Project Zenith: Monash HPR

Team 703 Project Technical Report for the 2025 IREC

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This paper presents *Project Zenith*, Monash High Powered Rocketry's most innovative entry into the International Rocket Engineering Challenge to date. Developed over a two-year design cycle, *Project Zenith* features the most powerful student-researched and developed (SRAD) engine in Australia, designed for the 10,000 ft SRAD hybrid category. The propulsion system incorporates an automatic tank fill algorithm controlled by a custom Motor Controller (MC) electronics system, utilizing capacitance for level sensing. Altitude control is augmented by radial Air Brakes offering over 2,000 ft of control authority, managed by the custom Strelka Flight Computer (SFC) and an active control algorithm. The avionics bay, located within the nose cone, houses extensive data logging capabilities and a camera for the Video Livestream challenge. An integrated 4U CubeSat is employed to investigate the application of artificial intelligence (AI) for enhancing data acquisition in rocketry, utilizing commercial micro-electromechanical system (MEMS) sensors. The vehicle employs a single-bay, dual-parachute recovery system, with primary deployment events actuated by the SRAD Galileo Flight Computer (GFC). A strong emphasis was placed on innovation and reliance on SRAD componentry throughout development, and the team leveraged in-house capabilities for the design and production of critical components. *Project Zenith* has successfully completed two validation flights in Australia in 2024, demonstrating system reliability. The team's in-house developed six-degrees-of-freedom simulator, SATURN, has proven accurate in predicting flight performance, ensuring safety at all times. *Project Zenith* represents the culmination of this extensive development effort, validated through rigorous testing and successful previous flights, positioning it as a highly competitive entry for IREC2025.

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Nomenclature

α = angle of attack

G = force imparting acceleration equivalent to the Earth’s gravitational acceleration

T_g = glass transition temperature

y^+ = a non-dimensional parameter that indicates how fine the mesh is near walls relative to the flow's viscous effects

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I. Introduction

Monash High Powered Rocketry (Monash HPR) is a university rocketry team from Melbourne, Australia founded in 2018. The team have been regular participants at IREC with great success, competing in the 2021 Spaceport America (SA) Cup with *Project Icarus*, 2022 SA Cup with *Project Aether,* and 2023 SA Cup with *Project Valkyrie*. After the 2023 SA Cup, Monash HPR decided to pivot to a two-year design cycle to develop the team's most ambitious project yet. This year, Monash HPR plans to showcase the team's many new innovations with *Project Zenith*, the team's 10,000 ft SRAD Hybrid entry for the 2025 International Rocketry Engineering Challenge.

A. Academic Program

Monash HPR has grown substantially since its inception, and consists of 139 active members from a range of faculties including Engineering, Science, IT, Arts, and Commerce. The team operates under Monash University's Faculty of Engineering, and receives funding and support through the Monash Student Teams Initiative (MSTI).

B. Stakeholders

As a student engineering team, the majority of support provided comes from Monash University, in particular the Faculty of Engineering. This support includes a contribution to the teams annual budget, workshop space, and ongoing access to a range of advanced manufacturing facilities within the Monash Makerspace, through the Monash Student Teams Initiative (MSTI) and the broader university. These specialized spaces include general machining resources such as lathes, mills, and Computer Numerical Controlled (CNC) machining, in addition to additive manufacturing support, composites workshops, electrical workshops, and more. Additionally, general operations are supported by vehicles, trailers, marketing gear, and other logistical equipment provided by MSTI, enabling the team to attend launches and outreach events in a professional and organized manner.

Monash HPR has two Academic Advisors, Dr. Callum Atkinson and Dr. Daniel Duke, who oversee the team's operations and developments on a day-to-day basis. They serve as the primary points of contact when working with Monash University to ensure the safety and efficiency of procedures. The team also maintains several partnership arrangements with various companies and sponsors that provide in-kind support, funding, software, training, and discounts to aid team operations. The team's mentor, David Boyd, has provided his facilities for Printed Circuit Board (PCB) assembly, while Isaac Sims, an HPR alumnus, also serves as a mentor and the Flyer of Record (FoR) for *Project Zenith*. Lastly, the Victorian Rocketry Association provides a launch site for the team to test-fly systems, including accommodating *Project Zenith*'s previous launches.

C. Team Structure and Management Strategy

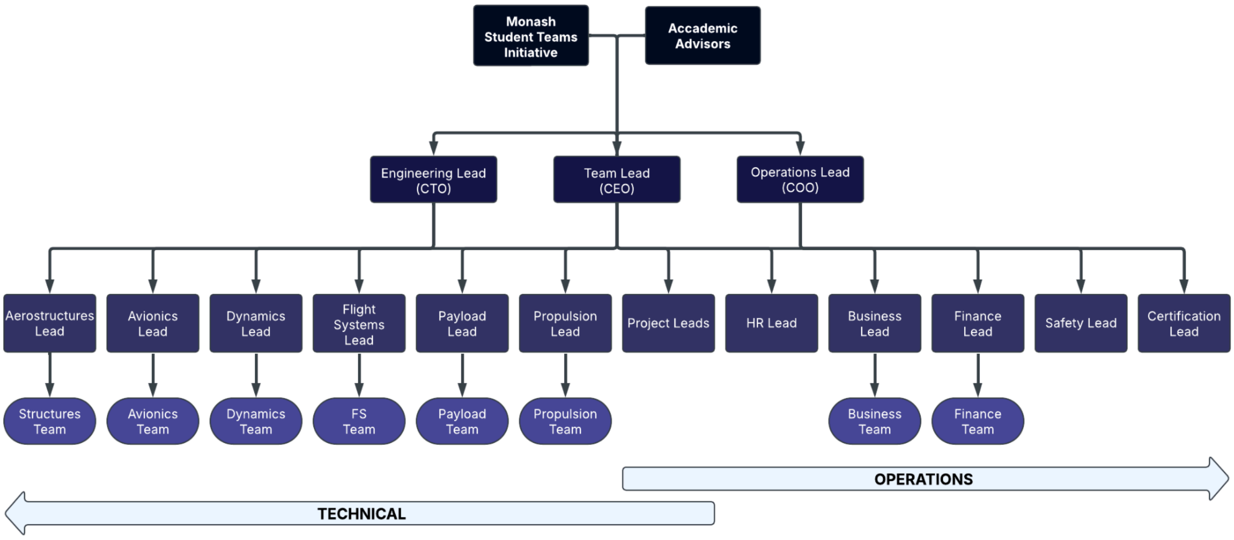


Fig. 1 Team Organization Chart

As seen in Fig. 1, Monash HPR is structured around eight core sections: Aerostructures, Avionics, Business, Dynamics, Finance, Flight Systems, Payload, and Propulsion. Each section has a Section Lead and designated Vice Section Leads to manage individual members and ensure technical progression. The team's management structure consists of a core Upper Management team, made up of the Team Lead (CEO), Engineering Lead

(CTO), and Operations Lead (COO), alongside supplementary leads responsible for overseeing areas such as Human Resources, Safety, and Hobby Rocketry Certifications. This core team collaborates closely with the Section Leads to ensure smooth operations. Additionally, each major project, such as *Project Zenith*, is managed by two Project Leads who work in tandem with the management team to ensure its successful execution.

D. Project Scope

The scope of *Project Zenith* extends beyond the development of launch vehicles. It provides the team with the opportunity to strengthen its systems engineering capabilities, placing a greater emphasis on safety, reliability and documentation. An important focus of the project has been the deeper integration of the propulsion subteam into team-wide projects, ensuring that these considerations are embedded across all stages of development. By undertaking this project, the team will elevate its technical capabilities and develop a more comprehensive approach to rocketry. To achieve these objectives, *Zenith* has been designed with the following core goals:

- **Innovative**: Challenging the team to develop a rocket that implements creative ideas and design solutions to achieve an original rocket.
- **Competitiveness**: As a competitor in the 2025 IREC 10,000 ft SRAD Hybrid propulsion category, the rocket shall achieve an altitude as close to 10,000 ft as possible. Alongside the development of a high-performing rocket, all other assessed deliverables (progress updates, technical report and design implementation evaluation) will be completed to a high standard.
- **Reliability**: To achieve numerous flight tests of SRAD systems, the rocket and its systems shall be highly reliable and consistent in their performance.
- **Safety**: All aspects pertaining to rocket manufacturing, assembly, operation and recovery do not present significant danger to any member of the team, external observer or infrastructure.

Project Zenith builds upon the structured design cycle and robust systems engineering processes established during *Project Valkyrie* (Fig. 2), which laid a strong foundation for technical development. These frameworks have been retained and further refined to meet the greater technical demands of this project.

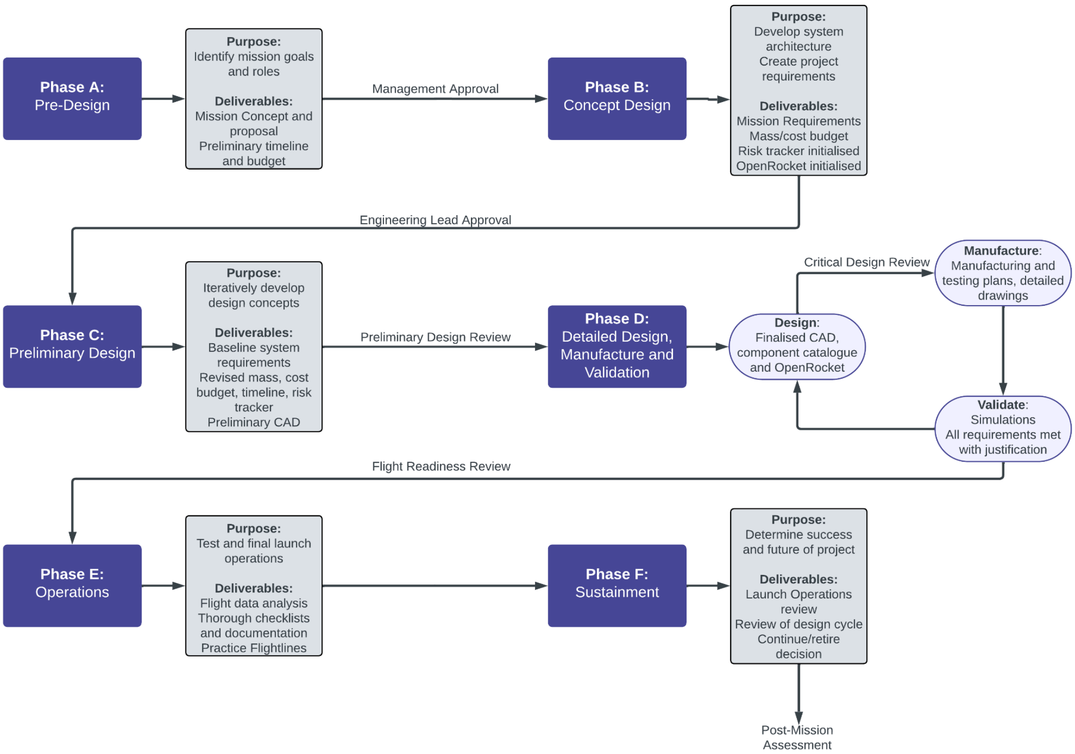


Fig. 2 Monash HPR Systems Engineering Lifecycle

Importantly, *Project Zenith* has adopted a two year design cycle, rather than the one year timelines we have followed previously as a team. This extended schedule gives all subsystems of the rocket greater opportunity for innovation, encouraging more ambitious technical developments while ensuring that strong systems engineering practices, thorough documentation and strict review processes are maintained. This shift reflects Monash HPR's commitment to delivering more innovative, competitive and reliable systems.

II. System Architecture

A. System Overview

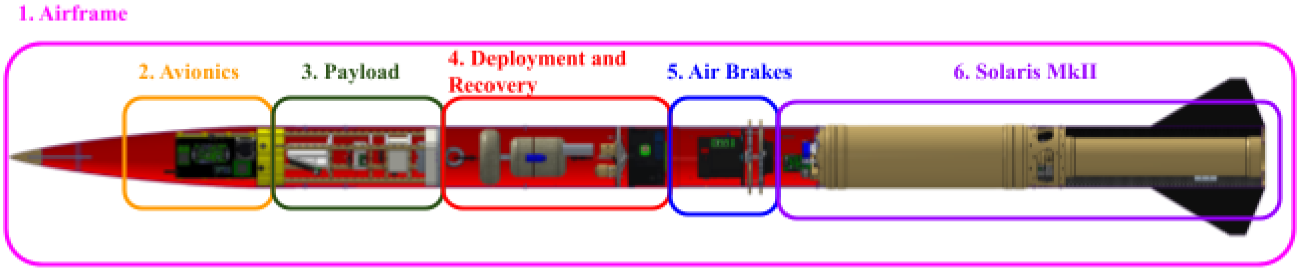


Fig. 3 ***Project Zenith*** **Internal Cross-section**

Project Zenith can be broken down into six main systems: the Airframe, Avionics Bay, Payload, Deployment and Recovery, Air Brakes, and Solaris MkII. The airframe is fully SRAD and consists of a 6 inch diameter airframe with a Von Karman fiberglass nose cone, fiberglass body tubes and couplers, and a carbon fiber rear tube with four surface mounted carbon fiber fins. The avionics bay is responsible for the team's entry into the Live Video Challenge and houses a first person view (FPV) camera, an SRAD data logger implementation of our primary flight computer, the Galileo Flight Computer (GFC), with GPS capabilities, and a BlueRaven altimeter. The payload system features a new 4U CubeSat chassis, KALKI, running an experiment to investigate the usage of Artificial Intelligence (AI) to improve rocketry data acquisition. The deployment system utilizes a single-bay, dual-event system and contains Monash HPR's first SRAD primary flight computer, GFC, backed up by a redundant RRC3. This will fire a deployment device at apogee, separating the rocket and releasing the drogue parachute. At 1,400 ft AGL, a second event will occur and release the main parachute. The deployment bay also houses a TeleGPS for additional GPS capabilities. The Air Brakes system incorporates four radially actuating flaps, controlled by an onboard active control algorithm, allowing over 2,000 ft of control authority.

