interference drag, which primarily comes from the the camera fairing and the fins, was minimized by using fillets to gradually reduce the change in angle between components. The overall drag of the rocket was determined with RASAero, a publicly available drag analysis software (Figure 2). This was used in conjunction with the NOP 3.2, an Excel calculator developed by the UCLA Rocket Project to estimate the maximum velocity and predict the maximum height of the rocket's trajectory.

Nosecone

The velocity profile of the rocket was used to determine the optimal shape for the nosecone. An analysis of engine performance predicted that the rocket was capable of transonic velocities. In this range, the LD Haack nosecone, which is a mathematically derived shaped optimized to reduce drag, has been shown to outperform most other nosecones in this region (Figure 3). [1,3,4]

The nosecone length was determined through a weight-drag trade study. Increasing the length of the nosecone increased the skin friction drag, decreased the wave drag, and increased the weight. Solidworks and RASAero were used to iteratively determine the optimum nosecone length. Using this data in the NOP 3.2 Excel calculator, a 30 in. (0.76 m) nosecone (fineness ratio 3.75:1) maximized the projected altitude of the rocket.

The effects of aerodynamic heating and radio transmittance were taken into account when selecting the material. The maximum stagnation temperature is approximately 144°F (335K) at the maximum velocity. To reduce the effects of aerodynamic heating, the nosecone tip was rounded to increase the surface area through which the heat was absorbed. This heat dissipation ensures that the stagnation temperature does not approach the glass transition temperature of the resin (T_g = 180°F/355K). After extensive research and contacting several composites companies, fiberglass with a room-temperature curing resin was found that satisfied these requirements [4].

In order to manufacture the nosecone, a male plug and a female mold were made. Once the plug was sanded to the desired shape, the female mold was made around the plug in two halves. A wet lay-up of resin over fiberglass applied to both halves before being combined to cure into one nosecone.

Boattail

The boattail reduces base drag by reducing the cross sectional area of the aft end of the rocket. Boattails can produce additional wave drag if the slope of the curvature isn't sufficiently gradual. [1,5] Thus, the LD Haack shape, which has better wave drag performance characteristics than a conical shape, was used for the boattail. This also enabled the boattail to be fabricated by truncating an extra nosecone.

Stabilizing Fins

Fins stabilize the rocket by ensuring that the center of pressure lies behind the center of gravity. A clipped delta shape with double-diamond (hexagonal) cross section was chosen due to superior stability, low fin flutter, and minimal drag [1].

The primary design factor for the fins was to provide a stability margin of 1.0 to 2.5 calipers, or reference diameters, for the entire velocity profile of the rocket. The RASAero software was utilized to determine a comprehensive center of pressure (C_p) location as a function of Mach number, as shown in Figure 2. The optimum dimensions of the fins were determined by iterating through the fin dimensions including the sweep angle, root-to-tip length, and the chord lengths.

The secondary design criterion was to minimize drag and fin flutter. Fin flutter is a major concern for rockets travelling at transonic velocities since it can lead to a catastrophic failure of the fins. To avoid fin flutter, the fins must be sufficiently stiff to prevent bending or twisting. Four aluminum brackets are used to secure each fin to the fin mount tube. The fins were then bolted and bonded to the tube with DP190 epoxy. Fiberglass strips were added to both the tube-fin and the boattail-fin interfaces to provide additional strength and minimize bending. The intersections were later filleted to smooth the corners and reduce a drag inducing turbulent flow.

PROPULSION

Basic parameters for the HyPE 1B2 hybrid rocket engine were derived from rocket propulsion principles. The layout of the engine is shown in Figure 4.

Propellant

The HyPE 1B2 hybrid propellant was determined through extensive literature research and data obtained from subscale, and full scale testing.

