LAUNCH CANADA 2023 CHALLENGE

Metropolitan Aerospace & Combustion Hub

LC2023 Design Report for the

Garolite Ablative Rocket-Engine

Competing Team [03]

REVISION HISTORY

Revision	Description	Date
R0	Initial Draft	Nov. 11, 22
R1	LC2023 Borealis Design Proposal	Nov. 12, 22
R2	Revised & Edited Borealis Design Proposal	Nov. 27, 22
R3	LC2023 GAR-E Preliminary Design Report	Feb. 17, 23
R3.1	Minor edits & formatting, minimal content changes.	Feb. 18, 23
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R4.0	Delta Report (handwritten in Documentation Binder)	Jun. 29, 23
R4.1	Overall Progress Update & Report for LC 2023	Aug. 2, 23
R4.2	Minor edits & formatting, minimal content changes	Aug. 12, 23

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ABSTRACT

Metropolitan Aerospace and Combustion Hub (MACH), formerly known as Ryerson Propulsion Group (RPG), is an engineering design team operating from Toronto Metropolitan University (TMU). MACH is participating in the technology development category of the Launch Canada 2023 challenge with the Garolite Ablative Rocket-Engine (GAR-E). GAR-E is a rapidly iterative bipropellant liquid rocket engine (LRE), using ethanol and nitrous oxide as propellants fed by a nitrogen pressurant system. The goal for Launch Canada 2023 is to perform a hot-fire test of the GAR-E engine in a live demonstration of the team's SRAD liquid rocket propulsion systems.

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ABBREVIATIONS & NOMENCLATURE

AIAA	American Institute of Aeronautics and Astronautics
ADC	Analog to Digital Converter
APCP	Ammonium Perchlorate Composite Propellant
BizDev	Business Development
BPVC	Boiler and Pressure Vessel Code
CEA	Chemical Equilibrium with Applications
CONOPS	Concept of Operations
COTS	Commercial Off-The-Shelf
CD	Combustion Dynamics
Cv	Valve Flow Coefficient
DAQ	Data Acquisition Unit
EthaNOS	Ethanol & Nitrous Oxide
FEA	Finite Element Analysis
GAR-E	Garolite Ablative Rocket-Engine
GSE	Ground Support Equipment
GUI	Graphical User Interface
I_{sp}	Specific Impulse
LOV	Loss of Vehicle
LRE	Liquid Rocket Engine
MACH	Metropolitan Aerospace Combustion Hub
MEOP	Maximum Expected Operating Pressure
MFV	Main Fuel Valve
MOV	Main Oxidizer Valve
MPV	Main Pressurant Valve
N_2	Nitrogen
N_2O	Nitrous Oxide
NASA	National Aeronautics and Space Administration
P&ID	Piping & Instrumentation Diagram
PM	Propellent Management
PCB	Printed Circuit Board
PLC	Programmable Logic Controller
PPE	Personal Protective Equipment
PRA	Probabilistic Risk Assessment
PSR	Probable Severity Rating
R#	Revision # (of this report)
RMS	Risk Management System
RPG	Ryerson Propulsion Group
SERM	Safety & Emergency Response Manual
SOP	Standard Operating Procedure
SRAD	Student Researched And Developed
SSR	Solid State Relay
STEM	Science, Technology, Engineering, & Math
T&C	Transfer & Control
TMU	Toronto Metropolitan University
UTS	Ultimate Tensile Strength