Lastly, *Project Zenith* will house Australia's most powerful SRAD hybrid rocket engine, Solaris MkII, with a specific impulse of 10,000 Ns and average thrust comparable to an M3400 motor. It features an active vent system that precisely controls oxidizer levels using a capacitive fill sensor, and a pneumatic main valve operated by high-pressure nitrous oxide, regulated by a three-way pilot valve. The onboard Motor Controller manages both systems, overseeing actuation of the active vent and main valve. It includes a set of embedded SRAD systems designed for power delivery, control, monitoring, and safety management of the electronics in Solaris MkII. This is done through the Intra-Rocket-Interface-System (IRIS), an in-house developed communications protocol, ensuring efficient and reliable data transmission within the rocket between electrical systems.

III. Propulsion System Architecture

A. Solaris MkII

1. *Engine Overview and Performance*

First conceived in June 2023, Solaris MkII is an SRAD hybrid rocket engine designed, manufactured and tested in house by Monash HPR's Propulsion team. The engine went from an idea to a hot fire in three short months, with the first achieved in September that year. The engine has since been hot fired 10 times and flown three times, two of which were on the team's IREC 2025 entry rocket, *Project Zenith*.

The engine originally used a 4 inch tank and CO_2 to control the main valve, but has since evolved into a 152.4 mm (6") tank and employed the use of a tap-off nitrous pilot valve to actuate the pneumatic main valve. The choice to switch to a 6 inch tank was made because the required length of the tank needed to take *Project Zenith* to 10,000 ft became excessive.

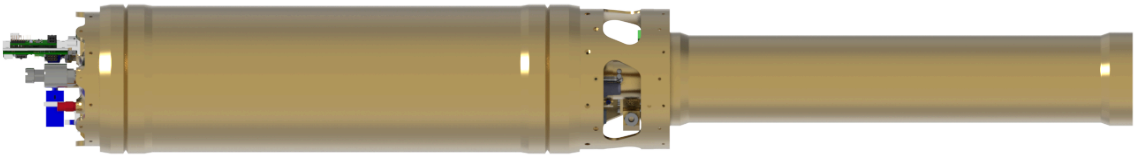


Fig. 60 **Render of Solaris MkII**

The engine produces a peak thrust of 4,000 N and an average thrust of 3,400 N. It produces an impulse of approximately 10,000 Ns, making this engine akin to an M3400. The engine has been shown to achieve ~160 seconds of specific impulse (ISP), fluctuating on the order of 10 seconds depending on a variety of environmental factors. More details about hotfire results can be found in Appendix B.2.

This engine features a pneumatically actuated main valve, controlled by a 3-way pilot valve, all designed and manufactured in house. This valve allows for precise timing over ignition and minimizes mass and space. Furthermore, the engine features an active vent and a capacitive fill sensor which is controlled through Pad Station and the onboard Motor Controller to automatically hold a constant mass and temperature in the oxidizer tank to achieve a predictable thrust curve.

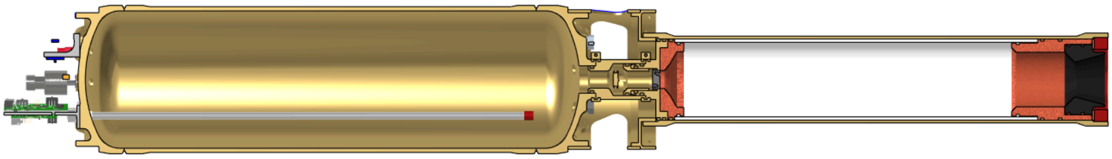


Fig. 70 Cross-sectional view of Solaris MkII

For ignition the engine uses a simple pyrotechnic charge, retained in the pre-combustion chamber. It is ignited approximately 8 seconds before the main valve to pre-heat the fuel grain and ensure successful ignition.

2. Tank and Structural Interface

The engine utilizes a 152.4 mm (6”) tank, the same diameter as the airframe, which holds the oxidizer used by the engine during combustion. It was designed to hold 8.8 litres of nitrous oxide when full, but the team underfills the tank such that it has an ullage volume and can provide extra margin if needed. This additional volume for the nitrous oxide vapor ensures that the pressure in the tank remains stable when the main valve is opened, since the ullage volume will not vary significantly as the liquid level begins to drop. The tank was designed to safely withstand a pressure of 1060 psi such that in the case that the tank is unable to vent, the relief valve will open before the structural failure of the tank. A wall thickness of 4.5 mm (0.18”) is used along the walls of the tank giving a FoS of 2.5 (see Appendix H.6.1), whereas a larger thickness of 6 mm (0.24”) is used around the tank’s welds to ensure a higher FoS around these heat affected zones. Radial bolts and threaded closures similar to the combustion chamber were considered, but both options require machining of the main tank wall, which was deemed infeasible due to internal machining resources.

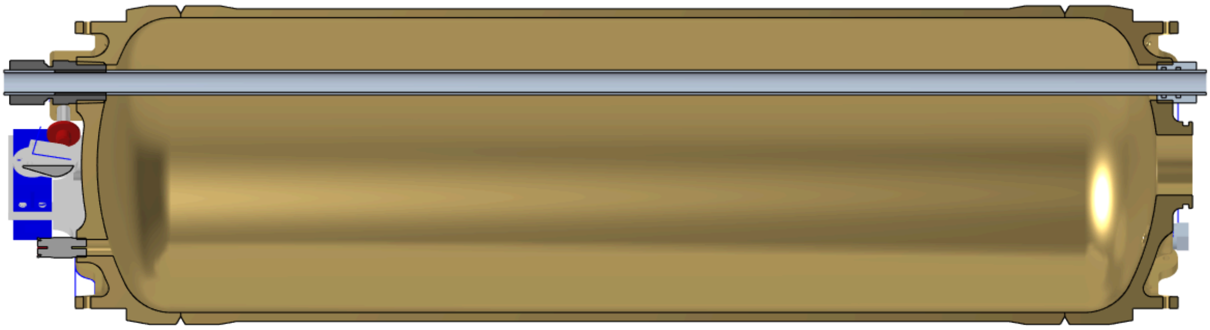


Fig. 71 Cross-section of the oxidizer tank

The tank is machined in three separate parts, which include the upper and lower bulkheads along with the body cylinder. The bulkheads are both machined using a CNC mill, whereas the body cylinder is able to be machined on a manual lathe. The bulkheads were simulated with the same 7.3 MPa pressure and passed FEA with a FoS of 2, which can be summarized in Table 8 with more details available in Appendix H.6.1. These parts are welded together, before being hydrostatically tested to validate the tank’s strength (see Appendix B.3).

Table 8 Tank FEA Results

Component	Minimum Factor Of Safety

Top Bulkhead	2.0
Bottom Bulkhead	2.08
Tank Wall and Welds	2.5

Both of the bulkheads feature ports to interface with sensors and other systems such as the fill line, active vent and the capacitive fill sensor. These bulkheads also both feature a “crown” of radial bolt holes, two rows of eight M4 tapped holes, which are used to attach the engine to the airframe of the rocket. An electrical passthrough is installed within the tank which also interfaces with the bulkheads and allows for wires to be connected between the electronics on either side of the tank. This avoids the need for a raceway outside of the tank which would interact with the airstream. Additionally, the bottom bulkhead connects to the main valve and the structural interface, transferring the thrust from the combustion chamber into the tank, allowing the force to ultimately be transferred into the airframe.

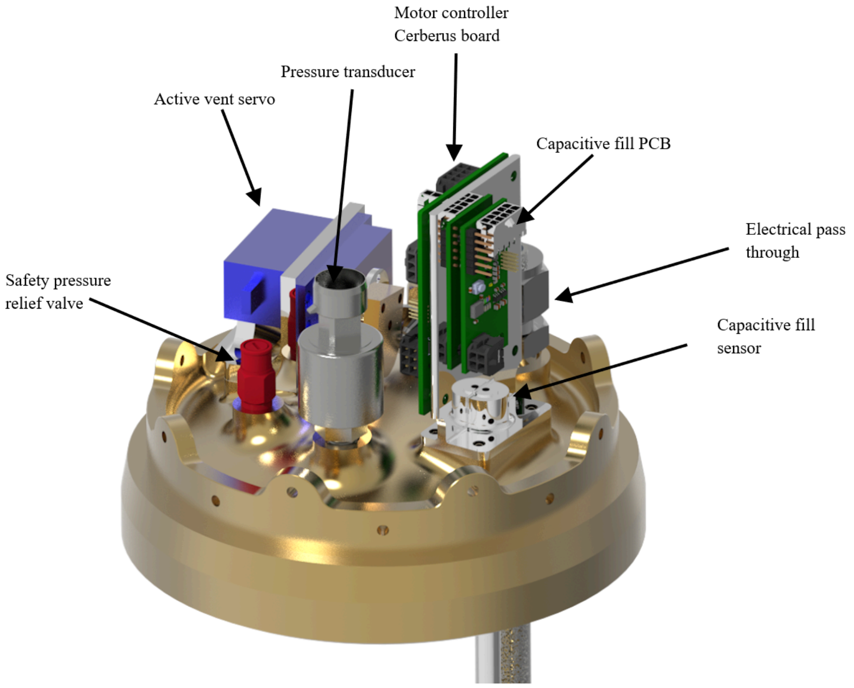


Fig. 72 Labelled render of the tank top bulkhead

As seen in Fig. 73, the structural interface is sized to match the distance between the tank and the combustion chamber, which the main valve occupies, while maximising the space for the pilot valve and internal fill line. Its diameter sits just below the inner diameter of the carbon fiber rear tube, allowing it to fit inside of the airframe.

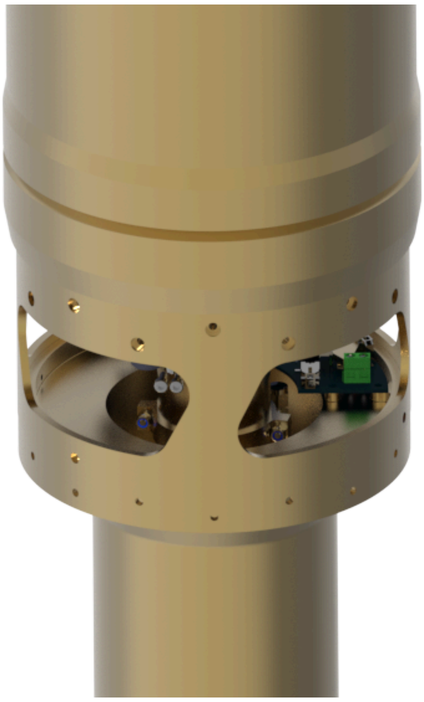


Fig. 73 Render of Solaris MkII mid-section with structural interface

FEA was performed on the structural interface to ensure that it could safely transfer the loads from the combustion chamber into the rest of the rocket while using as little material possible. The results of the structural interface FEA can be summarized in Table 9.

Table 9 Structural Interface FEA Results

Component	Minimum Factor Of Safety
Structural Interface Ring	4.18
Structural Interface Adapter	2.39

The ring design helps to minimize the weight of this component while also leaving as much empty space around the sides. The ring is constructed out of AL 6060-T5 and is CNC machined from tube stock to save machining down a large billet. The round nature and isogrid style windows allow for maximum diametric space while allowing a level of serviceability to the fittings and components within the structural interface. Furthermore, using the tube stock, which was used as a mandrel for the rear airframe tube, ensures a tight fit between the structural interface and the rear airframe. An alternative design with vertical struts was considered, but ultimately decided against. This ring design provides much greater space for serviceability, strength and limits the componentry required.

3. Combustion Chamber

The combustion chamber is machined 101.6 mm (4”) aluminum 6061 T6 stock and makes use of threaded closures at either end. The threaded closures allow for compression on all the internal components, allowing all of the internals to sit tightly against each other, engaging the seals. Another benefit of using threaded closures as opposed to radial bolts is the assembly time, allowing for quick cycling of the engine. The combustion chamber was simulated as shown in Appendix H.6.1, and the results can be summarized in Table 10.