Medical grade nitrous oxide was chosen due to its availability, manageability, and relative inertness when compared to other common oxidizers. The composition of the HyPE 1B2 fuel is 50% paraffin wax, 50% HTBP. The components were melted together in an electric convection oven and pour cast into a vertical mold containing a removable acrylic centering mandrel. The mold also serves as the ablative liner.

Data from subscale test bed and analysis in NASA's Chemical Equilibrium with Applications (CEA) program gave a c* of 4540 ft/s (1384 m/s), which was a significant improvements over previous compositions of aluminized paraffin. The specifications of the propellant are given in Table 1.

Table 1: Propellant Properties

Propellant	Components	State	Density
Fuel	HTPB-Paraffin	Solid	58.1 lb/ft^3
Oxidizer	Nitrous Oxide	Liquid	62.4 lb/ft^3

Pressurant System

The HyPE 1B2 employs a pressure regulation system to maintain constant oxidizer flow throughout the burn duration. A 30-minute, low pressure, fully carbon composite SCBA cylinder stores 3.2 lb (1.5 kg) of nitrogen at 2200 psi (15 MPa), enough for an almost completely pressurized burn. Pressurant flow is controlled via Dresser Mighty Mite high-flow regulator. This results in improved performance and reduced size over an unregulated blow down system. Additionally, increased thrust output reduces overall burn time, lending to greater flight course stability and lower combustion chamber thermal loading. This system also doubles as a supply to the Oxidizer Control System, detailed later in this report. The specifications of this vessel are given in Table 2.

Oxidizer Tank

The HyPE 1B2 oxidizer tank, constructed from 6061-T6 aluminum alloy, holds 36 lbs (16 kg) of soft-cryogenic liquid nitrous oxide around -40 °F (-40 °C). The aluminum alloy was chosen for its affordability and availability. The tank features a diffuser to even out the flow of pressurant into the oxidizer tank and minimize mixing of nitrogen gas into the liquid nitrous oxide. The bulkheads are held in with radial bolts and have Viton O-rings. They contain flanges to center the tank inside the rocket and allowing wire harnesses and tubing past. Additional ports in the top and bottom bulkheads allowed more components to be added while reducing plumbing length. While the nominal oxidizer pressure is 650 psi (4.5 MPa), the tank was proofed up to 1500 psi (10.4 MPa), a FOS of 2.0. Low temperature foam insulation around the tank helps maintain soft-cryogenic state. A relief valve on the tank depressurizes the tank if pressures exceed 900 psi (6.2 MPa). The specifications of this tank are given in Table 2.

Table 2: Tank Specifications

Vessel	Service (Proof) Press	Volume	Dry (Wet) Weight
Pressurant	2.2 (3.7) ksi	523 in^3	7 (10) lb
Oxidizer	0.65 (1.5) ksi	874 in^3	22 (58) lb

Oxidizer Control System

A compact pneumatic piston system was developed to open and close a ball valve for the HyPE 1B2. This design allows for multiple on-off cycles, reduced component weight, and eliminates dependence on an independent pressure vessel. Since the HyPE 1B2 does not have restart nor throttle capability, the valve was only required to perform one cycle. One cycle consists of opening the valve as part of the ignition sequence then closing it as part of the main engine cut off. A compact paintball regulator reduced high pressure nitrogen from the Pressurant System down to the operating pressure of the piston. Low pressure tubing routed the pressurant to a single three-way solenoid valve, which delivered and vented pressurant as required to operate the piston. The piston is connected to the ball valve through a rack-and-pinion gear connection.

Combustion Chamber

The HyPE 1B2 combustion chamber wall was constructed from an extruded 6061-T6 aluminum tube. The chamber consisted of the ablative liner, injector, igniter, pre-combustion chamber, fuel grain, post-combustion chamber, and nozzle. The outside diameter of the chamber is 5.0 in. (0.13 m) and the overall length from thrust plate to nozzle exit is 32.1 in. (0.81 m).

