

Seraphina Final Design Report

Non-Competing, Project 21

MACH



**LAUNCH CANADA CHALLENGE
2026**

Revision History

Revision	Description	Date
R0	Initial release	03-06-2026

Acknowledgements

MACH would like to thank Toronto Metropolitan University and the TMU Metropolitan Undergraduate Engineering Society for their assistance and contributions to Project 21 of the 2026 Launch Canada Challenge.

We also extend our sincere gratitude to team alumni and other TMU Rocketry student teams for their continued mentorship, technical guidance, and institutional knowledge, wisdom, and jokes, all of which played a critical role in the development and success of this project.

Authors

The following MACH team members have authored this report for Project 21:

A. Abergel-Preston, Head of Engineering

M. Hemmat, Media & Logistics Lead

S. Li, Administrative Lead

T. Okoh, Propulsion Lead

K. Pajak, Systems Integration and Automation Lead

J. Puszynska, Team Director

H. Trivedi, Propulsion and Structures Member

Abstract

MACH is an undergraduate rocketry team at Toronto Metropolitan University focused on liquid propulsion systems. This year, MACH is competing in the Technology Development Challenge with Seraphina, a highly automated ground support and testing system designed to rapidly and reliably evaluate propulsion subsystems. Seraphina builds on SPRINT, MACH's 2025 Launch Canada deliverable, by increasing automation, safety, and testing capability while providing a modular platform for future propulsion development.

A primary objective of this year's project was the development of a larger propellant tank to support higher-capacity propulsion systems and future engine testing. The system also incorporates an automated fueling process, significantly improving the efficiency, repeatability, and safety of filling operations compared with previous manual procedures. To validate the pressure vessel, the complete tank assembly was hydrostatically tested to 1.2 times the Maximum Expected Operating Pressure (MEOP) in accordance with the Launch Canada Design, Test, and Evaluation Guide. The hydrostatic test verified the structural integrity of the tank assembly, O-ring sealing performance, and the fit between the major components. In addition, new manufacturing procedures were developed to improve assembly accuracy, repeatability, and overall reliability.

The resulting system provides MACH with a scalable, automated testing platform capable of supporting future propulsion development while improving the safety, efficiency, and repeatability of subsystem testing.

Table of Contents

Revision History.....	1
Acknowledgements.....	2
Authors.....	3
Abstract.....	4
Table of Contents.....	5
List of Figures.....	8
List of Tables.....	9
Abbreviations.....	10
Nomenclature.....	12
1 Introduction.....	13
1.1 Updates & Lessons Learned.....	14
1.2 Team Organization.....	16
1.2.1 Team Development & Succession Planning.....	16
1.3 Outreach.....	19
2 Business Case Analysis.....	22
2.1 Academic & Business Goals.....	22
2.2 Value Proposition.....	22
2.3 Market Research & Stakeholders.....	23
2.3.1 Market Need.....	23
2.3.2 Intended Costumers.....	23
2.3.3 Current Technologies and Competitive Analysis.....	23
2.3.4 SWOT Analysis.....	24
2.3.5 Stakeholders.....	24
2.4 Financial Analysis.....	25
3 Concept of Operations (CONOPS).....	27
4 Requirements.....	35
4.1 Mission Requirements.....	35
4.2 System & Subsystem Requirements.....	35
5 Systems Architecture.....	40
5.1 Structures.....	40
5.2 Propulsion.....	40
5.2.1 Engine.....	40
5.2.2 GSE Plumbing System.....	41
5.2.3 Propellant Tank.....	42
5.3 Electronics.....	42
6 Structure.....	44
6.1 Test Stand Structure.....	44
6.1.1 Detailed Design.....	44
6.1.2 Manufacturing Process.....	45

6.1.4 Testing and Validation.....	46
6.2 Concentric Tanks.....	50
6.2.1 Detailed Design.....	50
6.2.2 Retaining Rings.....	51
6.2.3 Manufacturing Process.....	51
6.2.4 Analysis.....	54
6.2.5 Testing and Validation.....	55
6.3 Tank Stand.....	58
6.3.1 Detailed Design.....	58
6.3.2 Manufacturing Process.....	59
6.3.3 Analysis.....	59
7 Propulsion.....	62
7.1 SPRINT Engine.....	62
7.1.1 Combustion Chamber and Nozzle.....	63
7.1.2 Injector.....	64
7.1.4 Ignition System.....	66
7.2 Tank System.....	67
7.2.1 Vent Bulkhead.....	67
7.2.2 Fill Bulkhead.....	68
7.2.3 Piston.....	70
7.2.4 Interpropellant O-Ring Seals.....	70
7.2.5 Testing and Validation.....	71
7.3 Propellant Feed System.....	71
7.4 Auto Fueling System.....	74
7.4.1 Components.....	74
7.4.2 Testing and Validation.....	74
8 Electronics & Software.....	76
8.1 Hardware.....	76
8.1.1 GSE Overview.....	76
8.1.2 Power Analysis.....	77
8.2 Software.....	79
8.2.1 Overview.....	79
8.2.2 Software architecture.....	80
8.3 Data Analysis Plan.....	81
9 Range Safety.....	83
9.1 Hazard Analysis.....	83
9.1.1 Compressed Gases.....	83
9.1.2 Pyrotechnics.....	83
9.1.3 Oxidizers.....	83
9.1.4 Flammables & Explosives.....	83
9.1.5 Equipment Misuse.....	83

9.2 Risk Assessment.....	84
9.2.1 Lack of Budget.....	84
9.2.2 Transportation Logistics Failures.....	84
9.2.3 Brain Drain.....	84
9.2.4 Engine Mount Failures.....	84
9.2.5 Ignition Failures.....	85
9.2.6 Valve Sequence Failures.....	85
9.2.7 Sensor Failures.....	86
9.2.8 Propellant Leakages.....	86
9.2.9 Fuel Tank Failures.....	86
9.2.10 Engine Failure.....	87
10 References.....	88
APPENDIX A: LAUNCH CANADA COMPLIANCE REQUIREMENTS.....	90
A.1 System Requirements.....	90
A.1.1 Pressurized Fluid Systems.....	90
A.1.2 Ignition.....	97
A.1.3 Engine Controls & Function.....	99
A.1.4 Propulsion System Testing.....	101
Appendix B: Detailed Design Trade Studies & Calculations.....	105
Von miss stress Equivalent:.....	106
Stripping:.....	107
Appendix C - Videography.....	108

List of Figures

Fig. 1.1: MACH team picture, taken after the September 2025 coldflow test.....	14
Fig. 1.2.1.3.1: MACH Member Program Diversity Pie Chart.....	19
Fig. 1.3.1: MACH outreach booth at MARS x ACU Industry Night.....	20
Fig. 1.3.2: MACH outreach booth at the TMU Women in Engineering (WiE) conference.....	21
Fig. 1.3.3: Aerospace America article recognizing MACH's participation in the AIAA TMU Student Branch event.....	22
Fig. 2.3.4.1: SWOT Analysis.....	26
Fig. 2.4.1: Cash flow diagram measured between August 2025 to June 2026.....	28
Fig. 3.0: Nominal CONOPS for Hot-Fire Testing.....	30
Fig. 3.1: Pre-assembled System ready to be used.....	31
Fig. 3.2: Electrical and control system wiring integration for the test stand.....	32
Fig. 3.3: System Safing and Pre-Fuel Configuration.....	33
Fig. 3.4: Mission control verifying valve operation and system readiness prior to hot-fire testing.....	34
Fig. 5.1: Overview of all systems.....	42
Fig. 5.2.1: Thrust Chamber Assembly.....	43
Fig. 5.2.2: GSE Plumbing.....	44
Fig. 5.3.1: GSE electronics enclosure.....	46
Fig. 6.1.1: SPRINT engine mounted onto engine stand.....	47
Fig. 6.2.1.1: Cross Section of entire stank system.....	53
Fig. 6.2.2.1: Retaining ring for tank assembly.....	54
Fig. 6.2.3.1: External tank drilling template.....	55
Fig. 6.2.3.2: Center punching the external tank using the drilling template.....	56
Fig. 6.2.3.3: Comparison of center punched holes to pilot drill holes.....	57
Fig. 6.2.5.1: Hydrostatic Pressure Test Set-up.....	59
Fig. 6.2.5.2: Hydrostatic Low-pressure Leak Check on Fill Bulkhead.....	60
Fig. 6.3.1.1: Cross Section Tank Tripod Structure.....	61
Fig. 6.3.1.3: Real life picture of tank stand carrier top view.....	62
Fig. 6.3.3.1: Total Deformation in ansys static structural.....	63
Fig. 6.3.3.2: Non-destructive static test of tank stand.....	64
Fig. 7.1.1: Annotated cross section view of SPRINT Engine.....	66
Fig. 7.1.2: Full assembly of SPRINT Engine.....	66
Fig. 7.1.2.1: Injector. Cross Section.....	68
Fig. 7.1.2.2: Real picture of injector top view diagram.....	68
Fig. 7.1.2.3: Real picture of injector bottom view diagram.....	69
Fig. 7.1.4.1: Ignition Cartridge cross section view.....	70
Fig. 7.2.1: Full Tank Assembly.....	70
Fig. 7.2.1.1: Vent Bulkhead Diagram output view.....	71
Fig. 7.2.1.2: Vent Bulkhead Diagram input view.....	71
Fig. 7.2.2.1: Fill Bulkhead Diagram input view.....	72

Fig. 7.2.2.2: Fill Bulkhead Diagram Output view.....	73
Fig. 7.2.4.1: O-rings placed on the vent bulkhead.....	74
Fig. 7.3.1: GSE Plumbing CAD.....	75
Fig. 7.3.2: GSE Plumbing.....	75
Fig. 7.3.3: System plumbing and indication diagram.....	76
Fig. 9.2.11.1: Base components of autofuelling system.....	77
Fig. 8.1.1.1: High-level system architecture overview.....	80
Fig. 8.1.2.1: Sample power draw calculation for 5VDC consumers.....	81
Fig. 8.1.2.2: GSE power analysis diagram showing current draw.....	81
Fig. 8.2.2.1: Mission Control Server architecture.....	84

List of Tables

Table 1.1.1: Key design changes since the PDR.....	16
Table 1.2.1: Leadership Roster.....	17
Table 2.3.3.1: Comparison of modern liquid propulsion testing categories.....	24
Table 4.3.1: SERAPHINA Liquid Engine Subsystem Requirement.....	37
Table 5.2.1: SPRINT Rocket-Engine Properties.....	43
Table 6.2.1.1: Tank Dimensions.....	54
Table 6.2.4.1: Tank Parameters.....	58
Table 7.2.1: Seraphina Parameters.....	65
Table 7.3.1: Valve, Regulator and Line Orifice Sizes.....	76
Table 8.1.1.1: GSE Input/Output Connections.....	79
Table 8.1.2.1: Top-level system power draw.....	82
Table 8.1.2.2: CP1500AVRT relevant specifications.....	82
Table 9.2.1: Failure Mode Assessment Table.....	90
Table A.1.1.1: Launch Canada Compliance Requirements.....	93
Table A.1.2.1: Launch Canada Compliance Requirements.....	101
Table A.1.3.1: Launch Canada Compliance Requirements.....	102
Table A.1.4.1: Launch Canada Compliance Requirements.....	104

Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
AGL	Above Ground Level
AN	Army Navy
BJT	Bipolar Junction Transistor
CONOPS	Concept of Operations
COTS	Commercial Off The Shelf
DTEG	Design, Test, and Evaluation Guide
DOT	Department of Transportations
EGSE	Electrical Ground Support Equipment
ESA	European Space Agency
GSE	Ground Support Equipment
GTA	Greater Toronto Area
GPS	Global Positioning System
LC	Launch Canada
LDO	Low-Dropout
MACH	Metropolitan Aerospace Combustion Hub
MARS	Metropolitan Aerospace Rocket Society
MC	Mission Control
MGSE	Mechanical Ground Support Equipment
MEOP	Maximum Expected Operating Pressure
NASA	National Aeronautics and Space Administration
NDT	Non-Destructive Testing
NPT	National Pipe Tapered
PLC	Programmable Logic Controller
P&ID	Piping and Instrumentation Diagram
SOP	Standard Operating Procedures
SRAD	Student Researched And Developed
STEM	Science, Technology, Engineering and Mathematics
TC	Transport Canada
TMU	Toronto Metropolitan University

WBS **Work Breakdown Structure**

UTS **Ultimate Tensile Stress**

YTS **Yield Tensile Strength**

FS **Factor Of Safety**

Nomenclature

m/s^2	Acceleration
A	Amperes
CO_2	Carbon Dioxide
I_{sp}	Specific Impulse
ft	Feet
g	Gravitational Constant of 9.81 m/s^2
in / “	Inches
kg	Kilograms
m	Meters
O/F	Mixture Ratio
N	Newtons
s	Seconds
C_v	Valve Flow Coefficient
m/s	Velocity (also denoted by ft/s)
V	Volts
VDC	Volts, Direct Current
VAC	Volts, Alternating Current

1 Introduction



Fig. 1.1: MACH team picture, taken after the September 2025 coldflow test.

Metropolitan Aerospace and Combustion Hub (MACH) is a non-profit undergraduate student organization based at Toronto Metropolitan University (TMU), dedicated to designing liquid bipropellant rocket engines and their supporting systems. The team's propulsion systems use ethanol as the fuel and nitrous oxide as the oxidizer, providing members with hands-on experience in designing, manufacturing, and operating pressure-fed liquid propulsion systems. The team competes in and showcases its work at national events, which gives members hands-on experience with high pressure systems, engineering design, and experimental rocketry. Beyond engineering, MACH is committed to sharing its knowledge and passion for rocketry with other students, universities, and the broader community.

For the 2026 Launch Canada competition, MACH is competing with an upgraded system based on its 2025 SPRINT project. Over the past several months, the team has focused on reducing set up and take down time, refining the automation system (through projects like auto fueling), improving system capacities, and running repeatable hotfire tests. This year's upgrades target a larger propellant volume, higher thrust, and longer burn times, advancing the capabilities of our system automation. These improvements will allow the system to handle more demanding tests, support multiple engine configurations, and give the team a more detail oriented system to draw conclusions from test data in the future.

1.1 Updates & Lessons Learned

In the Initial Design Proposal, MACH aimed to build a new engine and upgrade its system from the one used in the 2025 Launch Canada competition. A launch vehicle project had also been planned, but for the reasons of logistics, safety, and simplicity, the team decided to put the flight weight project on hold and concentrate solely on Seraphina. Focusing on a single, manageable static test project made sense for our team given the number of new members who still needed to build foundational knowledge before approaching more complex systems. With that in mind, the team began developing ideas around reusing components from the SPRINT I system.

The decision was also influenced by significant organizational changes through the year. Midway through this project, several senior members and subsystem leads departed for co-operative work terms, requiring new members to fill in the leadership roles while simultaneously building technical knowledge. Although this was a challenge, it strengthened the team's resilience and highlighted the importance of effective knowledge transfer, succession planning, and thorough documentation to ensure continuity.

At Launch Canada 2025, the team recognized that the automated system introduced had become one of the project's greatest strengths. Originally developed as a part of the SPRINT I system, the automation system allows the team to pressurize, ignite, fire, depressurize, purge, and control valves all from the click of a button. This year, the goal was to make the automation more efficient and expand it further, which directly informed two of the biggest changes from the original proposal.

The first improvement was a significant increase in propellant tank volume. Our previous tank limited the potential burn time of our engine, thus limiting the thrust. In the near future, MACH is aiming to redesign our engine through our Seraphina project, and improving the tank capacity was the first step in this process. Additionally, designing a larger tank to be compatible with our SPRINT I system allows us to test our tank prior to complex engine changes, thus allowing us to identify flaws in our design more easily.

The second improvement was the development of an auto fueling system, which was designed to cut down setup time on test day and reduce human handling of liquid propellants whenever possible. Fueling has previously been an entirely manual process. The team would use a pump to transfer ethanol into the tank, which introduced contamination and safety issues in addition to being inefficient. This gap in our setup process was inconsistent with our improvements in automation, thus addressing this issue became a priority. This improvement resulted in an auto fueling subsystem that reduces setup time and removes personnel from directly coming in contact with the propellant during fueling.

Shown in Table 1.1.1, our key design changes are highlighted along with a brief explanation of why we made each decision.

Table 1.1.1: Key design changes since the PDR.

Original Plan (IDP)	Learning Trigger	Resulting Change
Baseline tank volume carried over from SPRINT I	Needed longer burn time (more propellant) to accommodate for future engine designs	Redesigned larger volume propellant tank
Manual fueling process	Slow setup, safety risk to those on pad, inconsistent with the other systems being automated	Designed and integrated an auto fueling sub system
Planned flight-weight vehicle alongside Seraphina	Team assessed logistics, safety, and personnel knowledge given new member educational needs	Flight weight project put on hold, focus shifted towards Seraphina

1.2 Team Organization

Table 1.2.1: Leadership Roster.

Name	Role
Dr. Ahmet Emre Karataş	Faculty Advisor
Julia Puszynska	Team Director
Audrey Abergel-Preston	Chief Engineer & Chief Safety Officer

1.2.1 Team Development & Succession Planning

MACH's approach to team development focuses on documenting the foundational technical skills and knowledge required to maintain and operate existing systems. This documentation ensures that essential technical knowledge remains accessible to current and future team members and reduces the risk of knowledge loss during team transitions.

For more advanced, specialized, or sensitive technical knowledge that is difficult to capture through formal documentation, MACH relies on mentorship and hands-on knowledge transfer. Team leads identify promising members and gradually develop their technical capabilities by involving them in increasingly complex projects and engineering activities. Through close collaboration, experienced members demonstrate their problem-solving approaches, engineering judgment, and decision-making processes while allowing developing members to apply these methods independently and establish their own technical approaches. This combination of formal documentation, practical experience, and mentorship supports technical continuity and the long-term development of MACH's engineering capabilities.

1.2.1.1 Knowledge Transfer & Documentation

Knowledge transfer is one of the biggest issues faced in MACH over the years. As members graduate or go on co-operative terms, they take with them valuable technical knowledge, project experience, and lessons learned throughout development. Without an effective system for preserving this information, new members face a steeper learning curve and are often required to rediscover knowledge that had been previously developed on the team.

To address this challenge, MACH strongly emphasizes the importance of documentation at every stage of development. Members completing research or system projects are expected to produce technical reports that must include:

- The purpose and motivation behind the work,
- Background information introducing the topic,
- The specific objectives of the investigation,
- Design decisions and results,

- Common challenges and recommendations, and
- References

These reports are stored to where all team members have access and can also be accessed by future team members. Even if projects are unfinished and rudimentary, they can still provide valuable information for future teammates to build upon and/or learn from previous work.

In addition to project development documentation, MACH enforces a system that encourages members to document any manufacturing procedures, testing methods, design calculations, and standard operating procedures to preserve practical knowledge that is often lost between academic years.

1.2.1.2 Interactive Learning and Work Environment

MACH leadership strives to provide as many hands-on learning opportunities as possible for general members. These activities naturally support multiple learning styles by combining visual, social, and kinesthetic experiences. Members not only observe and discuss engineering concepts but also apply them directly, reinforcing their understanding through practical experience. This creates a positive feedback loop in which increased participation leads to greater confidence, improved technical skills, and stronger engagement, ultimately encouraging members to take on more advanced responsibilities and contribute further to the team.

An issue commonly encountered with this learning is that students are afraid to participate and ask questions at the risk that they “sound stupid” when asking a question about highly technological systems advancing in the world of liquid bi-propellant rocketry. We intend to fail quickly and often, so desensitizing new members to the idea that failure is a good learning opportunity is core to our early onboarding process.

1.2.1.3 Team Development

MACH currently consists of a small but highly talented multidisciplinary team. While the majority of members come from engineering, the team benefits from a wide range of technical backgrounds and perspectives that strengthen problem solving and collaboration across all subsystems.

Over the past year, MACH achieved its greatest program diversity to date, welcoming members from disciplines including photography, business, mathematics, architecture, and several engineering programs. This diversity has introduced new perspectives, creative approaches to problem solving, and a more inclusive team culture. Whether contributing to technical design, project management, media, outreach, or operations, members from different academic backgrounds have demonstrated that innovation is strengthened when diverse experiences and ways of thinking come together.

Moving forward, MACH aims to continue expanding its outreach beyond traditional engineering disciplines. While rocketry is inherently an engineering-focused field, many of the challenges

involved in building and operating a successful team benefit from expertise in business, communications, design, media, and the sciences. By encouraging participation from students with diverse academic backgrounds, MACH hopes to cultivate an environment where curiosity, creativity, and collaboration drive innovation. We believe that the best ideas often emerge when individuals with different perspectives work together toward a common goal.

MACH Program Diversity

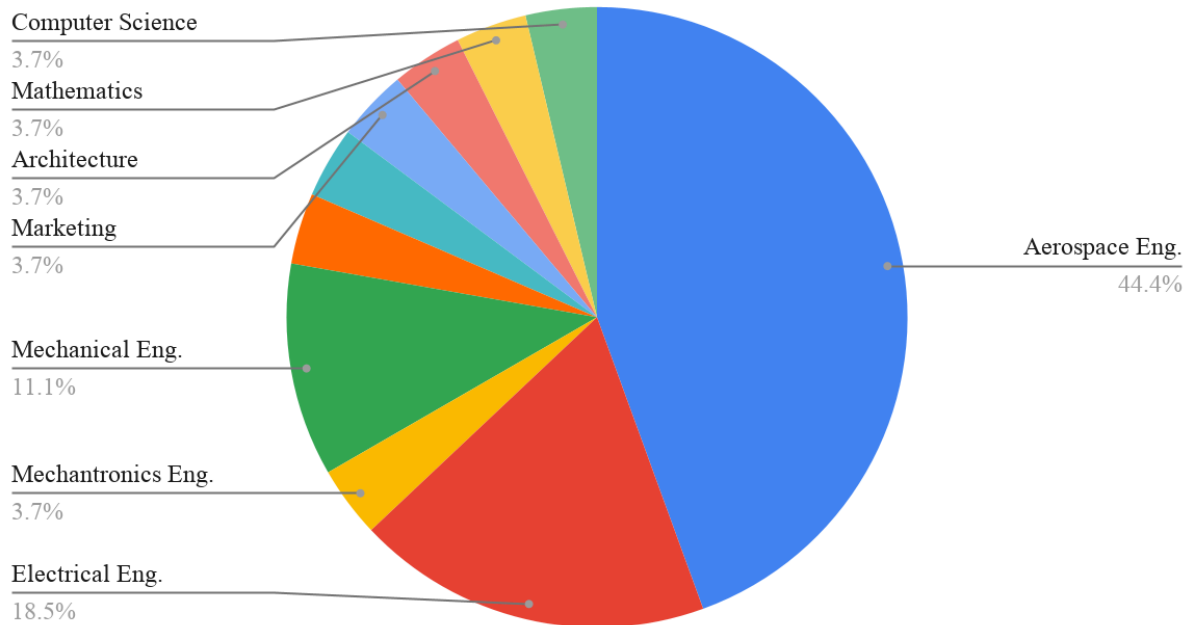


Fig. 1.2.1.3.1: MACH Member Program Diversity Pie Chart

1.3 Outreach



Fig. 1.3.1: MACH outreach booth at MARS x ACU Industry Night.

MACH has actively participated in many internal and external outreach events throughout the past year to promote our team, showcase our projects, and inspire the interest in rocketry and STEM. We exhibited our liquid propulsion system at over 10 events, including InspireTech MoonShot events, TMU Eng Expo, AIAA Kick-Off Conference, the MARS x ACU Student Team Event, and Women in Engineering, among others. Our participation in the AIAA Kick-Off Conference also led to MACH being featured in an *Aerospace America* article [11], further increasing the visibility of our team's work within the aerospace community.

In particular, the Moonshot conference reached out to secondary schools across the Greater Toronto Area and engaged young minds into liquid propulsion and grassroots rocketry. The Eng Expo helped reach new members as most people attending were already fond of rocketry and our involvement there gained us exposure and new members from the TMU community. Furthermore, a particularly notable outreach event was the Women In Engineering Conference, which allowed us to engage with talented future engineers and highlight the importance of diversity and inclusion within aerospace.



Fig. 1.3.2: MACH outreach booth at the TMU Women in Engineering (WiE) conference.