Table 10 Combustion Chamber FEA Results

Component	Minimum Factor Of Safety
Combustion Chamber Wall	4.08

In order to center the combustion chamber within the 152.4 mm (6”) rear airframe tube, a motor centering ring is attached to the aft end of the combustion chamber with axial bolts. This was chosen because it is easily adaptable to the retaining ring, it is not orientationally constrained and being at the aft end provides the most stability to the engine. The forward end is retained by a structural interface adapter, which acts as a closure and an adapter for the 152.4 mm (6”) tank and structural interface.

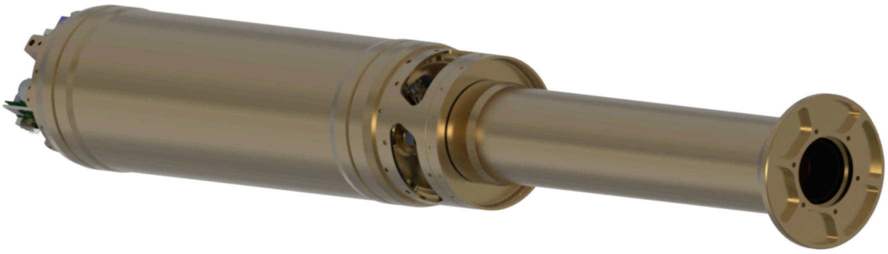


Fig. 74 Render of aft-end of Solaris MkII with centring ring

The combustion chamber also features pre and post chambers. From literature, the pre-combustion chamber is shown to have a limited effect, if any, on performance and therefore has been designed with the main purpose of shielding the forward closure from hot combustion gasses [6]. Whilst the length of the pre-combustion chamber was subsequently kept quite short, it is shaped to provide a transition for the expanding flow exiting the injector. On the other hand, the post-combustion chamber positively affects the performance of the engine. Thus based on literature [6], a length to diameter ratio of 1.5 was chosen for the best performance.

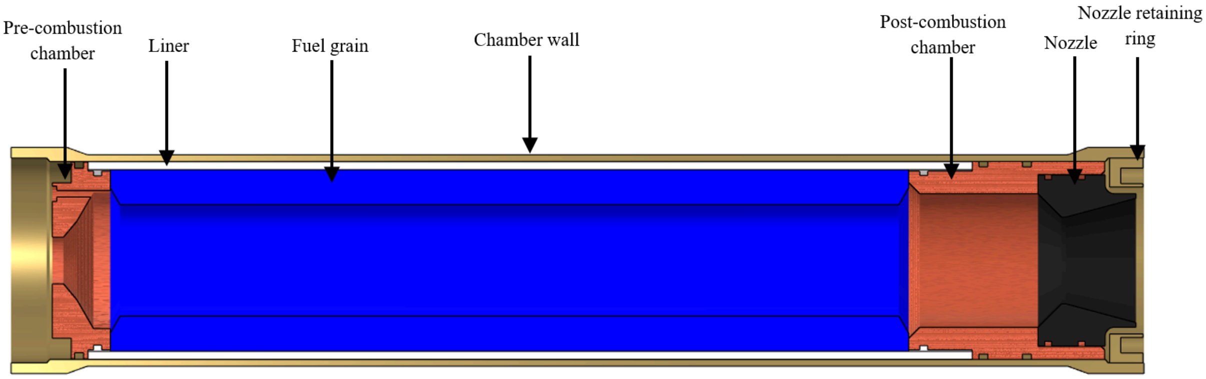


Fig. 75 Labelled cross-section view of the combustion chamber

The nozzle is a conical nozzle with a 15° diverging half angle and 39 mm (1.54”) throat diameter to achieve the target chamber pressure. The exit half-angle is chosen as any angle larger is known to cause internal flow losses [7]. Constructed for durability and thermal performance, the nozzle's throat and diverging section are made from solid graphite. Graphite was selected primarily for its thermal conductivity and longevity, offering an advantage over phenolic or aluminum options. To mitigate erosion caused by sharp edges, the throat incorporates a small 3 mm (0.12”) straight section. The graphite component is housed within a phenolic sleeve, which connects to the post-combustion chamber. This phenolic sleeve serves a crucial role in shielding the adjacent aluminum wall from the highly conductive graphite. The team tested with a phenolic nozzle with a graphite throat, however, this ablated too quickly and it was deemed not worthwhile for the trade-off.

4. Propellant Selection

The fuel grain for Solaris MkII uses a 3D printed ABS matrix with a gyroidal infill, which the paraffin wax is melted and poured into. The ABS matrix provides structure to the otherwise brittle paraffin wax and is printed with this gyroidal shape to allow for the melted wax to freely flow through it for cooling and hardening. The ABS itself acts as a lower regression fuel and thus energy is still able to be obtained from it during combustion.

The fuel grain features a simple cylindrical port due to the simplicity in casting and design. Other port shapes such as a star fuel grain were considered for its more constant surface area, but were deemed inappropriate without any implementation of flow regulation. The cylindrical shape of the port increases in area during the burn, which helps to offset the decrease in performance that comes as a result of the tank emptying, holding a more constant thrust profile.

The fuel grain's O/F ratio currently sits close to the optimal value of 5.6 [8], however it is slightly off due to length constraints in the manufacturing process. The 3D printers the team has access to do not have the build height to achieve the optimal fuel grain length, and was decided against splitting the fuel grain into multiple sections due to the unknown behavior at the intersection between fuel grains.

The fuel grain is housed in a PVC tube to separate the combustion gasses from the chamber wall. This was chosen over phenolic tubes due to available stock in the correct size and its low cost. PVC is a low regression fuel as well as being fire-retardant and self-extinguishing, meaning that it will not continue to burn after the tank is empty. A liner-less design was initially considered, but without validation of inhouse simulations it was deemed too risky. Hot fires and flights of the engine have proven this decision advantageous. In circumstances where the engine was overfilled with nitrous oxide, the liner has sustained damage and protected the chamber wall from burning through, as seen in Fig. 76.

Fig. 76 Solaris MkII burnt through liner

5. *Main Valve*

The flow of nitrous oxide into the combustion chamber is controlled by a pneumatically-driven piston valve. This valve was designed in-house to fit the required form factor, while preventing choked flow from occurring upstream of the injector. Another requirement was maintaining sufficient cross-sectional area to ensure the required propellant flow rates are achieved throughout the burn. An area ratio of 4.5 between the minimum cross-section area of the valve and the injector effective area was found, exceeding the internal requirements of 2. The valve is driven by tap-off nitrous oxide from the tank and so in order to keep the valve closed with pressure on both sides of the piston, the areas on either side had to be different. The area ratio between the bottom side (control piston) and top side (working piston) is 1.67, ensuring that the piston will remain closed with pressure on either side. The forces and pressure on the piston keeping it closed or open at various temperatures can be found in Table 11**.**

Table 11 Main Valve Operating Forces and Pressures at certain Temperatures

Parameters	Control Piston		Working Piston	
Surface Area (m^2)	5.50E-04		3.30E-04	
Temperature (°C)	5	30	5	10
Open Force (N)	0	0	1287	2376
Closed Force (N)	2145	3960	1287	2376
Open Pressure (MPa)	1.00E-07	1.00E-07	3.9	7.2
Closed Pressure (MPa)	3.9	7.2	3.9	7.2

All valve components are CNC machined from aluminum billets and sealed against the anticipated 1060 psi of pressure using nitrile o-rings. The hydrostatic testing report can be found in Appendix B.3, and the simulation report can be found in Appendix H.1.6.

To achieve the goal of maximising cross-sectional area for nitrous oxide flow, the main valve piston requires a 5-axis CNC milling machine for manufacture. The valve is held in place using collars between the bottom closure of the onboard oxidizer tank, and above the combustion chamber forward closure. However, these are not load bearing as thrust is directed through the structural interface, except during transient start up or off nominal cases. These collars are also used to attach the SRAD pilot valve, which provides the pneumatic control required to actuate the main valve.

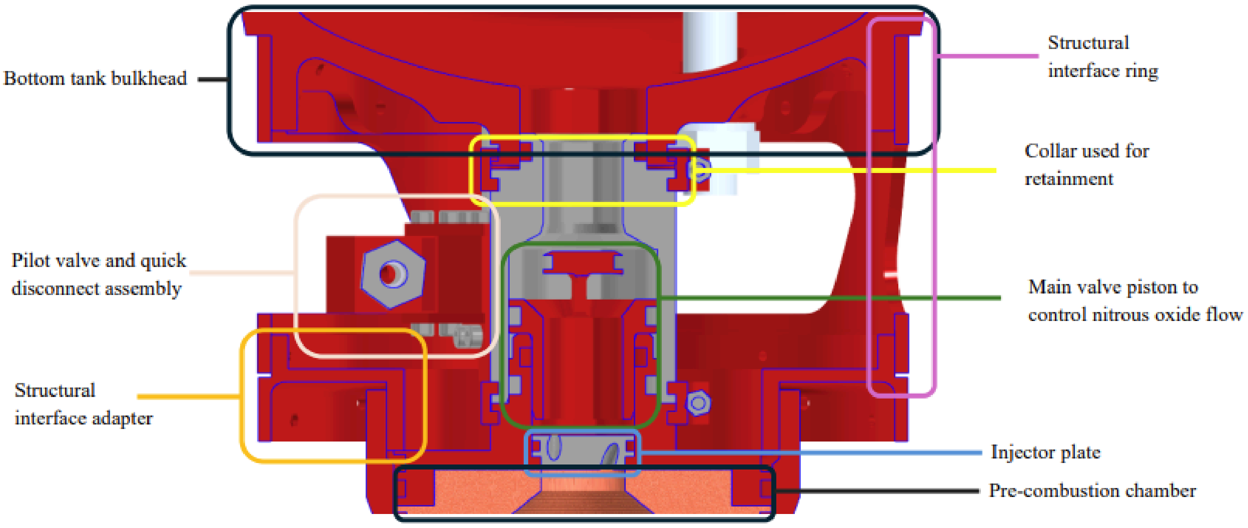


Fig. 77 Labelled cross-section view of the valve assembly

Development of the pilot valve was challenging due to the unique geometric constraints (as this valve had to fit in a very small form factor), as well as the high operating pressure (approximately six times higher than typical COTS compressed air pneumatic valves) of the nitrous oxide working fluid. Ultimately, a three-way piston valve design was selected to simplify the manufacturing and sealing of the pilot valve compared to other alternatives (such as a 3-way ball valve). A brushed DC motor was chosen to actuate this valve due to its very small form factor and high power density. This motor is linked to the valve piston via a lead screw, allowing it to actuate the piston ‘up’ and ‘down’, uncovering various ports on the piston shaft to allow nitrous oxide to pressurize or depressurize a cavity in the main valve, thereby controlling the main valve’s position. This motor is controlled by the onboard Solaris Motor Controller system.

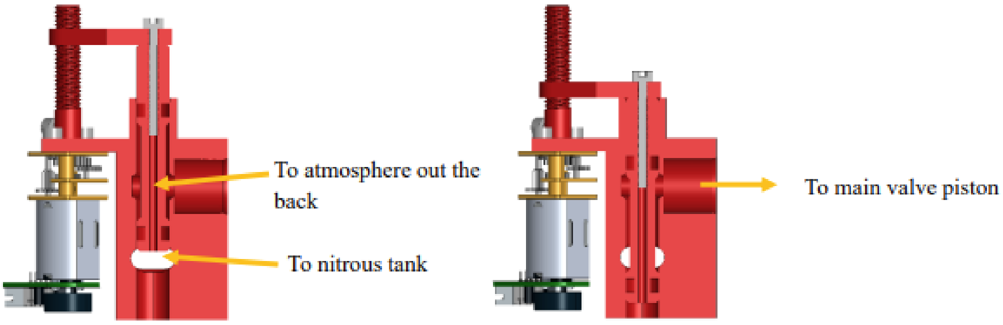


Fig. 78 **States of pilot valve in open (left) and closed (right) positions**

To supply the oxidizer for the Solaris MkII engine, an SRAD quick disconnect system is implemented to fill the onboard tank with propellant. This system consists of a check valve onboard the rocket, and a detachable fitting held on to the rocket prior to launch by nylon line. COTS quick disconnects were considered and have been used by the team in the past, however, finding a pressure rated, low form factor option that does not require a mechanical disconnect was challenging. The team instead opted to develop an inhouse solution utilizing pyrotechnics and small form factor machined to size components.

The onboard check valve is held open by the quick-disconnect fitting during filling operations, allowing the propellant to be dumped through the offboard Ground Support Equipment if necessary. After filling is complete, a primary and redundant e-match are fired to sever the nylon line, thereby ejecting the quick-disconnect fitting and allowing the onboard check valve to seal, preventing leaking of propellant prior to ignition. Furthermore, the check valve assembly is bolted together in one assembly with the pilot valve subsystem to supply the nitrous oxide working fluid. It is also connected to the onboard oxidizer tank via ¼ inch nylon tubing.