Injector

The HyPE 1B2 injector bulkhead is constructed from a cylindrical block of 6061-T6 aluminum. It features a chamber pressure tap and wide flange in order to transfer thrust from the chamber to the oxidizer tank without loading the plumbing. The bulkhead itself is held in through radial bolts and has Viton o-rings. The swappable injector plate is secured to the internal face using an internal snap ring.

The HyPE 1C's injector plate is a swirling, self-impinging-type triplet with 12 sets of impingement points in a ring. The O/F ratio was calculated to be approximately 4.6, with a total injector area of 0.09 in^2 (5.8e-5 m^2). The line of resultant jet momentum for each of the 12 jets is pointed at a secondary impingement point located at the center of the fuel grain's port [6]. The impinging streams break up the oxidizer jets into liquid fans which atomize the liquid nitrous oxide into droplets and lead to more complete, stable combustion [6]. These atomization effects were verified by cold-flow tests using water as well as liquid nitrous oxide as the working fluid. A strong recirculation region, calculated using Solidworks Flow Simulation, reduces the likelihood of a flame-holding (acoustic) combustion instability by entraining hot gases from the core flow to preheat the oxidizer in the pre-combustion chamber before it enters the boundary layer flame zone [6]. Figure 5 displays a depiction of the simulation for the oxidizer flow through the injector. Additionally, swirling the flow creates a longer residence time, promotes mixing of oxidizer and fuel droplets, and helps suppress combustion instabilities. These attributes were verified in a successful hot fire demonstrating stable combustion free of "chugging" instabilities.

The injector orifice drives the pressure drop across the injector (***ΔP***). The HyPE 1B2 optimized the ratio of pressure drop to chamber pressure (***$\Delta P/P$***) at 44%, ensuring no combustion backflow while maintaining modest structural requirements. Based on the oxidizer pressure of 650 psi (4.5 MPa), the HyPE 1B2's chamber pressure is designed at 450 psi (3.1 MPa).. The specifications of the injector are given in Table 3.

Table 3: Injector Properties

ΔP	$\dot{m}$	A
250 psi	4.43 lb/sec	0.09 in^2

Ignition System

The HyPE 1B2 utilizes a simple pyrogenic preheater grain ignition system, which provides heat to the grain for initiation of the combustion process. Ignition energy requirements in a hybrid rocket depend on initial oxidizer flow rate and fuel volatility, which can be met very simply through adequate heating of the fuel grain in the presence of an oxidizer [7].

A thin casted ring of sugar-potassium nitrate solid propellant acts as the igniter. Each igniter has a redundant pair of pyrogen-coated nichrome resistance charges triggered by a 12 volt power source. The wires run through the fuel grain port and out of the nozzle and are cleanly ejected upon engine start.

Pre/Post-Combustion Chambers

The pre-combustion chamber holds the ignition system and provides a space between the injector and fuel grain. This allows for the oxidizer to impinge before reaching the grain and allows a recirculation area for enhanced mixing and heating [8]**.**

The post-combustion chamber provides a space between the fuel grain and nozzle, allowing combustion to complete before the products enter the nozzle. The size used was based on a rule of thumb presented in Humble which suggests the optimal post-combustion length is twice the fuel port diameter [8]. Both chambers are constructed from epoxy-impregnated silica felt bonded into the ablative liner described below.

Ablative Fuel Liner

The ablative liner protects the combustion chamber wall from hot combustion gases. By burning sacrificially, the ablative produces a film of cooler gases that surround the chamber wall, protecting it [9]. This is one of the simplest and most cost effective methods of cooling an engine. The liner is expendable and must be replaced after each launch.

Out of availability and fabrication constraints, carbon fiber ablative sleeve with insulating outer cork sheet was investigated for use as a liner. Testing proved that the combination was superior to carbon fiber alone at insulating the chamber walls.