EVENT INSIGHTS

Toronto Metropolitan University Student Branch: Building a Professional Community



BY SARINA SOHAILI YEKTA - OCTOBER 29, 2025



SHARE



The first AIAA Toronto Metropolitan University (TMU) Student Branch event introduced AIAA to the TMU engineering community and marked a strong beginning for the new student

Fig. 1.3.3: Aerospace America article recognizing MACH's participation in the AIAA TMU Student Branch event.

2 Business Case Analysis

2.1 Academic & Business Goals

The primary objectives are academic based, with a focus on hands-on experiential learning, by working on engine and system design. The Seraphina system is not a theoretical design. This system will heavily depend on hardware and software in order to achieve improvements over past designs.

The goals of Seraphina are to advance our capabilities and current hardware. With Seraphina we plan to improve a series of subsystems including: fuel tank, fuel tank stand, and auto fueling system. These subsystems will be tested and incorporated into a future rocket. With several new members, MACH is striving to improve knowledge transfer and aims to use Seraphina to do so. Seraphina will be a learning opportunity for new members to participate in many aspects including: understanding tank sizing, range safety, dual flow fluids, and stress calculations.

Seraphina is a highly automated and iterable platform capable of easily swapping engine components. This enables commercialization by allowing customers to modularly test engine setups. By automating most of the labour, we are able to test different setups very rapidly. Seraphina is not only an asset to small businesses but also to other teams, it will allow for simple and rapid testing of a system as a whole or as individual components making it invaluable to fill this potential in industry use.

Through Seraphina, MACH aims to foster a strong and advancing environment for rocketry education while building a technical foundation for future launch-capable systems.

The key performance indicators used to evaluate our system shall be:

- its automated fueling capability, which completes a standard fill sequence of our fuel in under 5 minutes and for our oxidizers and pressurant (since high pressure gas) would take seconds. Compared to the average amateur liquid rocketry fill time being 5-15 minutes.
- smooth operational integration of newly developed systems to prove Seraphina's versatility.
- the effective data acquisition of pressure readings and thrust readings as it will help in quick diagnostics of ablative and heat sink engines
- the efficiency of abort sequence, proving safety and reliability system
- conducting an abort sequence of less than 30 minutes would prove the system's safety

2.2 Value Proposition

The MACH Engine Testing and Control Platform makes it possible for any organization to static test-fire liquid rocket engines with full safety monitoring, remote control, and datalogging. Our complete engine automation system prevents costly and hazardous human errors during propellant handling and engine ignition, venting, system shutdown, while improving the test repeatability and efficiency.

Compared to conventionally manually operated test stands, the platform lowers the technical and financial barriers associated with liquid propulsion by producing a modular, standardized solution that can be adapted to a variety of engine configurations. This allows university teams, research institutions, startups, and emerging aerospace companies to focus on propulsion development rather than designing and validating their own testing infrastructure. Ultimately, the platform aims to make liquid rocket engine testing safer, more accessible, and more cost effective, supporting innovation within Canada's growing aerospace and space sectors.

2.3 Market Research & Stakeholders

2.3.1 Market Need

Canada's commercial space industry continues to grow alongside increased interest in launch vehicles, propulsion technologies, and university research. Despite this growth, there are relatively few accessible liquid propulsion testing facilities available to student teams, startups, and small research organizations. Developing a liquid rocket engine test stand required substantial financial investment, technical expertise, and significant safety infrastructure, creating a barrier for many organizations wishing to conduct propulsion research.

The MACH automated liquid rocket test platform aims to reduce these barriers by providing a standardized, automated testing system fully capable of rapidly conducting hot-fire and cold-flow testing while incorporating integrated safety features, automated sequencing, and data acquisition. Rather than requiring each organization to develop its own testing infrastructure from the ground up, users could leverage a proven platform to accelerate their propulsion development whilst reducing cost and risk.

2.3.2 Intended Costumers

Potential customers include:

- University rocketry teams developing liquid propulsion systems (ie. engine components)
- Aerospace startups developing propulsion technologies
- Commercial launch companies requiring components or engine testing
- Research laboratories investigating propulsion systems
- Government research organizations
- Educational institutions seeking practical aerospace experience

2.3.3 Current Technologies and Competitive Analysis

Currently liquid propulsion testing generally falls into three categories:

Table 2.3.3.1: Comparison of modern liquid propulsion testing categories

Existing Solutions	Advantages	Limitations
Custom university test stands	Low cost, tailors to individual projects	Documentation, manual operation, difficult to reproduce

Commercial propulsion test facilities	Highly capable and professionally operated	Very expensive and limited accessibility
Government testing facilities	Advanced infrastructure	Restricted access and lengthy scheduling processes

MACH provides a platform that occupies a niche between these extremes by providing a relatively low-cost, automated, modular system that can be adapted for educational, research, and early-stage commercial testing.

Key features that distinguish the project:

- Automated fill sequence
- Automated vent and purge operations
- Integrated safety interlocks
- Modular plumbing architecture
- Pressure monitoring throughout the system
- Rapid turnaround between tests
- Compatibility with both coldflow and hotfire tests

2.3.4 SWOT Analysis



Fig. 2.3.4.1: SWOT Analysis

2.3.5 Stakeholders

The project relies upon numerous stakeholders throughout its development operations.

Internal stakeholders

- MACH executive leadership
- Propulsion team
- Structures Team
- Telemetry and Control Team
- Operations and safety personnel
- General Team members

These individuals are responsible for designing, manufacturing, operating, and maintaining the system.

External stakeholders

- Launch Canada judges and technical reviewers

- Toronto Metropolitan University
- Faculty Advisors
- Sponsors providing financial or material support
- Manufacturing suppliers
- Gas suppliers
- Future commercial customers
- Government and regulatory organizations responsible for launch and pressure-system safety

Each stakeholder contributes resources, expertise, funding, facilities, regulatory oversight, or technical feedback that directly influences the project's successes

2.4 Financial Analysis

For the 2025-2026 cycle; MACH operated with a total revenue of \$20,226. Consisting of \$16,000 in funding from the Toronto Metropolitan University Engineering Society, \$2,000 in Student Initiative Funding (SIF), and \$5,000 in conditional travel expense subsidies.

Expenses were split between: 6in OD propellant tank: Roughly \$2,036.38 was spent on the first tank purchase with another \$236.15 spent on shipping. This was followed by a \$461.66 reorder of certain components.

- Redesigned tank stand: \$107.36 on PETG filament and quick release pins. Costs were brought down by reusing certain parts.
- Autofueling system: \$250.70 on an ethanol tank, filter, pump, and required piping.
- Increased Ground Support Equipment (GSE) features: \$453.96 on features such as increased sensor capacity and extra safety/redundancy.
- Launch Canada logistics: \$5,602.05 on registration and team support.

While MACH does not generate profit, we closely track all expenses to ensure responsible spending and continued sponsor confidence. Our team also actively seeks funding through sponsorships, university grants, and fundraising initiatives to maintain long-term viability.

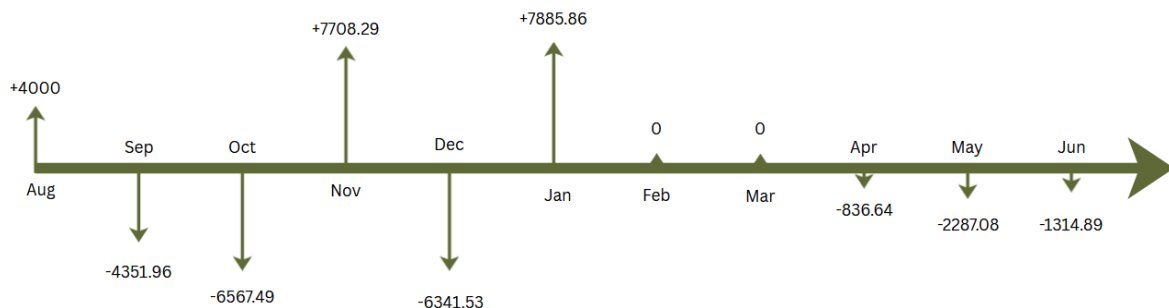


Fig. 2.4.1: Cash flow diagram measured between August 2025 to June 2026.

3 Concept of Operations (CONOPS)

The CONOPS for Seraphina are divided into several phases beginning with assembly and finishing off with post-test safing and data retrieval. They follow the same operational structure as our previous SPRINT I system. Please note, these are **not** our Standard Operation Procedures (SOP), and do not include specific details about system operation. A checklist is also used to validate each phase in the procedure.

A systematic view of our CONOPS can be found below in Figure 3.0, highlighting the major events during our tests.

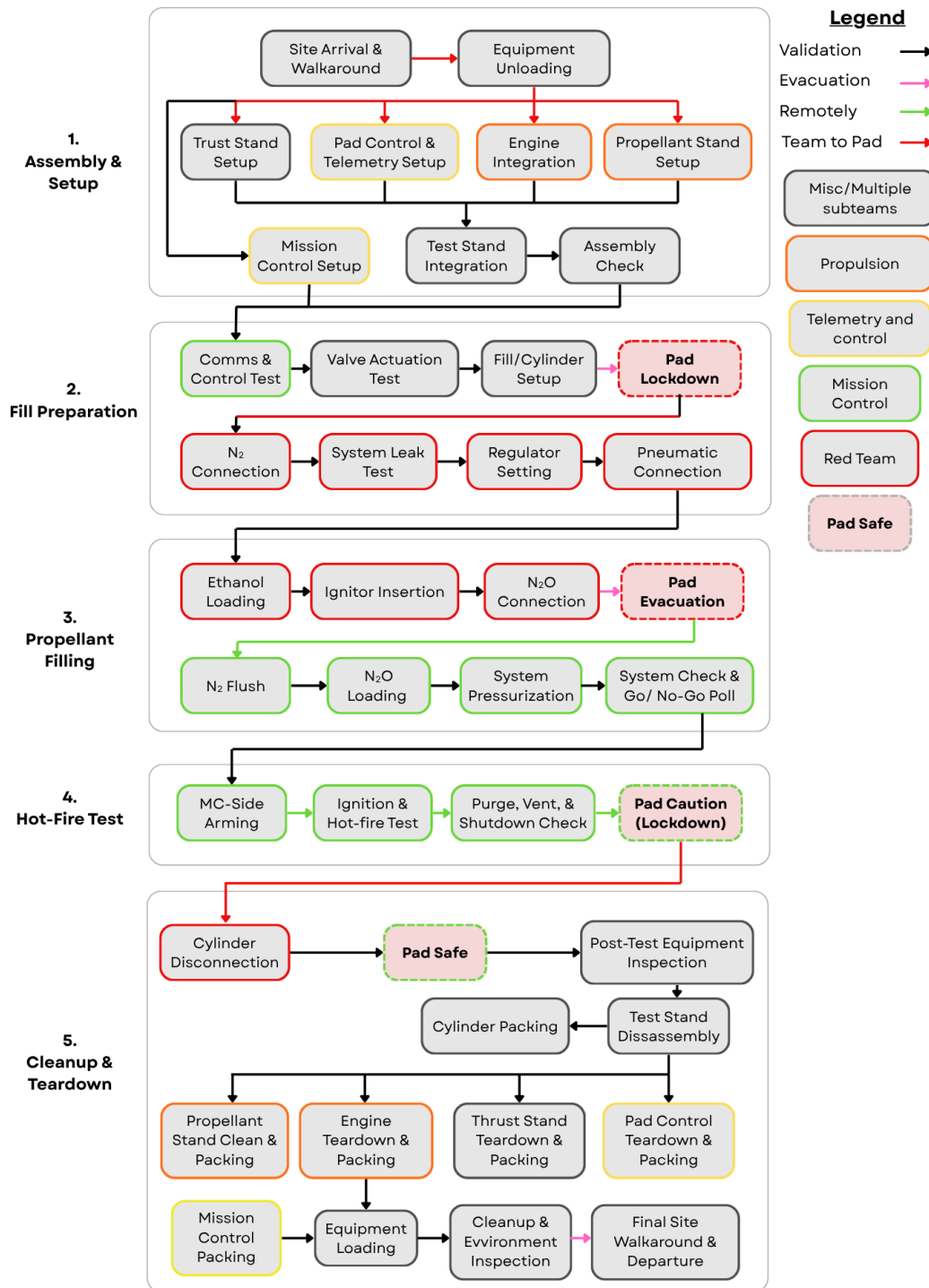


Fig. 3.0: Nominal CONOPS for Hot-Fire Testing.

PHASE 1: System Assembly and Mechanical Integration

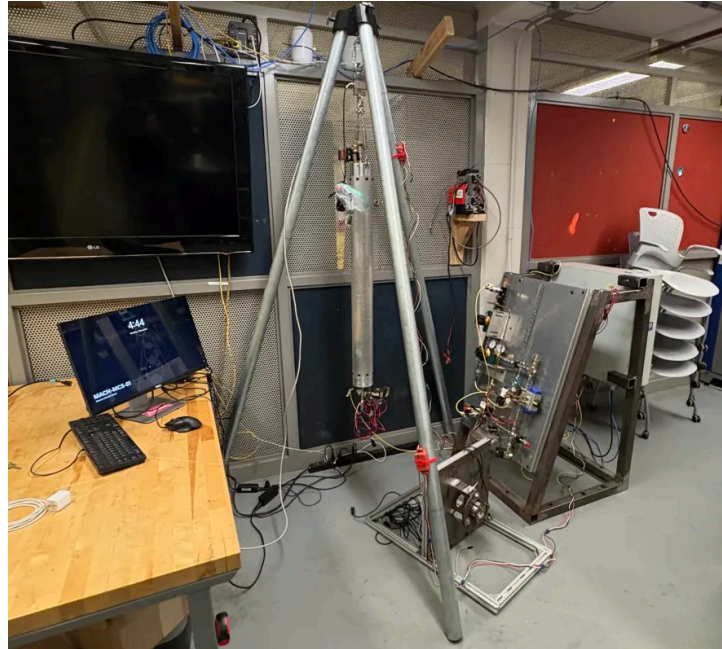


Fig. 3.1: Pre-assembled system ready to be used.

This phase involves the all structure assembly including engine and tank assembly, engine and tank stand, feed lines, valves, and instrumentation (load cells, pressure transducers). Some of our subsystem assemblies (engine and tank) are prepared prior to a planned hotfire/coldflow date to optimize pad time.

- Start Conditions:
 - All hardware is present and in nominal condition, and cleared for integration
 - Prior to assembly, all fluid lines, fittings, and flow paths are inspected for cleanliness and foreign object debris (FOD)
- End Condition:
 - Mechanical installations complete
 - Fasteners torqued and verified and cross-checked
 - Engine mounting varified
- Abort Conditions:
 - Structural misalignment
 - Damaged hardware

PHASE 2: Electrical, Control, and Instrumentation Integration



Fig. 3.2: Electrical and control system wiring integration for the test stand.

All electrical components and connections are completed. Control hardware, sensors, safety interlocks, are checked for continuity, functionality, correct logic behaviour, and undamaged. Active subsystems include PLC, data acquisitions system, valve actuators, safety interlocks and emergency stop.

- Start Conditions:
 - Completion of Phase 1
- End Condition:
 - Successful control logic
 - All sensors returning nominal values
 - All sensors plugged in snugly and wires cleaned up
 - Safety systems verified
- Abort Conditions:
 - Sensor failure
 - Actuator malfunctions
 - Control logic failure

PHASE 3: System Safing and Pre-fuel Configuration

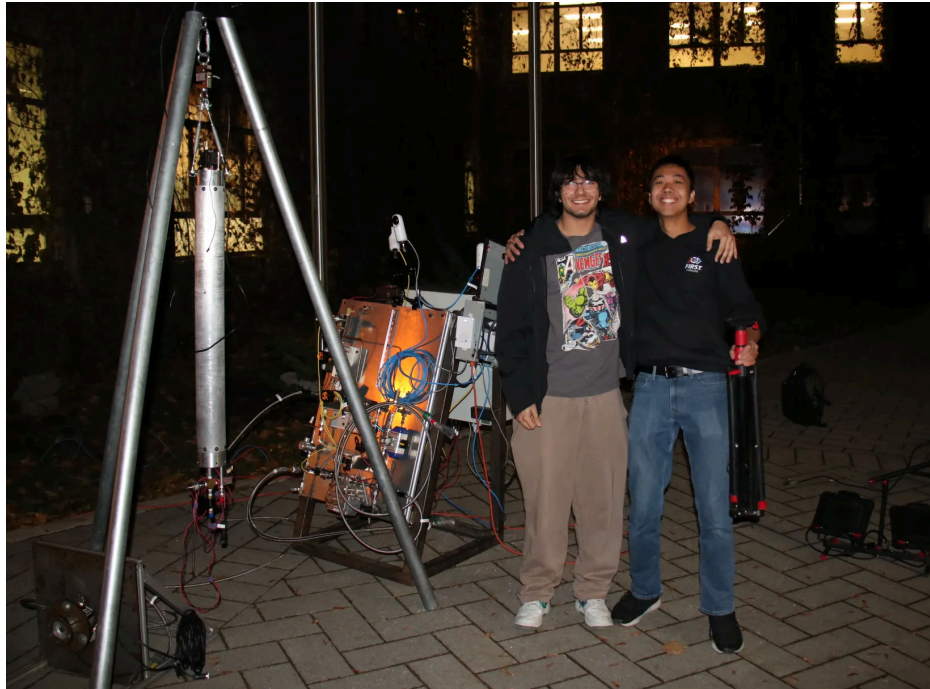


Fig. 3.3: System Safing and Pre-Fuel Configuration

The system is configured for propellant loading following verification that all manual and automated valves are in their nominal positions. Before any propellant is introduced, the complete plumbing system is leak checked using nitrogen gas while the system remains dry. Any detected leaks are corrected before proceeding. Pressure relief devices and other safety valves are also verified to ensure proper operation prior to propellant loading.

- Start Conditions:
 - Completion of Phase 2
- End Condition:
 - System is confirmed in safe, depressurized state
 - Leak check successfully completes
 - Relief valves and other safety devices verified operational
- Abort Conditions:
 - Inability to close or isolate propellant lines
 - Leak detected during nitrogen pressurization
 - Safety valve malfunction

PHASE 4: Propellant Loading

The fueling system and propellant loading is initiated. Ethanol and nitrous oxide tanks are filled to predefined mass and pressure targets. All personnel except the RED team must evacuate the pad.

- Start Conditions:
 - Operator command to initial fueling sequence

- Once fueling is done and successful, RED team approach tanks and open cylinder globe valves
- Manual dump valves in nominal condition
- End Condition:
 - Target propellant mass and pressure achieved
 - Tanks isolated and fill valves closed
- Abort Conditions:
 - Overpressure
 - Mass deviation beyond allowable tolerance
 - Leak detection (detailed information on this step is included in the SOP)

PHASE 5: Pressurization and Pre-Ignition Readiness



Fig. 3.4: Mission control verifying valve operation and system readiness prior to hot-fire testing. Propellant tanks are pressurized to operation conditions. The RED team evacuates the pad. The system is not in the hands of MC, the system will perform automated readiness checks, confirming valve positions, pressures, and sensor values. This phase targets the pressurization system, propellant valves, and ignition system.

Blue-Line Criteria (Proceed with Caution)

- Pressure readings exceed her working pressure but remain below MEOP due to temperature increase
- Delayed ignition sequence

Red-line Criteria (Immediate Abort)

- Pressure reached or exceeds MEOP
- Ignition failure

- Unexpected loud sounds originating from system
 - Failure of any automated valve to respond correctly
 - Loss of critical sensor feedback
- Start Conditions:
- Completion of Phases 1-5
- End Condition:
- All pre-ignition checks passed
 - System enters “armed” state
- Abort Conditions:
- Pressure instability
 - Valve position mismatch

PHASE 6: Ignition and Hot-Fire Test

Upon operator command, the automated ignition sequence is executed. Propellant valve opens in a predefined sequence and the ignitor is fired, initiating engine combustion.

- Start Conditions:
- Operator presses ignition command
 - All interlocks satisfied
 - All personnel are in range of safety
- End Condition:
- Control and data acquisition successful
 - Scheduled burn duration complete
- Abort Conditions:
- Thrust below minimum threshold
 - Chamber pressure anomaly
 - Emergency stop activation
 - Loss of electrical power
 - Loss of control system communication
 - Any red-line condition from Phase 5

PHASE 7: Purge and Venting

Propellants are purged from feed lines. Tanks and lines are vented to ambient pressure to place the system in a safe post-test condition. Purging is done through the automated system and pressures are closely monitored. Red Team returns to the pad to disconnect N₂ & N₂O cylinders.

- Start Conditions:
- Valves in close position.
- End Condition:
- All pressures reduced to safe levels
 - Lines are confirmed free of propellant

➤ **Abort Conditions:**

- Incomplete depressurization (manual valves used)
- Unexpected pressure rise

PHASE 8: Post-Test Safing, Data Retrieval, and Inspection

The system is fully depressurized and safe to approach and test data is retrieved and saved for analysis. Visual inspections are conducted prior to disassembly and clean up.

➤ **Start Conditions:**

- Valves in close position.

➤ **End Condition:**

- All pressured reduced to safe levels
- Lines are confirmed free of propellant

➤ **Abort Conditions:**

- Incomplete depressurization (manual valves used)
- Unexpected pressure rise

4 Requirements

4.1 Mission Requirements

Logical decomposition of the subsystems was performed based on the mission requirements of performing a 5 second static engine test with a 250 lbf thrust on startup and the propulsion system shall safely store and deliver propellant using the concentric tank configuration during a controlled ground test without structural failure, loss in pressure, or leakage. Identification of the subsystems served as an important step for deriving subsequent subsystem requirements. Each subsystem requirement was carefully revised to ensure that it was verifiable.

To ensure that Seraphina meets its mission objectives and complies with Launch Canada rules (see Appendix B: Launch Canada Compliance Requirements), we have defined a hierarchical set of requirements. High-level system requirements are decomposed into subsystem requirements that drive detailed design and verification.

4.2 System & Subsystem Requirements

Table 4.3.1: SERAPHINA Liquid Engine Subsystem Requirement.

Req. #	Requirement
1.1 Tank	
1.1.1	The tank shall be proofed to a pressure up to $1.2\times$ the MEOP without yielding.
1.1.2	The tank shall have a burst factor of safety of at least 2 at the MEOP.
1.2 Tank Relief Valve	
1.2.1	The tank relief valve shall open at a pressure above the tank's working pressure and below the MEOP.
1.2.2	The tank pressure at the fully open relief valve position shall be used to define the tank's MEOP.
2.1 Ox Tank Fill Vent	
2.1.1	The oxidizer tank fill vent shall be capable of operating in low temperature environments with no impact of valve operation and performance.
2.1.2	The oxidizer tank fill vent shall be a normally closed valve.
2.1.3	The oxidizer tank fill vent shall be capable of being operated remotely.