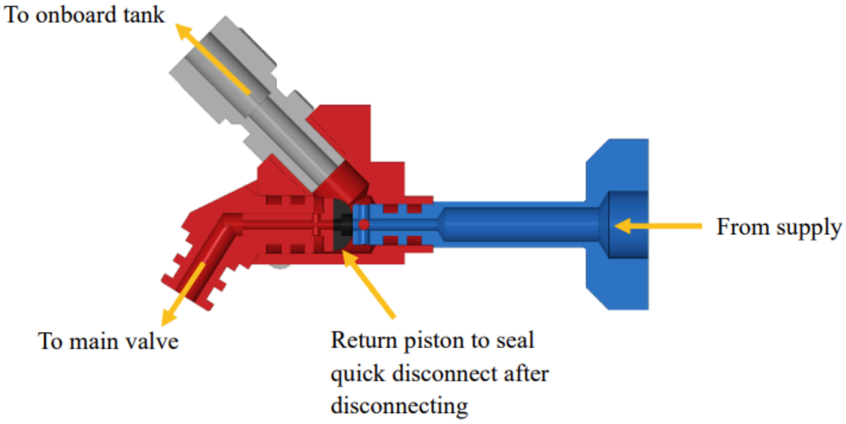


Fig. 79 **Labelled cross-section view of the quick-disconnect fill assembly**

6. Active Vent

A custom venting system has been designed to allow for a high degree of safety in addition to important performance enhancements of Solaris MkII. This active vent system allows for the control of the vent rate during filling procedures and the ability to fully close the tank, all while maintaining a completely fail safe operation to meet all DTEG requirements. The design features an equal area piston that is used to ensure nitrous pressure cannot actuate the valve, thus allowing consistent operation under normal conditions. The piston is sealed with two Viton (Shore Hardness of 75) o-rings which move over the outlet hole to seal off the tank when actuated. When unpowered, a spring that is compressed while the valve is closed, works to open the vent by overcoming the unpowered stall torque of the servo combined with the o-ring friction. This allows the vent to be fail safe with a passive vent rate capable of venting the system within 10 minutes (see Appendix H.6.2). The vent is actuated by a servo which rotates a cam to push down on the piston, compressing the spring and closing the vent.

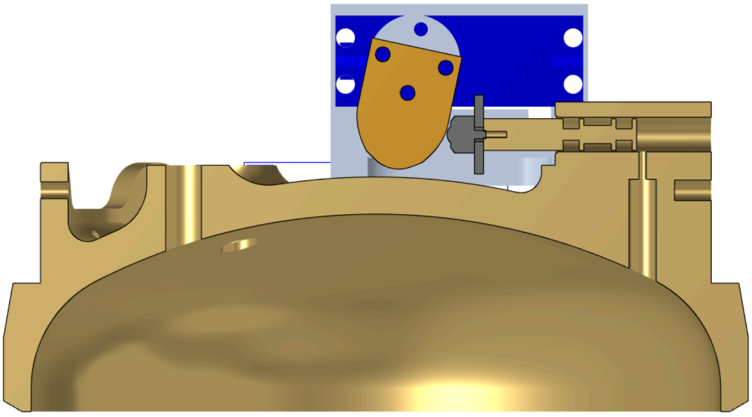


Fig. 80 **Cross-section view of the top bulkhead with active vent in the “open” position**

The active vent plays a secondary purpose of providing thermal control to the propellant loading. When open, the vent allows for nitrous oxide to vaporize and exit the tank. This process is endothermic and thus cools the oxidizer tank, allowing for a higher bulk density of nitrous oxide within the system. With the aid of sensors such as the capacitive fill, a target mass can be loaded onboard the rocket based on simulations, taking into account temperature and weather conditions on the day. Once loaded, the vent can close the oxidizer tank fully and allow the system to warm to ambient temperature. This increases the pressure within the tank and subsequently improves the thrust produced by the engine on startup.

For the case of *Project Zenith*, the increase in density is not important as the tank is never fully filled; the key metric is the control over temperature due to the high vent rate, and the ability to close, which allows the engine to launch with liquid nitrous oxide as opposed to supercritical nitrous oxide, which has been identified as a large risk at IREC2025.

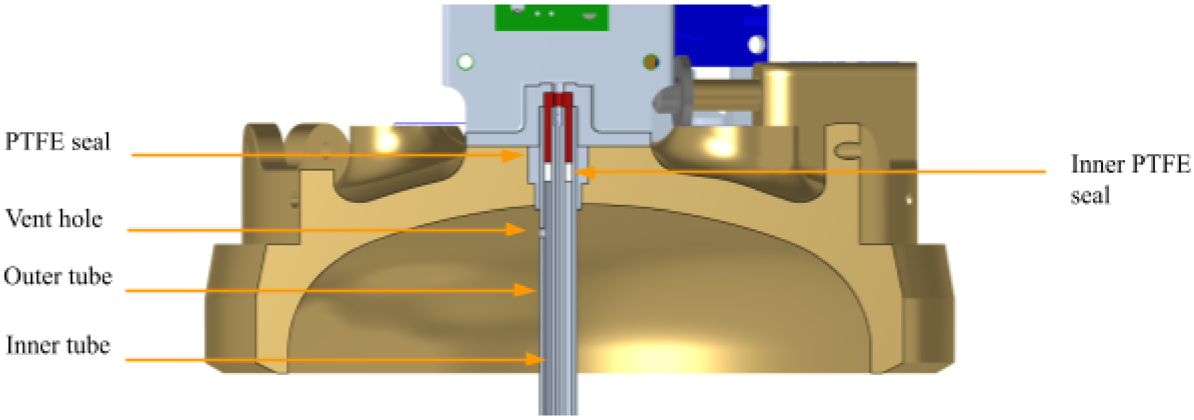


Fig. 81 **Cross-section view of the capacitive fill sensor**

The vent is integrated into the bulkhead of the tank with the vent hole drilled into the custom machined piece and mounting surfaces integrated to hold the servo. All pieces have been machined in house on manual and CNC machines which has allowed for the complex geometries and high accuracies needed for such a design. All parts have additionally undergone significant testing including hydrostatic, cold gas, actuation, fail safe and multiple test fires. This level of testing provides confidence in both the design and function of all parts of the active vent system.

Through the design of the active vent, a multitude of designs were considered, some more promising than others. Ball valves, solenoid valves and fully COTS systems were all investigated initially, all eventually being rejected. COTS solutions were prohibitively expensive, whilst ball and solenoid valves could not meet the size and weight constraints while also performing at the expected pressures and temperatures. Additionally neither ball valves or solenoid valves could perform the fail open state that was required to maintain a high level of safety. As such, the design shifted to an SRAD valve.

The equal area piston was quickly settled upon to ensure that the nitrous pressure played a minimal role in the actuation of the piston, providing reliable actuation in all states. Significant time was then put into the actuation mechanism, with linkages, linear actuators and rack and pinions all considered. Linkages were rejected due to previous poor experiences on Solaris MkI and linear actuators could not provide a reliable fail open. As such a rack and pinion with a spring return on the piston was investigated further. Testing of this design however showed significant deflection of the piston, resulting from the pressure angle between the rack and pinion. This combined with machining complexity (requirement of wire EDM as the tooth geometry could not be cut) eventually ruled this mechanism out.

During these investigations, it was decided that the final actuation method would need to provide a force collinear to the piston axis. This would prevent any torque and subsequent camming of the piston. As such, a cam actuator was proposed and investigated. This design required specific cam geometry to ensure a constant force on the piston, making sizing of the spring significantly easier. Springs were chosen to overcome the unpowered stall torque of the actuation servo and o-ring friction, whilst having a spring constant that allowed for at least 7 mm (0.28”) of actuation before the servo stalled.

Over the course of the testing campaign for Solaris some minor changes to the vent design occurred. After discovering a 1 mm (0.04”) vent hole did not sufficiently vent the tank in the required time, a larger hole and thus o-ring and piston were required. This resulted in an increase in piston diameter from 5.5mm (0.22”) to 7.6 mm (0.30”), alongside an alternate spring to accommodate the larger diameter. Initial calculations resulted in a spring with a constant of 5.3 N/mm (see Appendix G.4**),** however testing indicated that the calculations had overestimated the constant required. Thus, to accommodate a larger piston, a spring with a constant of 4.3 N/mm was chosen. During testing, design optimisations were made to the piston to include a ball bearing roller to reduce friction in the action and improve reliability. This final design was then tested extensively during hot fires and cold gas tests with over 60 fail tests resulting in the valve opening, which can be found in Appendix H.6.3.

7. Ignitor

The first option that has been typically used to ignite Solaris MkII in the past is a solid energetic ignitor. Three small pieces equally spaced are glued to an insert which sits at the top of the fuel grain port. Each piece contains one e-match which has been wrapped in steel wool to help with ignition of the propellant. The quantity used was decided iteratively after several tests with different quantities and configurations. It was found that three small pieces are enough to ignite the fuel without causing start up effects from the ignitor choking the combustion gasses. This method of ignition is effective and safe to handle making it a desirable ignitor choice. The limits of this system are the inconsistency between pieces and the arbitrary assembly, making reliability a concern. The team has experienced failed ignition on some launch and hotfire attempts and is currently looking into improving on this ignition method. Currently, this is elected to be the team’s ignition system for IREC2025.

The second option is the arc-pyro ignitor system, which works by creating an arc through 3D-printed ABS. This part has been designed to sit inside the pre-combustion chamber and has graphite electrodes embedded within the ABS shell and wires which precisely dictate the spark-gap distance. As seen in Fig. 82 below, there are four gaps of two different dimensions. These provide redundancy as sparks can be made at different voltages, allowing for ignition at different operating conditions. Insulated wires are attached to the electrodes and pass down through the nozzle throat. These are connected to an offboard high voltage power supply to initiate and maintain the arc. The pyrolyzed ABS acts as a catalyst for the exothermic decomposition of nitrous oxide, thereby causing ignition of the engine. This option is the easiest to manufacture, however requires a new print for each hot-fire and as of writing has never been tested in an engine of this size.

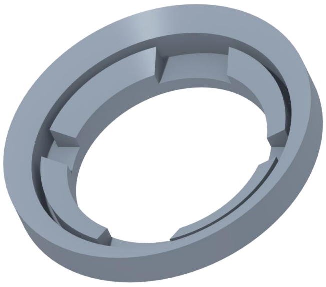


Fig. 82 Arc-pyro ignitor puck.

The third and final option is the torch igniter system as seen in Fig. 83, which unlike the first two options is an offboard ignitor set up below the nozzle. This minimizes the engine mass whilst also simplifying integration of parts. The torch igniter uses a separate supply of the fuel, gaseous propane, and the oxidizer which is gaseous nitrous oxide. Gaseous propane was chosen as the fuel over gasses such as acetylene and hydrogen due to its affordability and ease of use. Nitrous oxide was chosen as the oxidizer gas due to its accessibility and use in the engine. For maximum temperature and ease of ignition, a stoichiometric oxidizer to fuel ratio of 7:1 will be targeted with a glow-plug used to ignite the gas. In order to achieve top-down ignition in the engine, a PTFE line will direct the flame to reach as high in the combustion chamber as possible. Stainless steel or a hydraulic hose are flame resistant options that could have been used instead of the PTFE line, however, they are expensive and inflexible, making it a less desirable choice. The torch igniter is the most re-usable of the three ignition methods, as the only consumable is the PTFE line, which would need to be replaced between hot fires. The complexity of the GSE and untested nature of the PTFE extension line is not validated, therefore this option is currently the third preference.

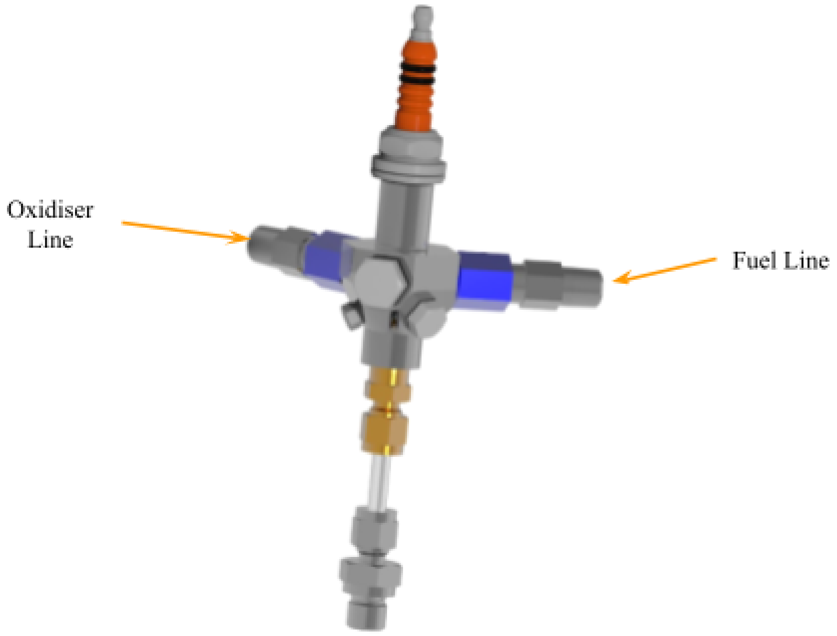


Fig. 83 Torch igniter

B. Motor Controller

1. *Overview*

Motor Controller is a set of embedded systems designed for power delivery, control, monitoring and safety management of the electronics in the Solaris Mk II hybrid engine. The major functionality covered by Motor Controller includes monitoring of temperature and pressure, controlling of the active vent and main valves, measuring the volume of oxidizer in the tank, as well as providing a pass-through for communication with the control station for the Air Brakes system. As an extension of the capabilities of the ground station equipment, a major requirement of Motor Controller is the inability to actuate or move to a different state without human input, with all the “smarts” of the system running on the ground station equipment. With unique, reliable and quick communication interfaces set up between the computers within Motor Controller and the ground station, highly accurate and fast updates of the engine state are available at all times at the control station, as well as locally saved on the boards for review after testing or launch.

