Space Challenge

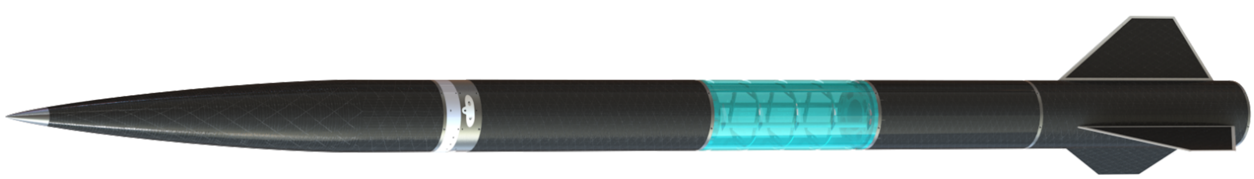
Phase 1 Preliminary Design Report

Submitted by:

The Portland State Aerospace Society
Portland State University
Maseeh College of Engineering and Computer Science
1930 SW 4th Ave suite 160, Portland, Oregon, 97201

Report Contact:

Risto Rushford - Team Captain, cbr3@pdx.edu
208-819-5997



Additional report authors:

Teresa Nguyen	- Systems Engineering Documenter
MacKenzie Kesler	- Chief Safety Officer
Bertrand DeChant	- Chief Engineer
Jacob Tiller	- Propulsion Lead
Eric Thomas	- Propulsion Team Member
Julio Garcia	- Electric Feed System Lead
Georges Oates Larsen	- TSAR Technical Lead and Airframe Lead
Marie House	- Recovery System Lead
Andrew Greenberg	- Faculty Adviser

Note: All referenced materials should be available in the PSAS Phase 1 Preliminary Design Report dashboard in the Dassault 3DExperience platform. This has been used in place of an appendix.

Table of Contents

1. Introduction

Overview and History

The Portland State Aerospace Society (PSAS, see Fig 1 below) is an interdisciplinary, systems-engineering student project hosted at the Maseeh College of Engineering and Computer Science (MCECS) at Portland State University (PSU). Our mechanical engineering, electrical engineering, computer science, physics, math, and business students work together in cross-functional teams, analogous to a small space startup.

Figure 1.0 - The PSAS rocketry team.

PSAS has a long history of innovation in amateur rocketry. Starting in 1998 with a small hobby rocket using amateur radio with an analog television transmitter, over the last 20 years PSAS has pioneered open source amateur rocketry systems. PSAS has had many firsts in amateur rocketry, including the first Linux and first WiFi system on a high power amateur rocket. PSAS has launched 4 generations of solid fuel rockets, starting with Launch Vehicle No. 0 (LV0), a small hobby rocket, and most recently Launch Vehicle No. 3 (LV3), a fully custom carbon fiber rocket with modular airframe sections.

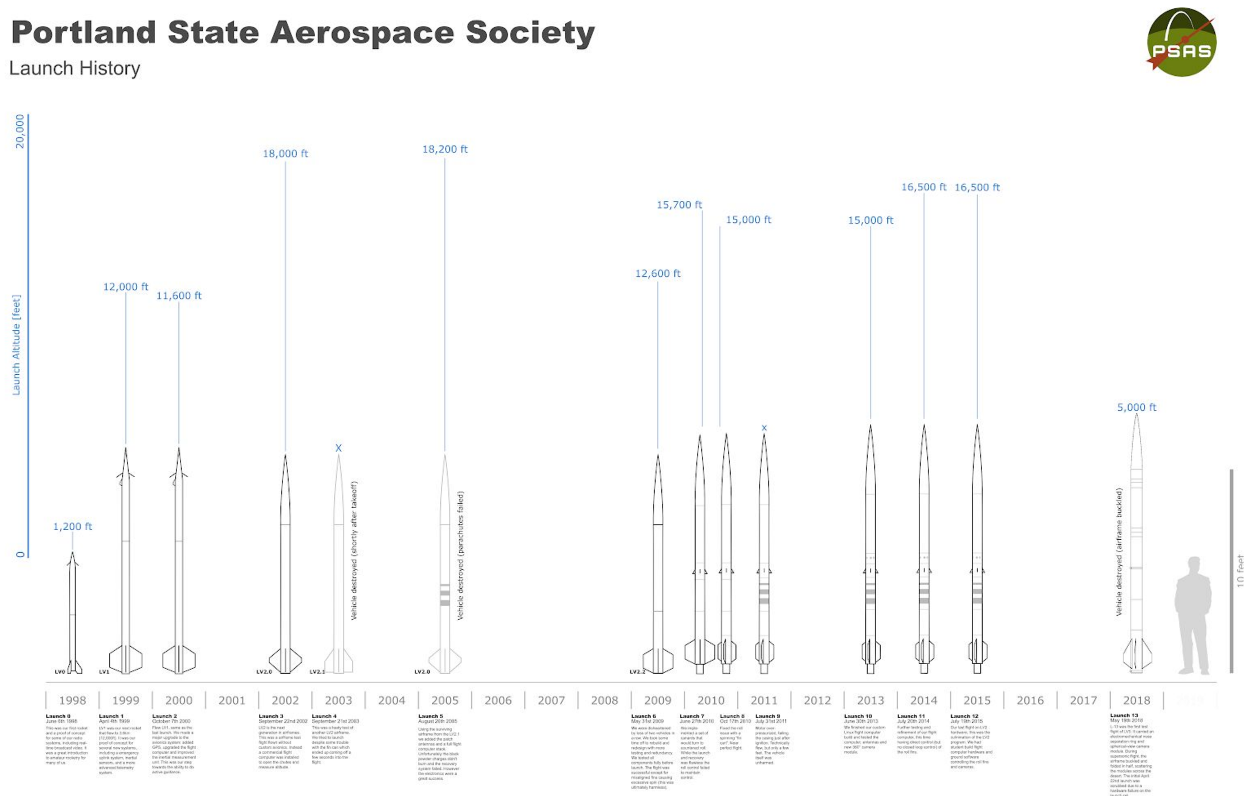


Figure 1.1 - 3 generations of rockets, 14 Launches, and only 3 airframe losses over 20 years

With the realization that solid fuel motors don't easily scale, PSAS began developing liquid fuel engines in 2016. With our entry into the Base 11 Space Challenge in 2018, PSAS has accelerated development on our liquid fuel systems and our next generation airframe, Launch Vehicle No. 4 (LV4).

Team Structure

FIgure 1.2 - The PSAS hierarchical structure for this project is depicted above. For a full size view of the graphic, see it in the PSAS Space Challenge Project Charter Appendix A (first tab). The document may be found in Reference Documents *of the 3DExperience 3DDashboard, heretofore referred to as* 3DX.

Over its 20 year history, PSAS has had tremendous success with a fairly flat organization using a matrix structure. In order of leadership responsibilities, PSAS is comprised of the following teams and groups:

- Student Leadership Team
    - Consisting of mostly junior and senior undergraduates, including both administrative and technical team leads. The student leadership team run PSAS and its projects, and attempts to keep projects on track and budgets balanced.
- System Team Leads
    - Each team has one or more leads: Airframe, Avionics, Liquid Propellent Engine, Safety, and Finance.
- Faculty Advisor(s)
    - One or more faculty members from the PSU college of engineering. We currently have one active faculty advisor.
- Industry Advisors
    - Engineers and managers from local industry who volunteer their time to help mentor and guide PSAS students. Industry advisors are the key to the long term health of a student organization for helping with institutional memory and continuation. PSAS has about a dozen industry advisors, with the goal of having one industry advisor in each major team.
- Capstone and Thesis Students
    - PSAS sponsors engineering undergraduate capstones (“senior projects”); as the “industry sponsor” for their capstone, PSAS runs system-level engineering projects for small teams of ME, EE, and CS engineering students. Several graduate students also will concentrate their master’s thesis on PSAS systems. Each year, PSAS sponsors roughly 1-2 theses and 3-5 engineering capstone projects. PSAS is interested in sponsoring business student capstones as well, but the current capstone structure in the PSU School of Business prohibits this.
- Student Members
    - The bedrock of PSAS is our over 50 undergraduate and graduate students who volunteer their time to help build open source amateur rocket and CubeSat systems.

Management Strategies and Systems Engineering Approach

LV4 will be our 5th generation rocket, but our first 100-km capable rocket design. We are actively prototyping and testing LV4 subsystems, attempting to give as much technology heritage to our subsystems as possible before pulling together the final system. Our current LV4 design will use our LV3-class carbon fiber composite airframe, novel composite-over-stainless propellant tanks, a 3D printed liquid oxygen and isopropyl alcohol regeneratively cooled engine, use a cold-gas jet reaction control system for minor trajectory adjustments, and use an existing CubeSat design as the avionics system.

Our composite airframe subsystem test platform is Launch Vehicle No. 3, which first flew Summer 2018. The flight failed due to aeroelastic buckling as it reached transonic speeds. We have redesigned the modules to account for the failure mode encountered in the LV3 launch. The next iteration, LV3.1 will fly this coming spring or summer 2019. Once optimized, the airframe design will be scaled up for the LV4 rocket.

In tandem with LV3, we have the Liquid Propulsive Engine Test Stand (LPETS) and the Electric Feed System (EFS) in development for the final liquid fuel engine design, both of which will also be tested in the spring. The engine will use a 3D printed design with regenerative cooling channels, and is optimized for a LOX-IPA mix.

Additional systems that will be used in LV4 are the Electromechanical Recovery System (ERS), which is being designed in-house for use in a vacuum, a cold gas reaction control system (RCS), and an avionics package which will be adapted from PSAS's Oregon Satellite (OreSat) project which is being developed in parallel to the rocket for NASA's CubeSat Launch Initiative.

Each of these subcomponent systems is a legacy project with some level of development before the Base 11 Space Challenge was announced. However, PSAS is not a well-funded group and so development tends to progress slowly as we develop our own systems that we can use more cheaply than commercial-off-the-shelf components. Our biggest non-safety risk factors are the time of development to reach the required technology readiness level, and funding to purchase parts and services that we cannot provide for ourselves.

To accommodate changes within a subsystem that would affect other parts of the whole, we are tracking revisions using a spreadsheet. We would love to eventually gain proficiency in the Dassault 3DExperience platform to manage design and integration, but the learning curve during what is the busiest time of the year at PSU has prevented this. We will onboard ourselves fully to the 3DExperience platform during the spring and summer terms of 2019 to avoid this problem in the future.

2. Description of Overall System Architecture

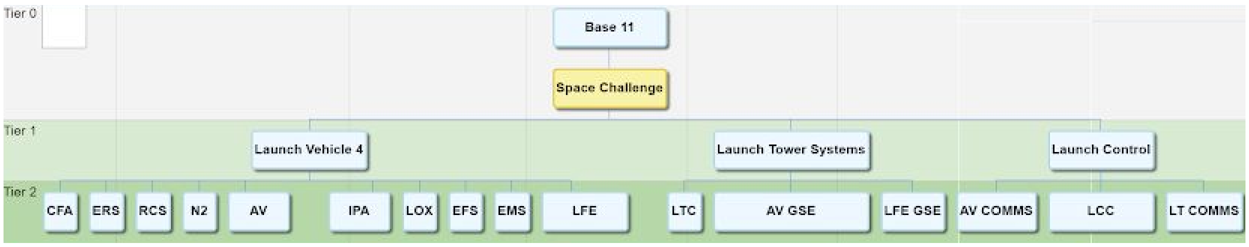


Figure 2.0 - The top three tiers of the system architecture are depicted hierarchically above (as shown in the Product Breakdown Structure document, viewable in 3DX under [Overall System Design](#)), and in integrated form below.

Table 2.0: PSAS Space Challenge System Architecture

Tier	System/Subsystem	Parent	Notes:
0	Space Challenge	Base 11	Mission Level
1	Launch Vehicle 4	Space Challenge	End Product
2	CFA	Launch Vehicle 4	Carbon-Fiber Airframe
2	ERS	Launch Vehicle 4	Electromechanical Recovery System
2	RCS	Launch Vehicle 4	Cold-Gas Reaction Control System
2	N2	Launch Vehicle 4	Compressed Nitrogen Tank
2	AV	Launch Vehicle 4	Avionics System
2	IPA	Launch Vehicle 4	Isopropyl Alcohol Tank
2	LOX	Launch Vehicle 4	Liquid Oxygen Tank
2	EFS	Launch Vehicle 4	Electric Feed System
2	EMS	Launch Vehicle 4	Engine Management System
2	LFE	Launch Vehicle 4	Liquid Fuel Engine
1	Launch Tower Systems	Space Challenge	End Product
2	LTC	Launch Tower Systems	Launch Tower Computer
2	AV GSE	Launch Tower Systems	Avionics Ground Support Equipment
2	LFE GSE	Launch Tower Systems	Liquid Fuel Engine Ground Support
1	Launch Control	Space Challenge	End Product
2	AV COMMS	Launch Control	AV Communications
2	LCC	Launch Control	Launch Control Computer
2	LT COMMS	Launch Control	Launch Tower Communications

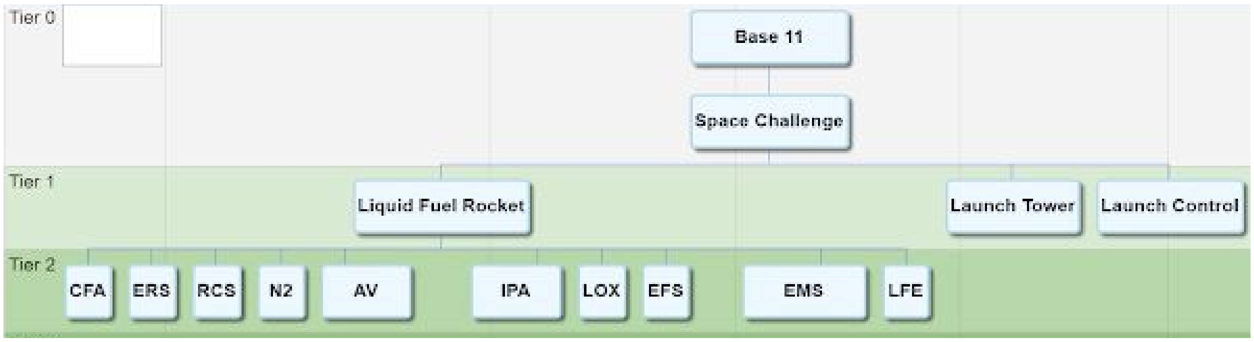


*Figure 2.1 - This report is primarily concerned with the system architecture of the **LV4 Rocket**:*

The forward part of the LV4 rocket (see below for another rendering) will use the ERS housed in the nosecone, with a cold-gas RCS and compressed N2 tank. The ERS and RCS modules are each designed for use in low to null atmospheric pressure, enhancing the rocket's reliable for a 100km flight.

Situated below the N2 tank in the mid-section of the rocket is the AV, which will consist of the flight computer (OreSat) which ports to the launch tower computer while loaded on the launch rail, and interfaces with the Launch Control Computer via amateur radio while in flight. The radio interface will broadcast real-time telemetry data as well as a live stream from an onboard camera while in range. Additionally, an AV subsystem (ARGUS) will consist of a 360^{o} degree camera ring to record full flight video coverage for later viewing. 360^{o} degree video is not required for the competition, however it is a staple of PSAS rocketry (check out the video at the top of the *Mission Concept of Operations* tab in the 3DX dashboard for footage taken from a previous launch.

The lower portion of LV4 consists mainly of the engine and related subsystems. Two low-pressurized tanks each holding part of the bipropellant mix (LOX and IPA) will be toward the top end of the engine section. Below that will be the EFS which will pressurize the fuel and pass it down into the engine. A section of the avionics package, the EMS will be located below the EFS and will regulate the feed rate and collect sensor data from the engine system. Finally, the 3D printed liquid fuel engine will sit at the bottom of the assembly to provide thrust.