Nozzle

The HyPE 1B2 graphite bell nozzle was designed using the method of characteristics (MOC) and is held in the chamber using a radially bolted aluminum securing ring. The angle after the throat was based on the Prantl-Meyer expansion fan. In previous versions of the HyPE engine, a divergent conical nozzle was used. Expansion ratio and thrust have been maintained, while efficiency increased and mass of the nozzle decreased. By more efficiently routing propellant flow parallel to the rocket path with a bell nozzle, improvements in nozzle efficiency and increases in usable thrust were achieved [10]. The final bell nozzle design was validated using simulations in SolidWorks Flow Simulation and a member developed program using a finite difference MacCormack scheme with artificial viscosity.

Tanking

All tanking is performed remotely with the assistance of the launch control system. Nitrogen pressurant is supplied to the Hype 1B2 directly from a standard K-sized Nitrogen bottle. Nitrous oxide is supplied from two standard K-sized bottles inverted on stands and connected in a daisy chain. In previous years, only one bottle was used in the tanking procedure, however a second bottle was added to the system make use of gas expansion due to venting in order to cool the nitrous oxide in the tank.. Solenoids connected to each bottle are toggled, opening the bottles in succession until the oxidizer tank is filled. Umbilical fill lines are the final connection from the pressurant and oxidizer supply lines. These are equipped with quick-disconnect couplings connected to a pneumatic piston-pusher system, which mechanically pushed the fill lines away from the rocket. This allows all filling to be conducted from a safe distance.

LAUNCH OPERATIONS AND AVIONICS

Testing and Launch Infrastructure

The launch control and data acquisition system consists of a launch control unit and a remote launch box. Four 300 ft (91 m) CAT5 Ethernet cables connect the two systems, allowing launch control, actuation, and measurement to be managed a safe distance. The system diagram is shown in Figure 6.

The remote launch box remains at a safe distance from the pad with the launch team. It contains toggle switches that are used to actuate the various oxidizer/pressurant fill solenoids, quick-disconnect umbilical solenoids, oxidizer ball valve solenoids, and propellant grain preheater e-match. Primary safety and ignition safety switches provide a means to quickly shut down the system in an emergency and ensure that no accidental ignitions may occur. This box also contains a NI-6218 USB data acquisition unit, which collects sensor data sent from the launch control unit.

The launch control unit is comprised of the launch control printed circuit board (PCB), two 12V sealed lead acid batteries, a National Instruments 9213 thermocouple DAQ unit, an off-the-shelf load cell amplifier, and a variety of connectors and status indicators. These components stays near the pad at a safe distance from the rocket and are housed in a waterproof plastic enclosure containing a number of clearly labeled circular connectors which allow easy connection of the launch control PCB to the appropriate sensors and actuators while providing ample protection from FOD and personnel damage. The 12V and 24V power indicators on the outside of the enclosure show that the system is powered without opening the enclosure.

The launch control PCB contains an array of transistor-relay switches activated by 5V signals from the remote launch box. This relay operation allows for switching of higher voltages and currents, necessary for solenoid valve actuation and ignition. Each relay is capable of outputting 12V or 24V, allowing flexibility in test setups that use a variety of 12V and 24V solenoid valves. The PCB also contains a delay circuit that opens the main oxidizer valve after predetermined amount of time from ignition of the grain preheater. This is adjustable from 0-10 seconds using a potentiometer on the board.

During motor tests, data is collected from a number of sensors including a 1500lb. (6670 N) Omega brand load cell, pressure transducers, and Type-K thermocouples. All sensors except for thermocouples are routed through the launch control board and run through CAT5 cables to a National Instruments USB-6218 data acquisition unit located in the remote launch box. A custom LabVIEW program is used to collect, analyze, and save sensor data to an output file for each test. The temperature readings are sent directly into our data-collection laptop running LabVIEW via Ethernet cable and protocol.