2.2 Oxidizer Tank Dump Valve

- 2.2.1 The oxidizer tank dump valve shall be positioned below the tank to ensure it drains liquid nitrous rather than gas.
 - 2.2.2 The oxidizer tank dump valve shall have an orifice size that is sufficiently large to allow a fully loaded oxidizer tank to be emptied in less than 30 minutes.
 - 2.2.3 The oxidizer tank dump valve shall fail in the open position to ensure that the oxidizer tank contents are dumped if communication is lost with the test stand.
-

2.3 Oxidizer Tank Section

- 2.3.1 The oxidizer tank volume shall be sufficient to accommodate the expected liquid volume and gas ullage according to filling ratios defined in standards for safe handling of nitrous oxide.
-

3.1 Main Oxidizer Valve

- 3.1.1 The main oxidizer valve orifice size shall be large enough to ensure that the flow is not cavitated and choked at the main valve.
 - 3.1.2 The main oxidizer valve shall be actuated to the fully open position in less than 1s at the MEWP.
 - 3.1.3 The wetted materials in the main oxidizer valve shall be compatible with nitrous oxide.
 - 3.1.4 The main oxidizer valve shall be servo actuated ball valve, capable of remote actuation.
-

3.2 Main Fuel Valve

- 3.2.1 The main fuel valve orifice size shall be large enough to ensure that the flow is not cavitated and choked at the main valve.
 - 3.2.2 The main fuel valve shall be actuated to the fully open position in less than 1s at the MEWP.
 - 3.2.3 The wetted materials in the main fuel valve shall be compatible with ethanol.
 - 3.2.4 The main fuel valve shall be servo actuated ball valve, capable of remote actuation.
-

3.4 Ethanol Tank Fill Valve

- 3.3.1 The ethanol tank fill valve shall have a pressure rating that exceeds the MEOP of the ethanol tank.
 - 3.3.2 The ethanol tank fill valve shall be opened and closed manually during fill.
 - 3.3.3 The ethanol tank fill valve shall be located above the fuel tank.
-

4.1 Chamber Casing

- 4.1.1 The combustion chamber casing shall have a yield FOS of greater than 1.5 at the maximum expected operating pressure.
-

4.2 Injector

- 4.2.1 The injector orifices shall be sized such that a minimum stiffness of 10% is achieved for the entirety of the burn duration, to prevent chamber-pressure fluctuations from affecting the propellant flows and thus from inducing combustion instability and vibrations
 - 4.2.2 The injector material shall be compatible with both ethanol and nitrous oxide.
 - 4.2.3 The injector material shall retain its structural integrity at the maximum expected operating temperature during the burn.
-

4.3 Graphite Crush Gasket

- 4.3.1 The engine sealing interface shall mitigate leakage by maintaining sufficient gasket compression throughout operation. It should be replaced upon reassembly.
 - 4.3.2 Required clamping force shall be verified using HalfCat simulation and supporting calculations. During assembly, bolts shall be torqued to the specified value and advanced an additional 45 degrees to account for torque measurement uncertainty and ensure the gasket remains seated.
 - 4.3.3 The graphite insert shall not crack or become dislodged at any point during the hotfire test.
-

4.4 Ignition System

- 4.4.1 The ignition system shall be capable of being activated remotely at mission control.
- 4.4.2 The injector face ignitor shall remain fixed until stable self-sustained combustion is attained.

- 4.4.3 The ignition system shall provide sufficient activation energy to vaporize and combust the mixed propellants during startup.
 - 4.4.4 The ignitor burn duration shall last the duration of the hotfire.
 - 4.4.5 The ignitor shall produce thick, visible smoke that can be seen using the camera system.
-

5.1.1 GSE Pressurization Control Valves

- 5.1.1.1 The pressurization control valves shall be remotely actuated.
 - 5.1.1.2 The control valves for the GSE pressurant panel shall be configured to ensure that the N2 cylinder contents are NOT passively vented.
 - 5.1.1.3 The GSE pressurant control valves shall have a pressure rating that exceeds the MEOP of the pressurant tank.
 - 5.1.1.4 The GSE pressurant control panel shall contain a relief valve that passively vents pressurant in the event of pressure excursions above the maximum expected working pressure.
-

5.1.2 GSE Purge Regulator

- 5.1.2.1 The Purge regulator shall be hand-loaded.
 - 5.1.2.2 The GSE pressurization control regulator shall have an inlet pressure rating that exceeds the supply pressure from a 6K nitrogen supply cylinder.
-

5.1.3 GSE Pressurization Vent Valve

- 5.1.3.1 The pressurization panel on the GSE subassembly shall passively vent pressurant contained within isolated portions of plumbing if control is lost.
-

5.2.1 Oxidizer Fill Valve

- 5.2.1.1 The oxidizer fill valve shall have a pressure rating that exceeds the MEOP of the nitrous supply cylinder.
- 5.2.1.2 The oxidizer fill valve shall be actuated remotely to allow for remote fill capabilities.
- 5.2.1.3 The wetted components of the oxidizer fill valve shall be compatible with nitrous oxide.

5.2.1.4 The oxidizer fill valve shall be actuated pneumatically.

5.3.2 GSE Pneumatic Regulator

5.3.2.1 The GSE pneumatic regulator shall allow for precise control of the outlet pressure, ensuring that the pneumatic pressure is maintained to 100 psi +/- 5 psi.

5.3.2.2 The GSE pneumatic regulator shall have an inlet pressure rating that exceeds the expected supply pressure range from a T nitrogen supply cylinder.

5.4.1 Thrust Mount and Tripod

5.4.1.1 The thrust assembly shall be capable of static operation of the engine.

5.4.1.2 The thrust assembly shall be capable of withstanding the maximum expected thrust (250 lbf) with a yield safety factor of at least 3.

5.4.1.3 The thrust assembly shall be capable of measuring engine thrust in the static engine configuration.

5.4.1.4 The tripod shall be capable of handling up to 3x the weight of the tank.

5.4.1.5 The tripod structure shall have load cells for measuring the propellant feed system during fill and drain.

5.4.2 GSE Structure/Blast shield

5.4.2.1 The GSE structure shall provide support for the GSE plumbing, and electronics enclosure.

5.4.2.2 The GSE structure shall be anchored to the ground such that no movement is possible at any point during the hotfire test of the engine.

6.1 GSE Electronics

6.1.1 The electronics shall be water/dust proof up to IP65.

The electronics shall be expandable up to 12 24V outputs, 6 thermocouple inputs, 8 pressure transducers inputs, 6 load cell inputs (two amplifier/junction boxes), and PWM outputs

6.1.2 Computers at mission control shall use Labview for all operations

- 6.1.3 Ladder logic on the PLC shall work in tandem with the LabJack as a back up to auto abort the system under non nominal circumstances.
-

5 Systems Architecture

The Seraphina Project is composed of broad, already proven and newly developed systems to serve as MACH's engine testing and control platform. The Architecture is used as a structure for which the system is assembled, data is managed and operational procedures are developed. The system is divided into 3 subsystems: Structures, Propulsion and Electronics. These are further divided into 6 subassemblies, as seen in figure 5.1.

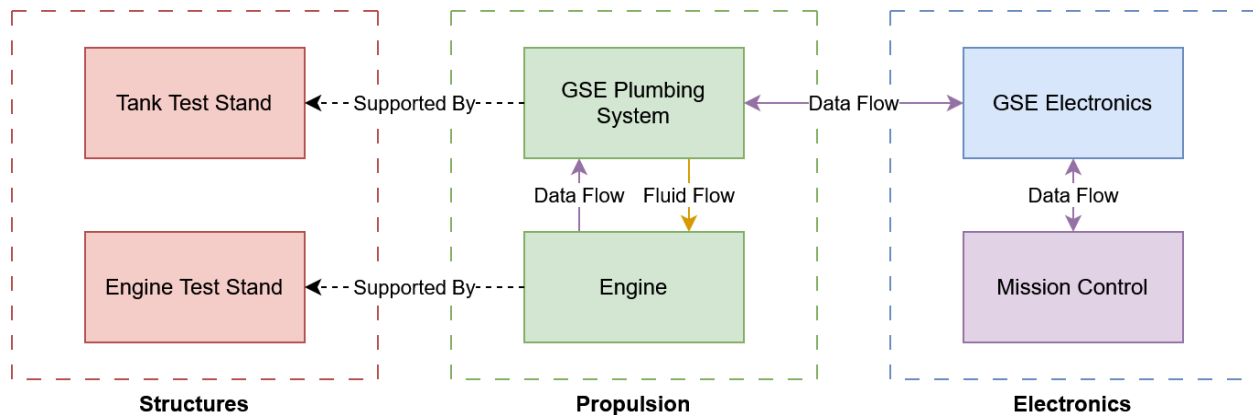


Fig. 5.1: Overview of all systems.

5.1 Structures

The Structure subsystem supports the propulsion hardware, ground equipment, and propellant handling assemblies while maintaining stable, controlled load paths during cold-flow and hot-fire testing. Both the test and tank stand have been operated in previous hotfires. The design follows Launch Canada DTEG expectations by preventing unwanted movement, providing rigid mounting interfaces, and maintaining safety margins under static and dynamic loads.

5.1.1 Test stand

The SPRINT test stand is built from 7071 aluminum T-slot extrusion with a ¼ inch HRPO A36/1008 mild-steel backplate. The extrusion frame provides a lightweight, modular base, while diagonal gussets improve stiffness and prevent racking. The steel backplate acts as the primary thrust reaction surface, transferring loads from the engine through the thrust plate, load cells, frame, and finally into the ground.

5.1.2 Tank stand

The structural backbone is a steel frame supporting the propellant tanks, engine thrust stand, and electronics enclosure. Quick-release pins and 3D-printed PETG coupler allow tool-free disassembly in under 10 minutes from the previous year. All load-bearing joints are configured in pure compression.

5.2 Propulsion

5.2.1 Engine

The SPRINT engine is a Mojave Sphinx-inspired liquid rocket engine using N_2O and ethanol, designed for 250 lbf thrust, a 5-second burn, and 250 psig chamber pressure. It uses a screw pintle injector and dual solid-motor ignition system, with sizing based on NASA CEA and hand calculations. The modular flange-clamped design supports easy assembly and torque verification. It has undergone 4 successful hot fires.

General properties of the engine are listed in Table 5.2.1 and the engine assembly is shown in Figure 4.2.1.

Table 5.2.1: SPRINT Rocket-Engine Properties

Parameter	Value
Propellants	Ethanol, N_2O
Total Impulse	5560.3 Ns
Nominal Burn Duration	5.0 s
Designed Thrust	1112.06 N (250 lbf)
O/F Ratio	2.1
Average Tank Pressure (25C)	819.72 psig
Chamber Pressure	250 psig
Cooling System	Heat Sink
Injector, Chamber & Nozzle Material	6061 Aluminum
Throat Material	Copper
Retainer Material	Steel

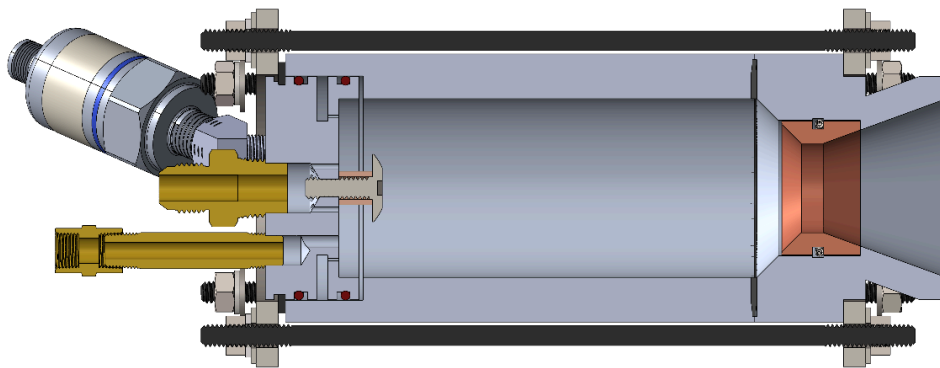


Fig. 5.2.1: Thrust Chamber Assembly.

5.2.2 GSE Plumbing System

The ground support equipment (GSE) plumbing system has been used for the past two years to supply oxidizer to the propulsion system and has undergone gradual upgrades to improve

reliability, serviceability, and performance. Planned minor improvements include replacing and reinstalling some fittings. To meet Launch Canada DTEG requirements, a COTS pneumatically actuated dump ball valve with a $\frac{1}{4}$ in orifice was added to the panel. This valve is normally open, allowing propellant to dump automatically in abort or loss-of-propellant scenarios. The GSE plumbing components are mounted on a common panel with the Electrical board. Pneumatic actuation for the valves is supplied through a tap-off from the nitrogen pressurant system. The system P&ID starts with nitrogen pressurant and nitrous oxide cylinders, both connected using quick-disconnect couplings on the bottles and AN fittings on the plumbing board. The board features regulators for the nitrogen lines and pressure relief valve for over-pressure relief, and a manual vent valve for redundancy. For data acquisition the board utilizes pressure transducers and regulators for obtaining pressure readings.

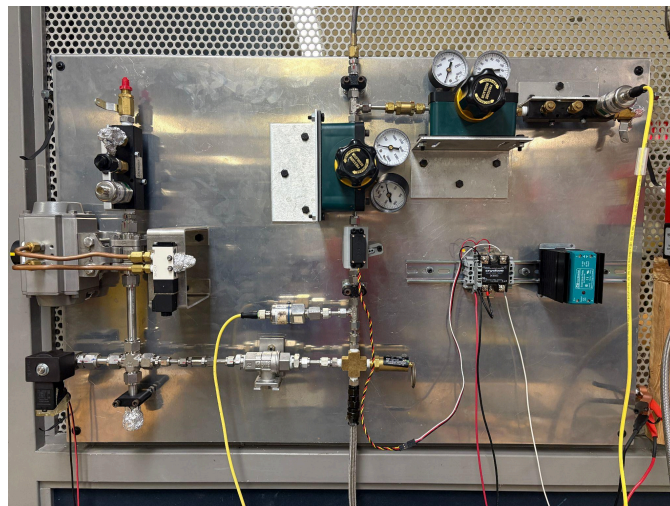


Fig. 5.2.2: GSE Plumbing.

5.2.3 Propellant Tank

The propellant tank uses a concentric, self-pressurizing design based on the Half Cat Rocketry document [14], and is machined from 6061-T6 aluminum. The outer extruded tank will be holding liquid nitrous oxide and the inner tank will be holding ethanol. Moving forward the system requires the use of two bulkheads to maintain control of the pressure and amount of fluid in the tank at any given time. A vent bulkhead seals the top of the outer tank and incorporates internal stringers that support the inner tank while leaving its top end open, allowing nitrous oxide to flow from the outer annulus into the inner tank and act directly on the top of a floating piston. Rather than relying on a separate pressurization system, the piston uses the vapor pressure of the self-pressurizing nitrous oxide to push down and displace the ethanol beneath it. The fill bulkhead at the bottom seals the outer tank and connects to the ground plumbing, using a combined fill/run line for both ethanol loading and delivery to the engine. On the oxidizer side, the same line serves as both the nitrous fill port and the emergency dump path through a normally-open ball valve. Both bulkheads are held in place axially by the retaining rings, each

secured with 28 radial 1/4-28 bolts, and sealed to the outer tank with static Buna-N O-rings. In operation, nitrous loaded through the top vent bulkhead pressurizes the ullage and drives the piston downward, forcing ethanol out through the bottom fill/run line into the feed system and on to the injector, while a burst disk and fail-open solenoid vent on the top bulkhead provide over-pressure protection throughout fill, pressurization, and firing.

5.3 Electronics

The electrical system provides the instrumentation, control, and communication infrastructure required to safely operate the ground support equipment (GSE). All control electronics are housed within an IP66-rated enclosure mounted on the rear of the GSE plumbing support frame, providing environmental protection for launch operations. The architecture supports remote operation while maintaining manual override and fail-safe capabilities to ensure safe system operation. A detailed description of the electrical hardware, control architecture, and software implementation is provided in Section 8.1.

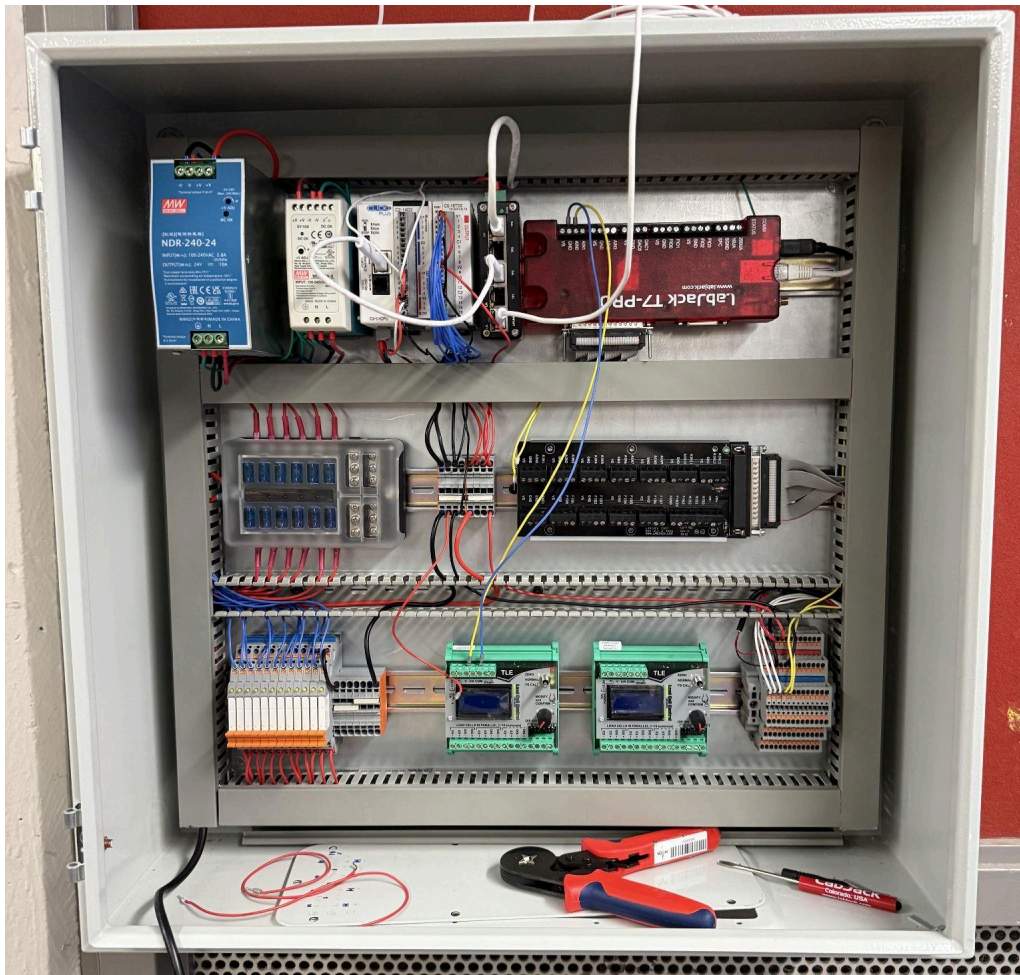


Fig. 5.3.1: GSE electronics enclosure.

6 Structures

This subsystem focuses on the structural elements responsible for supporting the propulsion hardware, ground equipment, and propellant handling assemblies while maintaining stability under operational loading conditions. In accordance with the DTEG, the structural architecture is designed to ensure controlled load transfer, prevent unintended movement during testing, and maintain sufficient safety margins for both static and dynamic loading scenarios. Emphasis is placed on providing rigid mounting interfaces for the thrust stand and propellant support systems, as well as ensuring that all ground-mounted structures remain securely anchored throughout cold-flow and hot-fire operations

6.1 Test Stand Structure

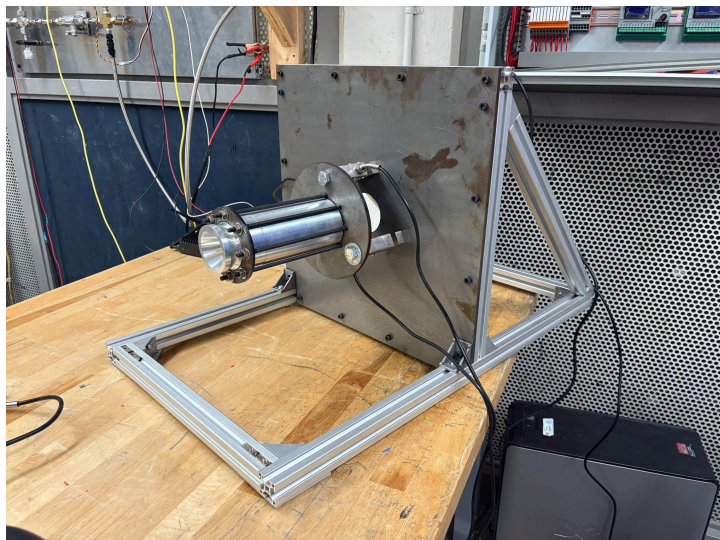


Fig. 6.1.1: SPRINT engine mounted onto engine stand

6.1.1 Detailed Design

The SPRINT test stand is built from aluminum extrusion and a steel backplate, providing a lightweight and modular base that can support both axial and off-axis reaction forces generated during hot-fire testing. This structure was developed against the DTEG in order to satisfy Launch Canada requirements by providing a rigid engine restraint, predictable load paths, and mechanical robustness during static propulsion testing.

Base Frame:

Profile: The profile of the base frame consists of 7071 aluminum T-slot extrusion assembled into a 600x400 mm rectangular footprint, providing a wide base to reduce the risk of tipping during high-thrust operations. This particular extrusion profile, 8020 T-slot, was selected for its high moment of inertia relative to the mass per unit length, resulting in a lightweight yet stiff construction.

Bracing: Installed at each corner are diagonal gussets to prevent lateral racking and torsional deformation. This bracing ensures that thrust reaction forces are transmitted directly into the base frame rather than inducing shear distortion within individual extrusion members. The triangular load path created by the corner gussets improves the in-plane stiffness and aligns the overall design with DTEG structural recommendations, ensuring that test stands maintain rigid geometry under dynamic engine loading.

Backplate:

Material: The backplate consists of a single piece of HROP A36/1008 ¼ Mild Steel cut using a waterjet and fastened to the extrusion frame. This backplate serves as the primary thrust reaction surface and load distribution interface between the engine mount and the frame. Steel was selected over aluminum because of its increased resistance to elastic deflection under axial thrust loads, and its increased fatigue resistance for repeated hot-fire cycles.

Attachment: The backplate is secured to the aluminum extrusion using socket-head cap screws threaded into drop-in T-nuts. The selected fastener spacing ensures shear loads are uniformly distributed along the extrusion frame and to reduce localized bearing stresses. This attachment method also allows for the backplate to be easily disassembled for inspection, maintenance, or configuration changes.

Engine Mount & Thrust Reaction:

Thrust Plate: The engine is fastened to a ¼ inch mild-steel circular thrust plate, which is subsequently fastened to the backplate through three in-line load cells. This configuration allows for the measurement of axial thrust while preserving symmetrical load transfer into the backplate. The thrust plate geometry was designed to minimize bending moments at the load cell interfaces and to ensure that the applied loads remain predominantly axial during engine firing.

Load Path Management: Thrust forces are transmitted sequentially from the engine flange to the thrust plate, through the load cells, into the steel backplate, through the aluminum extrusion frame, and finally into the ground interface. This clearly defined and continuous load path follows DTEG guidance for predictable structural load transfer and ensures the reliability of proof load verification and structural validation.

6.1.2 Manufacturing Process

1. **Extrusion Cut and Assembly:** The aluminum extrusion members were cut to length using a miter saw, drilled using a drill press, and deburred by hand. The base frame was then assembled using corner gusset plates and fasteners.
2. **Backplate Fabrication:** The steel backplate was waterjet-cut to achieve accurate hole placement and dimensional consistency with the extrusion mounting pattern. This process minimized material distortion and ensured flatness of the thrust reaction surface.

3. Final Assembly: Load cells were installed onto the thrust plate mounting brackets and secured to manufacturer torque specifications. The thrust plate assembly was mounted to the backplate, and all structural fasteners were torqued using a torque wrench. Final alignment checks verified proper engine axis orientation and frame centering.

6.1.3 Testing and Validation

Initial test stand analysis was performed using ANSYS Static Structural in order to validate the structural design against the maximum expected engine thrust load of 250 lbf, and to build a clear understanding of the failure modes and margins present in the current design. A simplified CAD assembly was used within the simulation to avoid the complexity of modeling the individual bolt-to-extrusion contacts. With this simplification in mind, the ¼ inch HRPO A36/1008 mild-steel backplate is still the component that absorbs the majority of the thrust load, since it forms the direct reaction surface beneath the thrust plate and load cells. The backplate is therefore the primary structural item being validated in this section.

Material properties for the backplate were taken directly from the ANSYS material library and cross-checked against the published ASTM A36 specification which is a tensile yield strength of 36,260 psi (250 MPa), Young's Modulus of 200 GPa (29,000 ksi), and Poisson's Ratio of 0.26. These values are standard room-temperature properties and are valid at the 30°C operating condition used in the simulation, since carbon steel shows no meaningful strength reduction until temperatures are well beyond this range.

The first result evaluated was total deformation under the full 250 lbf thrust load, shown in Figure 6.1.4.1. The maximum deformation was found to be 0.011251 in, occurring at the inner edge of the central mounting hole where thrust is transferred from the load cells into the backplate. This deflection is small relative to the ¼ inch plate thickness, confirming the plate is responding within the small-deflection and experiencing elastic behavior.