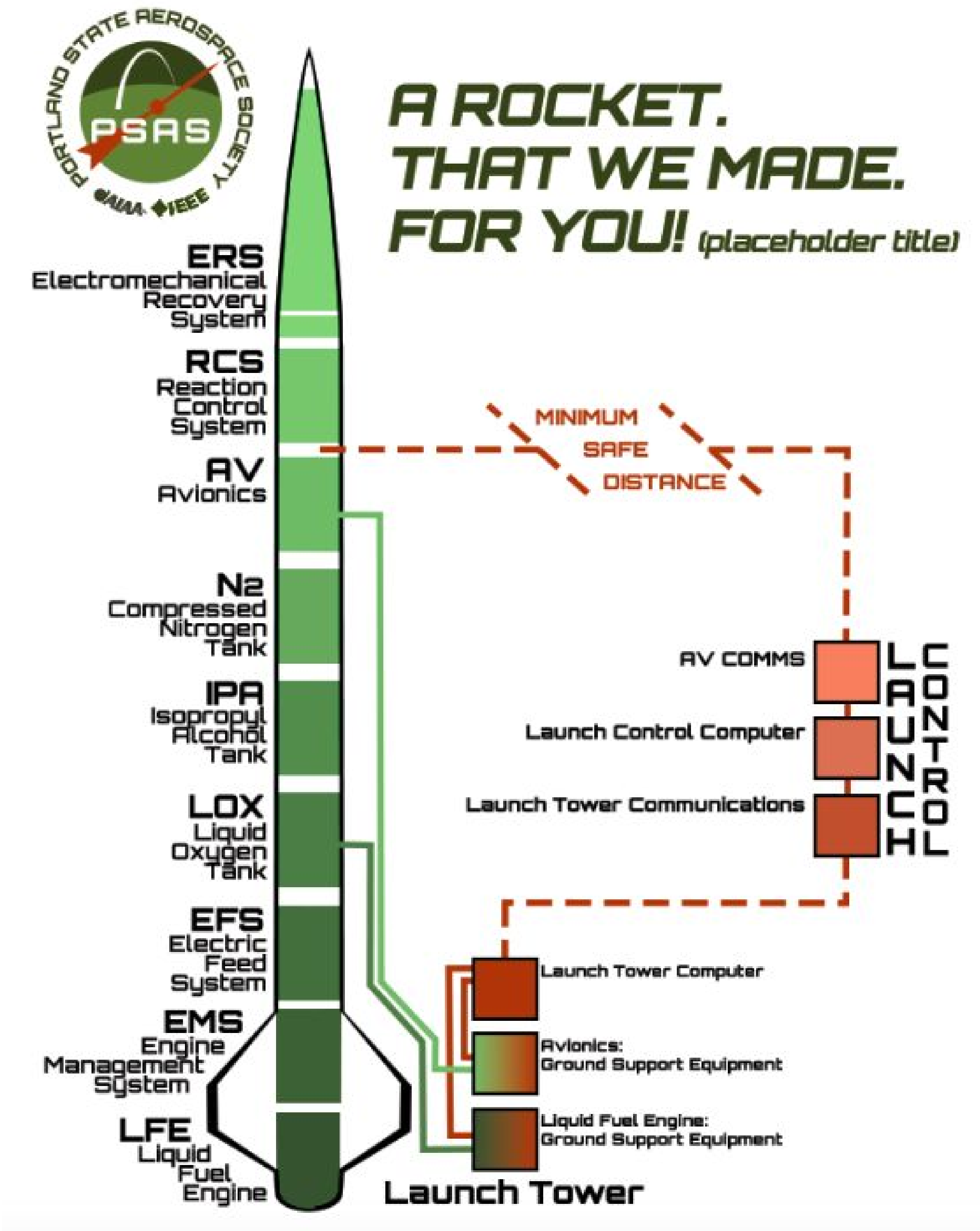


Figure 2.2 - LV4 System Architecture

3. Mission Concept of Operations Overview

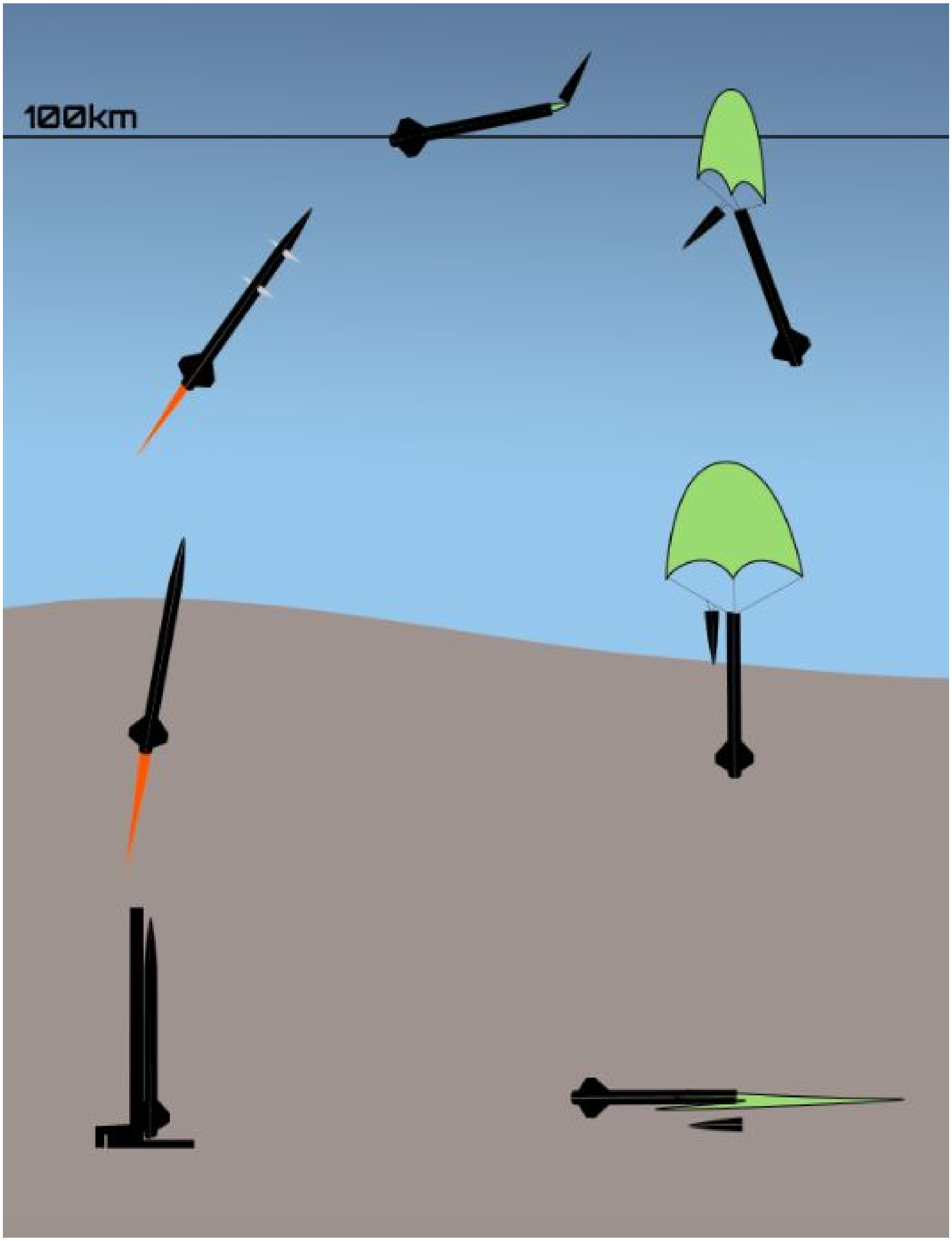


Figure 3.0 - See a stylized depiction of the LV4 Rocket launch in the image above. A more thorough Concept of Operations is detailed in the table below.

We assume that we are starting with a modular rocket but that has already been tested for integration, in unarmed and working order, built in the PSAS Rocket Room. The table below details the mission concept of operations (ConOps) as referenced from the PSAS Space Challenge Mission Analysis viewable in the *Mission Concept of Operations tab in 3DX*.

Table 3.0 - Detailed ConOps

Step ID	Phase	Description
COPS-1	1 - Prelaunch	-
COPS-1.1	1.1 - Launch Site Travel	
COPS-1.1.1	-	Perform pre-travel system integration test the week before travel
COPS-1.1.2	-	Pack all critical hardware and tools appropriately
COPS-1.1.3	-	Verify all items on flight tools and flight hardware checklists present
COPS-1.1.4	-	Unpack all critical hardware and tools at launch site
COPS-1.1.5	-	Verify all items on flight tools and flight hardware checklists present
COPS-1.2	1.2 - Rocket Preparation	-
COPS-1.2.1	-	Airframe & internals final assembly
COPS-1.2.2	-	Perform final integration test
COPS-1.2.3	-	Load rocket into launch-site transportation rig
COPS-1.2.4	-	Visual Inspection
COPS-1.3	1.3 - Launch System Activation Prep	-
COPS-1.3.1	-	Transport rocket to launch tower
COPS-1.3.2	-	Load rocket on launch rail
COPS-1.3.3	-	Verify all systems SAFED
COPS-1.3.4	-	Plug in umbilicals
COPS-1.3.5	-	Visual Inspection
COPS-1.4	1.4 - Launch System Activation	-
COPS-1.4.1	-	Disengage shore power safety lockouts
COPS-1.4.2	-	Engage shore power
COPS-1.4.3	-	Confirm Command & Control uplink
COPS-1.4.4	-	Visual Inspection
COPS-1.5	1.5 - Launch System Arming	-
COPS-1.5.1	-	Fill Fuel Tank
COPS-1.5.2	-	Fill LOX Tank
COPS-1.5.3	-	Verify onboard sensors report nominal
COPS-1.5.4	-	Disengage manual engine power lockouts
COPS-1.5.5	-	All personnel clear launch site

COPS-1.5.6	-	Command & Control informs avionics PERSONNEL ARE CLEAR
COPS-2	2 - Flight	-
COPS-2.1	2.1 - Launch	-
COPS-2.1.1	-	Final verification: All personnel clear launch site
COPS-2.1.2	-	Command & Control informs avionics ARM AND PREPARE FOR IMMINENT LAUNCH
COPS-2.1.3	-	Command & Control informs avionics LAUNCH
COPS-2.1.4	-	Avionics disengages software-controlled engine power lockouts and initiates ignition sequence
COPS-2.2	2.2 - Mid-Flight	-
COPS-2.2.1	-	Engine remains in operation until all fuel and oxidizer depleted
COPS-2.2.2	-	Excess fuel, oxidizer, pressurant vented once engine ceases operation
COPS-2.2.3	-	Avionics monitors, controls engine, detects apogee
COPS-2.3	2.3 - Recovery	-
COPS-2.3.1	-	Avionics triggers recovery system activation at apogee
COPS-2.3.2	-	Avionics awaits touchdown, begins transmitting TOUCHDOWN signal
COPS-2.3.3	-	Avionics performs full system purge (pressurant, LOX, Fuel) on touchdown, even if purge performed mid-flight
COPS-2.3.4	-	Avionics begins transmitting ALL-CLEAR signal
COPS-3	3 - Post-Flight	-
COPS-3.1	3.1 - Retrieval	-
COPS-3.1.1	-	Personnel approach last known location of rocket upon touchdown. If TOUCHDOWN signal detected, do not proceed closer until ALL-CLEAR transmitted
COPS-3.1.2	-	Once ALL-CLEAR detected, personnel retrieve engine and return to operations base
COPS-3.2	3.2 - Disassembly	-
COPS-3.2.1	-	Check all sensors for indications of system damage
COPS-3.2.2	-	Collect all data from onboard sensors
COPS-3.2.3	-	Shut system down
COPS-3.2.4	-	Disassemble airframe and rocket internals
COPS-4	4 - Post-Launch	-
COPS-4.1	4.1 - Pack up and leave	-

4. Mission Analysis

The Mission Analysis was performed based on the first four steps of the NASA Systems Engineering Engine (NPR 7123.1).

Table 4.0 - Qualitative Mission Analysis

Step ID	Step Requirement	Analysis	Source
MA-A	System Design Process	-	-
MA-1	Stakeholders Expectations Definition	-	-
MA-1.1	Analyze sponsor's directive	"Design, build and launch a liquid-propelled, single stage rocket to an altitude of 100 kilometers (the Karman Line) by December 30, 2021."	https://www.herox.com/spacechallenge
MA-2	Technical Requirements Definition	Performed in the Requirements Master Document, this analysis breaks down the competition rules, FAA regulations, and other requirements into functional project areas allowing each rocket subsystem team to easily reference requirements pertaining to their work.	https://docs.google.com/spreadsheets/d/13n1cXnVBiiJr3A0jSme5eZ7F5c1OHKR9IrS6eaD1xdY/edit?usp=sharing
MA-B	Technical Solution Definition Processes	-	-
MA-3	Logical Decomposition	-	-
MA-3.1	Develop a Concept of Operation	See the ConOps page of this document.	ConOps
MA-3.2	Develop a timeline for project work through mission completion	A detailed gantt chart was developed during the pre-phase of the Space Challenge, and PSAS project development has been charted alongside the official competition deadline.	https://instagantt.com/shared/s/744058557007966/latest
MA-4	Design Solution Definition	-	
MA-4.1	Develop the Product Breakdown Structure	Performed in the Product Breakdown Structure document, a mission level analysis determines the three end products: LV4 Rocket, Launch Tower Systems and the Launch Control Systems. Each product is broken down to the second tier, with the subsystems broken down further by project teams.	https://docs.google.com/spreadsheets/d/1LNj9oGaJcO-49A1q8yoCfXOJQKwgOmqV_unDAAbagQg/edit?usp=sharing

As discussed in the System Architecture section above, the PSAS 100-km rocket will meet the competition requirements by using a combination of sophisticated avionics and an IPA/LOX rated engine. The LV4 Rocket is still very much in its preliminary design stage, with two separate test beds for component development:

- Liquid Propellant Engine Test Stand (LiqPETS).
- The LV3 carbon-fiber airframe, which is launched using commercial off-the-shelf solid rocket motors

The information used in this analysis is still an assumption which will be verified or disproved at a later date based on testing. Below we will discuss the results of our project development and where applicable the on-going Multi-Disciplinary Optimization (MDO) efforts that inform our propellant choice, mass budgeting and flight dynamics.

Quantitative requirements of the LV4 rocket were calculated during an initial MDO analysis at the beginning of the PSAS 100-km rocket program using a Python script in Jupyter Notebook. The outcomes of that initial analysis set the direction for many of the current designs being developed for the Space Challenge currently. The analysis may be viewed in the *Concept of Operations* tab in 3DX.

Some deficiencies in that initial design prompted a second MDO analysis that is still on-going. The previous script was extended and its accuracy improved, and the constraints of the problem were refined.

Table 4.1 - Quantitative Mission Analysis taken from the MDO exercise:

This second-pass MDO was fed the following constraints which it met:

Length/Diameter ratio (c.f. < 18):	17.763
Sommerfield criterion (c.f. pe/pa >= 0.35):	0.625
Max acceleration (c.f. < 15):	6.943 gs
Thrust/Weight ratio at liftoff (c.f. > 2):	2.446
Altitude at apogee (c.f. > 107.401 km):	107.421 km
Speed when leaving launch rail (c.f. > 22 m/s):	33.216 m/s
Design thrust (ground level) (c.f. = 6 kN):	6 kN

And it produced the following optimized design variables:

Design tankage total length (including ullage):	1.637 m
Design mass flow rate:	2.437 kg/s
Design airframe diameter:	304.8 mm (12 in)
Design airframe length:	5.56 m
Design nozzle exit pressure:	53.518 kPa
Design GLOW:	177.492 kg

Along with the following minimum design requirements:

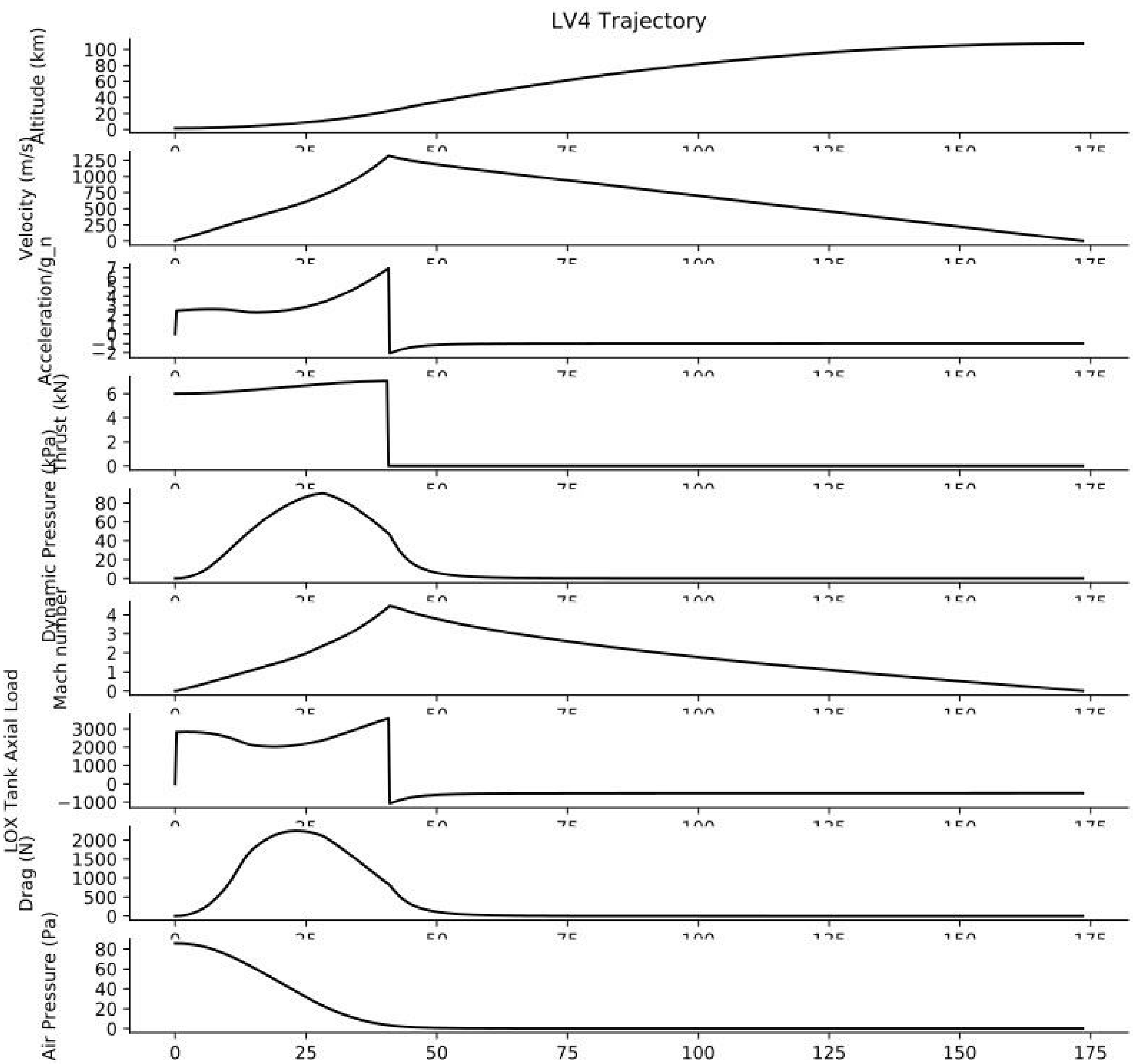
Design thrust (vacuum):	7.05 kN

Design expansion ratio:	7.521
Design throat area:	2.639 in^2
Design ISP (specific impulse):	268.315 s
Design chamber pressure:	350.0 psi

As well as the following theoretical flight behaviors and fuel requirements:

Mission time at apogee:	173.5 s
Design total propellant mass:	98.079 kg
Design burn time:	40.75 s
Design total impulse:	265.894 kN*s
Design delta-v:	2.115 km/s
Estimated minimum required delta-v:	1.452 km/s

And finally, the following flight timelines:



Important information that this MDO was not able to find is the performance of the carbon fiber modules. A test flight performed on the scaled down LV3 rocket demonstrated that the carbon fiber design has a higher aeroelasticity than the aluminum used to couple the modules together. A three-point bend test has been performed on the new module design to demonstrate the side load capacity (video of Bend test and other information on the previous flight failure is available toward the bottom of the *Airframe & Structure* tab in 3DX). Two modules coupled together at a combined length of 1.534 meters were subjected to 1100 pounds of force, and deflected by 12.7 mm with no discernible damage to the modules. When the force was removed, the modules bent back to the original shape with no obvious lasting deformation. This is a promising preliminary result, but more testing is needed to determine material properties for a truly in-depth analysis of the redesigned carbon-fiber modules during flight. More data will be obtained during the launch of LV3.1 in summer 2019.