2. *Electronics*

There are 3 PCB’s that each have an STM32 G4 series microcontroller loaded, all with the capability to communicate using the Controller Area Network (CAN) bus communication layer used typically in the automotive industry, chosen for its tolerance to faults, and the use of a twisted pair to eliminate common mode noise. This standard is particularly useful for Motor Controller as the network (see Fig. 84) can act as a decentralized peer network in which communication can be initiated and responded to by any node at any time. The three boards in the Motor Controller system are Cerberus (Top Board), Hades (Bottom Board) and Capacitive Fill (NFLS).

Fig. 84 Motor Controller Communication Network

Top Board is the entry point for the system, connected to a magnetic disconnect tether to the ground station equipment. On the magnetic disconnect tether there is a clean 12V and 6V supply provided from a car battery and buck converter, respectively. The former of the two supplies powers the Motor Controller System while the vehicle is on the pad, and the other acts as a toggleable supply to the active vent system, which will fail in an open state in an emergency or loss of power, allowing us to vent safely. The ground station equipment and Top Board communicate using RS-422, relaying the state of all sensors and actuators in the motor controller system. With this responsibility and added throughput required, Top Board has a second microcontroller that acts as a gateway between the CAN network and the ground station equipment, similar to a gateway in a car. Therefore, it also provides a link between the Air Brakes system and the control station. Besides communication and power delivery, Top Board measures tank pressure and can actuate the active vent servo motor. A block diagram summarising Cerberus's architecture can be found in Fig. 85.

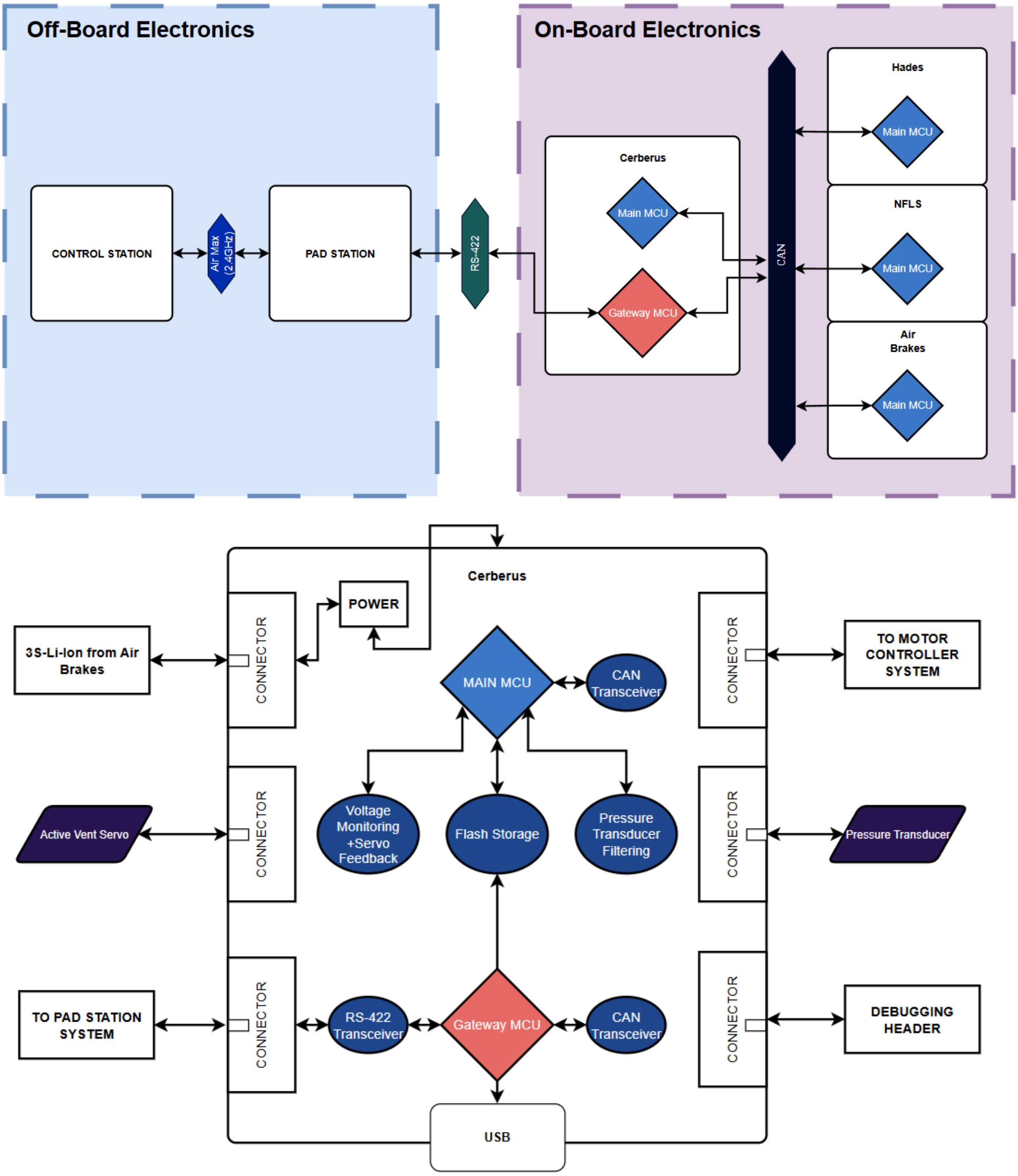


Fig. 85 Cerberus Architecture Block Diagram

Cerberus and Hades passed through two iterations before landing on the final, flight-ready design. Top board version one missed functionality for switching power supplies correctly between the onboard battery pack and the offboard connection to the ground station equipment. There were also various issues with routing, such as the incorrect footprint for the on-board flash data card and dimensioning that was too big to fit inside its enclosure in the rocket. Many of these problems were solved in version two of the Top Board, which successfully controlled and actuated the Solaris engine for a cold-gas test completed early in 2025, but ran into issues with current draw and power delivery due to the loading on the active vent servo being much higher than anticipated. Therefore, instead of powering the active vent servo, Cerberus is simply a pass-through for power to the servo, making for a much simpler hardware design, and much more fail-safe design. The final iteration of Cerberus (see Fig. 86) also added a second microcontroller to aid in the high-throughput that the custom communications protocol required. The team sees Cerberus as a highly capable PCB, and is proud to use it for controlling Solaris MkII.

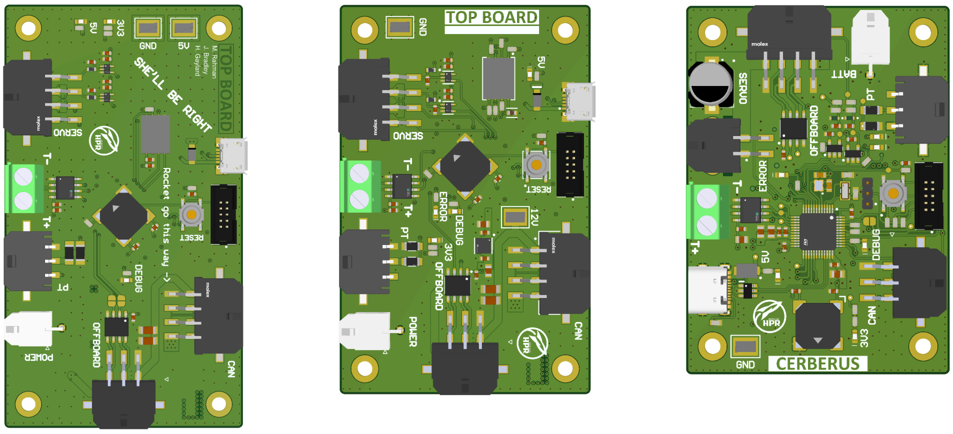


Fig. 86 Versions 1 to 3 of Cerberus (Top Board) from Left to Right

Bottom board is exclusively for temperature monitoring at the bottom of the tank, as well as actuating the main valve DC motor. Temperature is monitored through a K-Type thermocouple and relaying this information over CAN back to Top Board, while there is a mechanical limit switch mechanism that can send an interrupt to Bottom board when the main valve has either fully actuated open or closed. A summary of Hades' architecture can be seen in Fig. 87.

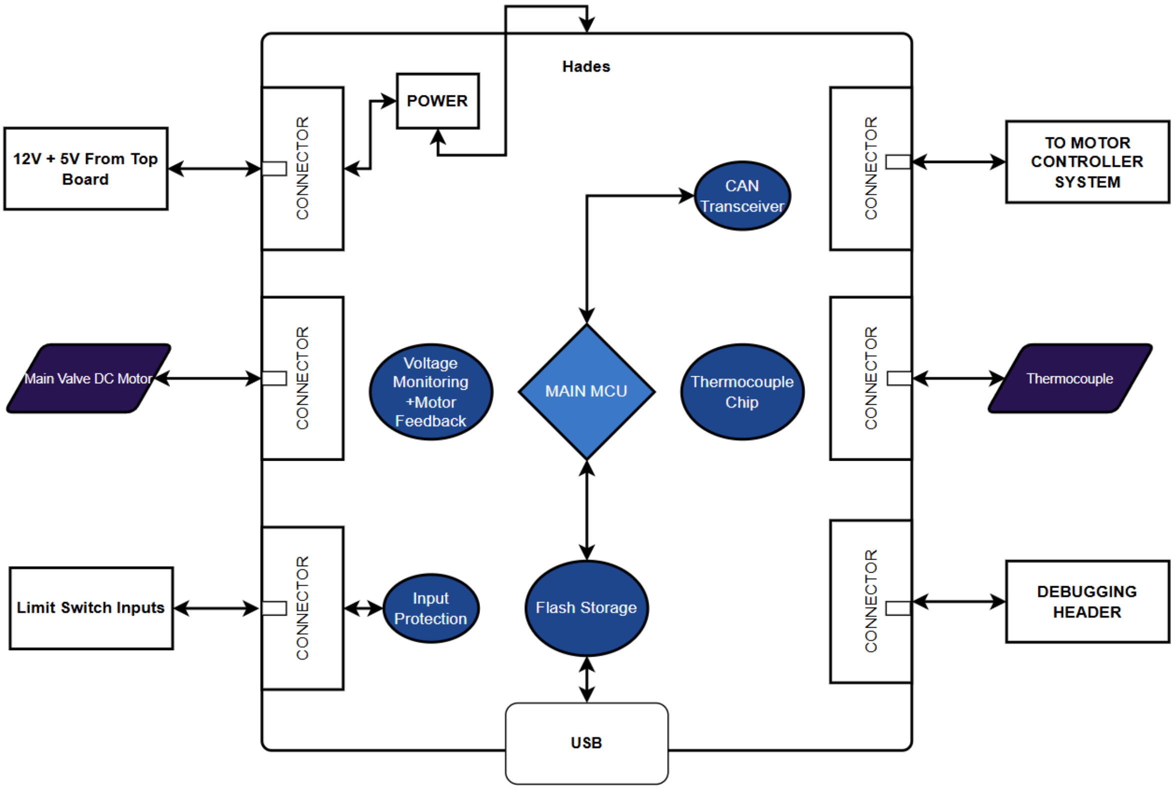


Fig. 87 Hades Architecture Block Diagram

Hades (see Fig. 88) was much closer to the flight-ready design from the beginning, and has undergone very little change from the first iteration. The team spent around 18 months developing the Motor Controller system and in that time significantly increased their hardware and software design knowledge. To make for a more stable design, improvements to CAN differential pair and external crystal oscillator routing alongside other refined details made Hades a much more reliable controller, and as the PCB responsible for the main valve actuation during launch, it has been well worth developing.

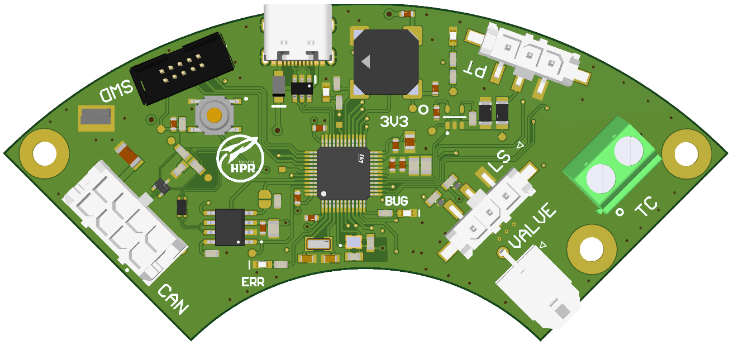


Fig. 88 Hades PCB

The benefit of using a CAN bus can be seen with this setup, as there is great opportunity for expansion into other parts of the rocket, where sensors or auxiliary computers can be continually added for monitoring or control by a central system. All boards in the system are running an RTOS to handle data acquisition, data logging, communications and actuation concurrently.