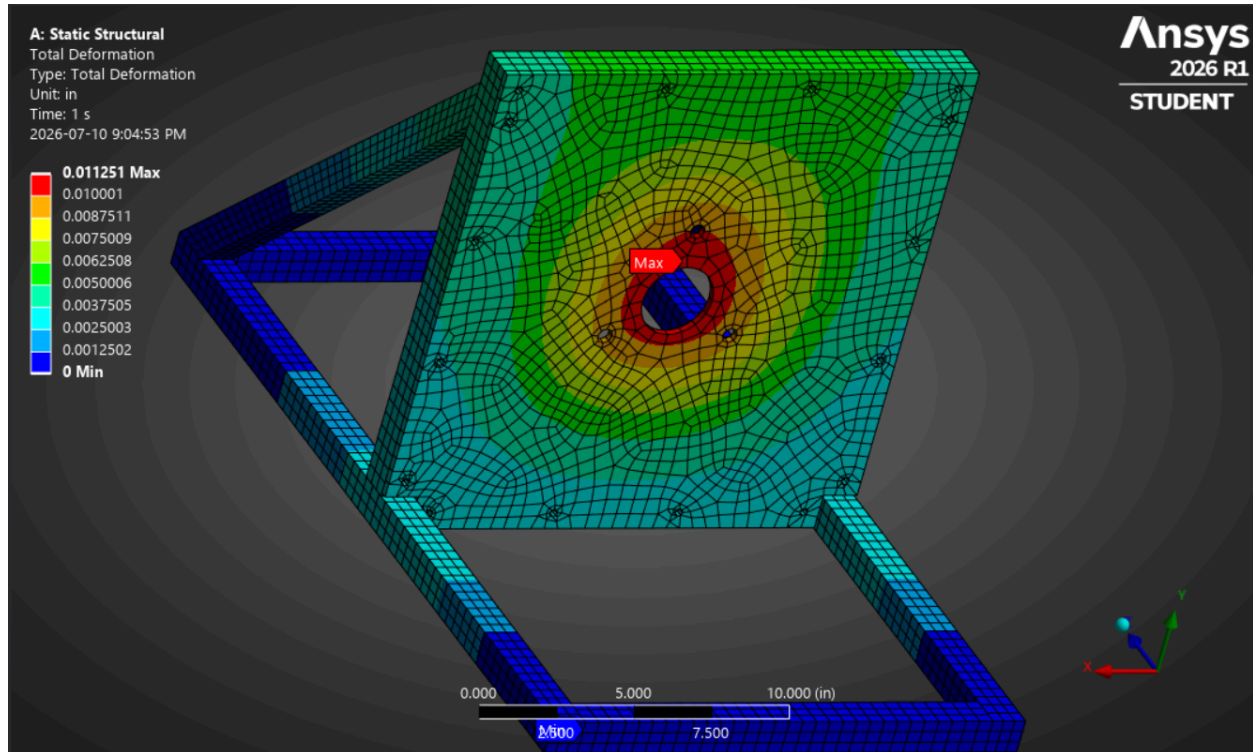


Figure 6.1.3.1: Minimum and Maximum Total deformation under the full 250 lbf thrust load

Figure 6.1.4.2 shows the equivalent von-Mises stress distribution across the assembly, which is the appropriate failure criterion for a ductile material such as mild steel. The maximum stress was found to be 8,021.8 psi, occurring at the same mounting hole location that drives the peak deformation. Comparing this directly against the material's 36,260 psi yield strength gives a safety factor of approximately 4.5, indicating that the peak stress in the backplate sits well within the elastic region, with substantial margin remaining before the onset of yielding.

To directly quantify design margin across the full assembly, a Safety Factor analysis was performed by comparing local stress against material yield strength at every point in the structure, shown in Figure 6.1.4.3. The minimum safety factor found anywhere in the assembly was 4.5201, located at the same backplate mounting hole region identified as the peak-stress location above. The majority of the structure, shown in solid blue, carries a safety factor at or above the plotted ceiling of 15, indicating that stress away from the mounting hole is negligible relative to yield.

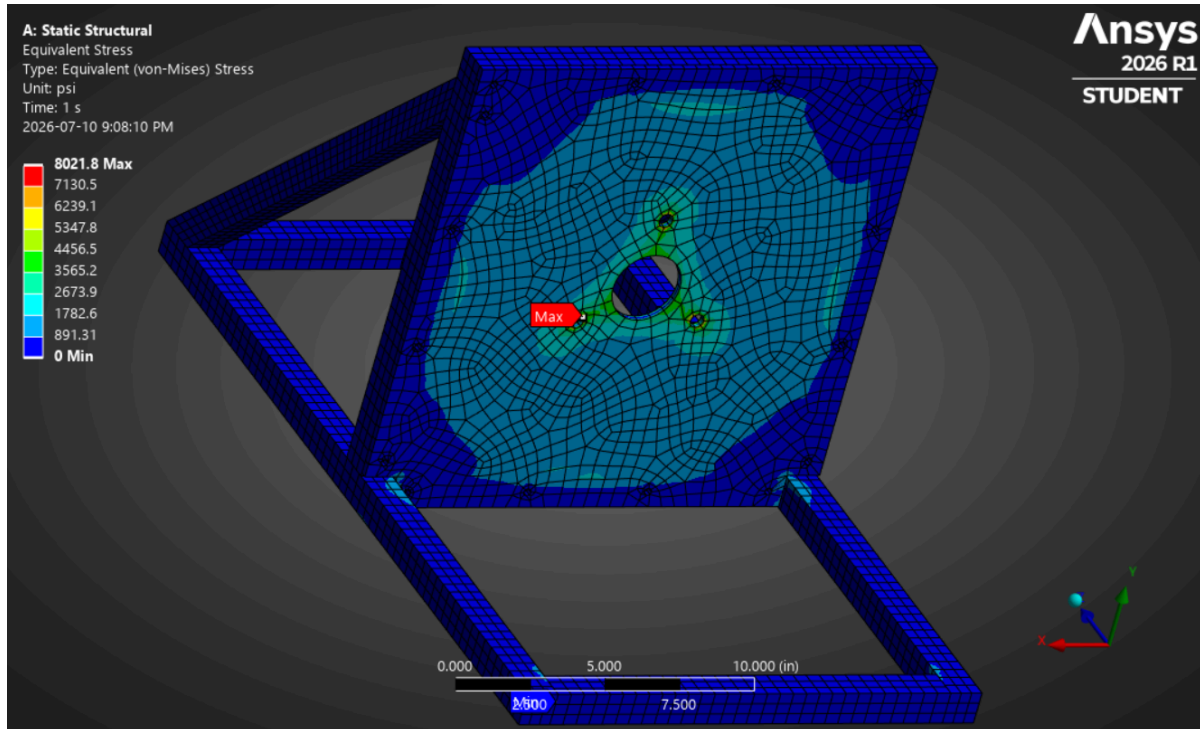


Figure 6.1.3.2: Minimum and Maximum Equivalent (von-Mises) Stress assuming max thrust of 250lbf

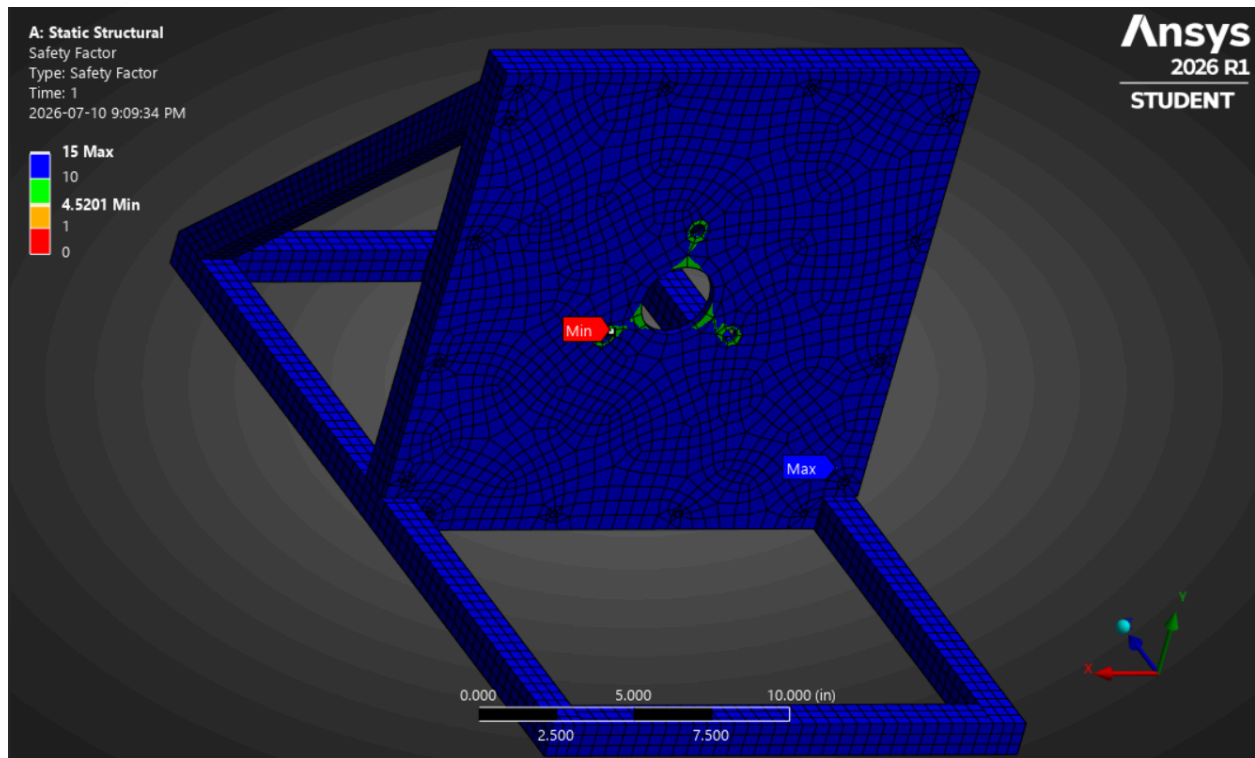


Figure 6.1.3.3: Minimum and Maximum Factor of safety for the thrust stand assuming 250lbf

These three results form a consistent, self-reinforcing picture of the backplate's structural behavior under the 250 lbf design thrust load. The location of peak deformation, peak stress, and minimum safety factor all coincide at the same feature, the inner edge of the central mounting hole, which is the expected behavior for a plate with a geometric stress concentration at a load-bearing cutout. The backplate carries more than 4.5 times the margin required before any permanent, plastic deformation would occur. This confirms that under the full 250 lbf design thrust load, the backplate, and by extension the test stand assembly as a whole, remains entirely within the elastic region and it will deflect a small, predictable amount (0.011 in maximum) during firing and will return fully to its original undeformed geometry once the load is removed. On this basis, the current backplate and test stand design is considered structurally valid for the SPRINT engine's 250 lbf maximum thrust load, with no expected risk of yielding, permanent deformation, or structural failure under static loading conditions.

6.2 Concentric Tanks

6.2.1 Detailed Design

Our system utilizes a concentric tank design, with nitrous oxide in the outer tank and ethanol in the inner tank. This can be seen in figures 6.2.1.1 below, which shows the overall tank design. The material selected for the tank is aluminum 6061-T6, with the outer tube extruded and the inner tube drawn. Drawn aluminum was chosen for the inner tube as precision and better surface finish of much importance for piston clearance and smooth piston displacement. This system takes advantage of nitrous' self pressurization properties to displace ethanol which is separated with a piston. To achieve this, the inner tank is open at the top end but rests on stringers which are designed into the upper bulkhead to keep the inner tank vertical. This allows the nitrous to come into contact with the top of the piston, and pressurize the inner tank. The tank is designed to a factor of safety of 2 and above. The bulkheads are secure in place with the use of a retaining ring, each with 28 radial holes and using 1/4"-28 bolts. The retaining mechanism is not reliant on preload hence the bolts are loaded in shear with minimal preload to clamp the retaining and outer tank. All components were modelled using SolidWorks. HalfCat sim were used to obtain an initial outline of requirements, then subsequent calculations were done to obtain tank length, thickness, pressures, forces, etc [3].

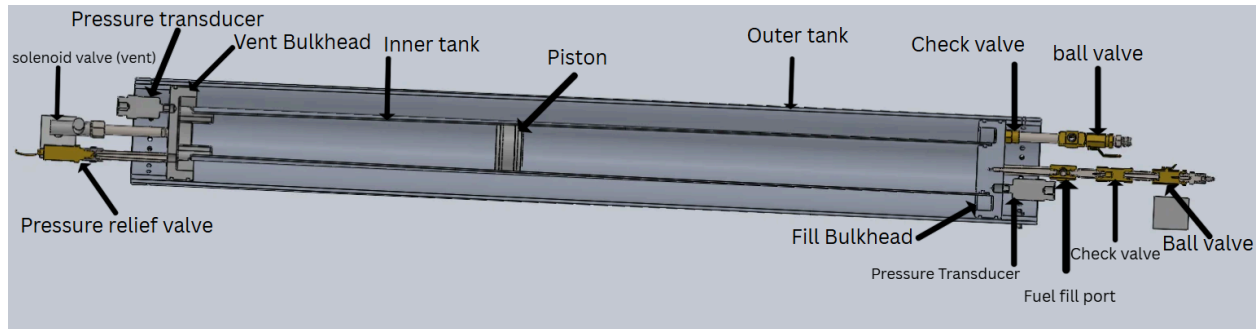


Fig. 6.2.1.1: Cross Section of entire stank system

The overall dimensions of the tank are presented in Table 6.2.1.2 below.

Table 6.2.1.1: Tank Dimensions

Measurement	Value (in)
<i>Outer tank</i>	
Diameter	6.000
Thickness	0.183
Length	51.000
<i>Inner tank</i>	
Diameter	3.000
Thickness	0.083
Length	45.000

6.2.2 Retaining Rings

There will be two retaining rings within this system, one on each end of the outer tank to secure the bulkheads. The retaining rings have one row of 28 1/4"-28 UNRF screws, as seen in the figures below. The spacing and sizing of these screws was determined through analysis of the various forces that the retaining rings will be exposed to. This analysis can be seen in Appendix B.



Fig. 6.2.2.1: Retaining ring for tank assembly

6.2.3 Manufacturing Process

The primary components for the tank assembly were sourced from the following manufacturers:

- **Tanks:** OnlineMetals
- **Bulkheads, retaining rings, and piston:** JLC CNC
- **Bolts, nuts, o-rings, and other miscellaneous hardware:** McMaster Carr

Retaining ring & External Tank Bolt Drilling:

To ensure accurate alignment between the external tank and the retaining rings, both components were drilled simultaneously. This approach was selected due to minor hole misalignment in the previous year's assembly when the components were manufactured separately.

A drilling template consisting of two pieces of paper and masking tape and having 28 equally spaced points based on the circumference of the external tank was used, and can be seen in Figure 6.2.3.1. The template was then carefully wrapped and positioned around the tank, and each hole was transferred to the tank's surface using a center punch seen in Figure 6.2.3.2.

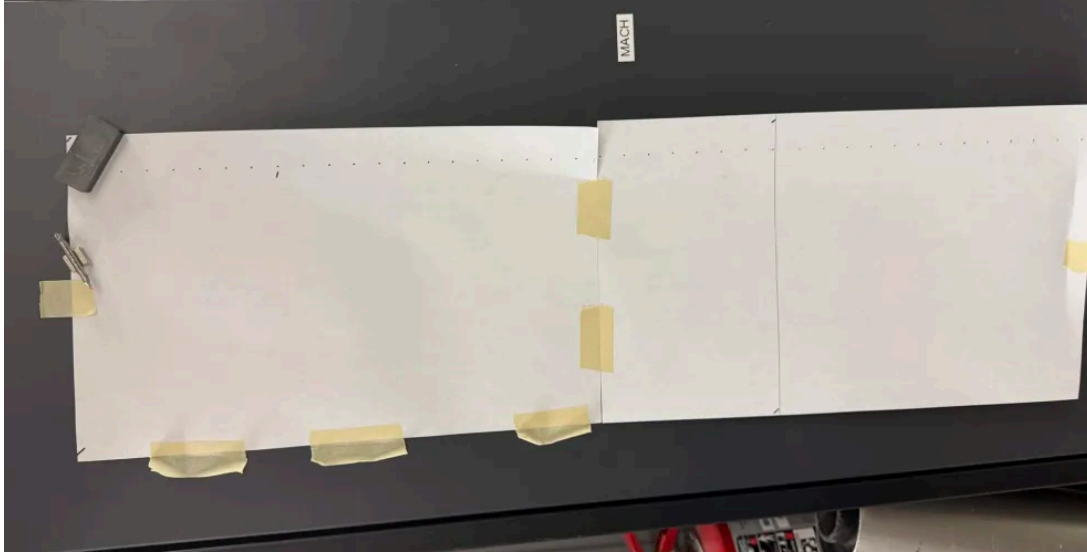


Fig. 6.2.3.1: External tank drilling template



Fig. 6.2.3.2: Center punching the external tank using the drilling template.

Once both sides of the external tank had been scribed with center punch holes, the center punch holes are used to drill pilot holes. The before and after of the center punch holes compared to the pilot holes can be seen in Figure 6.2.3.3.



Center punched holes



Pilot drill holes

Fig. 6.2.3.3: Comparison of center punched holes to pilot drill holes

After the pilot holes were drilled, the retaining ring was fitted snugly inside the external tank. Masking tape was applied around the retaining ring to eliminate the clearance between the two components and prevent the movement during machining. In addition, one pilot hole was then drilled completely through both components, and a bolt and nut were installed to establish and maintain alignment.

Before drilling each of the holes through both the parts, 3 holes were drilled as equally spaced from one another as possible. This would ensure the retaining ring does not shift in reference to the external tank and the holes are being drilled. The same procedure was then repeated for the opposite retaining ring.

Once all the holes had been drilled, each of the 112 holes were deburred on both sides, cleaned up, and ready to be used for testing. A reference video of the pilot hole drilling and the through-drilling process is provided in Appendix C.

6.2.4 Analysis

This section includes various calculations done to obtain the tank parameters. Sample calculations can be seen below, and a summary of results can be seen in Table 6.2.4.1 below [2], [3], [6].

First, the MEOP was determined from the maximum temperature that the nitrous oxide would be exposed to, to warrant an abort using the equation found in figure 6.2.4.1 below. This temperature was determined to be 30°C, with a corresponding tank working pressure of 937 psi and then a calculated MEOP of 1124.4 psi.

$$MEOP = pressure \times 1.2$$

$$MEOP = 937 \times 1.2$$

$$MEOP = 1124.4 \text{ psi}$$

Figure 6.2.4.1: Maximum effective operating pressure equations and calculation

To calculate the required thickness of the outer tank, the equation for hoop stress was used as seen in figure 6.2.4.2 below. As the thickness is needed, this equation was rearranged and the values for MEOP, outer tank radius, and allowable stress for 6061-T6 aluminum were used. To ensure a safe thickness, the allowable stress was multiplied by 2. For ease of manufacturing, this value was rounded up to 3/16 inches. This calculation can be seen below [7].

$$t_{outer} = \frac{MEOP * 3 * 2}{\sigma_{allowable}}$$

$$t_{outer} = \frac{3 * (1124.4) * 2}{(40000)}$$

$$t_{outer} = 0.1606 \text{ in}$$

$$t_{outer} = 0.1875 \text{ in}$$

Figure 6.2.4.2: Required thickness of the outer tank calculation

Table 6.2.4.1: Tank Parameters

Parameter	Value
Maximum Expected Operating Pressure (MEOP)	1124.4 psi
Outer tank thickness	3/16 (0.1875) in
Retaining bolt specification	ASTM A574 1/4-28
Ultimate Tensile Strength (UTS)	170,000 psi
Number of bolts	52
Bolt shear FS	3.07
Bolt tear-out FS	2.82
Edge Distance	1.000 in
Casing Tensile Stress FS (YTS)	3.77
Casing Tensile Stress FS (UTS)	4.16
Bearing Stress FS	2.62

Max Pre-Load	50 lbs
Von miss stress FS	2.95
Margin Of Stripping	3.47

6.2.5 Testing and Validation

To validate the structural integrity of our SRAD pressure vessel and closure system (the Seraphina tank), a hydrostatic proof test was conducted in accordance with the requirements outlined in the Launch Canada Design, Test and Evaluation Guide. A separate document was made outlining all the aspects of this test, which can be provided upon request. In this section, we will summarize the key aspects of that report.

In this case, the hydrostatic test hold time was required to be:

$$\text{Hydrostatic test hold time: } 2 (\text{fill time} + \text{hold time} + \text{abort time})$$

$$2 (30 \text{ s} + 5 \text{ mins} + 2 \text{ mins}) = 900 \text{ s or } 15 \text{ minutes}$$

The team made the decision to add 3 minutes for fill, abort, and hold time lenience, making the total hydrostatic test hold time to be 18 minutes.

The pressure we decided to hold the tank at, based on the Launch Canada Hydrostatic Test specifications, was 1.2 times the MEOP. Our MEOP was calculated to be 1124.24 psi.

$$MEOP * 1.2 = 1124.24 \text{ psi} * 1.2 = 1349.088 \text{ psi}$$

Which was rounded up to just over 1350 psi during the actual test. This pressure was provided using a high-pressure air compressor and was held using our pressure regulators on our GSE plumbing board which can be seen mounted on the wall in Figure 6.2.5.1. We also had 3 pressure transducers reading pressures throughout our system. From left to right in Figure 6.2.5.1, the pressure transducers (highlighted by the green squares) were reading the actuator pressure, fill pressure, and tank pressure respectively, although the actuator pressure wasn't.

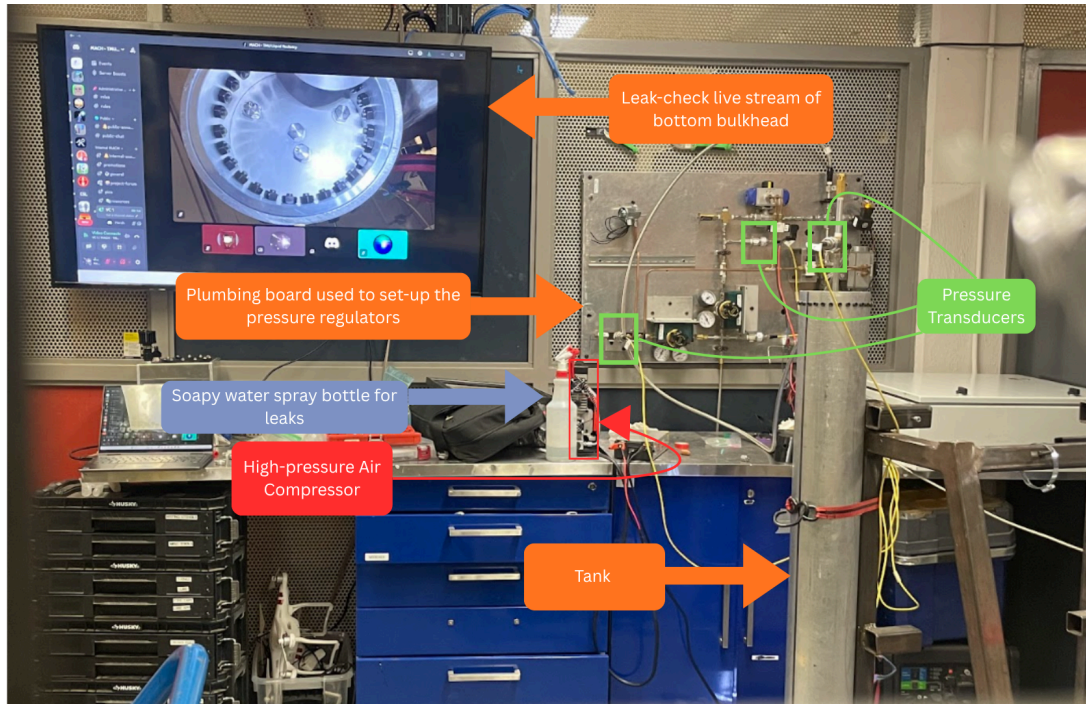


Fig. 6.2.5.1: Hydrostatic Pressure Test Set-up

The plumbing board was hooked up to our electrical hardware which measures and actively sends all readings to our Mission Control Server (in a separate room away from the high-pressure system). We also placed a phone connected to a discord call under the tank to see which of the NPT plugs were leaking. This made it easier to actively stop the leaking during our low pressure test (at 100 psi) since the leaks were minor and anyone watching the stream was able to point out any leaks. During the test, we had 6 people monitoring the plugs to check for signs of leaks. The top bulkhead had soapy water sprayed on the plugs so we were able to see foam from the other room if there were signs of any leaks.