1.0 INTRODUCTION

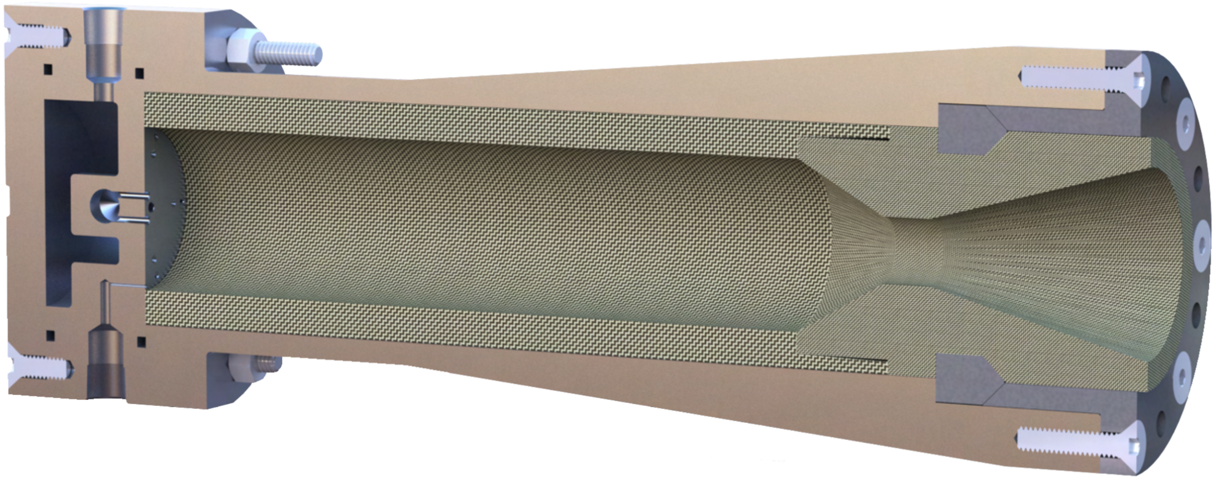


Figure 1.0.1: Cutaway render of the GAR-E assembly.

MACH is developing the Garolite Ablative Rocket-Engine (GAR-E) and plans to conduct a static hot-fire test at the Launch Canada 2023 challenge. This test will serve as a technological demonstration of our low-cost, safe, and rapidly iterative engine, propellant, control, and telemetry systems.

GAR-E is a pressure-fed, bipropellant, ablatively cooled liquid rocket engine. It is a static test engine, collecting data and providing operational experience for design validation and future development. The engine is designed with large safety margins and high manufacturability, but can be easily optimized into flightweight designs with material removal and aerostructure integration features.

GAR-E runs on ethanol (C_2H_5OH) and nitrous oxide (N_2O), a combination the team has been calling “EthaNOS” for short. Both propellants are pressurized by a nitrogen gas (N_2) system fed by commercial-off-the-shelf (COTS) cylinders. The engine, fluid, electronics, and supporting systems are designed with high safety factors and overheads to accommodate larger, higher thrust, and longer burning engines in the future.

The propellant system is built with safety and reliability as the top priority, with fail-safe isolation and vent valves for all fluid, pressurization, and fill lines. The system was also designed with modularity, able to test different propellant tanks, engine designs, and delivery rates with minor modifications.

The engine telemetry includes an in-chamber pressure transmitter and load cell integrated into the thrust plate, and the fluid systems contains a large suite of pressure and temperature sensors, collecting data for and control and analysis. These are used in an electronic control system to safely perform hot-fire tests with minimal manual intervention. A robust data acquisition, control, and telemetry system ensures and safe operation of the engine and propellant system.

1.1 SUMMARY OF PROGRESS & CHANGES

Since the R3 version of the design report [1], the overall high-level design of the system remains much the same. As the project has progressed towards a finalized system, the majority of design changes are refinements in systems lacking prior detail or due to various (primarily budgetary) constraints.

Though the system architecture was mostly complete by the R3 revision, limited hardware had been completed as designed at the time of submission. Additionally, experience from testing campaigns revealed significant shortcomings in hardware implementation and operational experience. The majority of time and effort have since gone towards improving these issues, as well as finalizing and manufacturing remaining hardware. Since February 2023, MACH has:

- Rebuilt propellant stand to improve construction & reassembly
- Rebuilt electronics system to design specifications
- Manufactured & installed thrust stand
- Redesigned & manufactured injector
- Manufactured majority of engine parts & thrust adapter
- Created & tested all SOPs for cold-flows & majority for hot-fires
- Overhauled inventory & logistics system
- Conducted two additional cold-flow tests with two successful inert cold-flows