5. Requirements

The Requirements Master Document (*Reference Documents* tab in 3DX) performs a comprehensive analysis of the competition rules, FAA regulations, and other requirements or limitations that may affect the design of the 100-km liquid propelled rocket. In addition to this, PSAS has several legacy technologies that had begun development before the Base 11 Space Challenge was announced, providing additional constraints or limitations.

Because of these legacy technologies, we are integrating the the Systems Engineering Engine model listed within the NASA Systems Engineering Handbook, (document NASA-SP-2016-6105-SUPPL-1.pdf) to create a traceable, repeatable documentation system in line with industry standard practice.

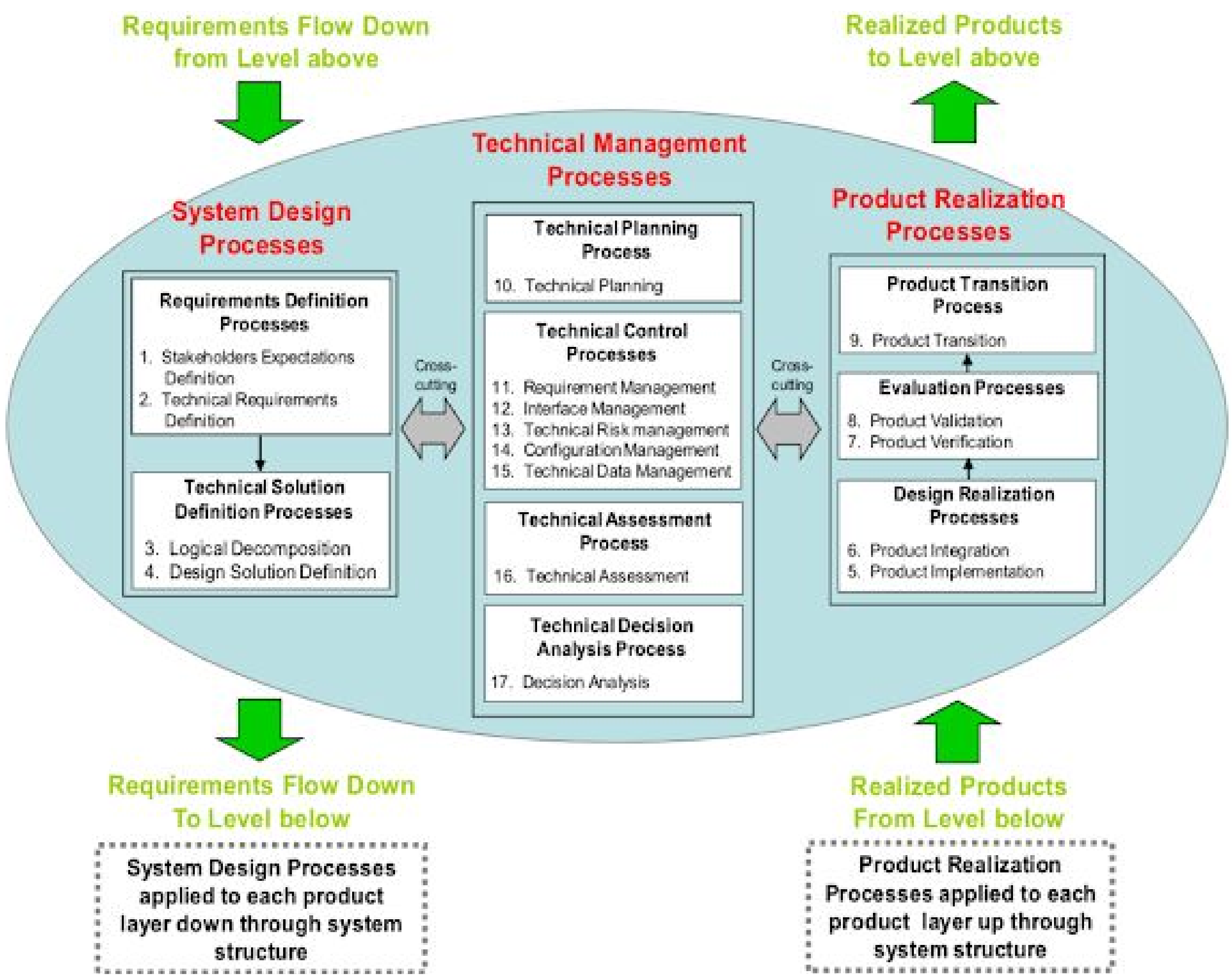


Figure 5.0 - The Systems Engineering Engine

We’re working through the left side of the SE Engine, utilizing stages 1 - 4 of our Systems Design Process, with some subsystems starting to work up the right side as well. Regarding the Base 11 requirements of the rocket launching no higher than 100km, design implementation involved reassessing the airframe (exterior), motor and propulsion strength, recovery system, and avionics based on our legacy technology from previous design executions.

The airframe shall meet the requirements of structural integrity through a lightweight carbon fiber material and honeycomb composite as laid-up into a modular airframe design. Revisions made to the hardware based on the rapid unscheduled disassembly from our LV3.0 launch ensures rigidity of the modules during flight. See the airframe structure section below for more details.

Motor and propulsion strength has been refined to support the lightweight composite airframe, utilizing liquid fuel that was chosen based on accessibility and control manageability supporting the safety requirements listed in the Base 11 Space challenge. The decision to use battery power supplied energy supports total control over the ignition system, adhering to the operational needs of the ground equipment that will remain in SAFED configuration until approved safety officers give permission to ARM the rocket for launch.

The recovery system was designed to use an in-house telemetry system to detect apogee, a barometer, and a temperature sensor. This is a restructured approach to ensuring the drogue parachute stabilizes the descent of tethered components providing sufficient drag to permit safe deployment. Once the parachute is deployed, the GPS system will signal the recovery team so that they will be able to recover all rocket components successfully.

Avionics is developing a flight computer module to communicate with the Reaction Control System, Electromechanical Recovery System, Electric Feed System, and Engine Management Systems. This allows a cohesive integration of LV4’s flight control systems of information relay to ground stations using an avionics antenna.

6. Mass budget

The LV4 mass budget was determined during preliminary MDO meetings (see the Mission Analysis section above) to give us rough estimations based on our access to resources and the technologies that we have available or in development. The mass budget that we have determined is as follows:

Vehicle Dry Mass estimates:

- Avionics package - 3.3 kg
- Recovery system - 4 kg
- Payload - 13 kg
- Propellant tanks ~ 4.81 kg, this includes a fudge factor of 2
- Engine - 3 kg
- Feed System - 10 kg
- Plumbing - 5 kg
- Airframe - 34.229 kg

This gives us a total estimated dry mass of about 77.339 kg.

Propellant (Wet Mass) estimates:

- Fuel (IPA) - 42.643 kg
- Oxidizer (LOX) - 55.436 kg

This gives us a total estimated propellant mass of 98.079 kg.

As such we are assuming a Gross Lift Off weight (GLOW) of 175.42 to 177.56 kg.

The IPA/LOX reaction is calculated to provide a thrust-to-weight ratio (TWR) at liftoff of 2.45 at a mass flow rate of 2.44 kg/s with an estimated time to apogee of 173 seconds.

7. Propellant Selection and Propulsion Design

Overview

The Liquid Fueled Engine (LFE) in *Figure 7.0 - 2.2 kN nozzle* was designed by a 2015 Portland State University senior capstone group for PSAS. The LFE design requires a propellant combination capable of regenerative cooling with a fuel which is safe for operators to handle. The design team also chose to see fuels which are less prone to coking than kerosene to reduce the impact on performance of soot. View the [Propulsion Tab] in 3DX for more CAD renderings.

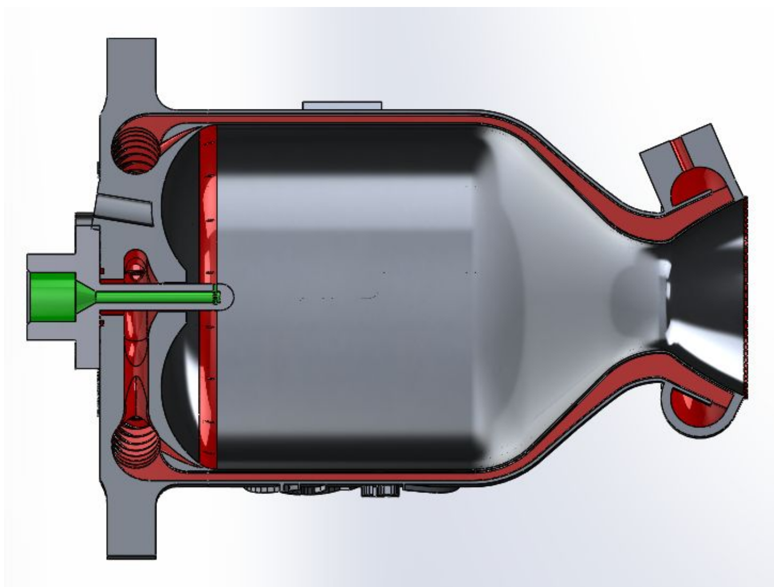


Figure 7.0 - 2.2 kN nozzle: Cross section of 2.2 kN engine. Fuel flow path shown in red, LOX flow path shown in green.

Propellent Choice and Justification

The propellants chosen for LFE are liquid Oxygen (LOX) and Isopropyl Alcohol (IPA, Isopropanol). Liquid Oxygen is readily available and other than hazards associated with combustible materials and ignition sources, flashes off quickly into oxygen gas. Other oxidizers considered were too hazardous for handling, required storage and disposal, or are otherwise less performant than LOX. IPA was chosen for its miscibility with water and correspondingly high heat capacity, ease of handling, and relatively low coking characteristics compared to kerosene.

Motor Design and Performance

We chose a 3D-printed, regeneratively cooled, LOX centered pintle injector design liquid-engine for LV4. The fuel inlet at the nozzle and runs through the walls to the base of the housing where the propellants are metered into the combustion chamber (See again *Figure 7.0 - 2.2 kN nozzle*). The fuel absorbs combustion heat and returns it to the combustion chamber by passing through an annular metering orifice created by the gap between the pintle outer diameter and the combustion slot as seen in *Fig. 7.1 Pintle Dimensions*. The LOX flows through the center of the pintle injector and is metered through orifices located radially about the tip. The two flows impinge to create an atomizing spray with a cone angle of 45 degrees as in the right side of Fig. X_Pintle FOD_X.

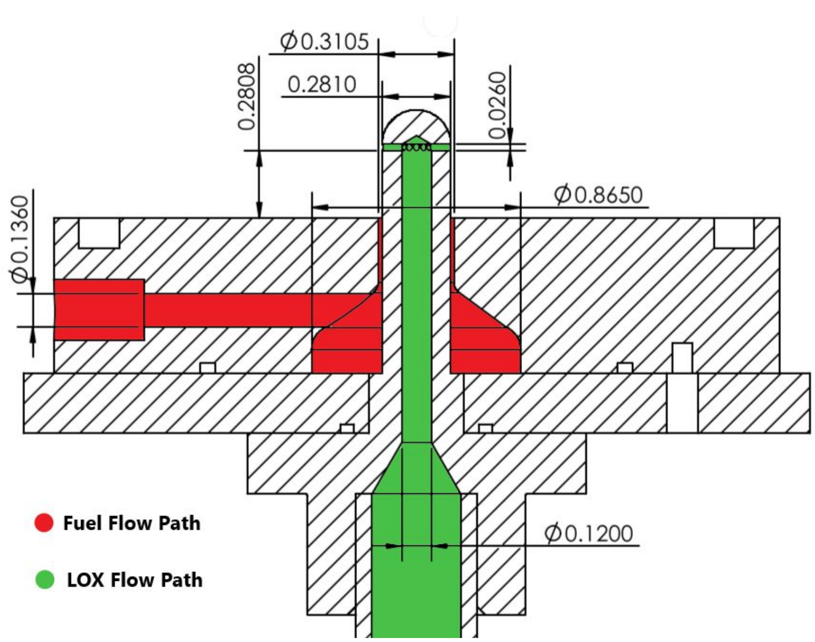


Fig. 7.1 Pintle Dimensions: A drawing of the original pintle design showing propellant flow paths

An aluminum injector of this design was machined and tested in January and February of 2019. The pintle failed to achieve the flow rates required by the engine at the pressure drops expected. A new design was developed and is currently being manufactured. Cold flow testing of the new design will be conducted in April, 2019.

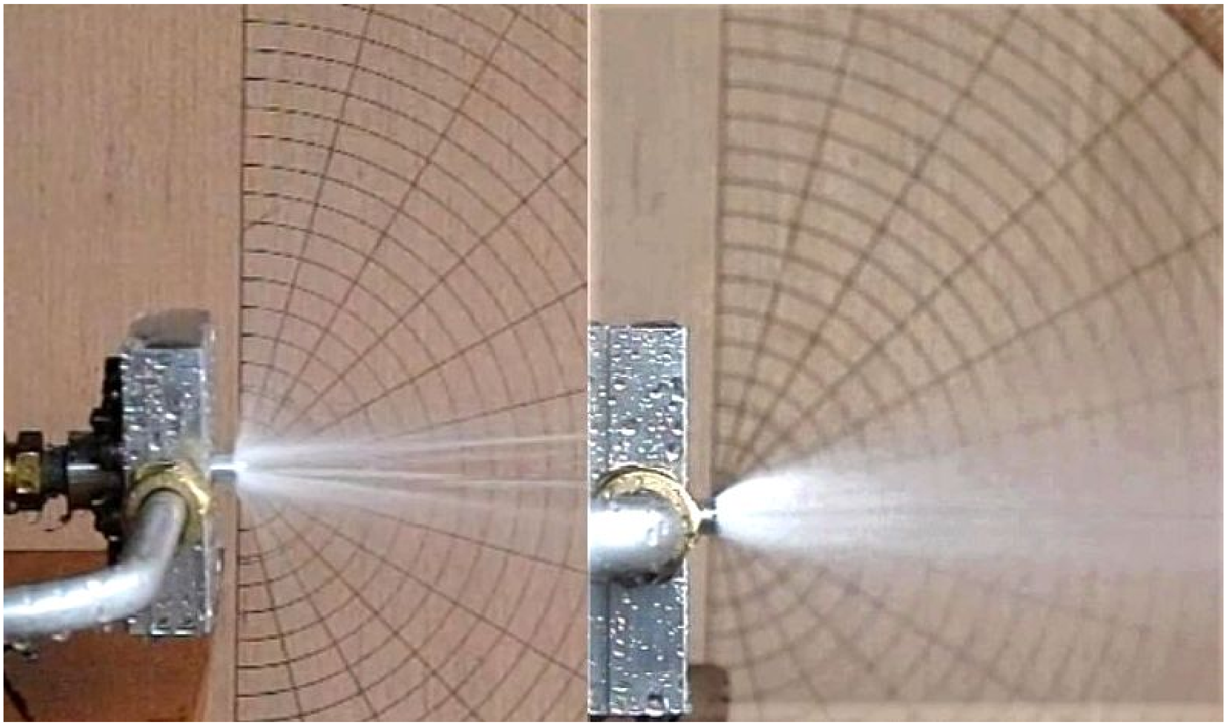


Figure 7.2 - Pintle FOD: The spray pattern through the pintle with burrs shown on left and after cleaning shown on the right.

Combustion analysis for the engine was accomplished using CEARun to maximize Isp versus oxidizer fuel ratio. This analysis will be made again with a variety of isopropanol to water mixtures once a static hot-fire has proved the base design.

Performance calculations were done in a Jupyter Notebook which calculated engine characteristics including chamber pressure, thrust, Isp, temperatures, Heat transfer, and pressure drops. Some notable performance characteristics for the 2.2kN engine are shown in *Table 7.0 Engine-Performance*.