The tank was filled with water to the top, surpassing the retaining ring holes, which were taped up using masking tape. The purpose of this was to have the tank filled with as much water as possible, and so that once we assembled the bulkhead and retaining ring onto the tank, there would be little-to-no air bubbles. This was verified though observing water in the valves attached to the bulkhead. The valves attached to the top bulkhead split into 3 passage ways: the manual dump, the pressure transducer as previously mentioned, and the air compressor hose connection.



Fig. 6.2.5.2: Hydrostatic Low-pressure Leak Check on Fill Bulkhead

Before reaching proof pressure, the system was gradually pressurized through intermediate stages of 100 psi, 500 psi, and 1000 psi. These pressure intervals were based on the MCAA Guide to Pressure Testing Safety [10]. At each pressure level, the system was held for approximately five minutes while all fittings, plugs, seals, and threaded connections were inspected for leaks or signs of distress.

After successfully completing the intermediate pressure tests, the pressure increased to the hydrostatic test pressure (120% of MEOP, or 1350 psi) which was held for 18 minutes. Throughout the hold period, the system remained leak-free with no signs of deformation or pressure loss. The hydrostatic test was completed successfully.

The system was safely depressurized and disassembled following completion of the test. A thorough inspection of the internal components was then conducted to identify any signs of deformation, damage, or other abnormalities. These internal components included the tank, o-ring, retaining rings and their bolts and nuts, and bulkheads. No evidence of permanent deformation or structural damage was observed.

6.3 Tank Stand

6.3.1 Detailed Design

The tank tripod consists of a center carrier, three legs, and anti-splay cables. Each leg section is press-fit into the carrier, and a quick-release pin is inserted through each leg to prevent it from falling out when the tripod is moved. It is important to note that these pins carry no structural loads. These cables connect each leg to a steel ring at the center of the base of the tripod, effectively preventing the “feet” of the legs from sliding apart. A cross section of said system can be seen in figure 6.3.1.1 below. The load cell and tank hang from an M12 eye bolt installed through the geometric center of the tripod legs. All carabiners, etc are human-rated.

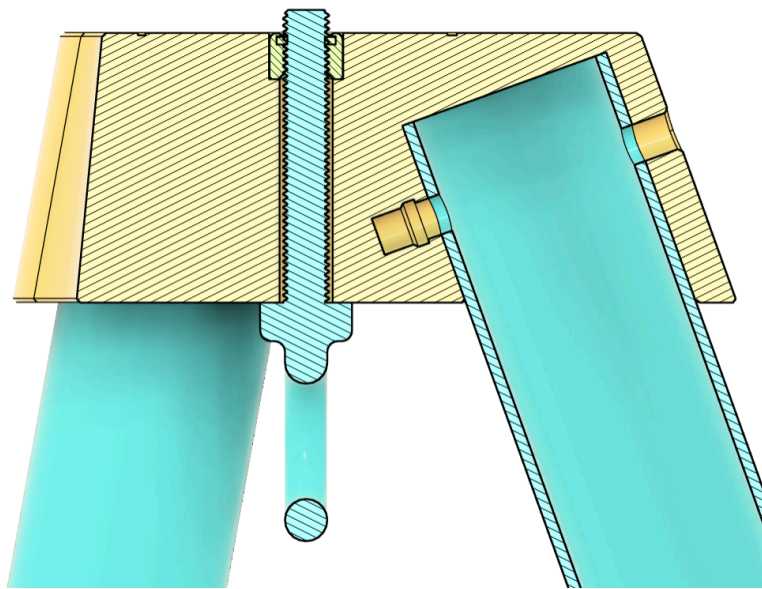


Fig. 6.3.1.1: Cross Section Tank Tripod Structure.

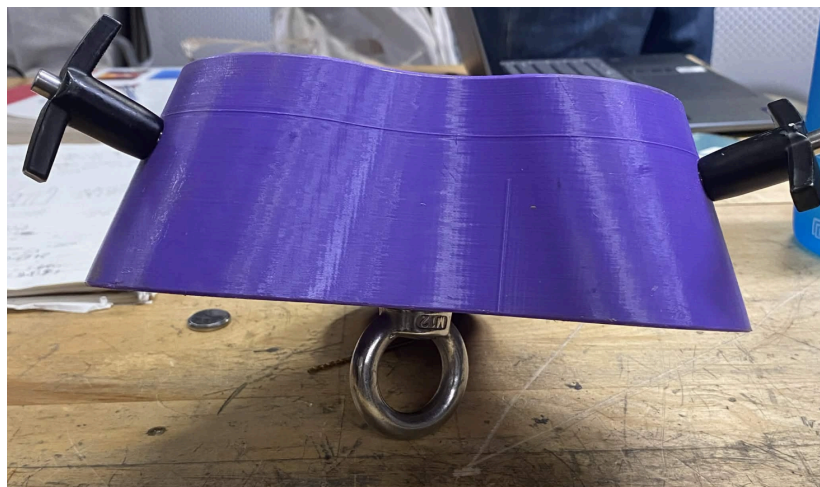


Fig. 6.3.1.2: Real life picture of tank stand carrier side view



Fig. 6.3.1.3: Real life picture of tank stand carrier top view

6.3.2 Manufacturing Process

The legs of the tank tripod consist of 2" galvanized steel pipe cut to length with a bandsaw. Holes for fixation to the carrier were drilled, guided by a 3D-printed hole cutting jig. The carrier was 3D printed in PETG with parameters adjusted to maximize inter-layer adhesion.

6.3.3 Analysis

The analysis for the tank stand was split into two parts, that being a simulation section and a real life static test to see if the tank stand meets the safety requirements. The goal was for the tank stand to be able to handle the weight of the tank with a factor of safety of two in testing environments.

6.3.3.1 Simulation testing

A static structural simulation was performed in ANSYS to evaluate the carrier under the 140lbs test load which is 2x the approximate weight of the tank. The load itself is applied at the central mounting boss, with the leg attachment points fixed to simulate real testing conditions. In terms of results, the total deformation, equivalent elastic strain, and equivalent (von mises) stress were all evaluated and pictures of each can be seen in figures 6.3.3.1 below.

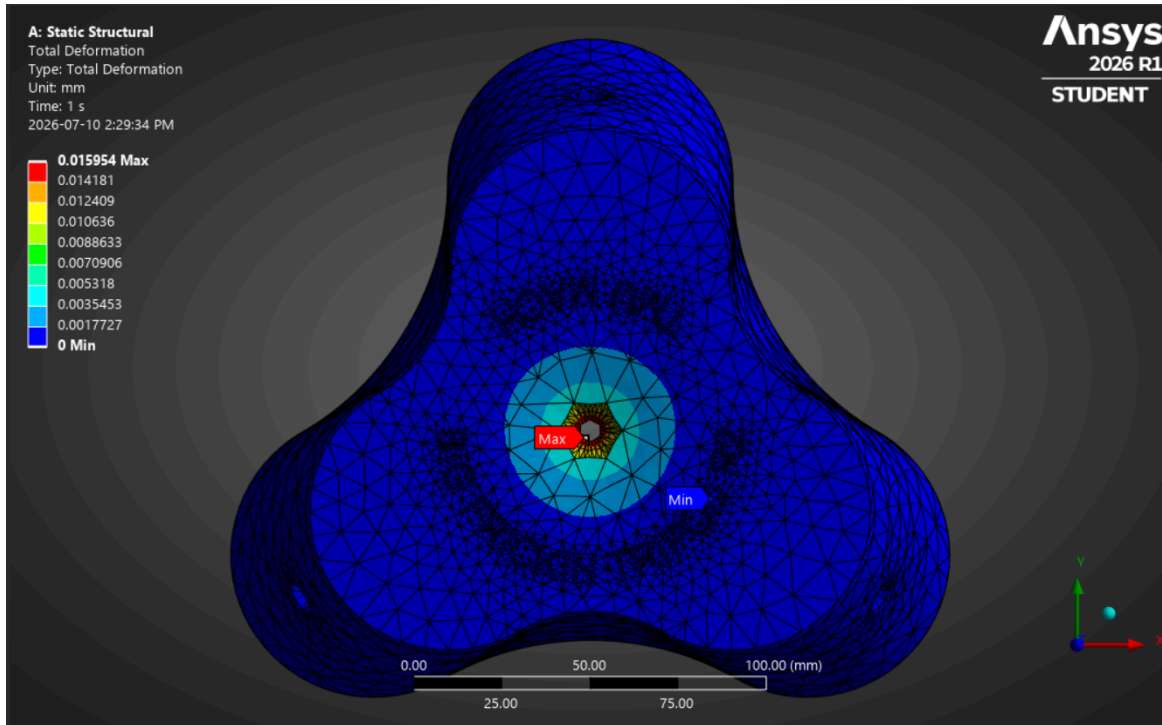


Fig. 6.3.3.1.1: Total Deformation in ansys static structural

The maximum total deformation was found to be around 0.01595mm, occurring at the central mounting boss where the load is applied. This deformation is negligible to the parts overall size of around 30cm across, indicating that the carrier remains effectively rigid under the current test load of 140lbs.

15.748mm

6.3.3.2 Real Life Static Test

The goal with the static test in real life was to see if the tank stand can handle the weight of the tank with a F_s of two. As the tank itself weighs in at an approximate 70lbs, we hanged 140lbs on the tank stand as seen in figure 6.3.3.1 below. To simulate 140lbs we used three 45lb plates and one 5lb weight all strapped onto the carrier.



Fig. 6.3.3.2.1: Non-destructive static test of tank stand

After the test, we found that there was no deformation on the carrier part proving that the tank can handle two times the weight of the tank.

7 Propulsion

7.1 SPRINT Engine

The SPRINT engine is a Mojave sphinx inspired liquid rocket engine utilizing nitrous oxide (N_2O) as oxidizer and ethanol (C_2H_5OH) as fuel. It provides a 250 lbs of peak thrust with a burn duration of 5 seconds, featuring a simple screw pintle injector and two solid rocket motor ignition systems. It performs at a chamber of nominal chamber pressure of 250 psig. Along with inspiration from Mojave, the initial engine sizing was done using NASA CEA and by subsequent hand calculations which helped in determining orifice sizes. The engine was designed to be modular and easy to assemble. Flanges at both ends of the chamber are used to clamp all the parts together by employing steel threaded bolts and lock nuts. The team maintains the doctrine on second party verification of these assemblies and torque specs. Torque verification of these fasteners and fittings will be employed in Post-fire sequences. The SPRINT engine has been hot fired at both internal team tests and Launch Canada 2025, proving the system effective performance for rapid engine testing [1].

Table 7.2.1: Seraphina Parameters

Parameter	Value
Propellants	Ethanol , N_2O
Total Impulse	5560.3 Ns
Nominal Burn Duration	5 s
Designed Thrust	1112.06 N (250 lbf)
O/F Ratio	2.1
Average Tank Pressure (25C)	819.7 psig
Chamber Pressure	250 psig
Isp (specific Impulse)	201.8s
Expansion Ratio	4
Combustion Chamber OD	3 in
Chamber Thickness	0.5 in
Throat Diameter	1 in
Cooling System	Heat Sink
Injector, Chamber & Nozzle Material	6061 Aluminum
Throat Material	Copper
Retainer Material	Steel

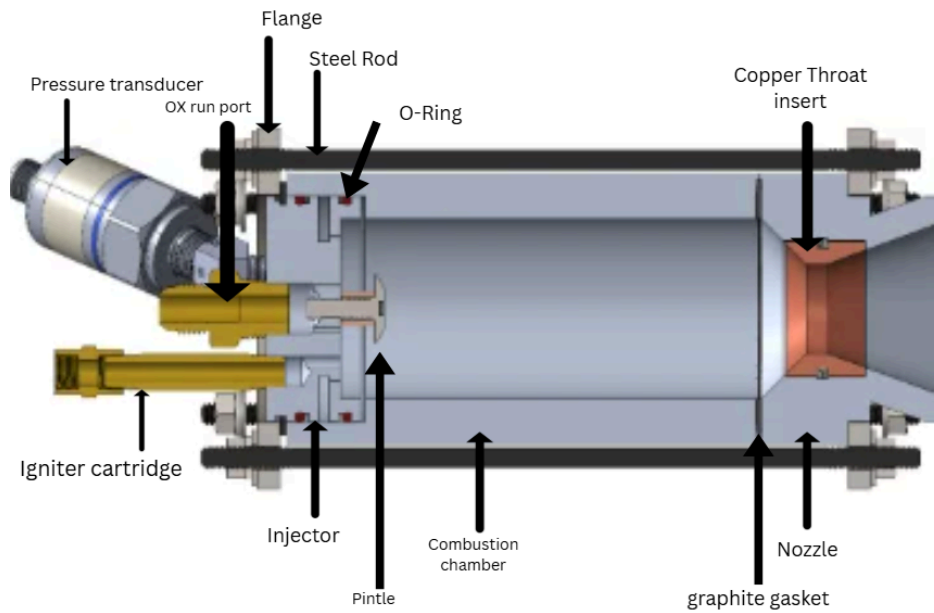


Fig. 7.1.1: Annotated cross section view of SPRINT Engine.

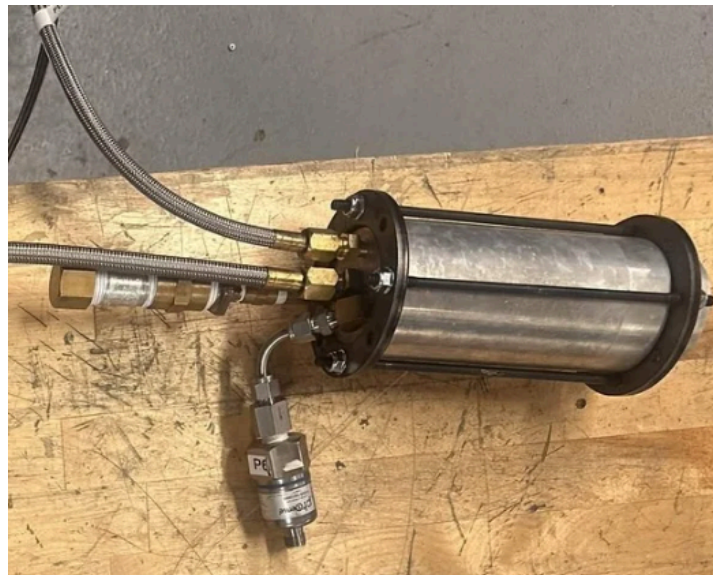


Fig. 7.1.2: Full assembly of SPRINT Engine

7.1.1 Combustion Chamber and Nozzle

Both the combustion chamber and the nozzle are made of 6061-T6 aluminum. The throat insert is made of copper. This was chosen due to copper's high thermal conductivity properties, which

would be beneficial in distributing the high heat flux experienced at the throat. These parts were manufactured with a lathe and a 3 axis CNC by JLC CNC. No team changes were made from the design developed by Halfcat. The interface between the combustion chamber and the nozzle is sealed with the use of a graphite crush gasket, which must be replaced after every disassembly.

7.1.2 Injector

The injector features a Oxidizer inlet, fuel inlet, pressure transducer port and an ignition port. The mating surfaces are sealed using two O-rings and are retained by a C-clamp upon which the flange rests. It employs a screw pintle design with the oxidizer coming down the center and gets deflected off a screw radially. The fuel flows into a volute between the O-rings and sprays into the chamber, colliding with oxidizer. The injector was manufactured with a lathe and a 3 axis CNC by JLC CNC. The injector itself follows a scrintle design based on the mojave handbook [1].

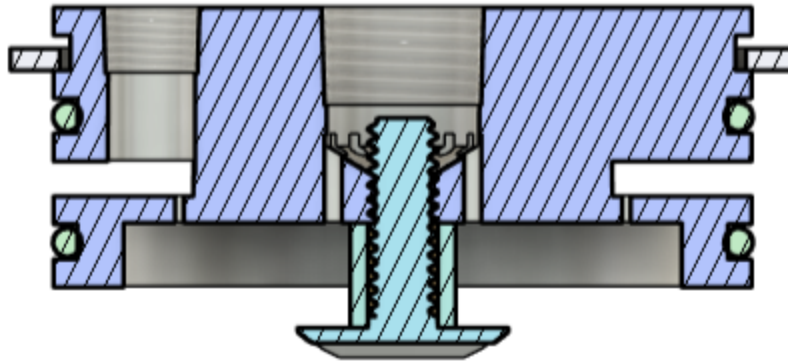


Fig. 7.1.2.1: Injector. Cross Section

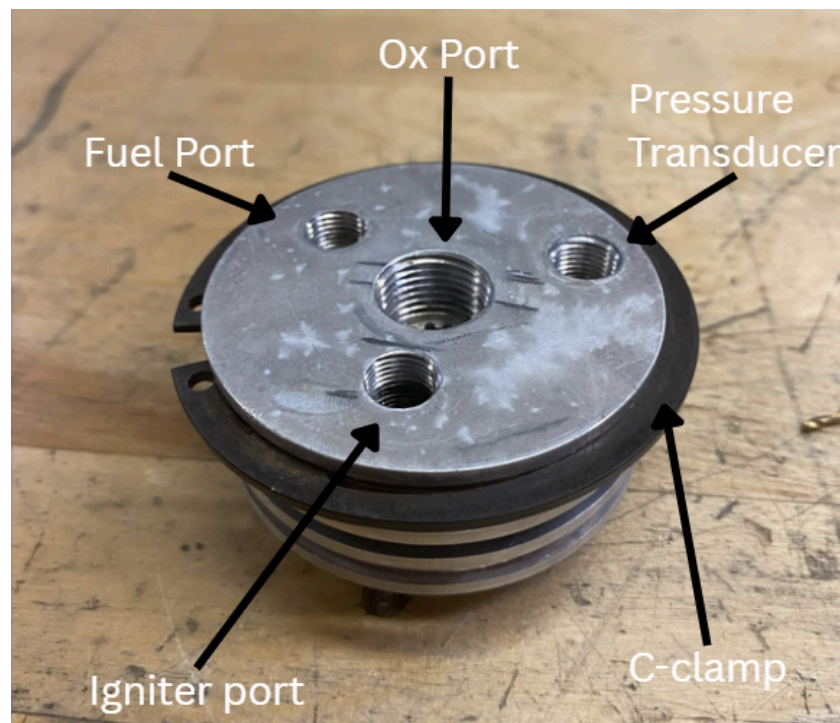


Fig. 7.1.2.2: Real picture of injector top view diagram

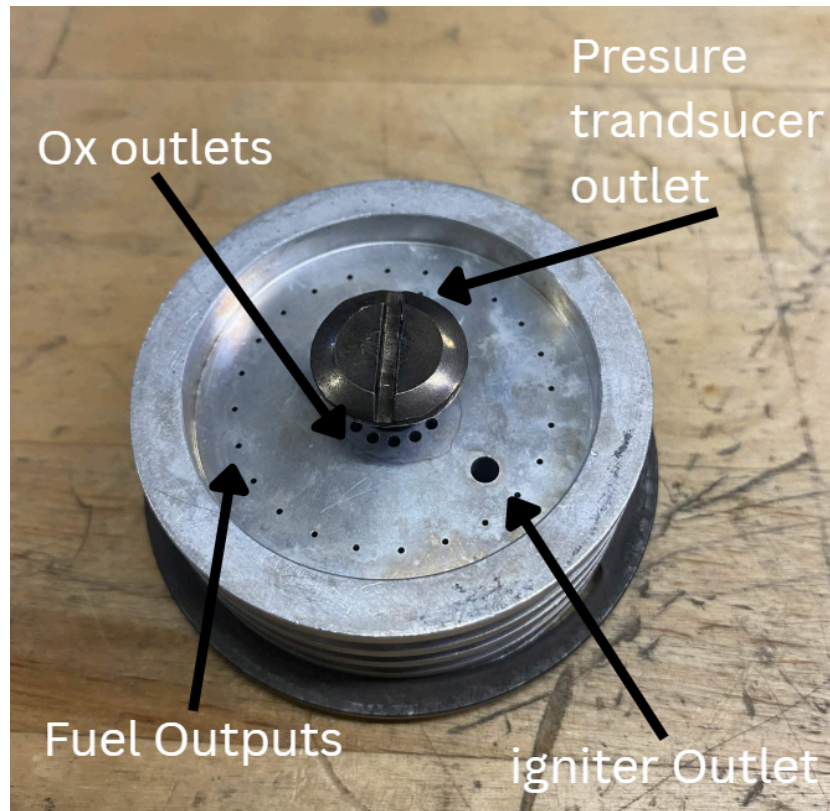


Fig. 7.1.2.3: Real picture of injector bottom view diagram

7.1.4 Ignition System

The engine used two Etes A3 motors housed in a cartridge installed onto the injector. The motors are ignited using e-matches to convert electrical pulse into extreme heat and a high-velocity flame plume. The ignition system has been validated with 4 successful ignitions at hotfires. After every hot-fire, the motors must be replaced but serve as an easy to assemble component with COTS brass and stainless steel plumbing parts from McMaster Carr. A key consideration of this method of ignition is the verification. The system employs visual confirmation from smoke of the motor ignition. The thrust of this motor is then read by the load cells and amplified. This reading puts the valve opening sequence into motion. It is important that the load cells are properly tuned as this was once the main cause of failed ignitions.

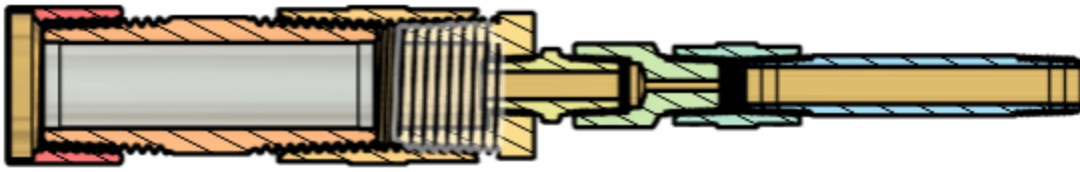


Fig. 7.1.4.1: Ignition Cartridge cross section view

7.2 Tank System

The propellant tank has a capacity of 13kg of propellant . This was due to the initial requirement of a burn for 7s when the initial goal was to achieve reignition through the development of a torch ignition system. The tank length was determined using Halfcat Sim, for a settled five second burn of 2.804 kg of Nitrous oxide and 1.402 kg of ethanol [3].

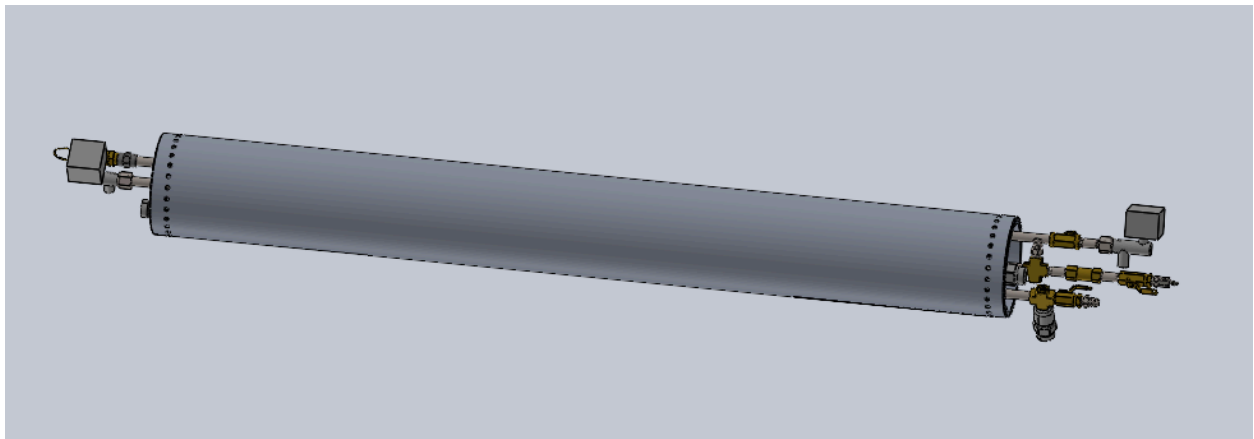


Fig. 7.2.1: Full Tank Assembly

7.2.1 Vent Bulkhead

This bulkhead is designed to sit within the top of the outer tank, secured with a retaining ring. Stringers can be seen within the bulkhead in figures 7.2.2.1 and 7.2.2.2, which are designed to support and keep the inner tank vertical. The inner tank is intended to sit on the lips of the stringer; this will also allow the nitrous to flow from the outer tank to the inner tank, pressurizing the ethanol. This bulkhead is equipped with three ports: pressure relief, pressure transducer for data acquisition, and vent ports. The bulkhead will utilize a burst disk pressure relief valve set at 1,000 psi with an orifice of $\frac{1}{4}$ ". A Normally Open solenoid valve will be utilized as a vent, to ensure it fails open in the event of loss of power. The orifice size is 0.3mm. The Bulk head will

be sealed with use of two BUNA O-rings seals (one for backup and redundancy) with dimensioning and sizing based on the Parker O-ring handbook guidelines for static sealing.