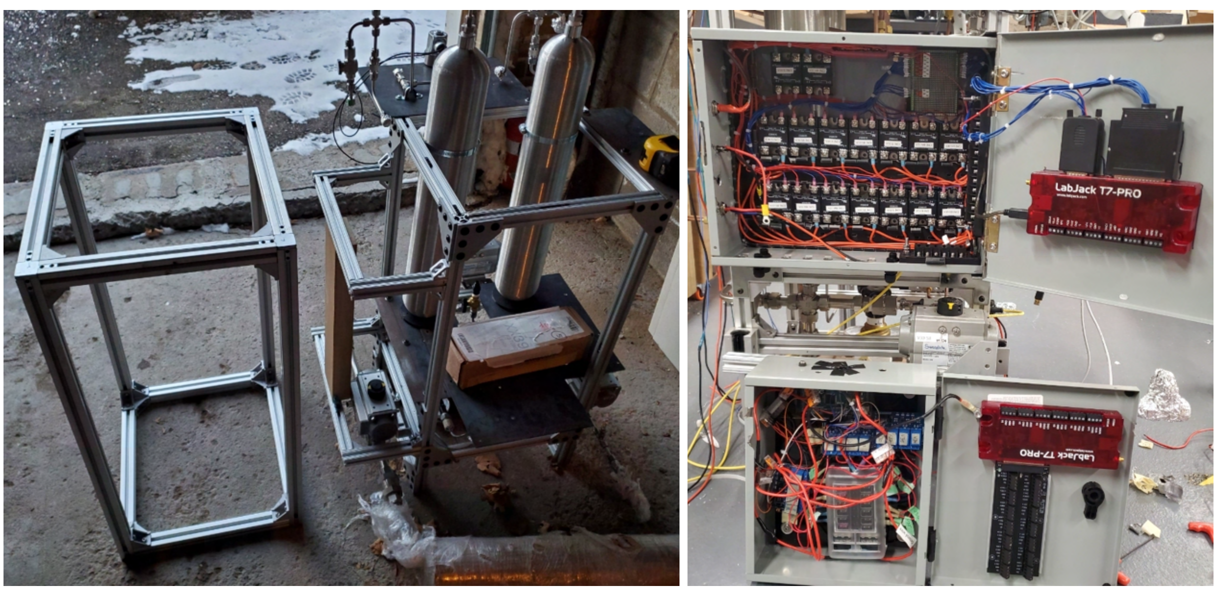


Figure 1.1.1: Rebuilt vs. old **a:** Propellant Stand frame **b:** Propellant Enclosure.

A summary of changes with significance to the report, design, operations, and team is presented on the following page for a quick reference. Numerous other improvements and updates have been made throughout this revision of the document. This report aims to be a comprehensive and transparent reflection of our systems and progress, both for internal documentation and to welcome detailed external feedback.

1.0 Introduction

1.3 Team Organization: Updated with Safety & Logistics subteam

1.4 Outreach Activities: Updated with activities since R3

3.0 Mission Concept of Operations

- Updated to reflect changes.

4.0 System Architecture & Design

- Updated to reflect changes.

4.1 Engine

- Updated to reflect changes & design details

4.1.2 Impinging Injector: Overhauled with new injector design

4.1.3 Ignitor: Updated with changes & testing data

4.2 Propellant System

- Updated with additional purge line & slow pressurization line

4.2.2 Cavitating Venturis: Updated with test data

4.2.4 Propellant Stand: Updated to reflect rebuild

4.2.5 Pneumatic System: Updated to reflect rebuild

4.3 Telemetry & Control

- Updated with power, control, & arming systems & components

4.3.3 Control Unit: Overhauled with LabJack as GPIO

4.3.4 Arming & E-Stop: Updated with new design & hardware

4.3.5 Mission Control: Updated with new GUI, setup, & hardware

4.3.6 Visual Telemetry: New section on camera systems

4.4 Test Stand & Support Equipment

4.4.1 Thrust Stand: Updated with design, installation, & configuration

4.4.3 Additional Equipment: Updated to reflect changes

5.0 Testing & Progress

- Updated testing overview for GAR-E & progress summary

5.1 Procedures & Operations

- New section detailing procedural development in testing & operations

5.2 Inert Cold-Flows Summary

- Updated with results from 2nd & 3rd cold-flow tests

6.0 Proposed Timeline

- Updated elapsed and upcoming timelines

8.0 Acknowledgements

- Updated to reflect additional supporters & sponsors

Appendix III - Safe Distance Calculations & Site Plan

Appendix IV - Thrust Stand Finite Element Analysis

Appendix V - FR-4 Ablation Testing

Appendix VI - GAR-E Production Drawings

Appendix VII - Inert Cold-Flow Data Analysis

Appendix VIII - Standard Operating Procedures (Modified for Jul. C-F)

1.2 TEAM HISTORY

MACH was founded in 2017 as the Ryerson Propulsion Group, with the goal of designing, manufacturing, and testing a bipropellant liquid rocket engine. With limited expertise in rocket propulsion and material support available on campus, the team's knowledge was built from the ground up using reference materials and external mentorship. After countless design iterations, learning opportunities, and a lengthy pandemic, MACH is making significant progress towards hot-fire testing in summer 2023.