Once a valid 2.2kN design is successfully tested, work will begin on the flight-ready 6kN engine which will be a larger version of the same design with all lessons learned incorporated into the design.

Table 7.0 Engine-Performance: Various parameters calculated for the 2.2kN prototype. See the **Propulsion Tab** in 3DX to see the full analysis.

Parameter (unit)	Value
Chamber Pressure (psi)	350
Effective Exhaust Velocity (ft/s)	7800
Mass Flow Rate (lb/s)	2.06
LOX Mass Flow Rate (lb/s)	1.13
IPA Mass Flow Rate (lb/s)	0.94
Specific Impulse (s)	242

Pintle Injector Design

After determining that the original pintle design did not meet the flow rate requirements, a new design was created. New hand calculations were performed and documented for estimating the needed flow geometry. The new pintle and annulus geometry was then analyzed using Computational Fluid Dynamics (CFD) software. This analysis lead to several changes in internal geometry aimed at improving the propellant flow into the engine and promoting even mixing of the propellants.

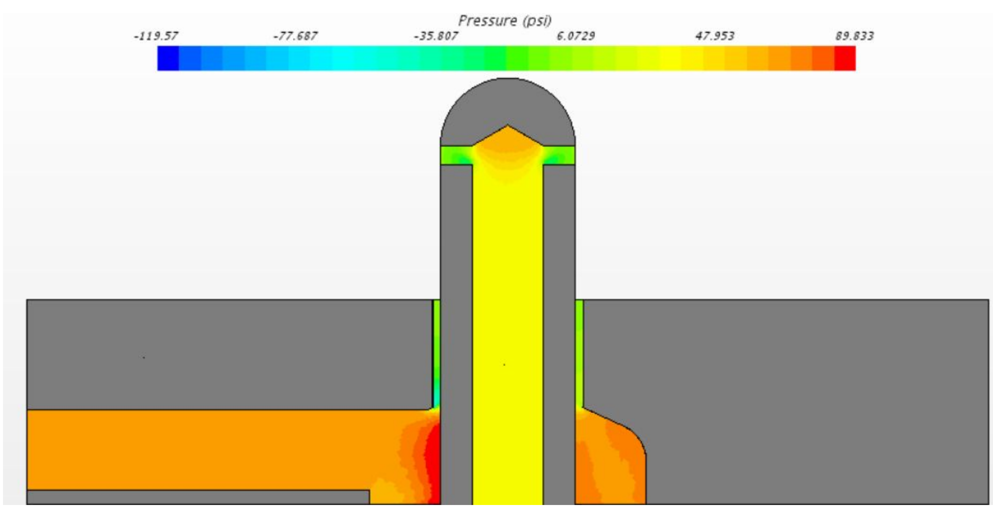


Figure 7.3 - Pintle CFD: Cross section of CFD model showing pressure in the fluid flow through the both the Annulus and Pintle. An analysis of the pressure requirements and required mass flow rates for LOX and IPA lead to design changes aimed at improving the propellant flow and mixing.

Manufacturing drawings for a new Pintle and Annulus test jig were created based on the geometry determined by this analysis and are being manufactured. An experiment will be conducted to determine the actual flow rates and pressure drops through the updated geometry after the new pintle and test jig have been machined. One of the goals for early next term is to compare the physical testing results with the simulation results in order to improve our design methodology. This design process is being fully documented and will begin exploring the designs for the 4.4 kN flight engine.

CT Scan Analysis of Printed Engine

Three 2.2kN engines were additively produced through Direct Metal Laser Sintering. Two out of the three engines produced were CT scanned via a helical acquisition method of capture. The two scans revealed that some of the thin walls, inside the coolant channels just before the annulus entrance, were broken and potentially not attached to the internal walls. This defect was consistent between the two scans and the broken chunks have the potential risk of becoming lodged during engine testing.

A conversation with the manufacturer and CT scanning company has been initiated to help determine the cause of these defects. The current theory is that the engine's wall thickness along the regenerative coolant channels are designed too close to the minimum wall thickness provided by the manufacturer. The thin walls of the coolant channel are designed to 0.018" compared to the minimum wall thickness recommended by the manufacturer to be between 0.012"-0.016" with material tolerance of +/- 0.004". At the bottom tolerance this is still within the minimum thickness recommended; however, the sections that broke are long thin members that are relatively unsupported. In the future, when scaling the parametrically designed engine from a 2.2 kN to a 6 kN engine, these walls will be thickened and should become a non issue. Adjustments to improve manufacturability will be made to future design based off the manufacturer's evaluation and recommendations. A video of the scans is viewable in the *Propulsion Design* tab of 3DX.

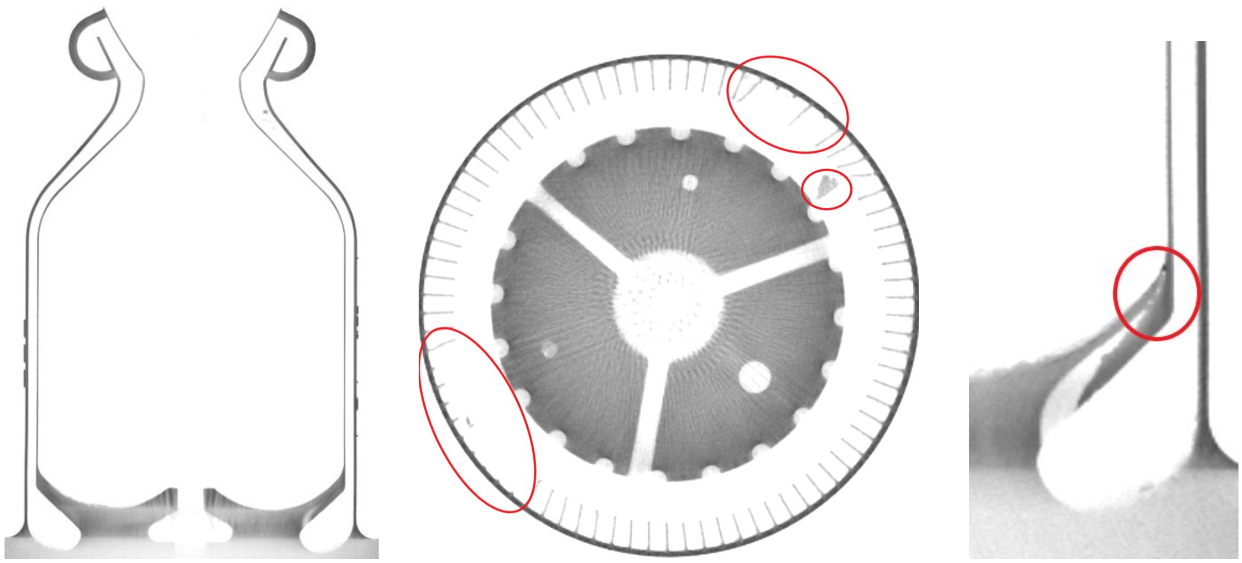


Figure 7.4 - CT Scans: CT scans of the engine showing side slice of combustion chamber, top down slice of broken walls inside fuel channel with solid chunks, and zoomed in side slice of potentially plugged film-cooling exit holes.

Pressurization Strategy

LV4 will not use a blowdown system consisting of heavy gas cylinders to supply regulated propellant pressure to the rocket engine. Incorporating heavy high pressure cylinders would radically redesign our lightweight composite airframe, as well as, introduce an extra refill expense to every engine fire. Large volumes of affordable gases, such as nitrogen and carbon dioxide, are too heavy for flight use and a lighter option of using helium is too expensive as a sustainable option. We are overcoming these challenges by creating a reusable onboard electric pump system to provide at pressure gain of 3.03MPa (440 psi) and flowing 0.925 kg/s (2.04 lb_m/s) of combined propellant into the engine.

The Electric Feed System (EFS)

To fulfill the liquid engine propellant pressure and flow rate requirement, we are using an electric feed system (EFS) onboard LV4t. Our EFS consists of two specialized pumps which simultaneously provide pressurized propellants into the engine chamber. Each pump has a machined case and impeller specifically designed to meet the pressure and mass flow rate requirements for the assigned propellant. Shaft power to the pump is provided by a brushless DC motor (BLDC), electric speed controller (ESC), and LiPo battery pack. All propellant plumbing will connect directly the to casing and use the pump as a support mount inside the rocket module. See figure (CAD) below for visual representation of the isopropyl alcohol (IPA) pump.

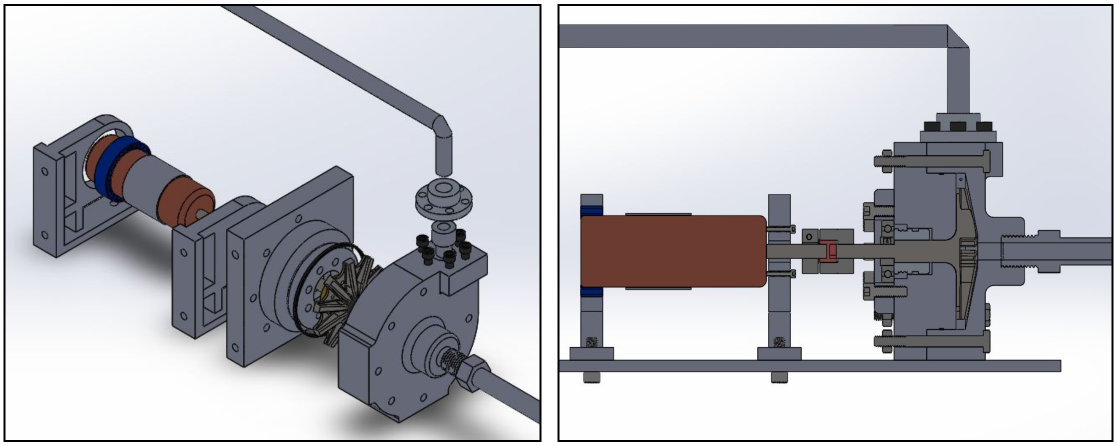


Figure 7.5: Electric Feed System isopropyl alcohol pump exploded view and cross section for finalized design

The first major stride we completed was selecting and testing the shaft power components in order to begin designing around the geometry for the selected BLDC. With almost 30,000 RPM of operating impeller rotation, it was important we selected a motor capable of continuously providing the necessary rotational speed without strenuous efforts or excess power consumption. The motor also needed to quickly and accurately respond to the internal flow through integrated sensor feedback. A previous EFS capstone design steered us towards using an aftermarket RC boat BLDC motor to power our pump. Due to their relative success, we focused our research on this affordable motor option along with the supporting speed controller and batteries. Through fluid flow and geometric calculations, 2 kW of power and 0.6 N*m of torque were identified as the base requirements for motor selection.

The base requirements aligned with selecting a TP Power 4070CM BLDC motor paired with a Swordfish 200A electronic speed controller (ESC) to power the IPA pump. Including the batteries and other accessories, this combination cost around $1000, and well exceeded the requirements for the IPA system. Purchasing an overpowered motor for the IPA pump allowed us to test a system also capable of meeting the LOX pump requirements. We made this decision to help streamline our overall combined design by verifying the power components for both pumps in one set of testing as shown in figure (test) below. See the *Propulsion Design* tab in 3DX for the comprehensive report.

Once verified, we could simply repurchase the components for the LOX pump and replicate all related hardware and mounts further simplify the LOX pump design.

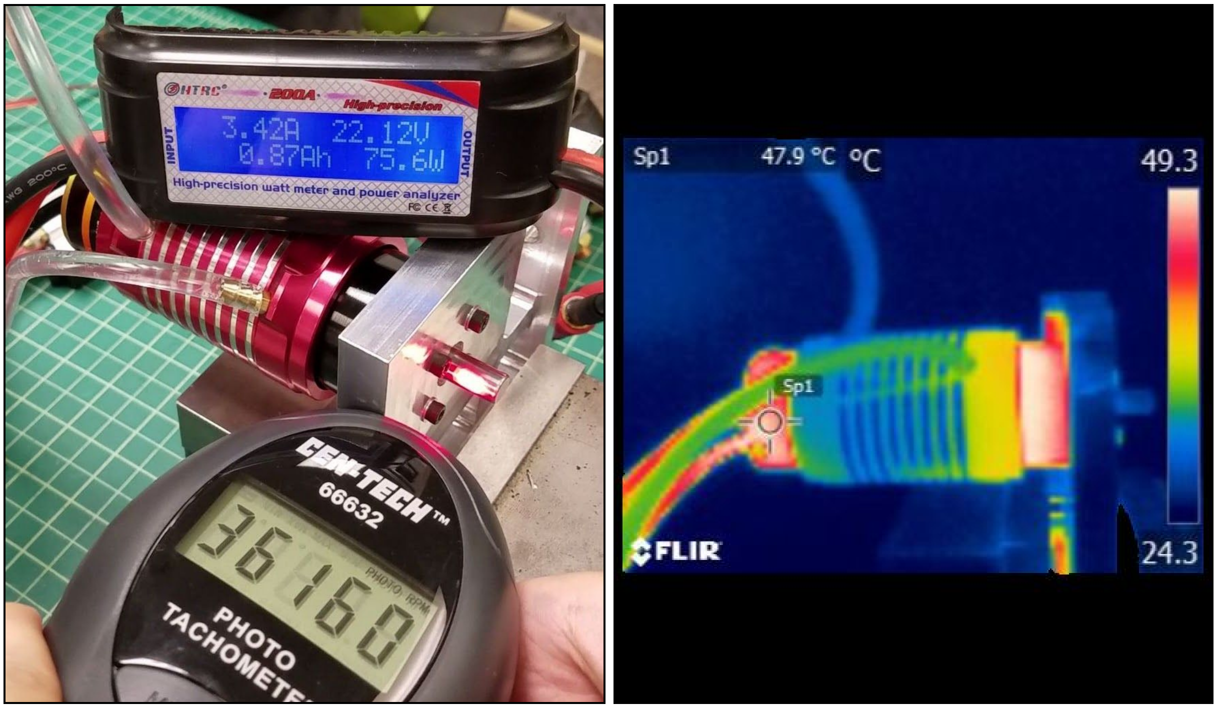


Figure 7.6: IPA pump motor rotational speed verification and thermal heat transfer analysis.

Following the motor selection, we began to designing and manufacturing mounting components for testing and project demonstration. We will optimize the mounting system for flight once testing identifies the strengths and weakness of our current design. At this stage we have designed and created a full pump system bracket out of 0.125” 6061 aluminum sheet along with two CNC machined electric motor brackets. We manufactured these components on campus using a three axis CNC mill for the motor brackets, and a TIG welder for the pump bracket. Figure (mount) shows our current mounting system mock up for our upcoming full system IPA pump test.

Our final major design stride was designing and machining the custom barske impeller for the IPA pump. This impeller proved to be our most complex component requiring months of research, design iterations, and manufacturing discussions. To finalize our decision, we put the final four designs into a decision matrix as shown in figure (table,) to determine which design was best. Three designs were a two pieces consisting of an impeller with a hub and a separate connecting shaft. Each design had a different method of mating the impeller shaft to the impeller hub. Our selected design, shown in green inside figure (table) below, combined the shaft and impeller as one solid piece. See figure 7.8 for two-piece vs single-piece design visualization. The completed prototype is currently manufactured out of 6061 aluminum as shown in figure 7.9 and will be later remanufactured out of 304 stainless steel for the flight model

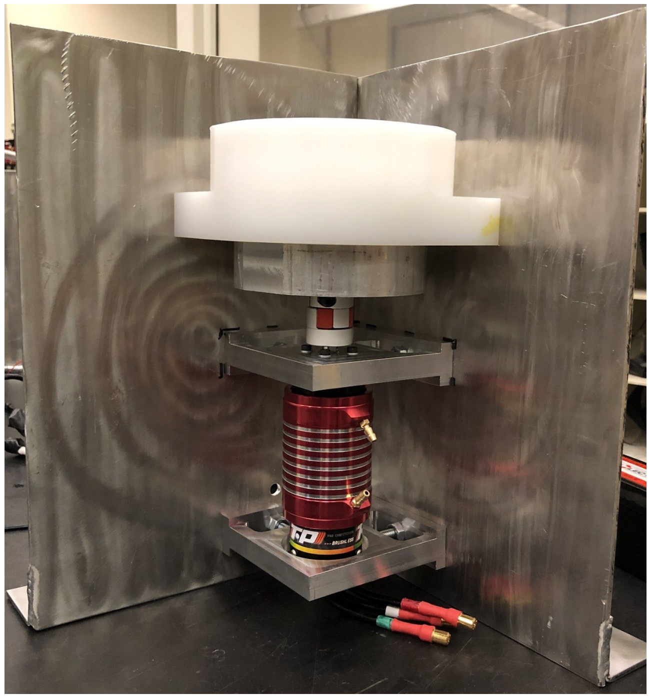
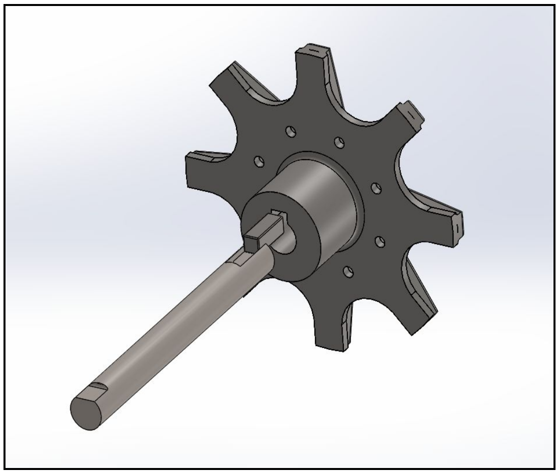


Figure 7.7: IPA pump testing and demonstration mounting system.