Data Acquisition

The GUI for monitoring live launch and test data was developed in National Instrument's LabVIEW programming language. The interface was designed to fit on a notebook screen for ease of use in the field and contains tabbed screens for organization. The program's front panel tabs display readings from pressure transducers, load cell, and thermocouples. Raw data is simultaneously recorded to a hard drive and displayed on a customizable time domain graphs. The calibration constants used to linearize our raw data were obtained through in-house calibration. Empirical calibration constants and slopes were acquired by loading the transducers with a known pressure or load, then recording the average voltage output from the device. Slopes and intercept points are manually input into the LabVIEW interface and can be easily adjusted for future calibrations.

Power Latching

On the rocket itself, a flight control PCB is mounted underneath the main oxidizer tank. This PCB interfaces with two on-board rechargeable 11.1V Li-Ion batteries and three custom made magnetic break away connectors, which cleanly sever electrical connections to the rocket during liftoff. During flight, a normally open oxidizer vent solenoid and a normally closed oxidizer control solenoid valve must be powered after receiving a signal from the ground launch control unit. The flight control PCB routes power to these valves continuously after receiving this momentary signal while allowing the vent solenoid to be toggled as part of the normal oxidizer filling procedure.

GPS

The HyPE 1B2 houses a GPS in its nosecone that will allow tracking of the rocket during ascent and descent. This GPS will allow for easier recovery of by providing the rocket's location up until loss of line of sight, which will significantly decrease the search area and should expedite rocket recovery. In addition to providing help with recovery, the GPS will be an integral part of the main engine cutoff system (MECO). The MECO will allow future versions of the HyPE to more accurately reach the target altitude by using a combination of GPS and accelerometer data to determine when oxidizer flow will be cut.

The GPS is a modified BeeLine 70cm GPS module, which takes in GPS signals and rebroadcasts them in the 70cm amateur radio band. The transmissions use the Automatic Packet Reporting System (APRS). The ground station consists of a Yaesu FT-5100 radio connected to a hardware based packet decoder. This allows real-time access to the GPS data on a computer. The major modification to the GPS was the addition of a ZX60-3011+ low noise amplifier to increase the range to a suitable distance. This amplifier provides a gain of approximately 15dB, which will result in transmission power of 27dBm, rather than the stand alone GPS transmission power of 12dBm.

RECOVERY

The HyPE 1B2 utilizes a dual deployment recovery system that includes a drogue and a main parachute. The same scheme is adopted for the HyPE 1B2 due to the heritage associated with the system. The drogue parachute is deployed at apogee with Rouse-Tech's CD3 CO_2 while the main parachute is deployed at 1500 ft above ground level with approximately 3.0 g of black powder. This system contains a single level of redundancy with two separate circuits, each leading to the drogue and main charges. The PerfectFlite Stratologger SL100 altimeter with built-in Mach compensation commands each circuit. The deployment system was ground tested several times to ensure its reliability.

The HyPE 1B2 uses a Sky Angle XXL for the main parachute and TAC-1 for the drogue deployment with a final descent rate between 15 to 25 ft/s. The GPS transmitter will aid in locating and recovering the rocket upon touchdown.

CONCLUSION

The HyPE 1B2 engine uses a mixture of paraffin wax and HTPB as fuel to generate approximately 873 lbs (3885 N) of thrust at an ISP of 205 seconds and a burn time of 10.1 seconds. This engine is capable of lofting a 12.7 ft (3.86 m) long 8 in (0.2032 m) rocket with a 10 lb payload to 25,000 ft above ground level. Efforts from the structures, propulsion, and electronic subsystems detailed in this report come together to form the HyPE 1B2 rocket system, which is the culmination of five years of research and development by the UCLA Rocket Project in pursuit of our overall objective by "pushing hybrid rocketry to its limits."