3. *Capacitive Fill*

The Capacitive Fill sensor is designed to estimate the mass of nitrous oxide within the onboard oxidizer tank. It operates on the principle of relative permittivity, where the dielectric constant of the medium inside a capacitor affects its capacitance [9]. The sensing element consists of two concentric aluminum tubes, forming a cylindrical capacitor that extends approximately 500 mm (19.7”) into the tank. As the tank fills with liquid nitrous oxide, the average dielectric constant between the capacitor plates changes, resulting in a measurable shift in capacitance. A summary of this architecture can be found in Fig. 89.

The capacitance varies linearly from approximately 60 to 70 picofarads as the tank transitions from empty to full. This relationship between oxidizer mass and capacitance is near-linear and, once calibrated, allows the sensor to estimate mass with high precision. However, confirming the absolute accuracy of this measurement is difficult, as the calibration process relies on load cells with significantly lower precision than the capacitive sensor itself. The capacitance is read by the Nitrous Fill Level Sensor (NFLS) board (see Fig. 90) with a resolution of ±6 femtofarads. This data is then transmitted via CAN to the Top Board, which forwards the reading to the Pad Station. At the Pad Station, the raw capacitance value is mapped to a mass estimate, enabling real-time feedback during the fill process.

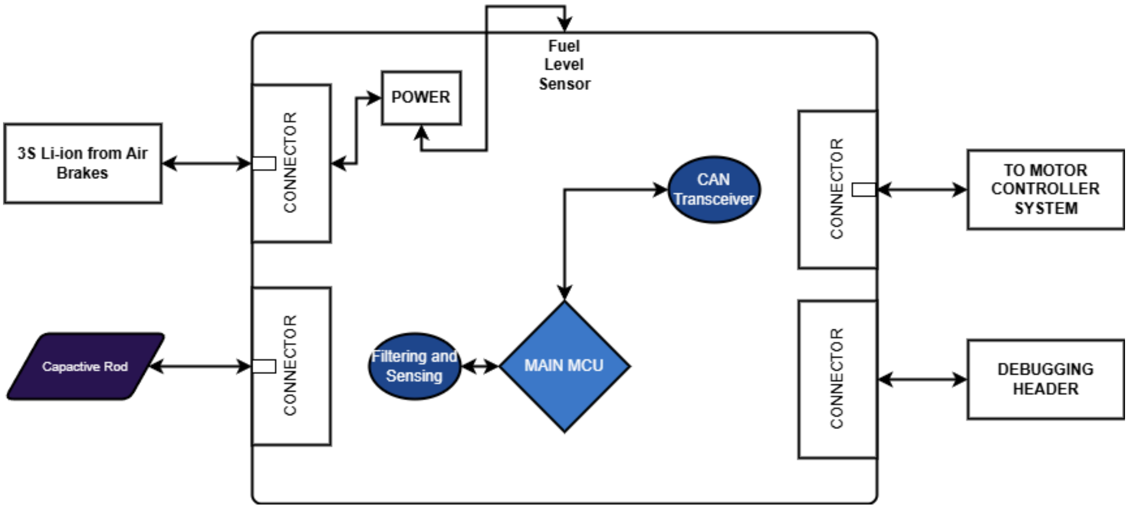


Fig. 89 Capacitive Fill Architecture

Capacitive Fill using the NFLS board has the sole role of measuring the level of nitrogen filled in the oxidizer tank and relaying this information to Cerberus to be handled by the ground station equipment.

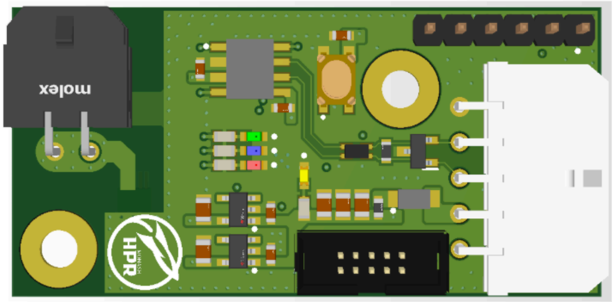


Fig. 90 NFLS PCB

The NFLS PCB only went through one iteration before the flight-ready configuration, and the only change came from needing a more powerful microcontroller in order to use a Real-Time Operating System (RTOS) for using the team’s custom communication protocol.

C. Ground Station Equipment

1. *Overview*

The Ground Station Equipment (GSE) for Solaris MkII consists of a fluids system, the “Fill Box” and an electrical and control system, the “Pad Station”. Together with the Motor Controller system, they are responsible for safely facilitating all engine processes such as filling, ignition and scrubbing. The Pad Station relays instructions to the Motor Controller, itself taking inputs from an operator logged on to the “Control Station” system at the flightline. The Pad Station was used for the rapid testing and iteration of Solaris MkII before the Motor Controller system became operational. This allowed for an extensive testing campaign to be conducted prior to integrating the onboard motor controller system. Consequently, the Pad Station can actuate servo motors, direct current (DC) motors, pyro channels, and the valves in the Fill Box. It also polls various sensors, including pressure transducers, thermocouples, and load cells. The Control Station communicates wirelessly with the Pad Station, displaying sensor values and system statuses, and providing controls to the propulsion operator.

2. *Fill Box*

The nitrous oxide Fill Box (see Fig. 91) is an aluminum fluids box containing all the team's plumbing hardware for filling the onboard nitrous oxide tank from the supply tank. The plumbing is all COTS rated components to ensure reliability and longevity. It has three inlets/outlets, the first is the supply line running from the supply tank to the box, the second is a dump line which is further extended away from all the flight hardware, finally, the rocket side of the Fill Box carries the nitrous oxide to the onboard tank. Each of the connections makes use of SwageLok quick fittings for ease of use.

Internally, the supply line runs to the Fill Valve, an industrial two position servo actuated ball valve, this valve is what controls the flow of nitrous to the onboard tank. If opened, the nitrous will flow into a tee-fitting where one end goes to the rocket side and the other to another identical valve, named the Dump Valve. This valve is left closed during fill and can be used to dump nitrous oxide from the onboard tank if required and to depressurize the system after launch. For monitoring and safety, the fill box features two pressure transducers before and after the fill valve, as well as a pressure gauge before the fill valve so that pad team members can visually see if there is any nitrous oxide in the lines.

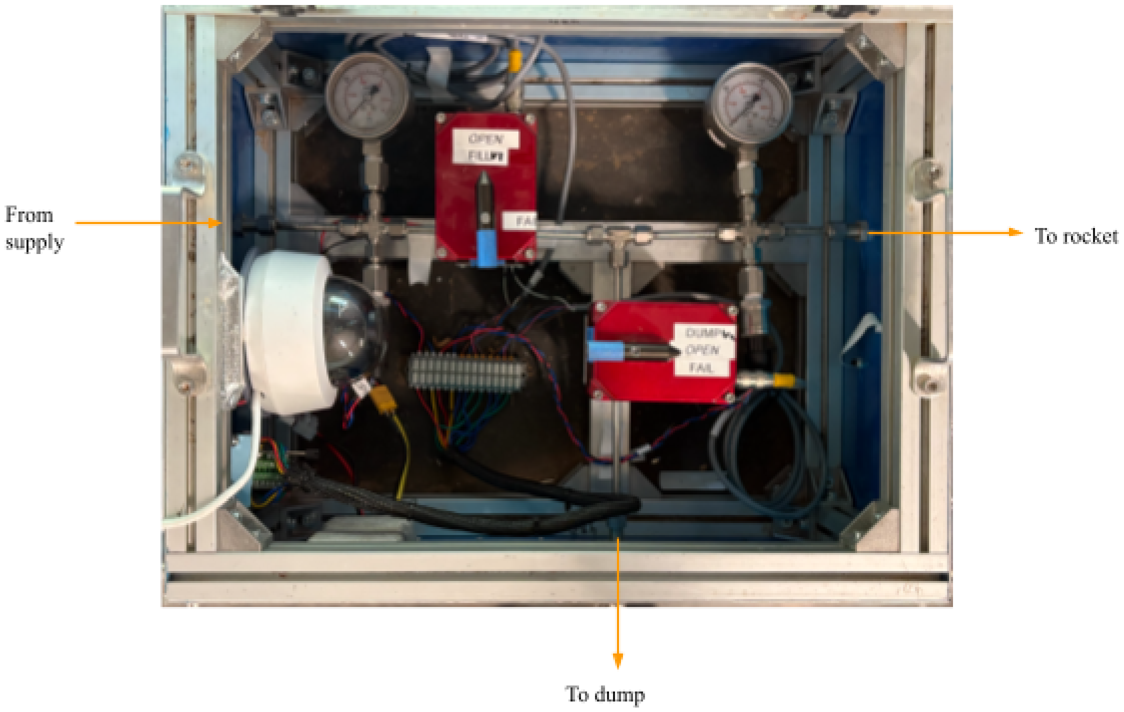


Fig. 91 Nitrous oxide fill box top-down view

Each valve is controlled through two digital inputs and provides digital positional feedback to the Pad Station electrical cabinet. If control signal or power is lost, the valves automatically return to their preset safe positions. The Fill Box also features an Internet Protocol (IP) camera for visual monitoring of valve positions if feedback from the Pad Station or Control Station is unavailable. In a fail-safe state, the fill valve closes while the dump valve opens, allowing any nitrous oxide in the onboard tank to vent safely through the supply lines and preventing flow from the supply tank to any onboard SRAD systems.

3. *Hardware*

The main computer of the Ground Support Equipment (GSE) is a Raspberry Pi 4, housed within the Pad Station electrical enclosure. It directly controls the Pad Station's sensors and actuators through a LabJack T7 Data Acquisition and Control (DAQ) device. The LabJack T7 provides extensive flexibility, featuring numerous analog inputs (up to 100 kHz with 16-bit precision), digital I/O lines, and Pulse Width Modulation (PWM) channels. This versatility was fully leveraged during the development of Solaris Mk II, where evolving system requirements demanded rapid adaptation and additional functionality.

In addition to local control, the Raspberry Pi communicates with the Motor Controller's Top Board via a dedicated USB-to-RS422 converter. RS422 communication lines, along with power lines for the Active Vent and Motor Controller, are carried by a Category 6 (CAT 6) Ethernet cable routed to an umbilical connection on *Zenith* engineered to sever upon launch.

Communication between the Raspberry Pi, LabJack T7, and the Control Station computer is facilitated through a dedicated Local Area Network (LAN). The network architecture includes a central router, multiple unmanaged network switches, and a pair of airMAX PowerBeam 2AC 400 wireless bridge devices. These bridges operate on the 2.4 GHz band using a proprietary airMAX protocol, ensuring reliable and high-speed connectivity between the Pad Station and the Control Station over distances exceeding 24 km.

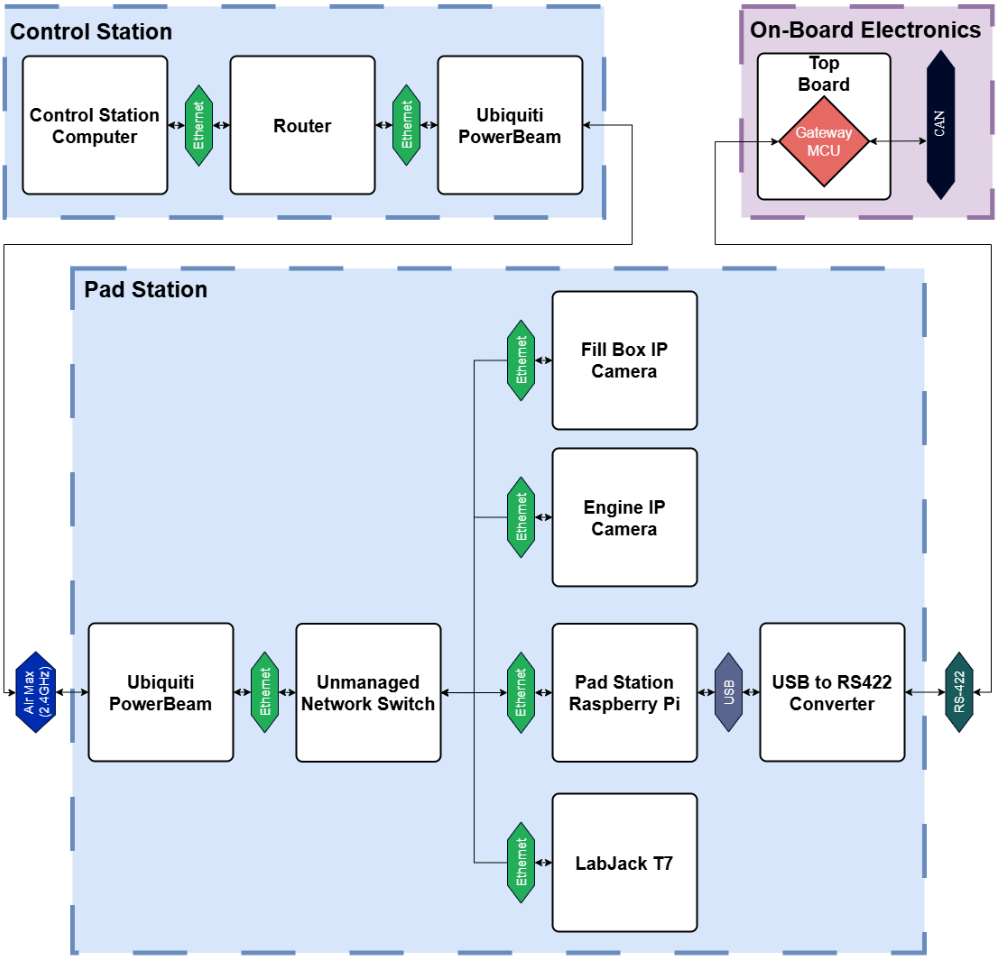


Fig. 92 Ground Station Equipment Network

Previously, airMAX NanoStation M2 LoCo devices were used, offering a maximum range of around 5 km. However, due to their limited performance in long-range and RF-noisy environments, the team transitioned to the more capable PowerBeam units. This upgrade provides increased confidence in maintaining stable connectivity during operations at IREC, where the RF environment is notably congested.