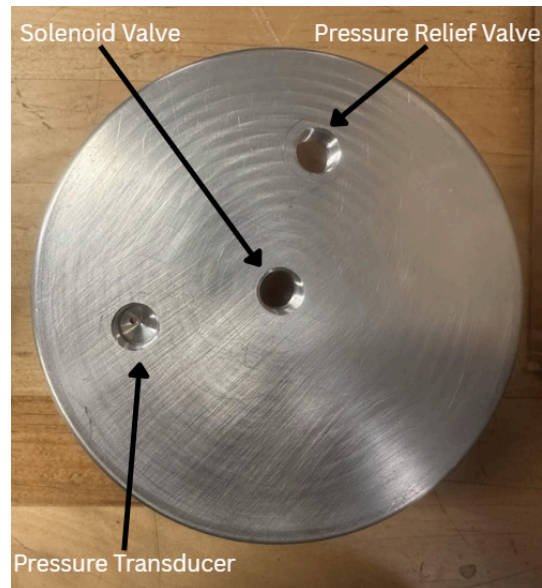


Fig. 7.2.1.1: Vent Bulkhead Diagram output view

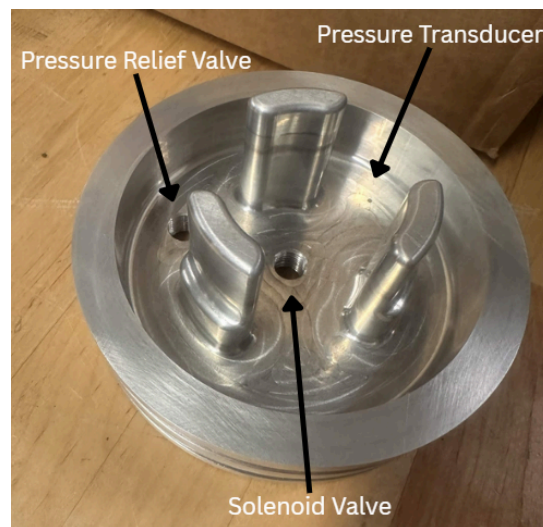


Fig. 7.2.1.2: Vent Bulkhead Diagram input view

7.2.2 Fill Bulkhead

This bulkhead seals the bottom of the outer tank, and is secured with a retaining ring. This bulkhead features ports that allow the tank to be connected to the fill and run lines, as seen in the diagram. The fuel line is to serve as both a fill and run line. This was done in order to optimize

space and for ease in assembly. The Oxidizer fill line will also serve as a dump for the tank, this will be done with the use of a normally open actuated ball valve on the GSE plumbing board. The orifice size will be $\frac{1}{4}$ ", which was chosen from the predetermined orifice sizes by Launch Canada in Design, Test and Evaluation Guide [8]. It also features a pressure transducer for obtaining fuel pressure readings. The bulkhead will be sealed with use of two BUNA O-rings seals (one for backup and redundancy) with dimensioning and sizing based on the Parker O-ring handbook guidelines for static sealing. In figures 7.2.3.1 and 7.2.3.2 below, the fill bulkhead can be seen.

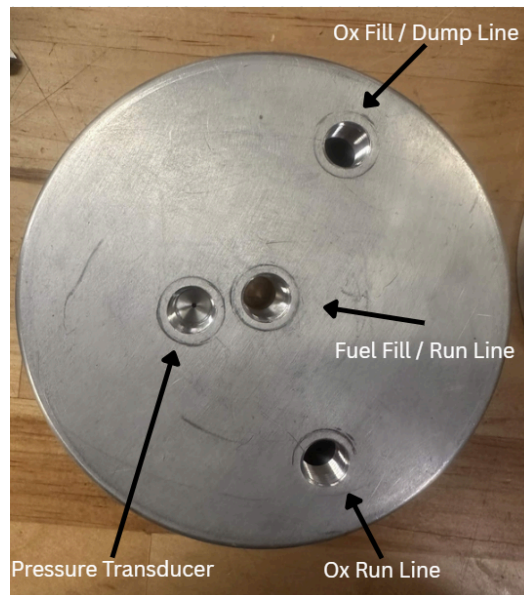


Fig. 7.2.2.1: Fill Bulkhead Diagram input view



Fig. 7.2.2.2: Fill Bulkhead Diagram Output view

7.2.3 Piston

The piston in our system will pressurize the fuel through the use of the self-pressurizing properties of nitrous oxide, and it will also be made of aluminum 6061-T6 like the surrounding internal tank. To ensure a proper seal as the piston slides through the inner tank, the piston will be equipped with 2 Buna-N O-ring seals to properly seal the both propellants as per the DTEG, with dimensioning and sizing based on the Parker O-ring handbook guidelines for dynamic piston sealing. The bore and length of the piston were sized based on guidelines to avoid the sticky drawer effect [5].

7.2.4 Interpropellant O-Ring Seals:

The O-ring sizes and groove dimensions were designed in accordance with the Parker O-ring Handbook using Buna-N seals [4]. The Fill and Vent bulkheads utilize identical sizes and groove geometries. The floating piston seals were designed using Parker's dynamic piston seal recommendations, while the seals between the internal tank and bulkhead were designed using Parker's static piston dealing guidelines.



Fig. 7.2.4.1: O-rings placed on the vent bulkhead

7.2.5 Testing and Validation

The components of the bulkheads, piston, retaining ring, and tank were validated during the Hydrostatic pressure test outlined in Section 6.2.5. This included testing the o-ring seals and the fit between each of these components. The parts were closely inspected following the test, and each of them maintained their structural integrity.

7.3 Propellant Feed System

The ground support plumbing system has been used for the past two years to supply oxidizer to the propulsion system [14]. Throughout this period, the system has undergone several incremental improvements. Minor upgrades are planned, including the replacement and reinstall of a few fittings to improve the system's reliability, serviceability, and overall system performance. For Launch Canada DTEG accordance, a COTS pneumatically actuated dump ball valve was fitted on the board with an orifice size of $\frac{1}{4}$ ". This valve has its default position set to open in order to initial propellant dump for abort or loss of propellant scenarios.

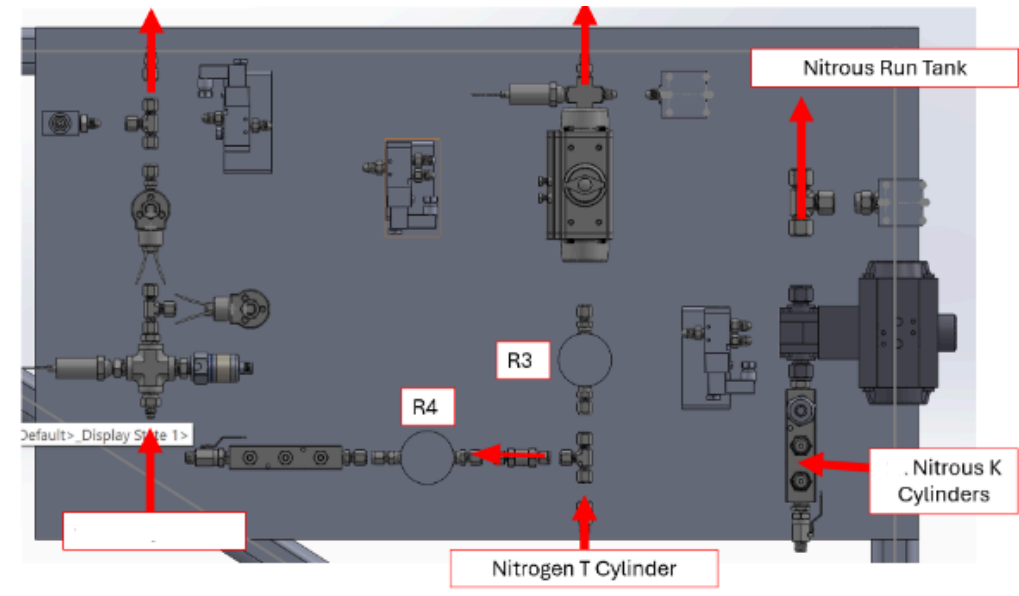


Fig. 7.3.1: GSE Plumbing CAD.

As can be seen in the preceding figure, the GSE plumbing components are to be mounted on a common panel. Pneumatic pressure supply to the pneumatic valves is supplied from a tap-off from the N_2 . The current assembled state of the GSE panel of plumbing has been presented in Figure 7.3.2.

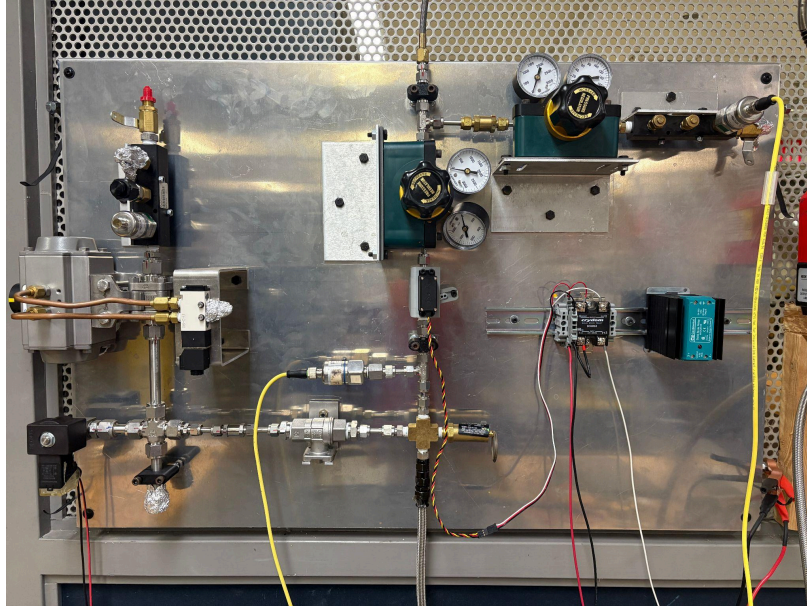


Fig. 7.3.2: GSE Plumbing.

Our P&ID (*Figure 7.3.3*) begins at the supply side, where both the nitrogen pressurant and nitrous-oxide cylinders are fitted with quick-disconnect couplings. Downstream of each bottle, a pressure regulator maintains the desired pressurization, and a high-capacity solenoid vent valve provides automated over-pressure relief. A secondary manual vent valve offers a redundant failsafe, and a linear-actuated valve in the nitrous feed line enables precise remote shutoff. Upstream of the nitrous-oxide, an interstitial purge valve connects the N_2 and N_2O circuits allowing us to flush the oxidizer plumbing with inert gas before and after testing. Ethanol is introduced manually via a hand-pump into the fuel side of the piston tank. Finally, four pressure transducers, strategically placed across the combustion chamber and feed lines provide real-time data for system monitoring and post-test analysis.

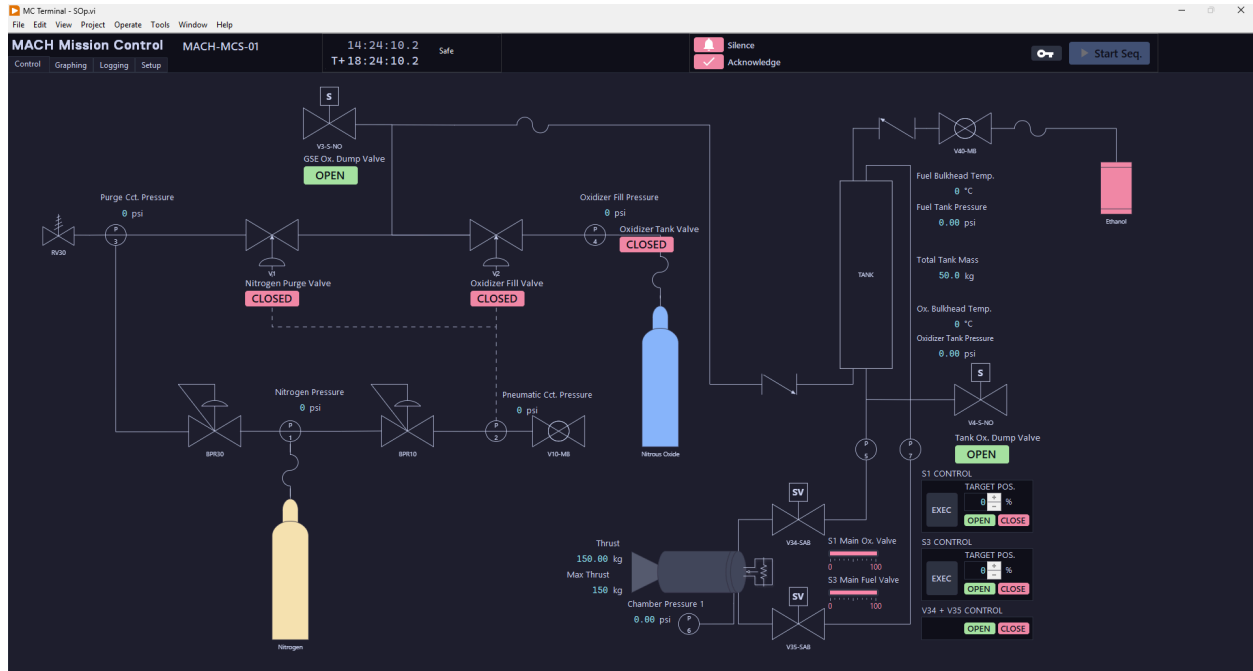


Fig. 7.3.3: System plumbing and indication diagram.

Table 7.3.1: Valve, Regulator and Line Orifice Sizes

Components	Orifice size (in)
Nitrogen supply line	0.250 (4 AN)
Pressure regulators	0.250 (1/4 NPT)
Manual ball Valves	0.250 (1/4 NPT)
Burst disk Pressure relief valve	0.250 (1/4 NPT)
Nitrous Oxide supply	0.500 (8 AN)
Nitrous Oxide Fill	0.375 (6 AN)
Pneumatic ball valves	0.250 (1/4 NPT)

7.4 Auto Fueling System

7.4.1 Components

Fuel filling has previously been an issue for MACH due to our fuel pump mechanism which consisted of a bucket, hose clamps, a plastic hose, and a manual hand pump. It was prone to spilling due to its design, making it hard to fill our (previous) fuel tank from the top. To alleviate this inefficient and messy procedure, the bucket-pump ethanol fill system was upgraded to an automatic fuel loading system. The new system uses COTS automotive racing-grade fuel handling equipment to allow the fuel tank to be automatically loaded from a ground-level holding tank into the inner pressurized fuel tank. This means that fuel is never handled by humans apart from pouring it into a holding tank below knee level. This significantly reduces the risk of fuel spillage and human contact with fuel.

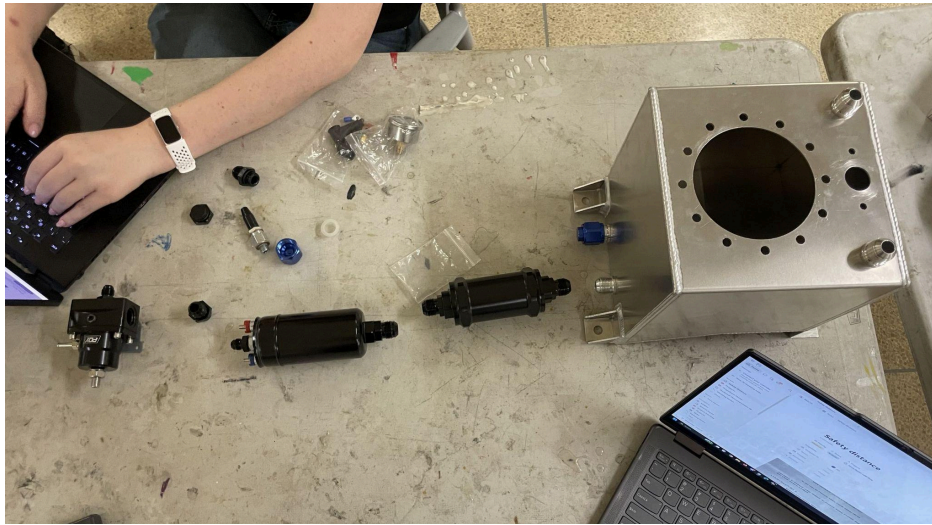


Fig. 7.4.1.1: Base components of autofuelling system

7.4.2 Testing and Validation

The auto fueling system is made up of Evil Energy components, including a fuel cell breather/vent air filter for filtering particulates, a fuel pressure regulator, and an electric fuel pump. An initial test was conducted with ethanol circulating through the fuel system at a constant rate of 255 litres per hour and a constant pressure of 20 psi, cycling back into itself, and a short clip of this test is included in Appendix C. Since the system requires a 1.402 kg ethanol charge per five second burn, as noted in Section 7.2, this flow rate corresponds to a fill time of roughly 25 seconds when using an ethanol density of approximately 0.789 kg/L, which is a significant reduction from the previous bucket and hand pump method that took around 5-10 minutes depending on if complications such as fuel spillage and cumbersome to operate.

8 Electronics & Software

8.1 Hardware

8.1.1 GSE Overview

The hardware system, pictured in figure 5.3.1, is designed to collect accurate telemetry and enable precise control over the bi-propellant liquid rocket while providing maximum possible safety. The system utilizes various instrumentation and control electronics to enable seamless and reliable control over the liquid rocket. The Labjack T7-Pro is the primary device utilized for instrumentation and control over the analog measurement devices. Moreover, the digital relays and servos are controlled by the CLICK PLUS C2-01CPU programmable logic controller. These systems are designed to be primarily operated on software, and are thus routed through the Ethernet Hub and then controlled remotely. Nonetheless, the control systems still include fail-safe contingencies and manual override capabilities.

The ground support equipment (GSE) houses all critical hardware, as such it is IP66 rated and can thus protect the electronics from the harsh conditions experienced on the launch pad. The GSE capabilities consist of analog measurement devices, PWM-controlled servo and mechanical relays. To ensure electrical performance and reliability the connectors utilized were IP67 rated. The capabilities of the system listed below:

Table 8.1.1.1: GSE Input/Output Connections

Input/Outputs	Amount	Connector	Use cases
	Supported		
Thermocouples	6	K-Type Connector	Measure temperature at critical points throughout the system.
3-wire Analog Sensors & Actuators	22	3-Pin M12 Connector	Monitor parameters such as fuel pressure and level. Control servo-actuated valves.
Load Cells	6	5-Pin M12 Connector	Measure engine thrust
12V Relay Outputs	12	2-Pin M12 Connector	Control solenoid valves Fire engine ignitor

While we were designing the physical architecture of our system, we drew inspiration from other launch companies, but more importantly, how similar systems are developed in other industries all together. We were looking for a distributed architecture that allows multiple devices to communicate in real-time with each other over a standard protocol. This is when we've

discovered that the industrial control and automation sector has been doing this for decades already, and was when we were introduced to Modbus. As Modbus allows you to interface with industrial control systems over Ethernet, we found it to be the best option for us to communicate between our systems reliably. As Modbus facilitates communication over TCP/IP networks, it's inherently error-prone and self-checking [9, p. 2]. Additionally, this turned out to be the most convenient choice, as LabJack, CLICK PLC, and LabView all natively supported the protocol. This allowed us to integrate all of our devices, both on the field and in mission control, over a single unified cable, as seen in Figure 8.1.1.1.

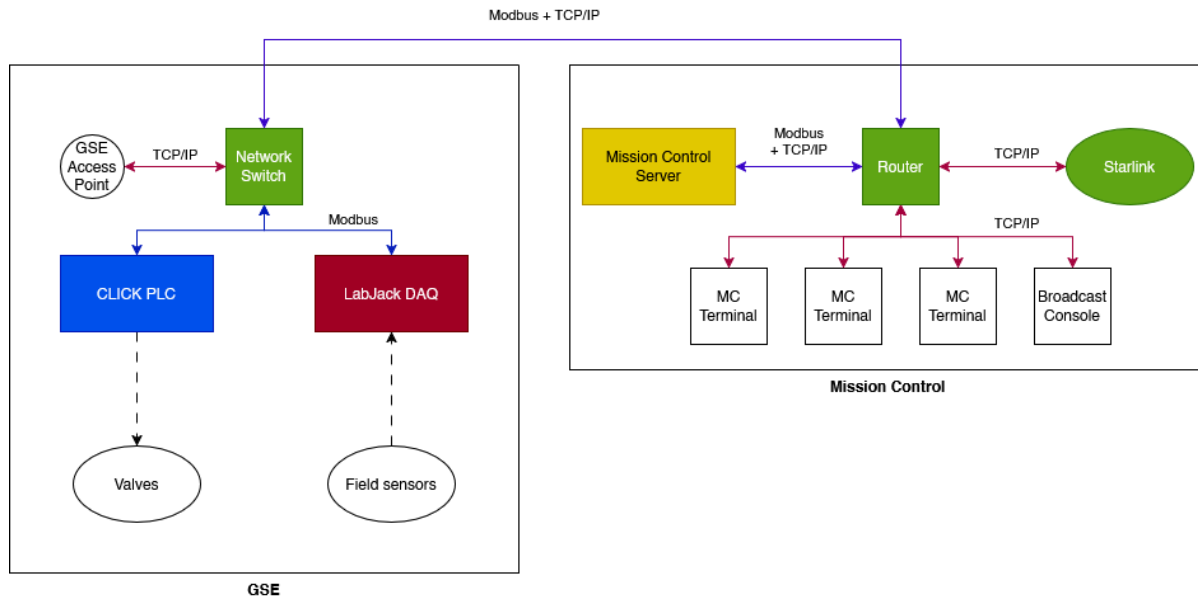


Fig. 8.1.1.1: High-level system architecture overview

For static tests, we relinquish all control to the MACH Mission Control Server, referred to as the MCS. The MCS, running LabView, acquires data from the Labjack, computes the corresponding action/reaction, and subsequently issues a command to the PLC to act on said action/reaction. In a way, this effectively “brainslugs” the PLC, leaving most of the logic to the MCS. This design decision allows us to develop complicated sequences and iterate on them faster than would be possible on just a PLC. However, that’s not to say that the PLC itself is not doing any computing. For low-level hardware control and safety interlocking, the PLC excels at doing these repetitive background tasks, hence why the responsibility of these two tasks remains with it.

8.1.2 Power Analysis

As seen in table 8.1.1.1, our GSE is able to support a large array of sensors, initiators, and actuators. In order to ensure the reliability of the system, it was imperative that our system would be able to supply a full-load of power consumers. Because of this, a comprehensive power analysis was performed.

Our system can be divided into 3 power “sections,” those being: 24VDC, 12VDC, and 5VDC consumers. As the power consumption of each individual consumer is characterized by the

manufacturer, a total current draw can be determined for each power section. A sample calculation for the 5VDC section is shown in figure 8.1.2.1.

$$A_{total} = A_{servo} \cdot n_{servo} + A_{LabJack}$$

$$A_{total} = 2A \cdot 4 + 0.280A = 8.3A$$

Fig. 8.1.2.1: Sample power draw calculation for 5VDC consumers.