Table 4: Major components in the HyPE 1B2 rocket and their source

Component	Source
Hybrid Propulsion System	Student-Built, includes purchased /donated components
Airframe	Student-Built, includes donated materials
Parachutes	Purchased
Recovery System	Purchased, Student-Built charges
Avionics and Payload	Student-Built, includes purchased/donated components
Launch Control System	Student-Built, includes purchased/donated components

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APPENDIX

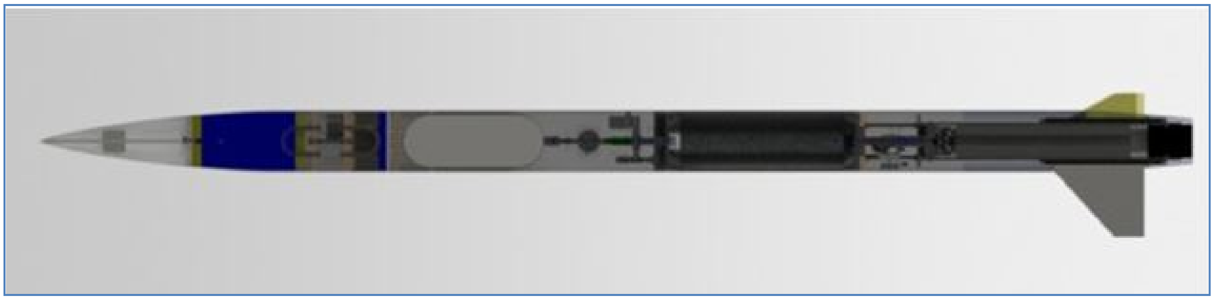

Figure 1: HyPE 1B2 Cross section

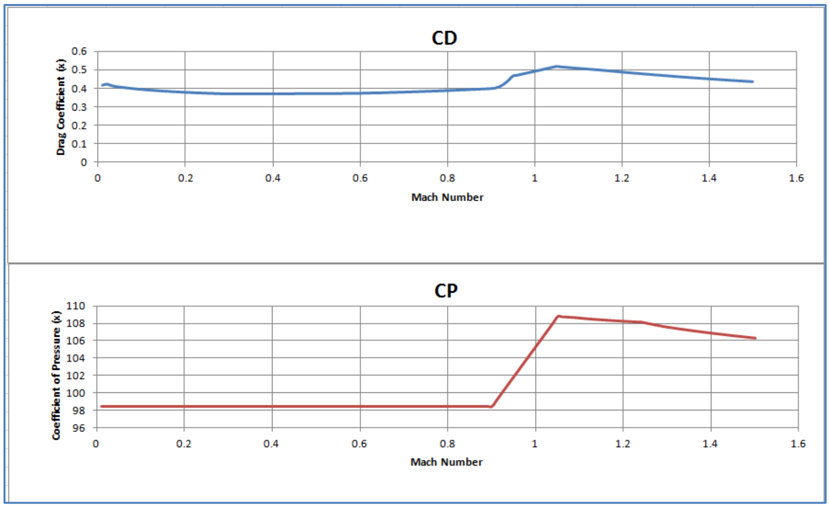

Figure 2 Coefficient of Drag and Coefficient of Pressure vs. Mach number, generated using RASAero

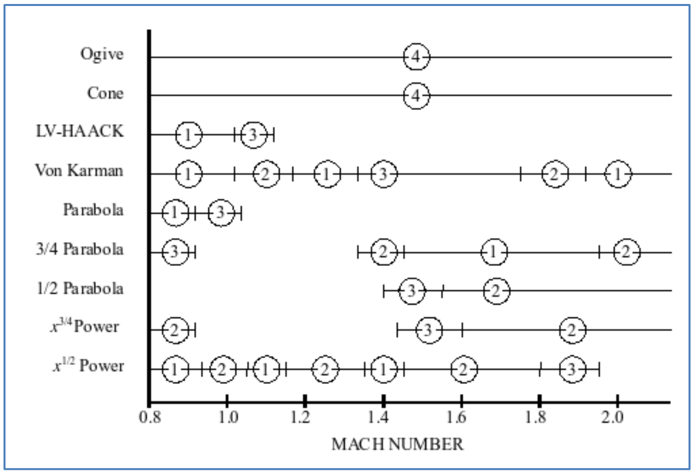

Figure 3: Nosecone Shapes and Efficiency Rating (Superior (1) to Inferior (4))