The GSE is powered by a roughly 12V source, currently two 12V car batteries wired in parallel. This power is routed into the Fill Box, where it is stepped up to 24V for the servo valves. Power is also distributed to the Pad Station electrical enclosure, where two buck converters regulate the supply to 12V and 5V, respectively. Devices such as the Raspberry Pi, IP cameras, and wireless bridges are powered using Power over Ethernet (PoE), which streamlines setup by combining power and data in a single cable.

The Pad Station's electrical enclosure is an IP66-rated metal box, suitable for harsh operational environments. External connections are made through a side-mounted gland plate, while internal components are secured on a plywood base. A summary of the GSE network can be found in Fig. 92.

4. *Failsafes*

Given a primary goal of *Project Zenith* is the focus on safety, failsafes are implemented and considered at every level of the GSE system to ensure the safety of both personnel and hardware in the event of power loss, signal interruption, or other fault conditions. These mechanisms span from physical interlocks and actuator behavior to software watchdog systems that monitor and react to changes in system state.

While personnel are working near the pad, direct safeguards are in place to prevent unintentional system activation. A keyed safety switch is used to electrically isolate the pyrotechnic firing channels, and the key remains in the possession of the propulsion pad team. Additionally, the oxidizer supply bottle remains physically closed until the team has cleared the area and pad operations are given clearance to proceed.

Once the system is live, the actuators responsible for bringing the system to a safe state in the event of failure must handle both power loss and loss of control signals. The Fill and Dump valves, located in the Fill Box, are industrial-grade, battery-backed servo valves with pre-programmed safe positions. In the event of power failure or control signal disconnection, their internal battery powers the valve and moves it to their known safe state specifically, closing the Fill valve and opening the Dump valve. Similarly, the onboard Active Vent system uses a servo motor to actuate a spring-loaded piston. Under normal conditions, the servo motor holds the piston in a closed position. If power is lost, or if the control signal to the normally open relay supplying power the motor is interrupted, the relay opens, the motor loses power and the spring extends the piston, opening the vent and allowing any remaining tank pressure to be safely released to the atmosphere.

Failsafes are also built into the GSE's communication network. The system involves three critical communication links: between the Raspberry Pi and the Motor Controller Top Board, the Raspberry Pi and the LabJack T7 DAQ, and the Raspberry Pi and the Control Station computer. In each of these links, watchdog systems monitor the state of communication and act if a failure is detected. For the Motor Controller link, the Raspberry Pi sends regular heartbeat packets, to which the Motor Controller must respond. If a valid response is not received, the Raspberry Pi instructs the LabJack T7 to transition the Fill Box valves and the Active Vent relay into their safe states. Conversely, the Motor Controller independently tracks these heartbeat signals from the Raspberry Pi, and in the event they are lost, it attempts to actuate the Active Vent directly. Should this action fail to drop the tank pressure, the Motor Controller escalates by opening the pilot valve to vent through the main valve.

The link between the Raspberry Pi and the LabJack T7 is also protected by a built-in watchdog timer inside the T7 itself. This timer resets whenever a valid request is received from the Raspberry Pi. If no such request is received within a two-minute window, the T7 automatically sets all outputs, including the Active Vent power relay and the valve control lines, to their programmed safe states. To protect against a loss of communication between the Pad Station and the Control Station, the system includes one more layer of monitoring. The Pad Station User Interface (UI), running on the Control Station computer, periodically sends heartbeat messages (every 10 seconds) to the application running on the Raspberry Pi. If these messages stop arriving, the Raspberry Pi assumes that the control link has failed and takes immediate action to command the T7 and Motor Controller to safe the system.

These combined electrical, mechanical, and software-based failsafes ensure the GSE system can respond appropriately to a range of fault scenarios, reducing risk to personnel and hardware. A summary of the failsafes and mitigation plan can be found in Appendix C.

D. Control Systems

1. *Intra Rocket Interface System*

Due to the safety critical nature of the Motor Controller system, the requirements for the communications protocol become quite lengthy. There are various open source and well-known transport protocols that can handle packet presentation, networking and queue management for serial communications, however there are none that support the team's custom hardware, as well as providing a transparent link between physical communications layers (i.e: RS-422 and CAN). Out of these requirements was borne the Intra-Rocket-Interface-System (IRIS) which is an in-house developed communications protocol that covers packet transport and networking, all the way up to the presentation layer, making setting up auxiliary interfaces within the rocket incredibly easy for the application or user to make calls to.

The main benefit of creating an in-house developed transport layer is the flexibility of porting the implementation between different languages and interfaces. For example, IRIS is written in C for the embedded hardware, known colloquially within the team as CIRIS, and can be imported as a simple library that runs its own threads in the application RTOS to handle sending and receiving packets for the application. For the ground station equipment, which is run using a Raspberry Pi with Linux, IRIS has been written in Python (PAPIRIS) to interface with existing libraries such as PySerial to seamlessly integrate into the already existing code architecture. Additionally, as IRIS was developed by the Motor Controller team, it was designed to be completely hardware agnostic, and seamlessly sends and receives packets across different physical standards, making the "Gateway Microcontroller" on Top Board an incredibly easy gateway to implement as it simply has to receive messages on RS-422, and place them on the CIRIS queue for CAN communications to reach its eventual destination.

With such minute control over the inner-workings of the transport protocol used for communications within the rocket, there is robust error handling implemented to ensure minimal packets are missed (due to being busy with other processes) or dropped (due to communication errors). This makes for an incredibly reliable system that will actuate, report and monitor as freely as the user would like it to, and have incredibly high throughput back to the control station.

2. *Message Queuing Telemetry Transport Protocol*

Communication between the Pad Station and Control Station is handled using the Message Queuing Telemetry Transport (MQTT) protocol. MQTT is a lightweight, publish-subscribe messaging protocol specifically designed for Internet of Things (IoT) applications, making it ideal for scalable and modular systems like the Pad Station. Devices communicate by publishing messages to specific topics, which can be subscribed to by other devices or applications that need the information. This decouples the sender and receiver, enabling a more flexible and fault-tolerant architecture. The MQTT broker – the central server responsible for routing messages between publishers and subscribers – runs on the Pad Station Raspberry Pi. This architecture proved particularly useful during the integration of the Motor Controller. A separate, standalone application was written to communicate with the Top Board using the PAPIRIS protocol, and it was able to interface seamlessly with the rest of the system by publishing and subscribing to relevant MQTT topics. Additionally, this setup enables robust data logging by forwarding MQTT topics directly into an InfluxDB time-series database, providing high-resolution telemetry for analysis and debugging.

3. *Automatic Fill Algorithm*

The automatic fill algorithm is responsible for managing the filling process of Solaris Mk II's oxidizer tank, aiming to reach a target propellant mass and temperature without manual intervention. This is achieved through a Finite State Machine (FSM) as seen in Fig. 93, which actuates the Fill Box's fill valve and the Active Vent in response to live data from the onboard pressure transducer and the capacitive fill sensor. The FSM prioritizes achieving the correct mass before addressing temperature conditions.

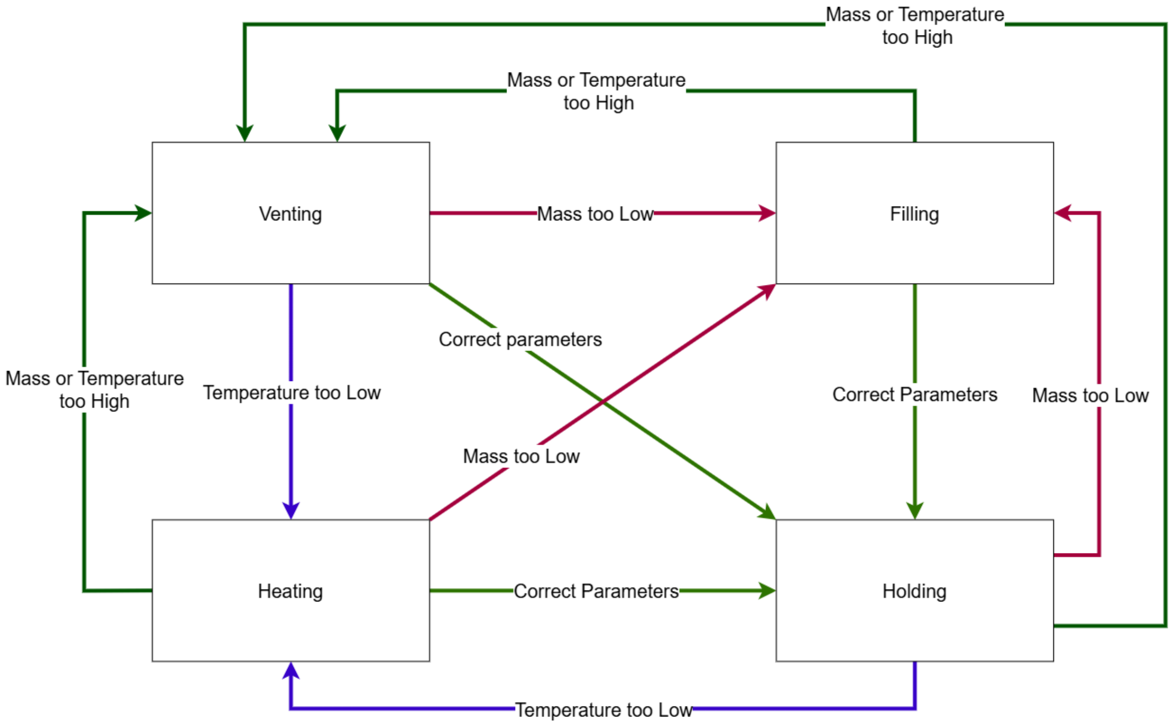


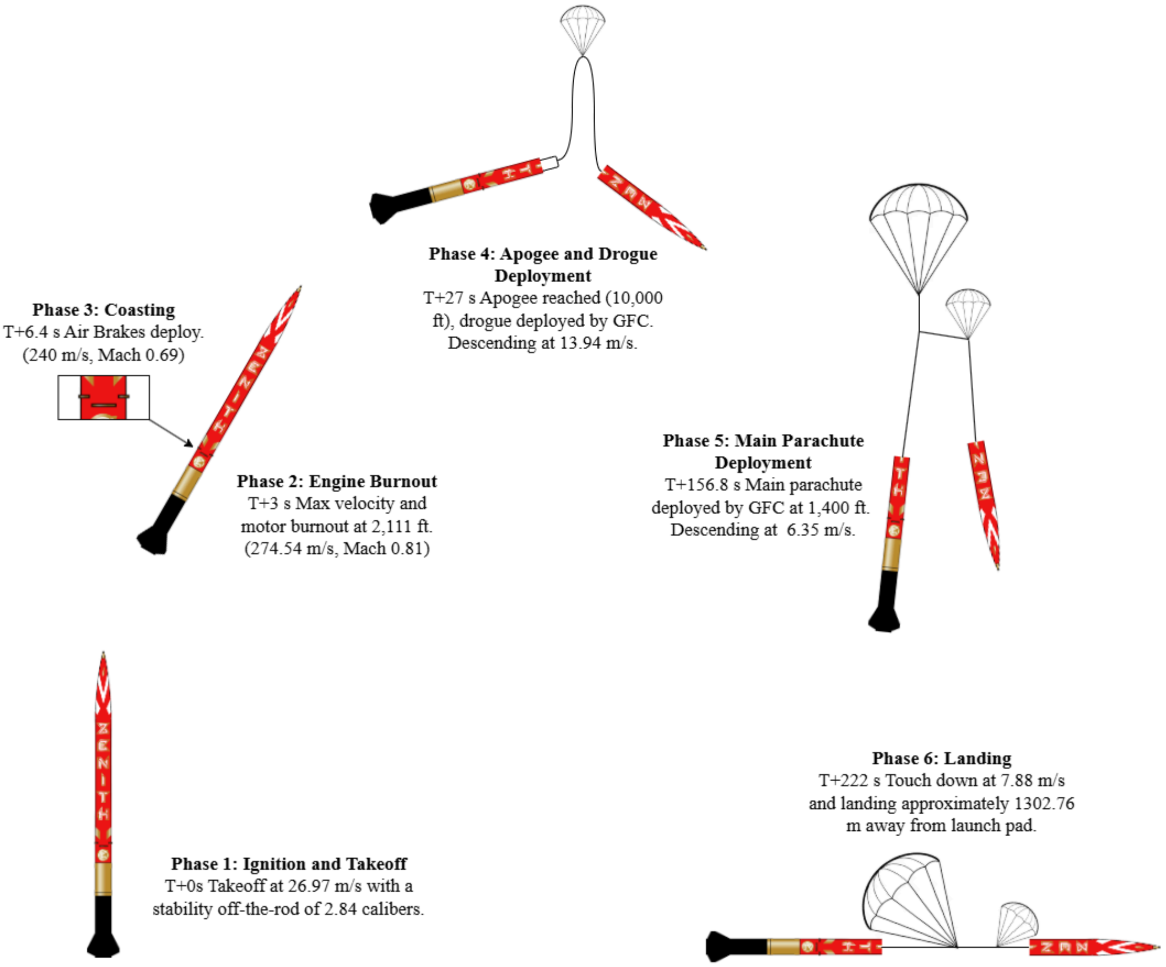
Fig. 93 Finite State Machine of Automatic Fill Algorithm

If the sensed mass is below the target, the algorithm opens both the fill valve and the Active Vent, allowing nitrous oxide to flow into the tank while displacing trapped gas through the vent. Once the correct mass is reached, the system evaluates the temperature. If the temperature exceeds the desired value, the algorithm responds by closing the fill valve while keeping the Active Vent open, allowing a portion of the propellant to boil off and vent, thereby lowering both the mass and temperature. Conversely, if the temperature is too low, both the fill valve and the Active Vent are closed, enabling the tank to passively warm through solar exposure. This control logic ensures efficient and autonomous conditioning of the tank's contents maintaining strict adherence to launch parameters.