These calculations are then used to select appropriate power supplies that can provide the necessary current. It's important to note that only power supplies with over-current protection (OCP) and automatic recovery from an OCP event are used, which prevents a sustained loss-of-power in case of an electrical fault. In addition to driving power supply selection, these calculations also dictate which wire gauge is appropriate for a particular circuit by referencing a current rating versus. AWG (American Wire Gauge) chart [12]. The complete power analysis diagram, along with the chosen power supplies can be seen in figure 8.1.2.2.

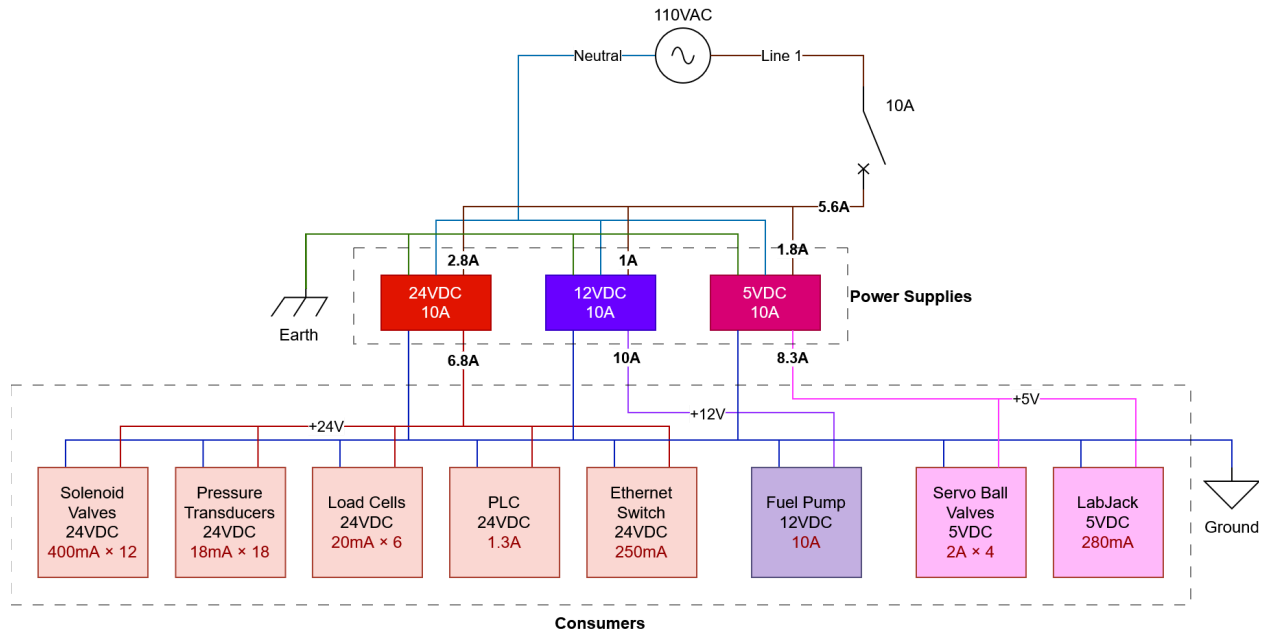


Fig. 8.1.2.2: GSE power analysis diagram showing current draw.

Of course, these calculations assume a worst-case scenario of every single consumer drawing max-current, while the actual total power consumption of the entire system is measured on average at 2A (35% of total power draw).

In order to provide power at remote sites, such as Launch Canada, MACH utilizes a 3MW (3000W) gasoline generator, providing ample power along with head-room for surges and in-rush events. However, this opens the possibility of a loss-of-power event caused by fuel-exhaustion. To prevent this, it was decided to add an uninterruptible power supply (UPS) in series with the GSE and generator. Based on maximum top-level power draw determined in table

8.1.2.1, the CP1500AVRT UPS from CyberPower was selected, where the relevant specifications for it [13] can be found in table 8.1.2.2.

Table 8.1.2.1: Top-level system power draw.

Top-level system component	Max power draw (W)
Ground Support Equipment	616
Mission Control Terminal (3)	65×3
Mission Control Server	65
Max total power draw	876

Table 8.1.2.2: CP1500AVRT relevant specifications.

Parameter	Value
Power output	900 W
Runtime at Full Load (900 W)	3 minutes
Runtime at Half Load (450 W)	11 minutes

As our expected total power draw is close to the rated full-load of the UPS, the runtime is likely to be roughly 3 minutes. This leaves ample room to abort and safely shut-down the system at any stage. More information about specific abort modes can be found in later sections of this chapter.

8.2 Software

8.2.1 Overview

A cornerstone of MACH's system is the software that runs the entire show. Developed over a year, we've found success in developing with LabView, an industry standard development platform used by giants such as NASA, SpaceX, and ULA. Using their language, we're able to rapidly develop, test, and deploy reliable, error-safe software.

When working with rockets, it's important to understand what risks we're undertaking, and what our sources of errors are. In our case, we found the most error-prone component of our operations to be humans. By depending on these already error-prone "machines" to execute a sequence of operations in perfect order and with tight timing, we wouldn't even be able to get a single ounce of thrust from our hardware. MACH has decided to eliminate this source of error directly at the source. We're the first team at Launch Canada to employ a fully automated

sequence during our terminal count and other critical phases of our operations. This means that at roughly 90 seconds before our engine fires, right after the Systems controller pushes the “Enable Auto Sequence” button, the software takes full control authority of the system, with the human operators supervising the entire process. While the operators still retain the ability to step in and manually change certain aspects of the process, or even abort if needed to, a large portion of the system is supervised by software as well.

To date, we’ve seen large amounts of success with our automated test and launch sequences. An example of our system performing as intended was during our January static hotfire. Due to nonnominal weather conditions that day, our propellant significantly outweighed our oxidizer. This caused a small fire to erupt at the throat of the engine at the conclusion of the test burn. Before any of our operators or field personnel could react to the situation, the system immediately entered a pre-programmed abort mode and extinguished the fire using purge gas, subsequently safing the system and preventing a catastrophic situation from developing.

A large portion of the time spent programming goes to developing the ground support equipment. This includes the GSE hardware itself, and the mission control terminals. Unique to Launch Canada, MACH makes use of multiple mission controllers, each responsible for a portion of the system. A non-exhaustive list of control positions at MACH are: Flight/Test Director, Flight/Test Conductor, System Operations, Ground Operations, Telemetry, and Recovery in cases where we’re launching. Each operator must be able to access real-time sensor readouts, states, alarms, and other data-points. As such, LabView was chosen because of its scalability and support for real-time control systems.

Over the past year, MACH has designed proprietary data logging systems, hot-swappable control sequences, a decentralized control architecture running on a dedicated server, and many other advancements in small liquid-rocket control systems. Our system, by design, allows for our team to develop new modules that integrate seamlessly with our custom control framework, with the only requirement being that the program has access to our control network infrastructure.

8.2.2 Software architecture

One of the largest risks that we face with our software is unreliability. When dealing with real time data and precision timing, having one system fail creates a domino effect, impairing all of its ancestor systems. To mitigate this, we divided our mission control server into multiple different programs, all running synchronously with each other. Sitting at the top of our system is a Watchdog routine, whose only responsibility is to monitor the state of its subordinate programs for errors, exceptions, or other halting issues. Of course, this brings the accountability of the watchdog program into question, as ensuring that it itself is error free is difficult. Our solution was to have the main server program also monitor the Watchdog, and to ensure that it’s running correctly.

Through various internal and external communication buses, all of the programs that comprise our mission control server are able to communicate with each other. Some buses allow for

extremely quick, FIFO (first-in-first-out) one-way communication, while others are bidirectional, as seen in figure 8.2.2.1. Additionally, a separate conflict monitor is responsible for ensuring that the commands being sent to the PLC Communication Handler do not conflict with the states being read by the DAQ Communication Handler (responsible for acquiring data from the Labjack).

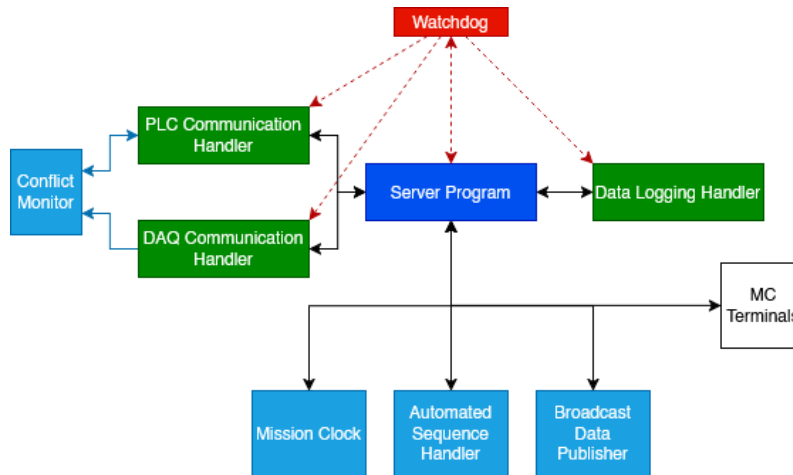


Fig. 8.2.2.1: Mission Control Server architecture

8.3 Data Analysis Plan

During tests or flights, all of the data produced by the various sensors is aggregated and sent in real time to the data-logging module of our software stack. Using our proprietary data logger for LabView, we're able to log at-rate, meaning we can review exactly what the computer gets at every single update, or for easier analysis, log at a set frequency.

Having data about what the sensors were reading is one thing, but knowing what was going on in the rest of the system can be crucial to understanding how certain actions play off of each other. To facilitate this, we log every single user action, system event, error, and interrupt, in addition to the sensor data we already collect. This allows us to trace issues back to the source, rule out issues with our software, and most importantly, increase the accountability of our mission controllers.

After each static or cold-flow test, the recorded data, formatted as comma separated value files (.csv), are saved, downloaded, and backed up for analysis using MATLAB or Excel. We generate time-series plots of all sensor channels along with gantt charts for sequence-related events. Using visual inspection while cross-referencing with our pre-programmed sequence and procedures, we confirm that each valve, pressure, temperature, force, and event line up with each other.

We apply basic scripts and formulas to compute key test metrics, including:

- Mean and maximum pressures across each transducer

- Temperature gradients and peak thermal loads
- Actuation delay and duration for each valve command

These graphs and processed data files can now be used in team reports and safety reviews, while the raw .csv files are archived for traceability and potential reanalysis. This approach supports quick feedback loops during test campaigns while ensuring traceable and well-documented data history.

9 Range Safety

9.1 Hazard Analysis

9.1.1 Compressed Gases

Compressed gases present several hazards to personnel and equipment on the test pad. High-pressure nitrous oxide (N_2O) and nitrogen (N_2) are stored in supply cylinders and used throughout the propulsion system. Failure of a pressurized cylinder, regulator, or plumbing component could result in the uncontrolled release of stored energy, producing high-velocity projectiles or flying debris. Additional hazards include frostbite from rapidly expanding gases and the potential for damage to pressure-sensitive equipment due to overpressurization.

To mitigate these hazards, personnel handling compressed gases receive documented training covering cylinder transport, regulator installation, leak checking, and emergency shutdown procedures. Engineering controls include pressure relief devices, appropriately pressure-rated components, secured cylinder restraints, and leak testing prior to operation. All pressure containing assemblies are proof tested prior to use, and pressure systems are remotely operated whenever practical to minimize personnel exposure.

9.1.2 Pyrotechnics

Pyrotechnic devices present hazards through their explosive and flammable properties. Our ignition system uses two A3 solid rocket motors and an electronic match (e-match) to initiate combustion. When installed, the pyrotechnic components remain mechanically isolated from the ignition circuit until it's physically armed on the pad. Electrical safing procedures, continuity checks, and controlled access to the ignition circuitry minimize the probability of inadvertent initiation.

During transportation and handling, all pyrotechnic devices are stored in secure, non-flammable protective containers and remain electrically disconnected from firing circuitry. Prior to installation, each motor and e-match is inspected for signs of physical damage or fouling.

9.1.3 Oxidizers

Nitrous oxide (N_2O) is a strong oxidizer capable of significantly accelerating combustion. Therefore, materials exposed to nitrous oxide are selected such that they are compatible with the oxidizer to reduce the risk of material degradation. Plumbing and components are cleaned prior to assembly to minimize contamination that could react with the oxidizer.

Following a hot fire or aborted test, the propulsion system is purged with nitrogen to remove residual oxidizer or fuel where applicable before personnel approach the system. This purge reduces the likelihood of unintended reactions during post-test handling and maintenance.

9.1.4 Flammables & Explosives

Flammable materials present significant hazards to personnel and equipment due to the risk of fire and explosion. Ethanol is the primary flammable liquid used by the propulsion system and has a flash point of approximately 13°C, making ignition possible under normal environmental conditions.

To reduce these hazards, ethanol is stored in approved containers and transferred only in well-ventilated areas away from potential ignition sources. Only the quantity of fuel required for testing is brought to the test site. Fire extinguishers and spill cleanup materials are positioned near fueling operations, and personnel handling fuel wear appropriate personal protective equipment throughout fueling and defueling activities.

9.1.5 Equipment Misuse

Equipment misuse includes improper assembly, incorrect torque application, installation of incorrect components, misuse of tools, and failure to follow established operating procedures. Such errors may compromise personnel safety, equipment integrity, or test success.

These hazards are mitigated through standardized assembly procedures, documented checklists, independent inspections, and appropriate personal protective equipment. Personnel receive training on the proper use of equipment before participating in testing activities. Required PPE includes, at minimum, safety glasses and closed-toe footwear, with additional protective equipment used where task-specific hazards are present.

9.2 Risk Assessment

The following table is used to evaluate various risks we identified and the measures taken to minimize their likelihood and potential impact:

Table 9.2.1: Failure Mode Assessment Table

Severity Probability					
	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Rarely (1)	1	2	3	4	5
Unlikely (2)	2	4	6	8	10
Possible (3)	3	6	9	12	15
Likely (4)	4	8	12	16	20
Certain (5)	5	10	15	20	25

Green - Acceptable

Yellow - Acceptable but Consider Risk Reduction

Orange - Acceptable with Further Risk Reduction

Red - Unacceptable; requires redesign/new mission parameters

9.2.1 Lack of Budget

Budgeting is important for us to consider in light of recent funding concerns. Inconsiderate appropriation of funds can leave too little left for important expenses such as manufacturing, transportation, or propellants. This can have severe (5) consequences, and without any checks in place is a risk possibility of (3). Implementations in place are to account for all incoming funding and to thoroughly plan outgoing expenses, including leaving room for the unexpected.

We are also making sure no unnecessary expenses are being taken, by carefully considering projects while avoiding taking on projects that would strain budgets. With proper monitoring, we will be able to keep the risk of going over budget to a low (1) level.

9.2.2 Transportation Logistics Failures

Transportation of the propulsion system, test equipment, and support structures to test sites presents significant logistical challenges. To manage these risks, we follow rigorous inspection procedures including multi-personnel verification to ensure all components are prepared and secure for transport. We also partner with logistics companies for reliable and timely delivery for long distance transportation. By designing modular components, transportation is simplified and assembly at the site can be carried out more efficiently.

9.2.3 Brain Drain

Having important talent in the team leave can cause issues with deadlines or even the ability to continue with certain projects. Without any warnings or anticipatory action, the severity is moderate (3) as workload and knowledge can be picked up by other members. However it still poses a threat as it would take considerable time to catch up. Since a majority of team members are upper year university students, it's a probable (3) risk that some will leave for co-op terms or graduation. To prevent the severity of this issue we first focus on keeping workload distributed. By spreading out responsibilities, the knowledge gaps become smaller, making the catch up time smaller. This also benefits newer members by allowing them to develop their skills and be put in a position to aid the team more quickly. The second approach is to stay organized and stay aware of when team members will be leaving. By mapping this out, important duties can be designated for more suitable members and avoid the catch up situation. By spreading responsibilities and staying organized, the severity of a member leaving becomes minor (2).

9.2.4 Engine Mount Failures

Engine mount setup consists of securing three earth anchors into the ground, with two positioned in the exhaust direction and one positioned behind the engine. These anchors secure the mount using guide cables that resist engine thrust during testing. Failure of the mounting system may result from improperly installed anchors, insufficient cable pretension, damaged hardware, or improperly secured cable attachments.

Without thrust stand verification procedures, the probability of failure is assessed as likely (4). The resulting severity ranges from moderate (3) to significant (4), depending on the failure mode. Loss of restraint could allow the engine mount to move unexpectedly, potentially damaging the engine, propellant tanks, or ground support equipment while compromising test data.

To mitigate these risks, cable pretension is verified before each test, attachment hardware is visually inspected, anchor installation is confirmed, and the completed mount is physically load checked prior to firing. Structural loads are validated against expected engine thrust with an appropriate factor of safety during design. These controls reduce the likelihood of engine mount failures to very rare (1).

9.2.5 Ignition Failures

The ignition system consists of two solid rocket motors that ignite the propellants within the combustion chamber. These motors are initiated by an electronic match positioned adjacent to the motors and fired through a digitally controlled ignition circuit. Failure may occur if the e-match fails to ignite, the solid rocket motors fail to ignite, or ignition occurs before propellant is present within the combustion chamber.

Without mitigation, ignition failure is assessed as likely (4) with moderate (3) severity. While ignition failures generally do not result in catastrophic hardware damage, they may require the engine and ground support equipment to be saved and reset before another test attempt.

To reduce this risk, continuity of the ignition circuit is verified immediately before arming, ignition components are inspected prior to installation, and solid rocket motors are stored in dry conditions until use. Ignition power remains inhibited until the automated launch sequence reaches the designated arming stage. These measures reduce the likelihood of ignition failures to unlikely (2) while maintaining the same severity rating.

9.2.6 Valve Sequence Failures

A series of manual and pneumatically actuated valves control the flow of nitrous oxide, ethanol, and nitrogen throughout the propulsion system. Failures may occur due to incorrect valve sequencing, incorrect valve position feedback, or software faults that result in valves operating outside the intended sequence.

Without mitigation, improper valve operation could cause significant (4) or severe (5) damage to the propulsion system or ground support equipment through overpressurization, unintended propellant flow, or improper purging. Less severe failures include premature propellant release prior to successful ignition. Without procedural safeguards, these failures are assessed as probable (3).

Risk is reduced through both engineering and procedural controls. The plumbing system incorporates check valves, pressure relief devices, burst disks, and physical separation between nitrogen and nitrous oxide systems to limit the consequences of incorrect valve operation. Automated valve sequencing substantially reduces the probability of operator sequencing errors while minimizing opportunities for incorrect manual intervention. Together, these measures reduce the residual severity to moderate (3) and the likelihood of occurrence to very rare (1).

9.2.7 Sensor Failures

Reliable sensor data is essential for evaluating engine performance and verifying safe system operation. Sensor failures may result in the loss of critical performance data or inaccurate measurements that affect post-test analysis. The severity of sensor failures is assessed as low (2), while the initial probability is moderate (3).

Prior to testing, all sensors are verified for proper communication with the data acquisition system, and measured values are compared against expected operating ranges to identify implausible readings before proceeding. These verification procedures reduce the likelihood of sensor failures affecting test operations to very low (1).

9.2.8 Propellant Leakages

To reduce these risks, all hoses are permanently identified using a standardized labeling system that matches their corresponding connection points. Torque specifications are documented for every fitting, and all critical connections are independently verified before pressurization. Leak checks are performed after assembly and before propellant loading to confirm system integrity. These controls reduce the probability of leakage to very rare (1).

For the quick-disconnect (QD) fueling system, the connector incorporates an internal shutoff mechanism that prevents fuel flow unless the fitting is fully inserted and locked. Proper QD connection is confirmed by an audible click and verified by pulling on the fuel umbilical prior to fueling. These design features and pre-fuel tests reduce both the severity and probability of improper QD installation to low (1).

9.2.9 Fuel Tank Failures

Fuel tank failures are catastrophic (5) events that may result from overpressurization, piston malfunction, structural defects, or manufacturing flaws. Without mitigation, the likelihood of such failures is assessed as moderate (3).

To reduce this risk, commercially-available pressure relief valves are installed on both the propulsion system and ground support equipment to prevent overpressurization. The piston geometry was designed to minimize the potential for tilting or binding within the tank, while PTFE bearing surfaces reduce friction and protect the tank interior from wear. In addition, all pressure vessels are tested prior to operation to verify structural integrity and identify defects before use.

These safety features and tests reduce the severity to moderate (3) by limiting overpressure events and reduce the likelihood of tank failure to unlikely (2).

9.2.10 Engine Failure

Engine failures may result from overpressure, combustion instability, injector blockage, structural failure, thermal damage, or nozzle failure. Such failures have the potential to damage propulsion hardware and ground support equipment and therefore pose a significant risk during static testing.

The risk of engine failure is mitigated through analytical design, structure analysis and verification, proof testing of critical components, and incremental static fire testing. All engine testing is conducted remotely out of line-of-sight.

The risk of fuel spills during loading has also been reduced through the replacement of the previous manual fueling method with an automated fuel loading system. The new system utilizes commercially available automotive racing-grade fuel handling equipment to transfer ethanol from a ground-level holding tank into the pressurized fuel tank. This design minimizes manual fuel handling, significantly reducing the likelihood of spills and personnel exposure while improving fueling consistency.

10 References

- [1] A. Sennott, C. Sharp, and Half Cat Rocketry, *Vehicle Design Guide HCR-5100*.
- [2] A. Sennott and C. Sharp, “How to Design Pressure Vessels, Propellant Tanks, and Rocket Motor Casings.” [Online]. Available:
<https://www.halfcatrocketry.com/s/How-to-Design-Pressure-Vessels-Propellant-Tanks-and-Rocket-Motor-Casings.pdf>
- [3] Half Cat Rocketry, “HalfCatSim.” [Online]. Available:
<https://www.halfcatrocketry.com/halfcatsim>
- [4] Parker Hannifin Corporation, *Parker O-Ring Handbook*. 2025. [Online]. Available:
https://www.parker.com/content/dam/Parker-com/Literature/Praedifa/Catalogs/Catalog_O-Ring-Handbook_PTD5705-EN.pdf
- [5] Kalsi Engineering, Inc., “Kalsi Seals Handbook, Chapter D21.” Sep. 30, 2020. [Online]. Available: https://www.kalsi.com/handbook/D21_Sticky_drawer_effect.pdf
- [6] Friends of Amateur Rocketry, “Liquid Nitrous Oxide – Temperature-Pressure-Density.” Nov. 2023. [Online]. Available:
<https://friendsofamateurocketry.org/wp-content/uploads/2023/11/Liquid-Nitrous-Oxide.pdf>
- [7] Aerospace Specification Metals Inc, “ASM Material Data Sheet, Aluminum 6061-T6; 6061-T651.” [Online]. Available:
<https://asm.matweb.com/search/specifcmaterial.asp?bassnum=ma6061t6>
- [8] Launch Canada, “Launch Canada Design, Test & Evaluation Guide.” 2026. [Online]. Available: <https://www.launchcanada.org/s/Launch-Canada-DTEG-R4.pdf>
- [9] Modbus, “MODBUS Application Protocol Specification V1.1b3.” Apr. 26, 2012. [Online]. Available:
https://web.archive.org/web/20250825211935/https://www.modbus.org/docs/Modbus_Application_Protocol_V1_1b3.pdf
- [10] Mechanical Contractors Association of America, *Guide to Pressure Testing Safety*, 2013. [Online]. Available:

<https://www.mcaa.org/resource/guide-to-safely-pressure-testing-steel-and-copper-piping-systems>

- [11] S. Sohaili Yekta, “Toronto Metropolitan University Student Branch: Building a Professional Community,” *Aerospace America*, Oct. 29, 2025. [Online]. Available: <https://aerospaceamerica.aiaa.org/institute/toronto-metropolitan-university-student-branch-building-a-professional-community>
- [12] The Engineering ToolBox (2003), *Wire Gauge Sizes: Current Ratings, Charts, Measurements, and Conversion Guide*. [Online]. Available: https://www.engineeringtoolbox.com/wire-gauges-d_419.html
- [13] CyberPower (2026), *CP1500AVRT, Specifications*. [Online]. Available: <https://www.cyberpowersystems.com/product/ups/avr/cp1500avrt/>
- [14] MACH TMU (2025), *LC2025 Design Report for SPRINT (Small-scale Prototyping for Rapid Iteration & Testing)*. [Online]. Available: https://machtmu.com/resources/MACH_LCR2025.pdf

APPENDIX A: LAUNCH CANADA COMPLIANCE REQUIREMENTS

A.1 System Requirements

A.1.1 Pressurized Fluid Systems

Table A.1.1.1: Launch Canada Compliance Requirements

No	Description	Notes (If required)
2.0	Propulsion Systems	The SRAD engine will use pressurized liquid propellants. Cold-flow tests will be carried out using water and liquid carbon dioxide.
R2.1.1	All SRAD motors shall be static fired, well characterized and tested before arrival at the competition, per Section 2.5. No second-party motors (i.e., those that are not COTS and not developed by the participating team) are permitted.	MACH will only static fire, so does not need to meet this requirement
R2.1.2	The total impulse for a rocket made with COTS components and entered into the Basic category shall not exceed 40,960 Newton-seconds (9,208 pounds-seconds, i.e., “O” impulse motor).	N/A, due to not being in basic category
R2.1.3	Non-Toxic Propellants Launch vehicles entered in the LC Challenge shall use non-toxic propellants.	The propellants for this engine design are: Fuel: Ethanol Oxidizer: Nitrous Oxide Pressurant: Nitrogen Safety Data Sheets from propellant suppliers.
2.2.1.2 Sealed Systems		
2.2.1.1	Pressure Definitions	All pressures will be defined according to 2.2.1.1. Eg. MEOP = 1.2x WP.