Table 7.1 - Decision matrix for impeller design

Criteria	Value (1-10)	Single-Piece (0-1)	Key Slot (0-1)	Lobe (0-1)	Dowel Pin (0-1)
Torque Capability	10	1	1	0.7	0.7
Rotational Balance Speed	8	1	1	0.6	0.8
Machinability	10	0.7	0.6	0.7	1
Tooling Cost	5	0.8	0.5	0.8	0.8
Robustness	7	1	0.9	0.6	0.6
Total	**40**	**36**	**32.8**	**27**	**31.6**



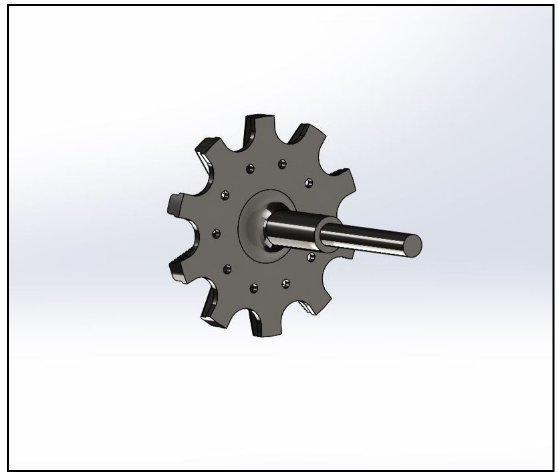


Figure 7.8: Impeller with shaft and key slot on the left and single-piece shaft impeller on the right

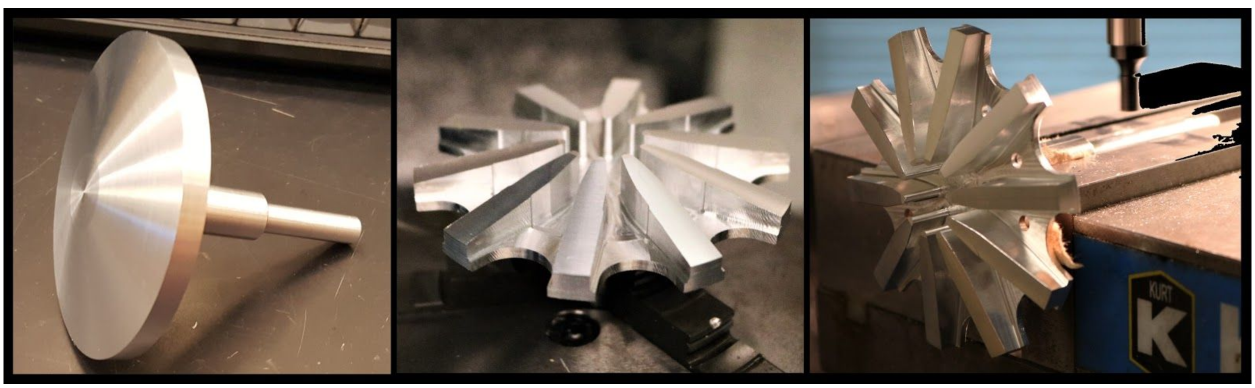


Figure 7.9: Impeller manufacturing process

Once the EFS is complete, we will have a reusable, lightweight, and scalable pressure system to use in all future liquid launch vehicles. Easily scaling our pressure system is a huge advantage to quickly redesign in the case of new engine thrust requirements as we scale our designs. Our modular EFS design allows for simple changes such as adding more batteries for longer run time and modifying internal pump case and impeller geometry for different pressures and flow rates without making any changes to the airframe. Another advantage for this system is ability to use our low pressure lightweight composite propellant tanks for flight. Keeping our weight as low as possible eases assembly and transport while also reducing our fuel cost and total emissions per launch.

Propulsion Requirements

Table 7.2 - Propulsion methodology based on Base 11 and FAA requirements.

Requirement	Planned Method to Meet
FAA 14 CFR § 101.23 (a), 14 CFR § 1.1	The 6 kN engine would need to burn for 200 seconds to meet this limit. It is planned to burn for much less than 60 seconds during flight and a 200 second limit will be observed.
FAA 14 CFR § 101.25 (g)(1)	The rocket will be launched in remote areas as provided by Base 11 Space Challenge.
FAA 14 CFR § 101.25 (g)(2)	The minimum radius for LV4 operation will be (much) greater than 1500ft from any human and the 1500ft. minimum will be maintained.
Base 11 SR Doc 3.1.16.3	LFE may only thrust along the longitudinal axis of the rocket.
Base 11 SR Doc 3.1.16.4	LFE may only thrust along the longitudinal axis of the rocket.
Base 11 SR Doc 3.1.16.5	LFE may only thrust along the longitudinal axis of the rocket.
Base 11 SR Doc 3.1.16.5	LFE may only thrust along the longitudinal axis of the rocket.
Base 11 SR Doc 3.1.16.5	LFE may only thrust along the longitudinal axis of the rocket.

8. Engine Test Stand Design and Test Plan

The design and testing of our liquid propellent engine is based around our flexible and portable Liquid Propellent Engine Test Stand (LiqPETS) in Figure 8.0 TEST STAND CAD (viewable in the *Test Stand Design* tab in 3DX). LiqPets is divided into two major systems:

1. LiqPETS mechanical systems, which consists of all mechanical subsystems involved in Liquid Propellant Engine tests.
2. Test Stand Automation and Regulation (TSAR), which consists of all of the electronic and software systems responsible for sensing and control during LV4's static test fires.

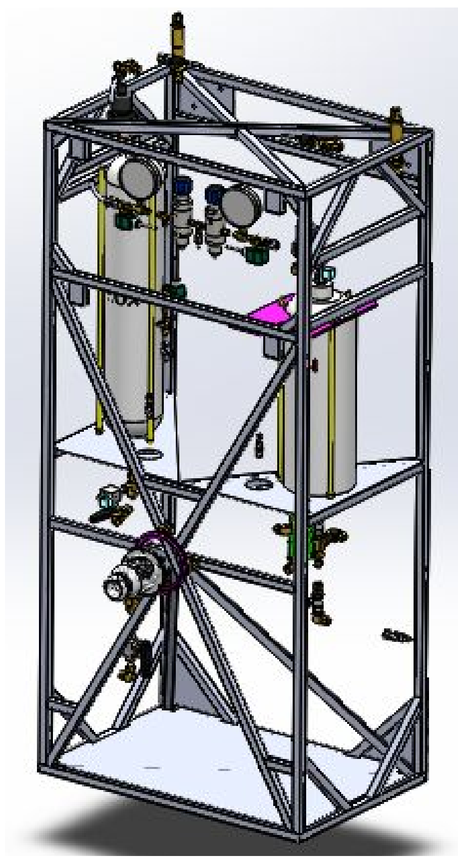


Figure 8.0 TEST STAND CAD: CAD model of the latest test stand design omitting runs of tubing and nitrogen supply cart.

8.1 LiqPETS Mechanical Systems

Test stand components are being tested to meet all operational and safety requirements. Individual components are designed with industry standard factors of safety(FS) for operation. The stand is designed to minimize human interaction. Ideally, operators will carry propellants to the stand, allow the stand to load itself using a pump for the fuel, and autogenous pressure for the oxidizer. Filling the stand with propellant will use controlled overflow to determine when the tanks are topped off. Isopropanol is to be loaded first, any splatter is then allowed to flash off. The fuel topping will occur a few hours to a day prior to oxidizer topping. The oxidizer will then be allowed to overflow through the vent valve. The first safety test is accomplished upon cycling of the vent valve after passing cryogenic fluid. After oxidizer topping, the dewar is removed and all operators will return to the base of operations. All propellant overflow will be routed away from the stand through stainless tubing. Overflow and vented propellants will not be allowed to mix.

Actuated Components

Active Sub-assemblies on the stand include electronically actuated ball valves, solenoid valves, and the ignition system. A LOX resistant encoder and DC motor combination is being designed to actuate both fuel and oxidizer system main, fill, and drain. Solenoid valves are used to control supply and venting of gaseous nitrogen for the propellant tanks.

Active Components

The stand uses two pressure regulators to control pressure to the tanks. these regulators are separated from both fuel and oxidizer sections by double check valves above the vent valves for each. Pressure relief valves are placed above pressure vessels and on any run of plumbing which may be isolated from the rest of the system. The igniter, now mounted externally, is allowed to swing away under the force of exhaust gasses.

Passive Components

Pressure vessels are rated and tested to a minimum FS of 1.5 to operating pressures. Pressures in every section of the system are monitored by pressure transmitters. Oxidizer tank temperatures and engine regenerative fluid temperatures are measured with thermocouples. Flow rates are measured using venturi flowmeters.

Engines are mounted to a thrust-plate with four temperature compensated load-cells. Fluid lines are provided enough of a run radially from the base of the engine such that thrust force will not be supported by plumbing.

Validation

All subsystems of the stand leading up to a static fire will undergo validation and non-destructive testing. An iterative approach is used in validation and is specific to the nature of each system.

Pressure Systems

All pressure components are first pressurized to low positive pressures. Leaks are checked for by spraying hardware and suspect locations with a soapy water mixture. The system is depressurized and leaks are fixed. The system is then pressurized to some fraction of operational pressure checked for leaks again. The process is repeated, pressurize, leak check, depressurize, until the system has been tested to an factor of safety (FS) of 1.5 per FAA AC43.13-1B.

Fluid Logic

Pressure relief, Solenoid Vent, and actuated control valves are tested separately from the system in the worst case conditions they will be exposed to during operation. All valves in or directly attached to the LOX section are tested by repeated cycling under cryogenic conditions by submersion in liquid Nitrogen (LN2) as seen in *Figure 8.1.1 - LOX VALVE AND TORQUE*. Valves are also tested at operational pressures. After installation to the test stand, and validation of the pressure system, all valves will be tested under pressure. LOX sections will be tested under pressure using LN2 as a placeholder for oxygen.

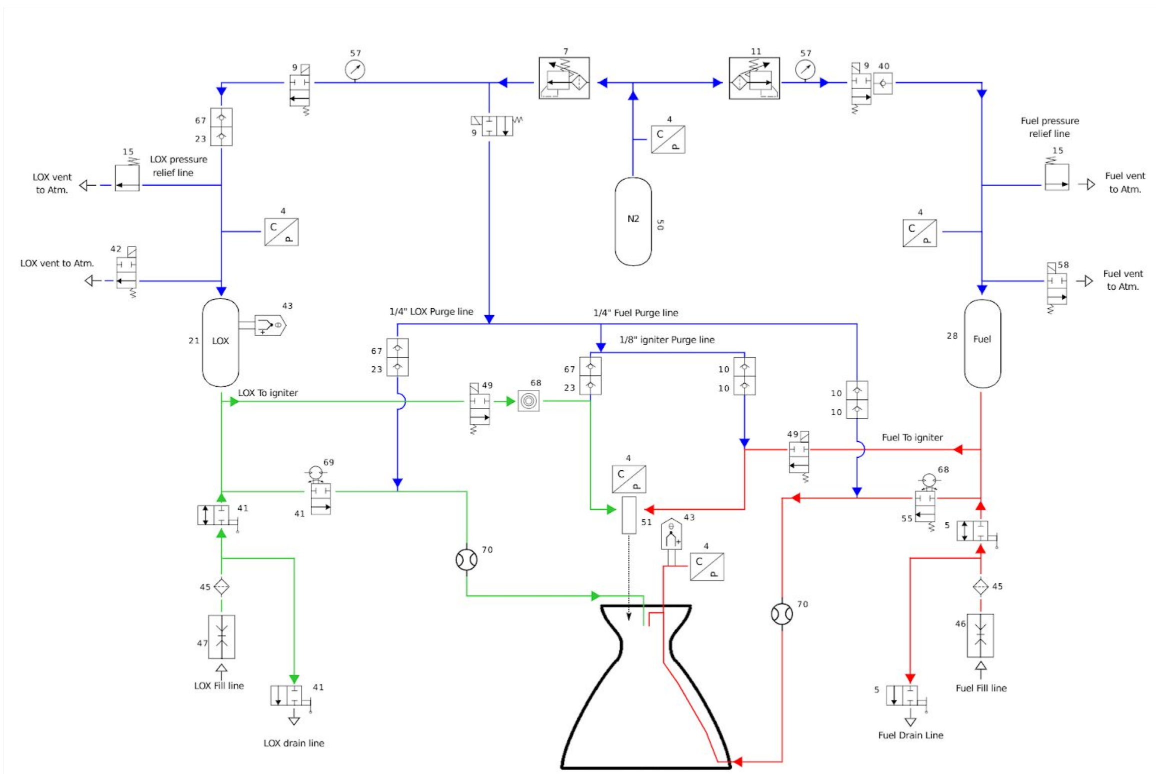


Figure 8.1.0 - PID: Parts and Instrumentation Diagram including fluid logic for the test stand. Shown in blue is the Nitrogen pressurant section, green is the LOX section, and red is the IPA section.

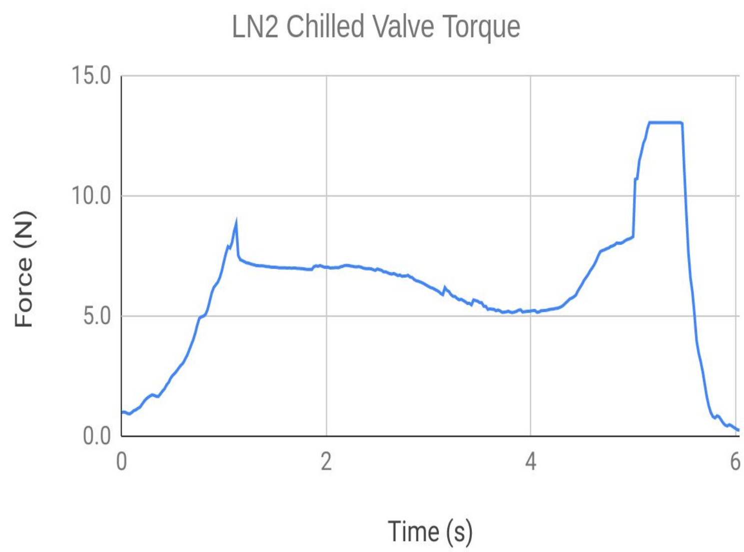


Figure 8.1.1 - LOX VALVE AND TORQUE: Experimental setup and cracking torque for a chilled valve

LOX Compatibility
All seals, metals, seats, and other valve or plumbing components from the outlet of the pressure regulator on the oxygen side of the system to the pintle are chosen for LOX compatibility. Stainless Steel (SS304 or SS316) is used for hardware and plumbing. PTFE or equivalent material replaces all non-metal components. Valves are specifically chosen for LOX compatibility and must show ability to cycle in worst case scenario even with the formation of water ice.

Structure
The stand frame is designed to test engines with up to 10kN of thrust. FEA analysis on the design was done in Abaqus and the stress analysis is shown in Figure 8.1.2 - FEA ANALYSIS. It is being statically tested to those limits before plumbing installation during the spring of 2019.

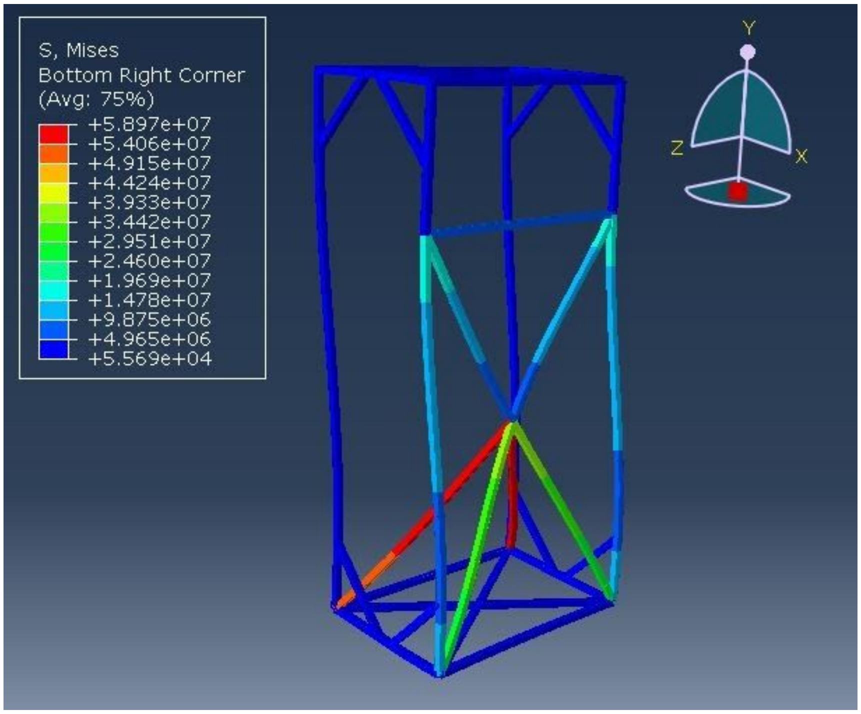


Figure 8.1.2 - FEA ANALYSIS: Test stand structural Finite Element Stress Analysis

8.2 Test Stand Automation and Regulation (TSAR)

TSAR is split up into six major subsystems:

1. **Command & Control** is the remote interface, consisting of the User Interface laptop and Remote Electrical Lockout Panel (RELP), which allows operators to command test fire and power management from a distance.
2. **Central Manager** is the Linux-based computer and software that implements and manages the firing sequence and receives, records, and retransmits all test data.
3. **Actuator Controller** is the microcontroller-based system responsible for directly managing all actuators.
4. **Actuation** consists of all TSAR subsystems that electronically alter the state of the engine, for example the main fuel valve, lox valve, or solenoid pressurant valves, and their associated drivers.
5. **Sensing** consists of all TSAR subsystems that collect diagnostic or control data, for example the thermocouples, pressure transmitters or load cells, and their associated digital interfaces.
6. **Power Management** powers and controls all of the various systems

TSAR Control Architecture

It is of utmost importance that the engine never be operated in a manner inconsistent with normal operation or safe shutdown. A loss of serial communication or abnormal sensor data must never result in improper or undefined operation of the engine, and must always result in a safe shutdown being initiated. TSAR ensures this through the Actuator Controller.