With the renaming to Metropolitan Aerospace and Combustion Hub in 2022, the team has refined its focus towards practical engineering, novel research, and community collaboration. Safety and learning remain the team's cornerstones, offering unique and challenging opportunities for Canadian students in one of the most difficult fields in engineering. Despite severe material and budgetary limitations for a project of this scope, MACH strives to use industry standard components and practices to maintain safety and integrity. This is achieved by intently pursuing sponsorships, industry feedback, and novel engineering solutions without compromising safety or our mission.

1.3 TEAM ORGANIZATION

MACH is divided into three technical subteams and two administrative subteams. The technical side is composed of the Combustion Dynamics (CD), Propellant Management (PM), and Transfer and Control (T&C) subteams. CD is responsible for the design, iteration, and manufacturing of the combustion chamber, nozzle, injector, and cooling systems for GAR-E, Borealis, and future engines. PM is responsible for the design, assembly, and testing of the propellant, pressurization, pneumatic, and ground support systems. T&C is responsible for the development, integration, and testing of data acquisition, telemetry, control, and communication systems. Technical leads are also the de-facto integration team.

The administrative side comprises the Safety & Logistics (S&L) and Business Development (BizDev) subteams. The S&L subteam's responsibilities include risk assessment, team safety training, hazard communication, regulatory compliance, inventory, and logistics. The BizDev subteam is responsible for sponsorships, recruitment, finances, and outreach activities such as social media and web presence.

Each subteam has dedicated Leads, who report to the Team Director and Technical Director. Lead-in-Training positions were created to better prepare future Leads and improve continuance of technical and organizational knowledge. After these positions are general team members, many of whom take on temporary roles of Task Leads for specific, often inter-subteam projects of varying scope. The leads team is listed in Table 1.3.1 along with the required LC roles [3].

Table 1.3.1: Leadership Roster

Role *LC Equivalent*	**Name**
Team Director *Team Captain*	Umar Shabbir
Technical Director *Chief Engineer*	Yiwei Luo
Safety Officer *Chief Safety Officer*	Jack Sinclair
Faculty Advisor	Dr. Ahmet Emre Karataş
Propellant Management Leads	Shivesh Maraj
	Rui Fernandes
	Rochelle Suarez-Tapanes
Combustion Dynamics Leads	Ben Kubica
	William Pirie
	Nikolai Sydorenko
Transfer & Control Leads	Georgia Jovanovic
	Kai Stewart
	Daniel Ibanescu
	Mark Paul
Safety & Logistics Lead	Jack Sinclair
Business Development Leads	Liana Farzaneh
	Laxan Puveendran

As of the date of publication, MACH consists of active members spanning a variety of disciplines, years of study, backgrounds, identities, and specializations. Though the majority of the team are expectedly from aerospace engineering, we also have significant membership from other engineering and non-engineering disciplines, as well as several members from outside the TMU student body.

1.4 OUTREACH & ACTIVITIES

One of MACH's priorities is recognizing the valuable support provided by our sponsors and strengthening our collaborative relationships. Our partners have been instrumental in bolstering our organization's capabilities and success. They have extended substantial operational funding and offered in-kind donations of parts, equipment, tools, raw materials, manufacturing support, and workspace access. Additionally, industry expertise and design reviews have significantly improved the work of our team.

As a token of appreciation and recognition for their support, sponsor logos are prominently displayed on our team apparel. This celebrates our partnerships, raises brand visibility, and creates a sense of shared achievement. The initiative not only showcases our partners on the merchandise but also extends recognition through our webpage, marketing materials, and social media channels. This multichannel approach ensures our sponsors receive valuable exposure to our growing audience.

Figure 1.4.1: Finalized T-Shirt Design.

Figure 1.4.2: Finalized Hoodie and Polo Design.

Furthermore, after MACH underwent a successful rebranding process, we recognized the immense potential to leverage this fresh identity and breathe new life into our group. The rebranding not only gave us a renewed sense of purpose and direction but also created a unique opportunity to connect with our members and followers in a more meaningful way. To capitalize on this momentum, we decided to design new merchandise that truly embodied our updated vision, values, and aesthetics. By doing so, we aimed to not only bolster team spirit but also offer our supporters and sponsors a tangible representation of our growth and evolution.

Displayed on the front left top corner of the designed t-shirts, hoodies, and polos, is our updated logo. On the right sleeve of the polos and t-shirts, a Canadian flag can be seen. This is meant to strengthen the team's identity and symbolizes our relationship with the country our team represents. Lastly, the back of the hoodie displays GAR-E with the newly appointed team colors. Overall, a great deal of time and effort was put into the design of the team merchandise.