R2.2.1	Any sealed system or segment shall have a pressure relief device.	
2.2.1.3 Operational Envelope		
R2.2.2	Teams shall define the operational ranges their engines can launch under in terms of fill percentage and oxidizer pressure.	N/A
2.2.1.4 Design Standards		
R2.2.3	Any system, subsystem or component that will be pressurized with personnel in proximity shall comply with a recognized standard for the design and safe operation of such systems.	
R2.2.4	Any system, subsystem or component that will be transported while pressurized shall comply with the applicable Transport Canada and US Department of Transportation (DoT) standards	MACH will not transport pressurized vessels
2.2.1.5 Wetted Materials		
R2.2.5	All wetted materials (i.e., those exposed to a fluid) employed in a rocket's fluid systems shall be compatible with the fluid(s) and conditions (e.g., temperature, pressure, shock, vibration) to which they will be exposed.	
R2.2.6	Any materials in a fluid system or component that would not normally be directly exposed to a given fluid but could be exposed during a credible failure or by migrating downstream shall similarly be compatible with that fluid.	
2.2.1.6 General Cleanliness		
R2.2.8	Caps, plugs or other protective covers shall be used on all ports and openings in fluid systems to prevent contamination when not in use.	
2.2.1.7 Oxidizer System Cleanliness		
R2.2.9	No hydrocarbons shall be employed in any oxidizer system component, or in wetted components upstream of an oxidizer system.	
R2.2.10	All oxidizer system hardware (valves, plumbing, etc.) shall be thoroughly cleaned to an acceptable standard for oxygen service.	All plumbing will be ultrasonic cleaned ✓

R2.2.11	After cleaning, components shall be thoroughly dried in such a way that contamination is not introduced.	A custom sealed clean drying container will be used
R2.2.12	Cleaned components shall be maintained in that condition. This is typically done by capping / plugging all ports, and then further protecting the part by bagging.	
R2.2.13	All caps, plugs, bags or other protective material that will be used with an oxidizer system shall themselves be cleaned for oxygen service to avoid re-contamination	
R2.2.14	All components shall be presumed contaminated unless all the following are satisfied: • They were supplied in an oxygen clean condition, or were known to have been cleaned to an acceptable standard, AND • They have been constantly maintained in that condition, for example by capping, double bagging, etc.	
2.2.2.1 Metallic Pressure Vessels		
R2.2.15	Vehicle propellant tanks shall not have a burst pressure of less than 1.5 times the maximum expected operating pressure, and other pressure vessels shall not have a burst pressure of less than 2.0 times the maximum expected operating pressure. Maximum operating pressure is the maximum pressure expected at any point during pre-launch, flight, and recovery operations.	
R2.2.16	If a propellant tank is designed with a burst pressure of less than 2.0 times the maximum expected operating pressure, hydrostatic burst testing shall be performed to demonstrate that the design and manufacturing process actually achieved or exceeded the design burst pressure.	
R2.2.17 - R2.2.23 are not applicable		
2.2.2.3 SRAD Pressure Vessel Testing		
R2.2.24	Teams shall comply with all rules, regulations, and best practices imposed by the authorities at their chosen test location(s).	
R2.2.25	Prior to use, pressure vessels intended for static testing or flight shall be proof tested.	

R2.2.26	Proof pressure shall be selected such that the gross stress level in the tank during the proof test does not exceed 95% of the yield strength of the material and does not exceed 75% of the ultimate strength of the material.	
R2.2.27	The tank shall be designed such that the above requirement can be met with a proof pressure not less than 1.5 times the maximum expected operating pressure.	
R2.2.28	The proof pressure shall be held for not less than twice the maximum expected system working time.	Working time shall not be more than 1 minute, therefore we will test for 2 minutes.
R2.2.29	Proof testing shall always be performed with an incompressible fluid such as water - NEVER with gas.	
2.2.2.3.2 Burst Testing applicable for:		
- Any metallic pressure vessels with a design burst pressure of less than 2.0 times the maximum expected operating pressure; - Any composite pressure vessel.		Burst testing will not be done.
2.2.3.1 Remote Operation		

R2.2.32	Any experimental pressure vessel, system or component thereof with a burst pressure less than 4.0 times the maximum expected operating pressure (i.e., factor of safety of 4.0) shall only be pressurized and de-pressurized remotely.	The only manual actuation will be opening the globe valve of our supply tanks. This ensures the only section under pressure when personnel are nearby are rated above a FOS of 4. All venting will be done remotely.
R2.2.33	Experimental pressure vessels shall never be approached by personnel while pressurized to more than 25% of its burst pressure.	
R2.2.34	Commercial pressure vessels pressurized above their rated pressure shall only be remotely pressurized and depressurized.	N/A We will not be pressurizing using COTS vessels rated above their rated pressure.
R2.2.35	Commercial pressure vessels pressurized above their rated pressure shall never be approached by personnel while pressurized above its rated pressure.	N/A
R2.2.36	Experimental pressure vessels shall incorporate electronic pressure measurement and telemetry to allow tank pressures to be monitored remotely.	Pressure transmitters on nitrous and ethanol sides will be employed
R2.2.37	Commercial pressure vessels pressurized above their rated pressure shall have electronic pressure measurement and telemetry to allow pressure vessels to be monitored remotely.	N/A
2.2.3.2 Overpressure Protection		
R2.2.38	Pressure relief devices or features shall be incorporated on all systems having a pressure source which can exceed the maximum allowable pressure of the system, or where the malfunction /failure of any component can cause the maximum allowable pressure to be exceeded.	
R2.2.39	Relief devices shall be sized based on the worst credible failure that would cause the pressure to rise to a hazardous level	

R2.2.40	Under no circumstances shall the pressure in the system exceed 110% MEOP. Relief devices shall be used where necessary to satisfy this requirement.	
R2.2.41	All pressure relief devices shall be sized to provide relief at full flow capacity at the pressure specified above, or lower.	
R2.2.42	Only commercial burst disks shall be utilized to satisfy these requirements.	
	R2.2.42, R2.2.43 are not applicable	
2.2.3.3 Filling, Draining & Venting		
R2.2.45	Propellant tanks shall be filled and drained from the bottom of the tank, near the top of the main propellant valves.	
R2.2.46	If a propellant has a high vapour pressure (i.e., above 40 psia) and its propellant tank is not a certified vessel with a safety factor of 4.0 or greater, the system shall be designed to allow remote filling and draining of the propellant.	
R2.2.47	Vents shall be routed to minimize the hazard they pose to personnel.	
	R2.2.48 - R2.2.51 are not applicable	
R2.2.52	The average oxidizer flow rate during abort shall be measured in testing, and data of this test shall be provided to LC staff.	
R2.2.53	The effective orifice of any plumbing used for draining the tank shall be in excess of the area of a single 1/8" diameter orifice for oxidizer tanks over 100 mL, 1/4" for oxidizer tanks over 2 L, 3/8" for oxidizer tanks over 10 L, 1/2" for oxidizer tanks over 25 L commensurate with a discharge coefficient of at least 0.3.	The tank vent will be a normally open solenoid valve

R2.2.54	For an engine test stand, fuel and oxidizer vents shall be kept separate to preclude the potential mixing of vented propellants.	
R2.2.55	For vehicles, fuel and oxidizer vents shall be routed to opposite sides of the vehicle.	
2.2.3.4 Failure Considerations		
2.2.3.4.1 Failsafe Remote Venting		
R2.2.56	Pressurized systems shall be designed to ensure that there is no credible failure case that would cause the loss of the ability to remotely depressurize the system. This requirement applies to all high-pressure sources on a vehicle or static test stand: propellant tanks, pressurant tanks, etc.	
R2.2.57	A rocket or engine test stand shall implement an emergency vent capability to relieve pressure to a safe level (less than 689 kPa (150 psig)) for all the pressurant and propellant tanks that is independent of the nominal control system.	
R2.2.58	Liquid and gaseous propellants having vapor pressures greater than 150 psig (e.g., N₂O) shall implement remote offloading for these propellants.	
2.2.3.4.1 Propellant Mixing		
R2.2.59	A rocket or engine static test stand that incorporates both a fuel and an oxidizer shall be designed such that a single malfunction of either the oxidizer or the fuel subsystems cannot result in the mixing of fuel and oxidizer.	
2.2.3.4.1 Leakage		
R2.2.60	Any separable fluid fitting is prone to leakage. Propellant systems shall be designed to ensure, as far as possible, that simultaneous leaks in fuel and oxidizer plumbing do not result in the propellants leaking to the same place and mixing.	
2.2.3.4.1 Use of Check Valves		
R2.2.61	Check valves shall not be used as flow restrictors, especially on high flow lines.	

R2.2.62	Check valves shall not be used as flame flashback arrestors.	
R2.2.63	Check valves shall not be used to seal the fill line after umbilical retraction unless the valve is inline with and actuatable through the connector.	
R2.2.64	Check valves shall not be placed downstream of a 90° elbow/bend.	
R2.2.65	Under no scenario shall a team use two check valves in a row.	
	R2.2.66 and R2.2.67 are not applicable	
2.2.3.4.1 Valves		
R2.2.68	Piloted valves shall abort in the depressurized state.	
R2.2.69	Control valves which provide the pressure to operate piloted valves shall depressurize the pilot line when the control valve is de-energized.	
R2.2.70	Dump and Vent Valves shall have a duty cycle 3 times the abort time or operational time whichever is more. Fill valves shall have a duty cycle 2 times the fill time or operational time whichever is more.	
R2.2.71	SRAD valves for use in a remotely operated system shall have a demonstrated probability of failure less than 5% over at least 20 tests using the same starting conditions, preparation and lubrication.	Our servo actuated ball valves will undergo rigorous testing
	R2.2.72 and R2.2.73 are not applicable	
2.2.3.4.1 Nitrous Line Filters		
R2.2.74	Nitrous line filters shall not be used in-line with any nitrous flow pathway between the mother/ supply bottle and the engine	
R2.2.75 - R2.2.81 are not applicable		

A.1.2 Ignition

Table A.1.2.1: Launch Canada Compliance Requirements

No	Requirement	Notes (If required)
R2.3.1	The action that arms the igniter shall be independent of the action that fires it.	Labview, with a PLC, a mechanical relay, and a remote lock out will be used as an ignition system.
R2.3.2	All ground-started propulsion system ignition circuits/sequences shall not be "armed" until all personnel are at least 15 m (50 ft) away from the launch vehicle.	
R2.3.3	The engine igniter shall be both physically and electrically isolated from the power source by a minimum of two independent inhibits.	
R2.3.4	The engine igniter shall be electrically isolated by switches in both the power and return legs.	
R2.3.5	The igniter shall be locked out to prevent any sort of ignition event when personnel are in the vicinity, and this lockout shall short and ground the igniter leads.	
R2.3.6	If pyrotechnic or otherwise electromagnetic interference (EMI) sensitive igniters are employed, the igniter wiring shall be in a separate cable, which is twisted, shielded, double insulated, and independent of all other systems.	
R2.3.7	Protection of igniter wiring by use of physical barriers or by physical location of components shall be employed such that short circuits to other power systems are impossible, even assuming loose or broken wires.	
2.3.3 Propellant Valve Interlock		
R2.3.8	The system shall incorporate features that prevent the main propellant valve(s) from opening until confirmation of nominal igniter operation has been	A camera will watch for smoke, then upon visual confirmation we

	received	will open the MFV and MOV. A thermocouple will also be installed to verify it.
R2.3.9	Systems that employ a fully automated open-loop start sequence that automatically opens the propellant valve(s) after firing the igniter, without any confirmation that the igniter is actually operating nominally, are deemed to be a safety hazard and shall not be used	

A.1.3 Engine Controls & Function

Table A.1.3.1: Launch Canada Compliance Requirements

No	Requirement	Notes (If required)
R2.4.1	The main pressurant valve open command shall be considered a hazardous command.	
R2.4.2	The main pressurant valve close command shall be considered a safety critical command.	
R2.4.3	The main pressurant valves shall be actuated remotely.	
R2.4.4	The main fuel and oxidizer propellant valve open command shall be considered a hazardous command.	
R2.4.5	The main fuel and oxidizer propellant valve close command shall be considered a safety critical command.	
R2.4.6	The main fuel and oxidizer propellant valves shall be actuated remotely	
R2.4.7	The fuel and oxidizer propellant tank vent valve open commands shall be considered a safety	

	critical command.	
R2.4.8	The fuel and oxidizer propellant tank vent valves shall be actuated remotely	
R2.4.9	If vent valves are controlled by a computer-based system, they shall be operable independently of the computer, in case of a software, power or control system failure.	
R2.4.10	Not applicable	
R2.4.11	When the pad controller is in the “lock out” condition, the control point shall be capable of commanding safety critical commands (vent valves open for the pressurant and propellant tanks).	
R2.4.12	When the pad controller is in the “lock out” condition, the control point shall be capable of monitoring safety critical measurements (pressurant and propellant tank pressures and temperatures).	
R2.4.13	When the rocket or static test stand pressurant or propellant loading operations are in progress, the pressurant and propellant tank pressures and temperatures shall be continuously monitored at the control point.	
R2.4.14	When the rocket or static test stand pressurant or propellant tank pressures and temperatures are at unsafe levels, the control point shall: • Warn the pad personnel to immediately stop loading pressurant or propellants into the rocket or static firing test stand. • Warn the pad personnel to immediately evacuate the area around the rocket or static firing test stand. • Command the pressurant and propellant tank vent valves open to vent the tank to safe levels	

R2.4.1 5	The rocket or static test stand shall protect safety critical command, hazardous command, and safety critical measurement wiring and pneumatic controls from fire during a launch or static firing.	
---------------------	--	--

R2.4.20 - R2.4.23 are not applicable

A.1.4 Propulsion System Testing

Table A.1.4.1: Launch Canada Compliance Requirements

No	Requirement	Notes (If required)
R2.5.1	Teams shall comply with all rules, regulations, and best practices imposed by the authorities at their chosen test location(s).	
R2.5.2	The following test shall be performed before firing a rocket engine: • Rocket Engine Combustion Chamber Test	
R2.5.3	The following tests shall be performed before each rocket or rocket engine test: • Function Verification Test • Leak Test	
R2.5.4	The following tests shall be performed as part of a rocket engine static firing: • Rocket Engine Test Stand Propellant Fill and Drain Test • Rocket Engine Test Stand Propellant Cold Flow Test • Rocket Engine Static Test Firing	
	R2.5.5 is not applicable	

2.5.1 Combustion Chamber Pressure Testing

R2.5.6	SRAD and modified COTS propulsion system combustion chambers shall be designed and tested according to the SRAD pressure vessel requirements.	
---------------	--	--

2.5.1 Leak Testing

R2.5.7	Leak testing shall be performed on fluid systems prior to operation, and any time a change to the system that could impact leak-tightness has occurred.	
---------------	--	--

R2.5.8	Air from a compressor shall not be used for leak testing an oxidizer system, as it is highly prone to contaminating the system with moisture or oil.	
---------------	---	--

R2.5.9	Leak testing shall be performed at pressures well below MEOP: typically, less than 150 psig, and not more than 25% of normal operating pressure.	
---------------	---	--

R2.5.10	Leaks shall be tested with soap solution, a leak detection fluid such as Swagelok “Snoop”, or a suitable leak detector.	
----------------	--	--

R2.5.11	Leak testing shall be performed on all fitting and line joints, valve stems and flanges.	
----------------	---	--

R2.5.12	My leak detecting fluid used on an oxidizer system shall be compatible with the oxidizer to avoid a fire or explosion hazard in case the fluid leaks into the system, or the oxidizer leaks out.	
----------------	---	--

2.5.3 Propellant Fill & Drain Test

R2.5.13	Rockets or rocket engine test stands employing SRAD or modified COTS propulsion systems using liquid propellant(s) shall successfully complete a propellant fill and drain test in their final configuration without any anomalies that would prevent test completion or compromise safety	
----------------	---	--

R2.5.1 4	Any anomalies encountered during a test shall be documented and provided to Launch Canada upon completion of the test.	
R2.5.1 5	If a proxy fluid is used, the system shall be disassembled, cleaned and dried as necessary to prevent contamination of the propellant.	
R2.5.1 6	Under no circumstances shall a hydrocarbon-containing test fluid be used in an oxidizer system.	
R2.5.1 7	A full fill and drain or full abort test shall be conducted after a ten-minute hold or a quoted maximum hold time which if less than 10 minutes will not be allowed to exceed 10 minutes.	
2.5.4 COLD FLOW TESTING		
R2.5.1 8	During development of a SRAD propulsion system employing one or more liquid propellants, cold flow testing shall be performed prior to progressing to hot-fire testing.	
R2.5.1 9	A cold flow test shall be performed on both rocket engine test stands and the rocket vehicles prior to first firing.	
R2.5.2 0	For cold flow tests performed without a thrust chamber, you shall ensure that the discharge does not present a hazard to personnel and equipment via the impact energy of the flow.	
R2.5.2 1	Cold flow tests shall provide the same pressure drop as the injector and combustion chamber and develop the same volumetric flowrate of the proxy fluid as would be expected with the real propellant.	
R2.5.2 2	If a cold flow test will involve release of propellants or test fluids to the environment, those fluids shall pose no hazard of environmental contamination.	
R2.5.2 3	If a fluid other than the propellant is used, the system shall be disassembled, cleaned and dried as necessary to prevent	

	contamination of the propellant.	
R2.5.2 4	Under no circumstances shall a hydrocarbon-containing fluid be used in an oxidizer system	
R2.5.2 5	For any propulsion system where emptying a propellant tank by dumping a propellant through the combustion chamber is part of the abort procedure, or an option, the thrust generated by that action shall be determined	
2.5.5 Static Hot-Fire Testing		
R2.5.26 is not applicable		
R2.5.2 7	Prior to hot fire testing, the team shall submit their test stand design and procedures for a safety review per the Launch Canada Requirements for Static Test Firing Approval.	
2.5.5 Engine Test Stands		
R2.5.2 8	Final testing for all deliverables including cold flow, hot fire and abort testing shall be performed on the flight hardware with all systems available on the flight vehicle present.	
R2.5.2 9	If a test stand is used with liquid propellants, it shall employ materials that are tolerant of propellant spills and minimize the chance of a fire occurring or spreading.	
R2.5.3 0	The test stand shall be firmly anchored to the ground in such a way that it cannot move or slide under at least 2x the maximum load to which it will be exposed.	
R2.5.31 - R11.2.5 are not applicable		

Appendix B: Detailed Design Trade Studies & Calculations

Tank bolt calculations:

The following calculations show our process for calculating the number and size of screws needed, along with any relevant stresses they may experience.

Bolt Shear Stress:

$$\sigma_{bolt\ shear} = (\frac{\pi}{4}D_{i,casing}^2 \times MEOP) / (N \times \frac{\pi}{4}d_{bolt,minor}^2)$$

$$\sigma_{bolt\ shear} = (\frac{\pi}{4}(5.625)^2 \times 1124.4) / (28 \times \frac{\pi}{4}(0.2062)^2) = 29883.43642\ psi$$

$$FS_{bolt\ shear} = \frac{0.75 \times UTS}{\sigma_{bolt\ shear}} = \frac{0.75 \times 170000}{29883.43642} = 4.266577586$$

Bolt Tear-out Stress:

NOTE: Calculations are based on a single row of 28 bolts on either side of the tank

$$E = 1\ inch$$

$$E_{min} = E - \frac{d_{major}}{2} = 1 - \frac{0.2489}{2} = 0.87555$$

$$F_{bolt} = \frac{\frac{\pi}{4}D_{i,casing}^2 \times MEOP}{N} = 997.9246274\ lbf$$

$$\sigma_{tear-out} = \frac{F_{bolt}}{E_{min} \times 2t} = \frac{997.9}{0.87555 \times 2(\frac{3}{16})} = 3039.383633\ psi$$

$$\sigma_{tear-out, Actual} = (\sigma_{tear-out})(k) = (3039.4)(3.5) = 10637.84271\ psi$$

$$FS_{tear-out} = \frac{Shear\ Strength}{\sigma_{tear-out}} = \frac{30000}{10637.8} = 2.820120658$$

Shear Strength is 30ksi as per 6061-TI aluminum

Casing Tensile Stress:

$$\sigma_{tensile} = \frac{\frac{\pi}{4}D_{i,casing}^2 \times MEOP}{[(D_{o,casing} - t)\pi - \frac{N}{2} \times d_{bolt,major}] \times t} = \frac{\frac{\pi}{4}(5.625)^2(1124.4)}{[(6 - \frac{3}{16})\pi - \frac{28}{2} \times 0.2489] \times \frac{3}{16}} = 10085.56754\ psi$$

$$FS_{Tensile}(YTS) = \frac{YTS}{\sigma_{tensile}} = \frac{38000}{10085.56754} = 3.767760203$$

$$FS_{Tensile}(UTS) = \frac{UTS}{\sigma_{tensile}} = \frac{42000}{10085.56754} = 4.16436654$$

Bearing Stress:

$$\sigma_{bearing} = \frac{F_{bolt}}{d_{bolt,major} \times t} = \frac{997.9246274}{(0.2489)(\frac{3}{16})} = 21383.14455 \text{ psi}$$

$$FS_{bearing}(BYS) = \frac{BYS}{\sigma_{bearing}} = \frac{56000}{21383.14455} = 2.618885163$$

Von miss stress Equivalent:

Using minimal preload of 50lbs

$$\sigma_v = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)}{2}}$$

$$\sigma_x = 0$$

$$\sigma_z = 1370.153001 \text{ psi preload}$$

$$\tau_{xy} = 29883.43642 \text{ psi}$$

$$\sigma_v = 51777.76198 \text{ psi}$$

$$FS_{von\ miss} = \frac{YTS}{\sigma_v} = \frac{153000}{51777.76198} = 2.954936524$$

Stripping:

$$F_{tensile\ force} = A_t S_y \simeq \frac{\pi}{4} \times (0.9 \times d_{bolt, Major})^2 S_y$$

$$F_{nut\ stripping\ force} = \pi \times d_{bolt, Major} \times (0.75 \times t) \times S_{sy}$$

$$Shear\ strength, S_{sy} = 0.58 \times S_s$$

$$\text{Equating } F_{tensile\ force} \text{ to } F_{nut\ stripping\ force}$$

$$\text{In practice } t \geq 0.875d$$

Chosen thickness is 0.4375

$$\textit{Margin of stripping} = \frac{F_{\textit{nut stripping force}}}{F_{\textit{tensile force}}}$$

$$\textit{Margin of stripping} = \frac{5583.318062}{19345.74397}$$

$$\textit{Margin of stripping} = 3.464918846$$

Since $\textit{Margin of stripping} \geq 1$, the bolt is predicted to fail before the nut

Appendix C - Videography

A video documenting the retaining ring and external tank drilling process is available at:

https://drive.google.com/drive/folders/1QhKHZ2OdDD4w_FIHuJ_1SPJUV7n065Je?usp=drive_link