TSAR forces all actuator control to be done via the Actuator Controller, which is implemented in as simple a fashion as possible on a basic, single thread processor. The Actuator Controller's purpose is kept as simple as possible: It is to reliably relay control instructions from the Central Manager, and at all times monitor basic sensor inputs and the connection to the Central Manager for signs of a failure. In the event of a failure, the Actuator Controller automatically puts the engine in the appropriate shutdown mode and thereafter ignores any engine control commands from the Central Manager until a full system shutdown occurs. During normal operation, the Central Manager constantly sends information to the Actuator Controller about what the most appropriate emergency shutdown response currently is, depending upon sensor data. (This is in the form of an emergency shutdown protocol code constantly transmitted with each heartbeat. Actual emergency detection logic is implemented on the actuator controller and its reactions to emergency may be altered by the most recent shutdown protocol code).

The Central Manager is designed to be a dedicated, high-level orchestrator for test-fires. It is implemented on a multi-core processor and has direct access to all sensor data from throughout the system. It is responsible for determining what the next safest shutdown mode is for the Actuator Controller, and for ensuring high-level safety protocols are observed. It observes, collects, saves to disk, and transmits to Command & Control all sensor data from Sensing subsystems. The Central Manager accepts very basic high-level commands from Command & Control, such as "Start Test Fire", or "Range Safety Officer confirms personnel have left the area", or "Emergency Stop". However, outside of these commands, the Central Manager is completely independent of Command & Control. Connection loss or abnormal sensor data results in a manual emergency shutdown code being sent to the Actuator Controller, which shuts the engine down and locks the entire system out until full shutdown.

Command & Control serves as a remote user interface allowing test stand operators to easily enter high-level commands from a large distance, view life sensor readouts, and save a backup of all collected test data. It consists of a laptop (connected over ethernet) and Remote Electrical Lockout Panel (connected with twisted pair).

TSAR Power Architecture

TSAR's Power Management has a large number of redundant lockouts. First, power is sourced from two 12V Lead-Acid batteries. This power is passed through an on-stand fuse, emergency stop, and power key switch located at minimum safe distance for operators from the stand, and is then passed to the Remote Electrical Lockout Panel, as well as the Control & Sensing relay. The Control & Sensing Relay defaults to open, and its gate is driven by an emergency stop,

power key switch, and in-line shorter bar receptacle. Once power passes the Control & Sensing relay, it is delivered to the Control & Sensing power subsystem. There is a shorter bar present across the supply and ground rails for Control & Sensing power.
Control & Sensing power boots the Actuator Controller, Central Manager, and all sensing subsystems, but does not power any actuators.

Power from Control & Sensing is also passed off to the Actuation Manual Relay, which once again defaults to open, and has its gate driven by a power key switch and in-line shorter bar receptacle on the Remote Electrical Lockout Panel.

This power is immediately passed off to the Actuation Automatic Relay, which defaults to open, and is directly managed by the Actuator Controller. In this way, both the Actuator Controller, and operators at Command & Control must sign off on power delivery to Actuation before it occurs. This power is then finally delivered to all actuators in the system.

Finally, just after the Actuation Automatic Relay, there is another shorter bar across the supply and ground rails for Actuation power.

The end result is that, in order for a test to successfully occur, the following steps must be observed:

1. Disengage shorter bar on sensing & control power before test begins.
2. Turn on-site power key, and check on-site emergency stop disengaged.
3. Insert the shorter bar into the sensing & control shorter-bar receptacle
4. Personnel turn Sensing & Control power key at the Remote Electrical Lockout Panel and ensure the emergency stop is not engaged.
5. Personnel launch Command & Control client, connect to Central Manager, and initiate test fire.
6. Personnel disengage actuation shorter bar, leave test area, insert the bar into the receptacle for actuator power, and confirm personnel no longer near stand on Command & Control.
7. Personnel engage Actuation power key on Remote Electrical Lockout Panel, tell Command & Control to begin the firing.
8. Actuator Controller engages Actuator power, test fire begins.

The shorter-bars ensure that when a subsystem is not supposed to be engaged, if it is ever accidentally engaged it immediately blows a fuse. The in-line receptacles at the Remote Electrical Lockout Panel also guarantee that a system cannot be powered on until its shorter bar is removed. The shorter-bars are different sizes to guarantee they are never swapped by accident. The emergency stops ensure that on-site and remote personnel can immediately kill all system power at any time.

TSAR Software Architecture

TSAR top-level control is handled by FRESHMEN, (Forward Range Engine System Hotfire Management and Emergency Notification). This software presents a heads-up display for test fire status and sensor data, and a simplified command interface for generating high-level commands to be sent off to the Central Manager. FRESHMEN connects to the Central Manager using JSON over TCP, with physical layer being Ethernet.

The Central Manager is responsible for coordinating all test fire operations. It has direct access to all sensor data, and has explicit control over all actuators, and actuator power itself. While the Central Manager is directly connected to most sensors, it does not directly control any actuators. Instead, all actuation is accomplished by sending commands to the Actuator Controller. The central manager must handle saving and retransmission of all engine test data. The Central Manager program has black box regions dedicated to sensor hardware interface and communication with the Actuator Controller.

The Actuator Controller is the central pathway for all control over actuators. It serves as a final defense against system failure. Its programming is kept as simple as possible, and is focussed solely on producing reliable control signals for all actuators on the test stand. The Actuator Controller requires a consistent heartbeat an emergency response code corresponding to the currently most appropriate way to detect and handle emergency indicators, such as connection loss. If for some reason this heartbeat stops, or any other emergency indicator is tripped, the Actuator Controller will execute an emergency shutdown routine in accordance with the emergency response code most recently sent.

From Test Stand to Launch Vehicle

When LV4 transitions into flight testing, the Actuator Controller will be integrated mostly as-is, and the Central Manager logic will be absorbed into avionics with most of its test-specific functions removed.

8.3 Static Engine Hot Fire Procedures

Full test stand procedures are a work in progress. The procedure is based on a valve state document currently written in excel in Appendix X_TEST_PROCEDURE_X. Above all else, safety is the major concern in operating the test stand. A summary of operational procedure is given.

Five field operators perform operations on the stand during tests:

1. Manager

   Runs through the checklist and marking each step as it is accomplished, confirming each step is accomplished with three point-verbal communication, and making visual confirmation of the action.

   For example, the manager will state, “Open Fill Valve.” To which the operator assigned to the task will reply, “Open Fill Valve.” This is followed by the manager restating, “Open Fill Valve.” After which the operator will actuate the valve to open.

2. Operator

   Some actions such as closing the fill valve require immediate operator manipulation. These are priority tasks are verbally called by the operator, and confirmed by the manager.

   The operator follows the checklist with and as prescribed by the manager and acts on priority tasks followed with confirmation to the manager.

3. Field Safety Officer (FSO)

   The FSO observes the operation, the surroundings, and communicates with the base of operations. Their main task is to be focused on the overall operation, not the task by task operation

4. LOX Transport Team (2 members)

   The LOX Transport Team manages the LOX cart and are responsible for the safe transportation of the LOX dewar to and from the stand.

On-Site Setup

The stand will be moved to the test location at least one day prior to the static fire test. Pressure and leak checks will be accomplished for exposed parts of the test stand. Nitrogen and IPA will be on-site. At least three full dry runs of the procedure will be done with Nitrogen only.

Operators will meet remotely or in person with any authorities who are participating in the event. The on-site route for the vehicle carrying LOX will be determined along with any vehicle and footpath routes for exiting the test stand area to a safe location.

Fresh Nitrogen tanks are installed and the pressure system is cycled quickly to confirm operation. The IPA tanks are filled to allow for any splatter to flash off before the testing the following day.

Before the test

Every Procedure run through begins with a safety briefing. All participants are encouraged to voice opinions and concerns about safety, use of protective equipment is covered, and emergency procedures are considered. At least three dry runs are made. If any participant does not feel the safety of the operation is at a maximum, the concern will be worked until it is resolved.

Once every participant is confident and three dry runs have been achieved(without expending Nitrogen) flawlessly, a final go/no-go decision is made.

The Static Fire Process

(see also the Stages Valve State Reference guide and PID in the *Test Stand Design* tab on 3DX)

LOX Fill

1. All mechanical lockouts of the system are engaged and the system is confirmed to be in the mechanical fail-to-safe condition.
2. TSAR is booted up and will confirm this condition.
3. The stand field operators give a final inspection and confirm the go-ahead for LOX to be transported from the remote holding area to the stand by cart.
4. The LOX is connected to the fill port of the LOX system and the tank is topped.
5. Upon topping, the fill valve is closed and the LOX dewar is disconnected from the system.
6. The LOX cart is removed from the stand and returned to the designated holding area.
7. The LOX Transport Team leaves the LOX cart and moves to the base of operations.
8. The Manager finishes the set-up checklist.

9. The Field Operators move away from the stand and removes the mechanical interrupts located a minimum safe distance from the stand.
10. The Field Operators return to the base of operations.
11. Once the Field Operators arrive at the base of operations, control is formally handed over to TSAR by the FSO handing the lockout key to the TSAR manager.

TSAR Checks and Final Go/No-Go

1. The key is is inserted into the Actuator subsystem remote lockout and enables the actuators.
2. The LOX vent valve is cycled to ensure it is operational.
3. The TSAR manager and team checks for any issues reported by TSAR.
4. The LOX main valve is cracked to chill the system, then closed.
5. The LOX vent valve is closed
6. Tank pressurization is initiated and confirmed via TSAR
7. The Igniter is activated.
8. The main valves actuate allowing first LOX then IPA into the engine.
9. TSAR confirms engine ignition
10. After the burn time, TSAR puts the stand in shutdown mode.
11. Main valves are shut
12. Pressure valves are closed
13. Vent valves are opened
14. TSAR ensures that all mechanical valves are in fail-to-safe condition

Post-Fire

1. LOX is allowed to flash off from the stand tank through the vent system
2. TSAR informs the TSAR manager once the LOX tank temperature rises
3. The LOX vent valve is closed
4. TSAR monitors tank pressure
5. If tank pressure rises, the Post-Fire procedure restarts.
6. Once the vent valve is closed and tank pressure does not rise the team decides whether the stand is safe to approach.
7. **Site Cleanup**
8. The LOX dewar is returned to the supplier
9. The Nitrogen is removed from the stand and returned to the supplier
10. Isopropanol is drained from the tank into a waste tank
11. General operations cleanup is done.

9. Range Safety Systems

The Human Factor:

The first and foremost factor in the range safety systems is the human factor. To provide adequate training and protection to team members and any other people involved with field operations. Under the purview of the Chief Safety Officer, PSAS has formed a partnership with Oregon Rocketry to develop a Range Safety Officer (RSO) Training regimen, in which PSAS student members will gain amateur rocketry experience, through workshops and launch events, during their first year of involvement in PSAS (usually the sophomore or junior year, but we hope to begin attracting more freshmen through this training program).

The RSO training program will see students through their L1 and L2 TRA certifications, and qualify them for RSO training. All three certifications/trainings will provide the students with launch operations experience and embed technical and operational safety methodologies which they will take to their project teams. Our goal by the end of the Base 11 Space Challenge is to have at least one RSO trained team member on each major project team, with the majority of the larger team trained up to L2 certification.

Technical Systems:

To meet the range safety system requirements as laid out in the Base 11 System Requirements document, we plan to incorporate safety features from the TSAR program being developed for static test fires into the LV4 rocket and relevant ground support equipment. Prior to installation on the launch tower, LV4 rocket systems as well as relevant sections of the Launch Tower and Launch Control Computers will be keylocked, and shorting barred with REMOVE BEFORE FLIGHT tags, which will remain in place until the Launch Safety Officer (LSO) approves the activation of those systems.

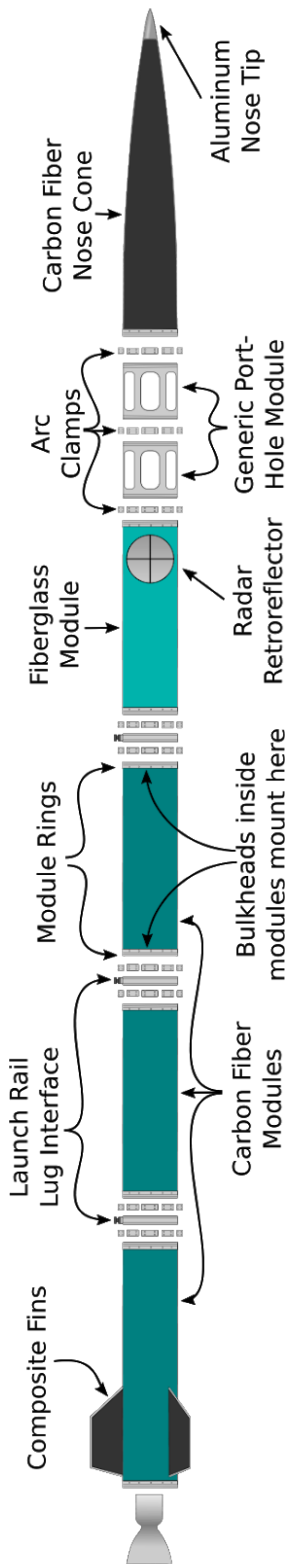
- Launch Tower - the launch tower provided by Base 11 will be outfitted with a Launch Tower Computer which will act as the command node for the avionics and propulsion system ground support equipment while the rocket is on the launch rail. The GSE system will monitor fuel and oxidizer tank pressures as well as the status of the electric feed system and the engine. It will maintain a SAFED mode for all systems until the launch installation and operations crew has performed all safety and systems checks.
- Launch Control - the command center of the operation. From here, mission command will coordinate the launch vehicle installment activities with the New Mexico Spaceport Authority, and monitor the systems status from pre-flight through the recovery stage of the operation.

- LV4 rocket systems will be ARMED from Launch Control if all personnel have been safely removed from the the launch radius, and the rocket passes all systems checks. Systems will remain in this state until the LSO approves the rocket for flight and initiates the START sequence.
- Prior to liftoff, the LSO will retain the authority to transmit a LAUNCH ABORT signal in case of any irregularities or concerns that could affect the performance of the vehicle especially with regard to safety at any stage of the operation.

- LV4 Rocket - the workhorse of the mission and the vehicle for mission completion. The LV4 rocket will maintain a signal link to Launch Control to provide real-time telemetry and systems status information.
  - In the event of a LAUNCH ABORT, the LOX tank will be set to depressurize on the launch rail. The tank will vent with the assistance of gravity until it reaches atmospheric pressure through an umbilical away from the tower. The IPA, while considered less hazardous, will be similarly vented away from the LOX and from the tower.
  - The Avionics system will maintain a flight orientation to keep the rocket within the predetermined flight zone by use of:
    - Reaction control system - a cold-gas based system, the RCS will be used solely to maintain the rocket's orientation during flight, not for controlled guidance and navigation of the rocket, as per FAA suborbital rocket regulations.
    - Engine throttling - the feed system will provide a controlled fuel rate to the engine to regulate specific impulse and throttle the engine to mitigate the effects of MAX Q. This will reduce the risk of a mid flight rapid unscheduled disassembly as the rocket approaches transonic speeds.
    - The default mode will be for the rocket to fly until fuel exhaustion, however if a fuel system status occurs during flight then the Flight Director may initiate a mid-flight engine shutdown sequence and recover the rocket early in an attempt to save the rocket hardware

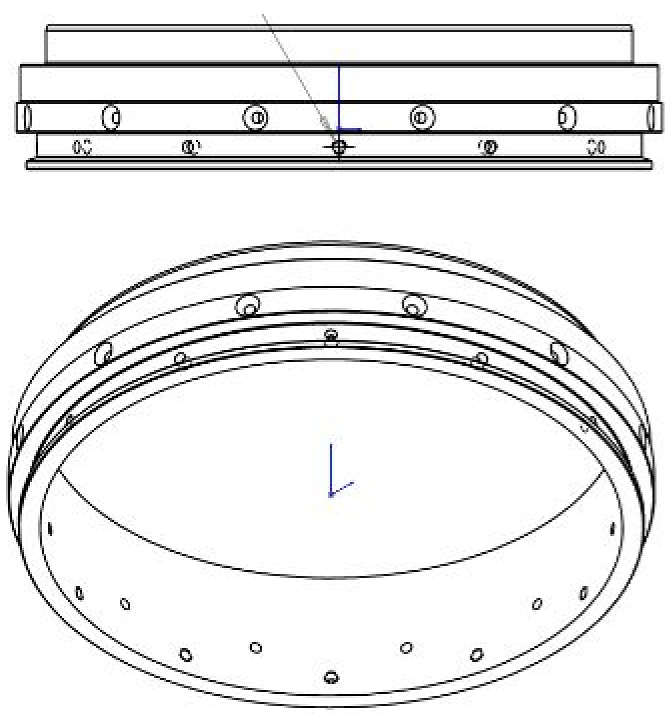
Additional safety features will be implemented into our design as it is further developed. Even if it means a longer time waiting to launch, or if it sets our program behind the Base 11 Space Challenge timeline, PSAS is committed to maintaining the safety of its members as it pursues the completion of the 100-km LV4 rocket.