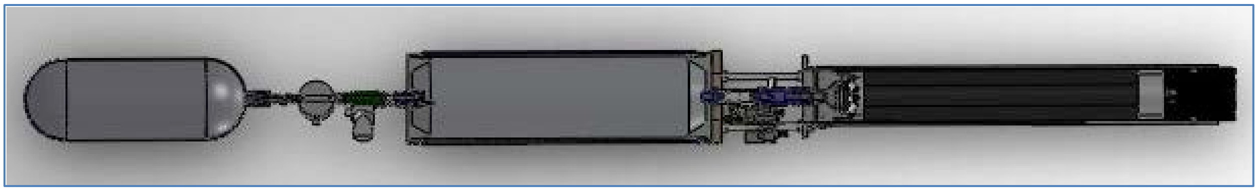

Figure 4: HyPE 1B2 Engine Layout

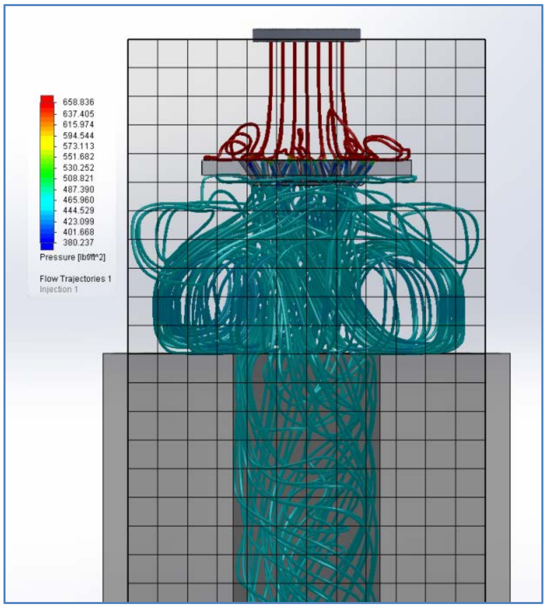

Figure 5: Swirl Injector plate flow simulation in SolidWorks

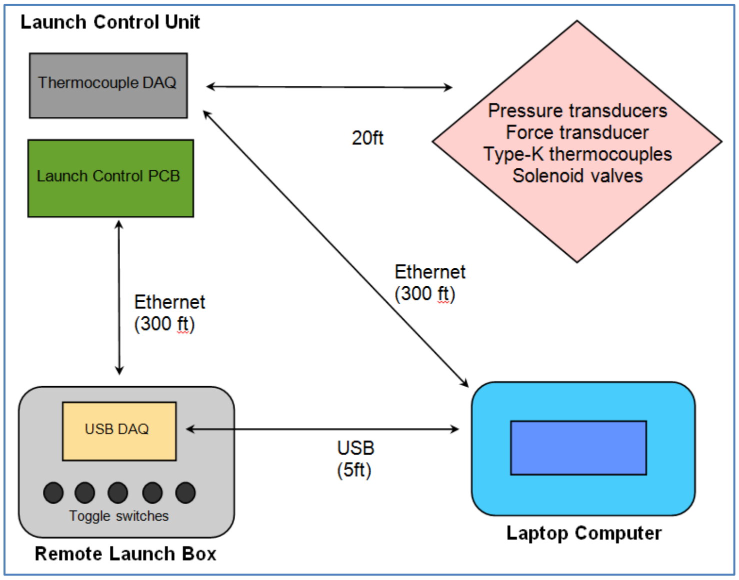

Figure 6: Electronics Control Diagram