IV. Mission Concept of Operations Overview

Mission success for *Project Zenith* is defined as achieving an apogee as close to 10,000 feet as possible, followed by a safe recovery of the launch vehicle. Non-critical objectives include; collection of scientific data from the payload, providing a competitive entry to the Live Video Challenge, securing performance data from SRAD flight computers such as GFC, Strelka V2 and Motor Controller, with a high level of accuracy to the flight path predicted by the team's trajectory simulator, SATURN.

While at competition, the safety of team members, spectators and all other individuals interacting with *Project Zenith* will be the highest priority on Monash HPR. Significant practice and preparation is undertaken prior to the day, checklists will be followed at all times, and clearly defined go/no-go bounds dictate the progression leading up to takeoff, showcased in Fig. 105. The extensive testing and validation campaign followed, including multiple test launches, ensures all operations are conducted safely with minimal risk.



Phase 4: Apogee and Drogue Deployment
T+27 s Apogee reached (10,000 ft), drogue deployed by GFC. Descending at 13.94 m/s.

Phase 3: Coasting
T+6.4 s Air Brakes deploy. (240 m/s, Mach 0.69)

Phase 2: Engine Burnout
T+3 s Max velocity and motor burnout at 2,111 ft. (274.54 m/s, Mach 0.81)

Phase 5: Main Parachute Deployment
T+156.8 s Main parachute deployed by GFC at 1,400 ft. Descending at 6.35 m/s.

Phase 6: Landing
T+222 s Touch down at 7.88 m/s and landing approximately 1302.76 m away from launch pad.

Phase 1: Ignition and Takeoff
T+0s Takeoff at 26.97 m/s with a stability off-the-rod of 2.84 calibers.

Fig. 105 Flight Profile Graphic of *Project Zenith's* Flight Stages

Phase 0: Pre-Launch

1. Assembly

To maximize the efficiency of the team's operations on launch day, assembly of *Project Zenith*'s systems and integration of the forward assembly and rear assembly will take place prior to launch. This is detailed in Appendix E, which extensively details the steps taken to prepare each system and integrate them together for flightline the following day.

2. Flightline

Prior to flightline operations, the team conducts briefings to review planned operations, timelines, safety hazards, and controls for the day. The official flightline then begins with the insertion of energetics and integration of the assembled forward and rear halves of *Zenith*, as documented in Appendix E.

While the payload is officially weighed, select members of Flight Systems wire E-matches and load black powder into deployment devices, then parachutes are packed and inserted into the rocket.From here, Aerostructures members will then assist Flight Systems members in joining the rocket halves and inserting shear pins. Once the rocket is fully assembled, the Flightline Lead verifies all checklists and ensures adherence to Go/No-Go criteria across all sections. Final steps include obtaining Automated Flightline Checklist (AFLC) results from Dynamics members on the required filling parameters and securing RSO approval.

3. *Pad Station*

This phase begins when the rocket is first racked horizontally. The avionics and payload bays are powered on while the rocket is horizontal, as their location becomes inaccessible once the rocket is racked vertically. Once powered, the rocket is moved to its vertical position, and the remaining electronics are armed. Telemetry checks are conducted to ensure communication between the onboard electronics and the control station, and between the GSE and the Pad Station. After verifying system telemetry, the team confirms the Go/No-Go status, notifies the LCO to seek launch authorization, and opens the nitrous bottles. The team then evacuates the pad and waits for clearance to begin filling.

Solaris MkII will be filled to an appropriate pressure based on nominal Dynamics simulations, and operations will be held until confirmation for launch is given. Once confirmation from the LCO is given, the fill valve and active vent will be closed, and countdown for ignition will begin.

Phase 1: Ignition and Takeoff

This phase commences upon the end of the countdown at T-0 s. From the control station, the launch operations lead will initiate ignition through the Pad Station User Interface. At the launch pad, black smoke is expected to be seen from the bottom of the engine once ignition has been initiated. The rocket will takeoff at 26.97 m/s (88.48 ft/s), with a stability off-the-rod of 2.84.

Phase 2: Engine Burnout

Project Zenith will burn in its liquid phase for 3 s, reaching a max velocity of 274.54 m/s (900.72 ft/s) (Mach 0.81) at 643.43 m (2,111 ft) before transitioning to its gaseous phase for another 3.4 s.

Phase 3: Coasting

After motor burnout at approximately T+6.4 s, *Zenith*'s velocity will drop to Mach 0.69 and Air Brakes will begin actuating after checking its angle bounds, with its active control algorithm taking over for *Zenith* to hit its 10,000 ft target apogee.

Phase 4: Apogee and Drogue Deployment

At T+27 s, *Project Zenith* will reach an apogee of 10,000 ft and GFC will fire GODS to separate the airframe, releasing the drogue parachute. If GODS fails to deploy, the RRC3 will fire PODS after 2 s. *Zenith* will then descend under drogue for the next 130 s, reaching a descent rate of 13.94 m/s (45.73 ft/s) relative to the wind.

Phase 5: Main Parachute Deployment

At approximately T+156.8 s, GFC will fire line-cutters, releasing the main parachute at 1,400 ft, and allowing the rocket to drift gently down at 6.35 m/s (20.83 ft/s) . The rocket's GPS location will also be carefully tracked at this stage, in preparation for Phase 6: Landing and Recovery.

Phase 6: Landing

At T+222 s, *Project Zenith* will gently touch down at 7.88 m/s (25.85 ft/s) . After landing 1302.76 m from the launch pad, the GPS coordinates of the rocket will be recorded and given to the recovery team.

Phase 7: Recovery

The recovery team will wear recovery backpacks containing essential equipment, and be briefed on safety procedures. After the briefing and permission to go out onto the range is received, the recovery team will venture out to recover *Project Zenith*.

Once the rocket is located, the recovery team will approach the rocket following the Recovery Checklist in Appendix E. Actions will include downloading data from the Blue Raven, safely disabling energetics and disarming all electronics.

V. Conclusions and Lessons Learned

A. Technical Lessons Learned

Adopting a two-year design cycle proved highly beneficial from a technical standpoint, affording the team significantly more time to thoroughly refine and iterate on design, compared to previous single-year projects. This extended timeline was particularly valuable as *Project Zenith* represented the most comprehensive SRAD endeavor undertaken by Monash HPR to date. The longer timeline drove substantial improvements in inter-subteam communication and integration, extended validation periods for rigorous testing regimes, and introduced systems to directly track the meeting of requirements through this process. Reviewal activities were implemented to reflect the teams focus on electrical and software competency, and new precedents were set for intermediary reviews to continuously improve designs. A major milestone for the team was the ability to conduct multiple test launches prior to the competition - a feat accomplished for the first time with *Project Zenith*. This staggered the approach to system validation, enabling focus on specific subsystems across flights, driving improvements with deployment mechanisms, telemetry, and more. Operational processes were also refined, limiting bottlenecks during flightline and pad operations, adapting procedures to improve safety and efficiency. Consequently, implementing a stronger and more rigorous validation approach across all subsystems became paramount, providing the team with much greater confidence in the performance and reliability of its in-house developed systems before competition.

Iterative design and rigorous testing proved vital across many subsystems. Significant strides were made across several systems: deployment systems like GODS and PODSv3 were validated, resolving issues from piercer design to airframe damage. The Solaris MkII engine evolved, notably integrating a novel Motor Controller system. The Air Brake algorithm was refined with new verification methods, including HITL, while the Payload progressed from datalogging to exploring relevant AI experiments. Avionics were also simplified through revised PCBs and a new sled design. This iterative process underscored the critical interplay between simulation tools like FEA, CFD, and SATURN, which provided initial design guidance. Invaluable physical validation came through tests such as hydrostatic, cold gas flow, hot fires, full-scale flight, deployment system ground tests and more. These tests validated models and uncovered unforeseen issues like premature parachute release, leading to a stronger retention system. Furthermore, integrating multiple complex SRAD systems presented significant challenges. Robust strategies like the development of standardized interfaces and communication protocols were emphasized, such as IRIS utilizing the CAN bus. Improvements in integration processes, including connector accessibility and cable management, streamlined assembly and flightline procedures. This complemented the growth in in-house manufacturing capabilities, which provided valuable insights into materials and processes including composites, machining, material selection, and material testing.

B. Team Management Lessons Learned

While the two-year design cycle proved to be technically beneficial, it introduced new team management challenges, particularly concerning continuity and knowledge transfer during the handover between management cycles. Maintaining comprehensive and accessible documentation throughout the entire design cycle was reinforced as absolutely critical for ensuring project knowledge was retained during transitions. Furthermore, the increased complexity and prevalence of electronic systems across nearly all subsystems highlighted a critical gap in the team's structure. This led to the recognition of a need for, and the subsequent formation of, a dedicated Avionics section. This new section aimed to collect, centralize, and standardize electrical systems knowledge and practices across the team, fostering better integration and reliability. A new electrical systems engineering process was borne from this initiative, improving how electronics were designed, validated, and integrated project-wide.

C. Knowledge Transfer

As a constantly evolving and expanding team, Monash HPR is deeply committed to fostering a supportive environment for all individuals who wish to be involved. A critical component of this endeavor is ensuring a smooth and comprehensive knowledge transfer between the generations of Monash HPR members. To achieve this, the team utilizes various strategies and platforms designed to deepen every member’s understanding regarding both the team's internal workings and the broader space industry.

The team leverages two primary cloud-based collaborative services to manage and share information effectively. Nuclino functions as a central, user-friendly repository for essential information, including documentation, policies, and an archive of past projects, thereby facilitating efficient knowledge sharing. Complementing this, Google Drive is used as the primary storage service for all documents and work-in-progress files. Integrated with the other services provided in Google Workspace – such as Docs, Slides, and Sheets – allows for real-time collaboration between team members. Together, Nuclino and Google Drive provide a convenient and organized method for recording and sharing information, making it easily accessible to newer members of the team.

In addition to these platforms, Monash HPR has incorporated a robust system of both general upskilling workshops and dedicated knowledge transfer sessions, building upon practices implemented from previous projects like *Project Valkyrie*. Knowledge transfer sessions are planned and run by individual subteams and are intended as a fundamental resource for all team members to learn the specific operations and activities of that subteam. To ensure accessibility, all knowledge transfer sessions are recorded, allowing members who cannot attend in person to still benefit from the information.

Separate from these are the general workshops, which are run by experienced members and made available to the entire team, rather than being limited to respective subteams. These workshops serve to educate the team about critical software used across disciplines, such as Creo Parametric, Windchill, and ANSYS, and to reinforce the standards that HPR adheres to. This structured approach significantly streamlines knowledge dissemination. For example, the creation of the Avionics section highlighted the benefit of consolidating electrical expertise; running workshops specifically for all electrical members, such as those focused on Altium, allows for efficient, simultaneous upskilling, a significant improvement from previous arrangements where scattered electrical members had limited opportunities to collaborate and share knowledge together.

Finally, a previously underutilized methodology has spawned from this design cycle. Deliverables created both through subsystem design cycles and for the competition are the best documentation of the team's work. Therefore, employing these as learning tools for junior members is exceedingly effective, teaching them both about the history of the team and typical design considerations for certain systems onboard. Coupled with internal testing and mission reports, demonstrate stepping through methodology for validation, critical analysis and implementing learnings into design iteration.