10. Airframe Structure



Current Design

At present, the LV4.0 Airframe is planned to consist of interchangeable, 12 inch inner diameter cylindrical modules, made from carbon fiber and flexible honeycomb composite with standardized aluminum coupling rings on each end. Each module has a specially shaped circumferential channels that allow the modules to be clamped together using specially designed arc-clamps which are fastened into place. These arc-clamps are superior to the traditional method of screwing modules directly together because they offer a wide circumferential load path rather than transfer load between modules directly through screws as shear. This drastically increases the rigidity of the rocket. Each coupling ring also has additional threaded holes for mounting internal hardware.



Figures 10.0-10.1 - Airframe structure and current design for standard coupling ring for carbon fiber modules

Mixed throughout the rocket are various specialized modules and clamps which serve specific purposes and attach via the standard coupling ring interface. These specialized modules and clamps are:

- **Nosecone Tip**: Aluminum nosecone tip that screws into the Nosecone Module.
- **Nosecone**: Ogive carbon-fiber nosecone with a standard coupling ring at the bottom.
- **Porthole Module**: A short, all-aluminum module with circumferential holes for mounting external access ports for cameras, umbilicals, and electrical lockouts.
- **Airframe Module:** standard carbon fiber - nomex honeycomb module with aluminum coupling rings.
- **Avionics Module**: Identical to the carbon-fiber modules, but constructed with fiberglass to allow radio transmissions. Contains avionics, as well as radar retroreflector in compliance with system requirement 3.1.12.3.
- **Launch Lug Module**: A specialized module which provides load interface for launch lugs.
- **Fin-Can Module**: A standard carbon fiber module which has been laid up onto a second time to support fins.
- **Engine Load Interface Module**: A specialized module at the bottom of the rocket which serves as the primary load interface for the Liquid Fuel Engine.

Technology Heritage

We have flown half-scale (6 inch ID) carbon fiber modules already during the summer of 2018 on our LV3.0 test vehicle. The composite modules performed perfectly, but our original coupling ring design was never meant to hold tension, just compression. The coupling rings were ripped apart when the airframe experienced bending caused by aeroelastic forces.

Figure 10.2 - LV3.0's airframe modules and coupling rings. Also visible are the all Aluminum portal module with installed cameras and electrical shutoffs

The coupling rings were redesigned with the current arc-clamps described above, and have already been 3 point tested. They will be flight tested on our new LV3.1 rocket during the summer of 2019, proving (or not!) the new design.

FIgure 10.3 - Two half-scale LV3.1 coupling rings coupled together with arc-clamps

While we see no manufacturing issues with the full-scale 12 inch ID LV4 modules, we have not yet determined what loads we should expect for LV4. The modularity of our design should aid in flexibly handling various load conditions once they are identified.

11. Flight Dynamics

Flight dynamics for amateur rocketry are a critical part of the *final* design of the rocket. We've had a history of four generations of rocket airframes and 14 launches, all of which were successfully passively stable because:

- The Cp/Cg stability margin on the rocket be ≥ 2.0 calibers even in the worst case weight distribution. Cp is calculated based on aerodynamic simulations from both OpenRocket (http://openrocket.info/) and RASAero (http://www.rasaero.com/), and Cg is calculated during final design, and of course verified by measurement before each flight.
- The vehicle must leave the launch rail at a sufficient enough speed for the fins to passively stabilize the rocket (for our shorter 5 m launch rail, this was by guaranteeing a thrust to weight ratio (TWR) to be ≥ 5).

Given the current unknown state of the the various subsystems, most importantly the final engine thrust and the final weight of the propellant tanks, it would be disingenuous to say that we have a final rocket design that we can claim is passively stable. Instead, the previous requirements *must* hold on the final design of LV4.

- We plan on leaving LV4's fin design as undecided until we have a actual test fire data from our flight engine and initial system weight distribution numbers. Once we have these numbers, we'll set the size of the fins to give LV4 a worst case Cp/Cg stability margin of ≥ 2.0 calibers.
- Our latest simulations (see Mission analysis, above) are predicting that, given our current 6 kN engine design and predictions of airframe mass, our current design has a TWR of 2.45 : 1. In addition, we're predicting that the rocket will leave the 60 ft launch rail at around more than 30 m/s.

12. Electronics and altitude monitoring

Overview

The avionics systems of Launch Vehicle No. 4 (LV4) consists of four parts:

1. The **Altus Metrum "Telemetrum" v2.0** commercial off-the-shelf flight computer (see https://altusmetrum.org/). This flight-tested flight computer is one of two redundant flight computers that trigger the drogue deployment based on inertial flight data, via our electromechanical recovery system (ERS; see above). The Telemetrum also triggers the main parachute deployment based on barometric altimetry and live streams basic flight telemetry including GPS position on a low power UHF amateur radio band (430 MHz) transmitter. We don't believe the TeleMetrum has ever flown to 100 km, however, so the system will need to verified that it will perform properly, including upgrading the ground station antenna to reach the 100 km altitude.
2. The **Engine Management System (EMS)** is used to control the engine and engine feed system. he EMS is essentially a flight-ready version of the Test Stand Autonomation and Regulation (TSAR) system described above under propulsion testing. It actuates valves, senses temperatures, pressure, and flow rates, and controls the Electric Feed System (EFS).
3. **CubeSat 0 (CS0)** avionics system is a stripped down, rocket-centric version of the OreSat 2U CubeSat. The avionics section of our current half-scale test vehicle (LV3) and the future LV4 will both use CubeSats as their avionics system, contained in the fiberglass avionics module. CS0 has all of the essential avionics system: a custom software-defined radio GPS receiver, a full 6 degree of freedom inertial measurement unit, magnetometers, a high speed S band telemetry system, and a UHF (down) + L band (up) command and control radio system. PSAS has always planned to switch from rocket avionics systems (see below) to a CubeSat form factor.
4. The **PSAS 360° video subsystem**, which uses a combination of 9 cameras to capture full 360° 30 fps HD video which can be used on phones and VR headsets.

Further parts of the avionics system include:

- Launch Control, which includes:
    - **TeleMetrum ground station**, a laptop running Altus Metrum's AltOSUI connected to the TeleMetrum hand-pointed antenna and receiver for receiving basic flight telemetry.
    - **CS0 telemetry station,** a computer connected to an S band hand-pointed antenna to capture high speed telemetry (including video) from CS0.
    - **CS0 command and control computer**, connected to omni-directional antennas for CS0's command and control L band and UHF band radios.

- Launch Tower Computer
  - A Linux-based launch tower computer that sequences the flight using WiFi to launch control, and provides power and safety interlocks with the on-board avionics system, and eventually LV4's fueling system.

Technology Heritage

PSAS has a strong heritage of avionics system since its inception. Our latest full avionics system, last flown and retired in 2015, consisted of an Linux-based Intel Atom processor run off of a custom Lithium Ion battery pack with 10 Mbps Ethernet links to its subsystems, including a software-defined GPS receiver, a WiFi telemetry system, a full 6 degree of freedom inertial measurement unit, a live streaming camera system, and a canard-based roll control module.

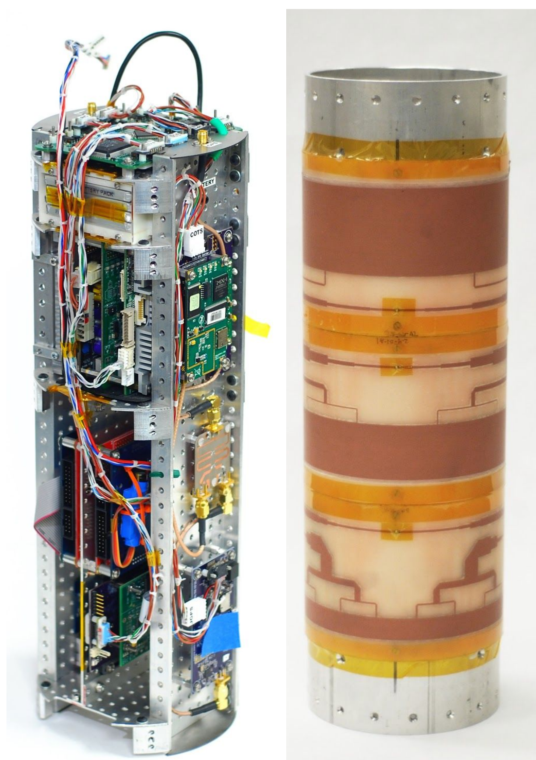


Figure 12.0 - Last generation avionics system (left) and custom microwave wrap-around patch antennas (right) for the 2.4 GHz (WiFi) and 1.5 GHz (GPS) radio systems.

13. Software

PSAS also has a long history of developing open source software used on Linux-based computers both on and for amateur rockets. All of our software is hosted on Github, and includes:

- Linux-based event driven flight computer code (https://github.com/psas/av3-fc) that handles sensor data streaming in and control data streaming out via Ethernet and WiFi.
- A full test harness to do simulations and hardware-in-the-loop testing of flight computer code (https://github.com/psas/fc-test).
- A full browser-based telemetry viewing system (https://github.com/psas/telemetry) for IP packets being streamed from the rocket.

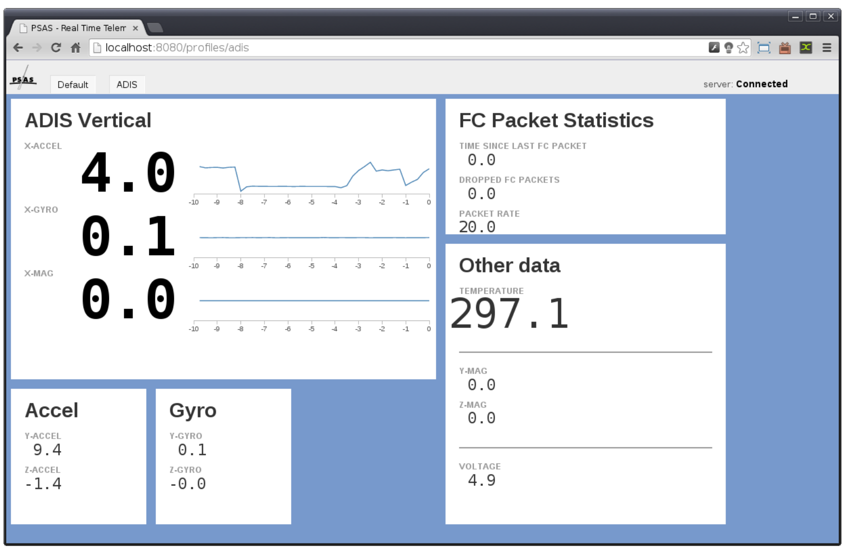


Figure 13.0 - Real-time web-based display of rocket telemetry from Launch 12

For LV4, PSAS will combine:

- The event-driven flight computer code, test harness, and telemetry viewer from previous avionics systems.
- The Test Stand Automation and Regulation (TSAR) system (see above) which will be prototyping and testing engine control and sensing software.
- The software being developed for OreSat, a 2U CubeSat that is replacing PSAS avionics systems (see avionics, above).

These three systems will sequence and control the flight of LV4.

14. Recovery System

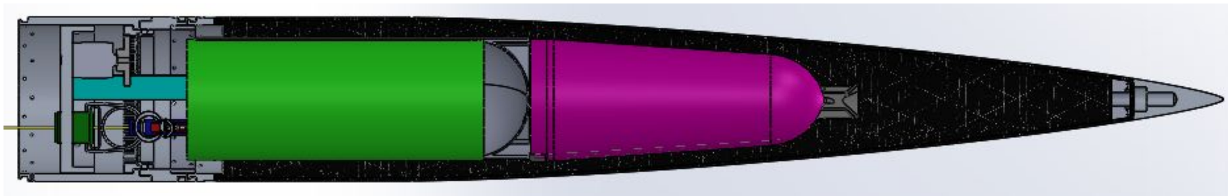


FIgure 14.0 - Electromechanical Recovery System within the nosecone

Overview

The LV4 recovery system is a standard two-stage recovery system that is electromechanically actuated. At apogee, the first system separates the nose cone from the body of the rocket, consequently deploying the drogue parachute. Then, at a predetermined altitude, the second system separates the drogue parachute from the body of the rocket and simultaneously deploys the main parachute. Currently, the LV4 recovery system is being prototyped and tested on LV3, our half-scale airframe.

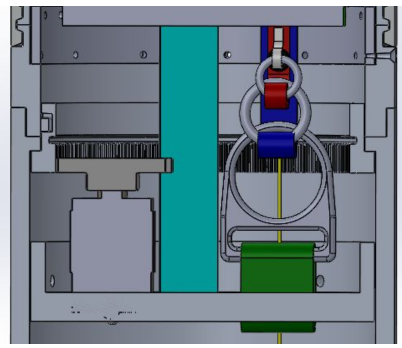


Figure 14.1 - Parachute Release

Flight Computer

LV4 will use a standard Altus Metrum TeleMetrum commercial off-the-shelf (COTS) flight computer to detecting apogee and the correct altitude for main parachute recovery. For more information on this system, please see the Electronics and altitude monitoring section.

Parachute Selection

The main criteria for selecting the proper parachutes is the the desired steady-state descent rate. Descent rate is controlled by both the weight of the payload and the diameter and shape of the parachute (see Fruity Chutes reference in the *Airframe & Structure* tab of 3DX). For the LV3 half-scale airframe tests, the drogue descent rate for the 70 lb LV3 rocket is roughly 100 ft/s. The design for the main descent rate is only 15-20 ft/s so as to not damage the airframe and payload.

The drogue parachute also requires strength during deployment. The drogue system is designed to be successful up to a worst case scenario defined as deploying five seconds before and after apogee. To ensure that the drogue parachute can withstand the worst case deployment velocity of approximately 200 ft/s, the parachute will be made of bullet proof nylon sewn together with tubular nylon webbing (see the Rocketman reference in the same 3DX tab).

Minimizing the main parachute's volume is also a selection criteria, so we chose a toroidal main parachute design that results in a drag coefficient of 2.2. This is significantly more than other popular designs such as the standard elliptical and cross-form (see the NARCON PDF in the 3DX tab). A higher drag coefficient dramatically reduces the required diameter (and thus packed volume) of the parachute.

Drogue and Main Parachute Deployment

Design criteria were developed based off of the initial engineering requirements; these criteria are tabulated in Table # along with a 1-5 rating of importance for each criterion. Accidental actuation was defined as premature (before apogee) release of the nose cone from the rest of the rocket body. Vibration resistance was deemed an important attribute. Simplicity was defined by the work required for manufacture and system mechanics assembly. Ease of assembly was focused on launch day set-up and integration with the rest of the rocket. Using commercial-off-the-shelf (COTS) parts, and making sure they are readily available, was an important feature of the design because it makes replacement parts easier to obtain for future teams. Space saving was defined by the volume taken up by the system. Lastly, lightweight was defined with a maximum of 5 kg, the goal being as much under the max as possible.

Accidental actuation and vibration resistance were defined as a major requirements since both would cause system failure. Simplicity, ease of assembly, and COTS parts all scored in the middle since together they define an efficient design. Space saving and lightweight scored lowest because they describe wants more than needs.

Table 13.0 - Design Criteria	
*****	Accidental actuation
*****	Vibration resistance
****	Simplicity
***	Ease of assembly
***	COTS parts
**	Space saving
*	Light weight

Using the design criteria, the team evaluated concepts for both the nose cone separation and main parachute deployment. The results are tabulated in Tables 13.1 and 13.2

Table 13.1: Decision Matrix for the Nose Cone Separation Design

Attribute/ Criteria	Weight	Twist Coupling	Twist Coupling Weighted Values	Vertical Motor	Vertical Motor Weighted Values
Vibration Resistance	5	3	15	5	25
Accidental Actuation	5	4	20	5	25
Simplicity	4	5	20	2	8
Ease of Assembly	3	5	15	2	6
COTS parts (use and availability)	3	3	9	4	12
Space Saving	2	5	10	2	4
Lightweight	2	5	10	3	6
Total			**99**		**86**

Table 13.2: Decision Matrix for the Drogue Parachute Separation Design

Attribute/ Criteria	Weight	SMA Plunger	SMA Plunger Weighted Values	Screw and Motor	Screw and Motor Weighted Values	3 - Ring Release	3 - Ring Release Weighted Values
Vibration Resistance	5	4	20	5	25	4	20
Accidental Actuation	5	4	20	4	20	2	10
Simplicity	4	2	8	4	16	4	16
Ease of Assembly	3	3	9	3	9	4	12
COTS parts (use and availability)	3	2	6	3	6	5	15
Internal Space Saving	2	4	8	2	8	5	10
Lightweight	2	2	4	1	2	5	10
Total			**75**		**86**		**93**

The results of the decision matrices lead us to use the twist coupling method for the nose cone release and drogue deployment, and the 3-ring design for the main parachute deployment. The nose cone release design is a four piece assembly that includes a retaining ring, twist coupling, outer housing, and top ring that is attached to the nose cone. The twist coupling is driven by the motor. The motor rotates the coupling until the nubs, shown in the top ring, are able to pass through the end of their respective channel and release the nose cone from the body of the rocket. The main advantage of this design is how open it leaves the center for the integration of the main parachute deployment mechanism. It also utilizes the concept of lost motion in the length of the tracks to help prevent unintentional activation.

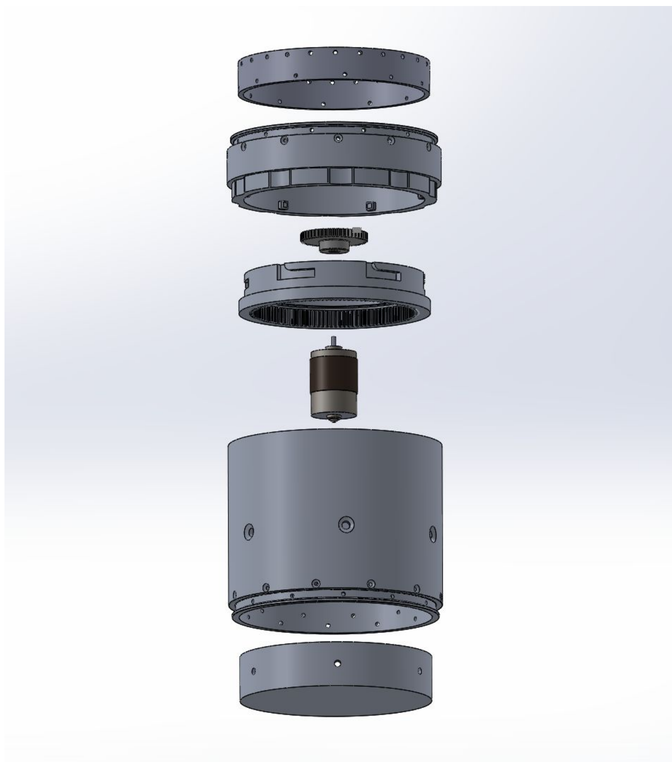


Figure 14.2: Breakout of Twist Coupling Nose Cone Release Design

The main parachute deployment system, shown in Figure 14.3, was modeled after a common device used in sport parachuting. It uses mechanical advantage to reduce the force exerted on the top loop of the system. The top loop is kept in place by a semi-rigid cable (shown in yellow) which, for our application, will be pulled by winding a motor. The green webbing at the base of the design will be attached to the body of the rocket and the middle blue webbing will be attached to the drogue parachute. When the system is triggered, the smaller 2 of the 3 rings will fly away with the drogue and the base ring will stay attached to the rocket. A static line will also be included and attached to the cup encasing the main parachute so when the drogue flies away the main parachute is deployed.

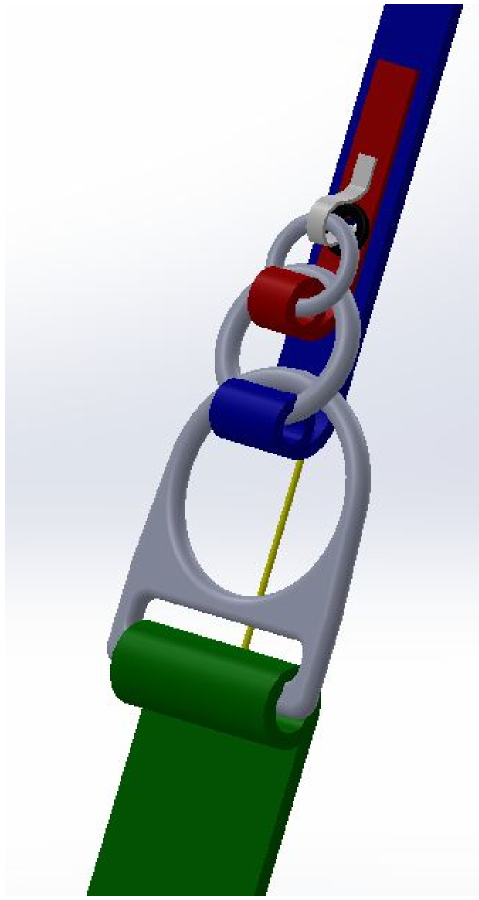


Figure 14.3 - Ring Drogue Parachute Release Design

Next Steps

The next two months will be filled with design verification testing of each system independently, then as an integrated assembly. Commercial part selections will be refined, primarily with regard to the motor selection. The gear ratio for the nose cone separation will also be refined, and the sizing of the nubs may be increased to prevent deformation when they are under load. For the main parachute deployment system, the spacing of the rings will be refined and the torque required to pull the yellow release line will be the main design verification.

For final verification, the entire recovery system assembly will be dropped from a helicopter at an altitude appropriate to allow for the drogue parachute to deploy, reach steady-state, and then the main parachute to deploy and also reach steady-state. This is a test that has been completed by each past PSAS recovery team as a last deployment verification before actually integrating the system with the rest of the rocket for launch. For the LV4 recovery system, the LV3.1 half-scale systems launch will also be considered a verification test.

15. Ground Support Equipment

PSAS Ground Support Equipment is broken up into two sections:

Launch Control

Launch Control (LC) is located according to the Tripoli Rocketry Association's required back-off distance from our launch tower. From the LC, the entire flight is directed and tracked. It includes:

- A 20 ft or longer truck, which contains our portable workshop including tables, chairs, rolling tool cart, rocket holder, and supplies. For the day of the launch, tools and supplies are pushed back and the back of the truck is used as a protected launch control area.
- Several "pop-up" 10-ft tents which are secured together for protection from the sun for observers.
- A telescoping radio tower with a WiFi link to the launch tower, and a 2m amateur radio antenna for communicating with team members at the tower and on the recovery teams.
- A loud speaker system for communicating status to observers

During launch operations, the Launch Control Officer (LCO) and Launch Safety Officer (LSO) sit in the truck and direct the launch. They have the Launch Control Computer (LCC), which communicates with the Launch Tower Computer and the LV4 avionics system to sequence the launch. Also at the LC is the Altus Metrum ground computer which receives basic flight data from the COTS TeleMetrum flight computer.

Launch Tower

At the launch tower, the Launch Tower Computer (LTC) communicates with the launch control computer to sequence flight. The LTC has:

- A solar-powered battery system for all-day operation
- A Linux-based computer
- An umbilical system to provide power to the rocket, and carry signals back from the rocket
- A safety critical three-interlock system for igniting the main motor of the rocket, which includes a switch, a local shorting bar, and a remote (> 100 ft) that uses the shorting bar as a key.
- A safety-critical relay system, which includes two independent relays, and a third relay actuated by the rocket via the umbilical cable.

For our future LV4 launches, the launch tower will also assume the role that the test stand (LiqPETS) and the Test Stand Automation and Regulation (TSAR) currently plays with the liquid propellant engine. Although all TBD, the liquid engine provides another kind of safety along with the standard amateur rocket launch.

Figure 15.0 - Launch Tower and Launch Tower Computer (beige box on left), showing WiFi antenna (top) and launch rail (on right)

16. Hazard Analysis

In regards to hazard analysis prerogatives, the ultimate priority has been to develop a safety team; which will be composed of myself, a technical risk safety officer, and for each subsequent subsystem to have a safety officer. The intention with this is for the subsystem safety officers to have prior experience with specified subsystem so they are intrinsically knowledgeable on the technological facets and hazards pertaining to their subsystem. The subsystem safety officer’s role is to address, correct, alter, incorporate warning and safety devices, and test the equipment to the necessary degree required for the risks being considered. As drafted in the Risk Management Plan; the subsystem safety officer will be in charge of creating and developing Standard Operating Procedures for their subsystem, report their intended Design and Designation(D&D) test plans as well as their teams intended Systems Integration and Validation(SI&V) timelines, report and document all identifiable risks to the safety risk registry and actively use or be trained on how to use the risk matrix, be L1 and L2 certificated and actively pursuing their Range Safety Officer(RSO) certification verified through Tripoli, differentiate and document who on their team is of student status versus volunteer status and have them complete the correlating liability waiver.

In addition to their deliverables, the subsystem safety officer will be required to attend two required monthly meetings; the first will be in meeting with chief safety officer and the technical risk safety officer. The second will be with their team leads, the chief safety officer and the technical risk safety officer at a systems engineering meeting. Lastly, the safety officer will be required to deliver to the chief safety officer and the technical risk safety officer different American Society For Testing Materials manuals, materials, and certifications that they believe would best serve their team. The objective for enforcing the safety team is for the subsystems safety officers to be the operational bridge between the subsystems and the systems with regards to assessing technical safety, record management, and ultimately address and correct potential hazard errors.

As of currently the safety team is composed of:

Chief Safety Officer: MacKenzie Kesler

Project Manager (and Team Captain): Risto Rushford

Technical Risk Safety Officer: Ryan Medick

TSAR: Georges Oates Larsen

The PSAS team have been making advancements on getting Range Safety Officer (RSO) training provided by Oregon Rocketry (OROC) for interested PSAS members. Beyond the fact that this is a base11 requirement, we believe that it is imperative a portion of our members are familiar with the process in its entirety. The objective is to have AT LEAST one individual from each subsystem RSO trained.

Due to the fact that we are still in the preliminary phase of designing and prototyping our rocket and are not at the fabrication and manufacturing stage; the identified hazards list is not a finalized risk registry. Moreover, the team is actively adding and editing hazards and mitigation plans to the risk registry. For reference, a few of the hazards that have been identified are the following; 1.3.1: Airframe Manufacturing Processes and Templates, Fiber materials handling, 1.3.2: Machine shop accidents, 2.1.2: D&D Test Execution accidents, LOX Handling, Systems Validation Test Execution accidents, and launch procedures.

Table 16.0 - Airframe manufacturing process and templates hazards: Only personnel who have complete the airframe manufacturing training can work manufacture the carbon fiber and fiberglass airframe modules.

	hazard	risk level	mitigation
pre oven curing	Sharp edges on manufactured rings	3	Gloves and eye protection
	Hazardous fumes	6	Use PPE Utilize Fume hood Follow MSDS
	Hazardous chemicals	2	Gloves and eye protection Utilize fume hood Follow MSDS
Loading/unloading airframe oven curing	Burns when using oven	3	Gloves
Sanding airframe	Dust particles	4	Use PPE Utilize well ventilated area Follow MSDS
	Splinter hazards	3	Use gloves Follow MSDS

Table 16.1 - Machine shop accidents

	hazard	risk level	mitigation
During machining	flying shrapnel	9	Use eye protection
Post machining	Sharp edges on manufactured rings	6	deburr parts after machining

Table 16.2 - D&D Test Execution, LOX Handling, Systems Integration & Validation Test: Each D&D Execution and System Integration & Validation Test will have a their own hazard table. These have not been made yet, but will be made and reviewed by the lead safety officer and the D&D team before the test.

	hazard	risk level	mitigation
LOX handling	cryogenic burns from LOX	12	Use PPE
D&D Tests	TDB, each test will have their own hazard table	TDB	Use PPE as needed
System Integration & Validation Tests	TDB, each test will have their own hazard table	TDB	Use PPE as needed

17. Risk Assessment

The PSAS team is undergoing a comprehensive risk assessment based on the project review we have undertaken in preparation of writing this report. The PSAS leadership team has developed a risk management plan, which includes a risk registry and a risk matrix. The risk matrix was developed with the notion that most risks are hazardous and innately unacceptable. The risk matrix was formulated to include a variance of 20% risk to most tasks that are considered benign and safe as a baseline. The team leaderships' intention is that the subsystem safety officers will utilize the developed risk matrix when assessing the risks of their subsystems and documenting those in the risk registry.

It is important to note that the PSAS team has experience writing and assessing FMEAs due to our past LV3s rapid disassembly. The team performed these assessments with enthusiasm and tenacity, and not out of force or rigidity from upper management. This safety oriented culture is highly prevalent in PSAS. However, while we are making the adjustment towards a systems engineering approach in managing our subsystems, our risk assessment component is not in its finalized state. PSAS maintains a philosophy of continuous improvement, and will refine our risk assessment and other models we develop or adopt so that we can publish and share the material for other rocketry groups to use. The PSAS team aspires to have a more comprehensive approach to risk assessment in the near future.

Table 17.0: Risk Assessment Matrix

		1	2	3	4	5
Risk Matrix		Probability				
		Almost Impossible	Not Likely	Probable	Likely to Occur	Common
Impact	Severe	5	10	15	20	25
	Critical	4	8	12	16	20
	Moderate	3	6	9	12	15
	Limited	2	4	6	8	10
	Minor	1	2	3	4	5

18. Team development

Succession Planning

Several of the PSAS team leads will still be involved in their roles during the 2019-2020 academic year. This includes:

- Team Captain - Risto Rushford, who will begin his graduate program in Systems Engineering
- Chief Engineer - Bert DeChant, who will begin is graduate program in Electrical Engineering
- Airframe Team Lead - Georges Oates Larsen, who is continuing his undergrad in Physics and Mathematics

These team members will retain their current roles for the following year. These critical positions will be vacated at the end of the academic year due to graduation”

- Chief Safety Officer - MacKenzie Kesler, graduating with a bachelors in Public Health Administration
- Business Development Director - Hannah Webb, graduating with a bachelors in Business Marketing
- LPETS Team Lead - Jacob Tiller, graduating with a bachelors in Mechanical Engineering
- EFS Team Lead - Julio Garcia, graduating with a bachelors in Mechanical Engineering
- Recovery Team Lead - Marie House, graduating with a bachelors in Mechanical Engineering

The PSAS Space Challenge leadership team has determined that relying on the normal rate of incoming students who take interest in the rocketry program will be insufficient to meet our project goals. Therefore we have planned a recruitment campaign to present about the PSAS LV4 rocket and its entry into the Space Challenge to classes during the spring quarter, beginning the first week of April.

Targeted classroom visits will be made in the engineering and business schools to attract current sophomores and juniors to join our program. Reason for this is to begin the onboarding process in advance of the 2019-2020 academic year so that students are better prepared at the beginning of the year. In addition to the general recruitment procedures, we will also recruit specifically for key positions internally when the option is available, because we find that the better team leads are typically students who have been involved for a while.

Knowledge Retention

PSAS is careful to document system development in GitHub and Google Drive, and we are working on developing our understanding of the 3DExperience platform for the sake of portfolio display. The real challenge though is onboarding the students such that they understand how to use the documents and information preserved for them. We have a two-part strategy to address this:

Outgoing project teams (often teams of graduating seniors) will perform a formal handoff presentation of their project to the next year's seniors. This is recorded and uploaded to the PSAS Youtube Channel. Each outgoing team will also have at least one contact person for successive sub-project owners to contact. At this point we have been fortunate to have a community of alumni who have maintained this form of relationship to ensure knowledge transfer for our incoming students.

Incoming students will begin amateur rocketry training, following a series of workshops developed in partnership with Oregon Rocketry (OROC). This ensures that new students to the program will get trained early on in aerodynamics and solid rocket propulsion. This will prepare them to get up to L2 (Level 2) amateur rocketry certification, which then qualifies them for Range Safety Officer training by OROC (a Tripoli Prefecture). The goal is to have at least one L2 and RSO trained individual in each rocketry project team for PSAS. This training strategy will be maintained past the Space Challenge conclusion.

Outreach

The Portland State University Student branch of the American Institute of Aeronautics and Astronautics and the Portland State Aerospace Society plans to host an Oregon Aerospace Conference this next fall. The event will be the first of an annual celebration of Oregon's contribution to the national aerospace industry.

It stands out us that although Oregon lacks a large recognized aerospace presence, there are a LOT of aerospace suppliers and smaller aerospace companies within the state, some of which produce critical components ranging from commercial Boeing aircraft to SpaceX rockets. We're also discussing the event with OSU to perhaps have it occur every other year at each university, and have reached out to Base 11 about further making it a collaborative effort since two Base 11 teams will be participating in the event.

We have three professional speakers lined up for this Fall, with the potential to get several more depending on how many we want/need:

- Heather Bulk, Founder/CEO of Special Aerospace Services, who is advising me as I plan the event
- Dan Dombacher, Executive Director of AIAA national and former NASA administrator
- Agnes Blom-Schieber, Vice-Chair of PNW AIAA

RIsto, the Team Captain, met Heather and Dan at the AIAA Sci-Tech Forum in January while networking in the interest of helping the Portland State AIAA student branch gain some credible contacts in the industry (with the hope that the effects of doing so would turn some heads here in Portland). They have already to come to PSU campus on September 28th to speak, and PSU is interested in officially sponsoring the event.

Regarding the event structure, we will have a keynote speaker in an event space fitting 300+ people, coupled with technical sessions from students around the state and space for exhibits of local companies such as D.H. Sutherland (expressed interest), student groups and other aerospace organizations that choose to participate such as the Viking Mars lander Preservation Project (confirmed) and the Evergreen Aviation & Space Museum. We are working on our event marketing plan for our general event invitations.

Organizing and hosting this event at PSU helps AIAA to build inroads into the state, which is why they are interested. PSU benefits by establishing itself as a node for AIAA activity in the state of Oregon (along with OSU), and positions PSU to insert its vision and values into the regional and national aerospace conversation regarding sustainability, green technologies, and smart cities.

19. Business and Marketing

Through extensive fundraising and grant writing efforts in the Fall 2018 quarter, PSAS finds itself well funded through the remainder of the current year. In that sense there is no budget update since the previous report.

However, our marketing plan at this time is wrapped up in the outreach event that was mentioned in the previous section. The Oregon Aerospace Expo is planned to encompass business networking, student outreach (from middle school through college), and business outreach. We do plan to charge admission and the funds will go toward funding our rocketry projects for the 2019-2020 academic year.