Figure 1.4.3: MACH members on the weekend of July 22nd and 23rd

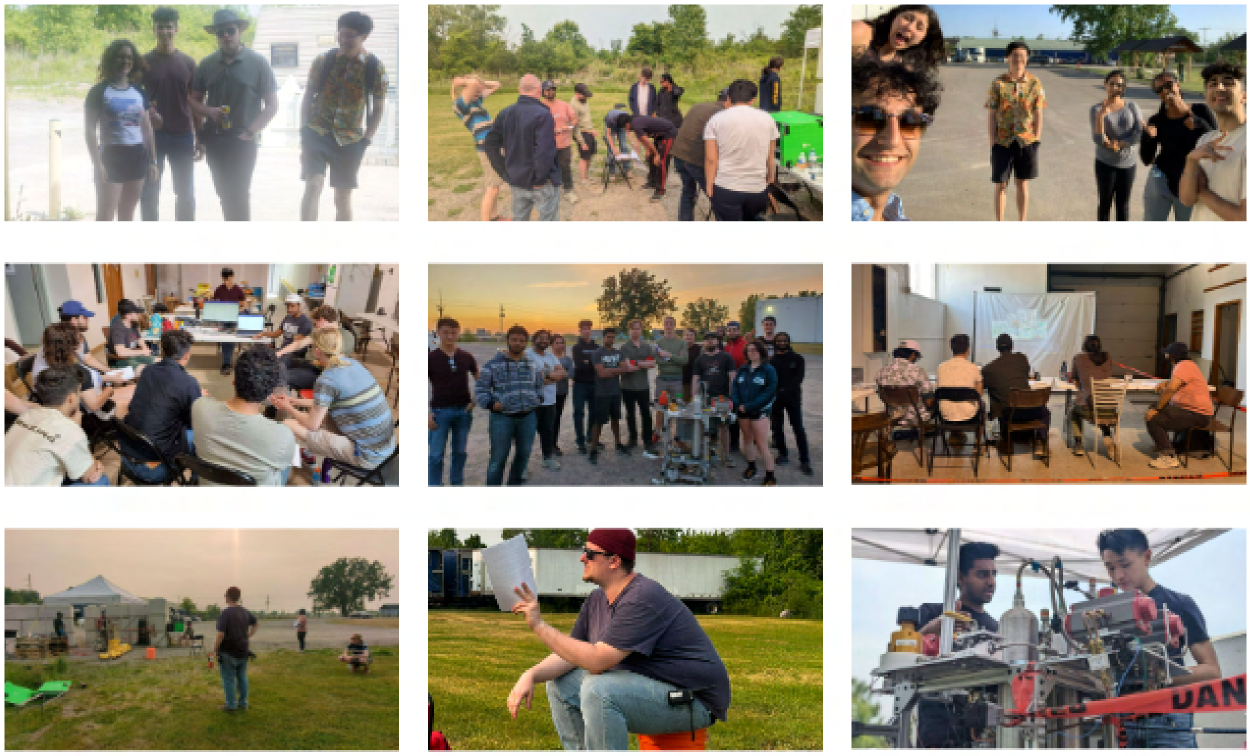


Figure 1.4.4: MACH members at the team's 2nd Cold-Flow attempt.

Figure 1.4.5: MACH members at the team's 3rd (& successful) Cold-Flow attempt.

In the pursuit of continuous improvement, the BizDev team has consistently worked on our website development and graphic designs as well, to revamp our team aesthetic on external facing assets (especially the website and sponsorship package). As the team continues to grow, constant changes are necessary in order for transparency. These changes include updated timelines and newly secured sponsors. With updated timelines, visitors and potential sponsors gain real-time insights into our progress, reflecting challenges faced, triumphs celebrated, and lessons learned. These moments are showcased with great pride within this report as the team takes great pride in our step-by-step development and progress.

In addition to the previously mentioned branches of the BizDev subteam, social media is a significant component that has yet to be mentioned. For instance, in April, social media platforms were used as a valuable tool for team recruitment. Specifically, we focused on our Instagram and LinkedIn pages to reach potential members, highlight our different subteams, and summarize our team mission. Moreover, through Instagram posts and stories, we were able to provide an inside look at our various testing processes (as shown below). Our shared updates and news about our team's progress and achievements on LinkedIn were a bit more extensive than those displayed on Instagram, as the content there is more professionally-oriented. On one hand, Instagram enabled us to target a younger, visually-focused audience, while LinkedIn allowed for a larger reach with a career-oriented audience, including any working professionals and advisors who are interested in assisting the team. This approach has helped us connect with like-minded individuals who were genuinely interested in joining our team and contributing to our project.

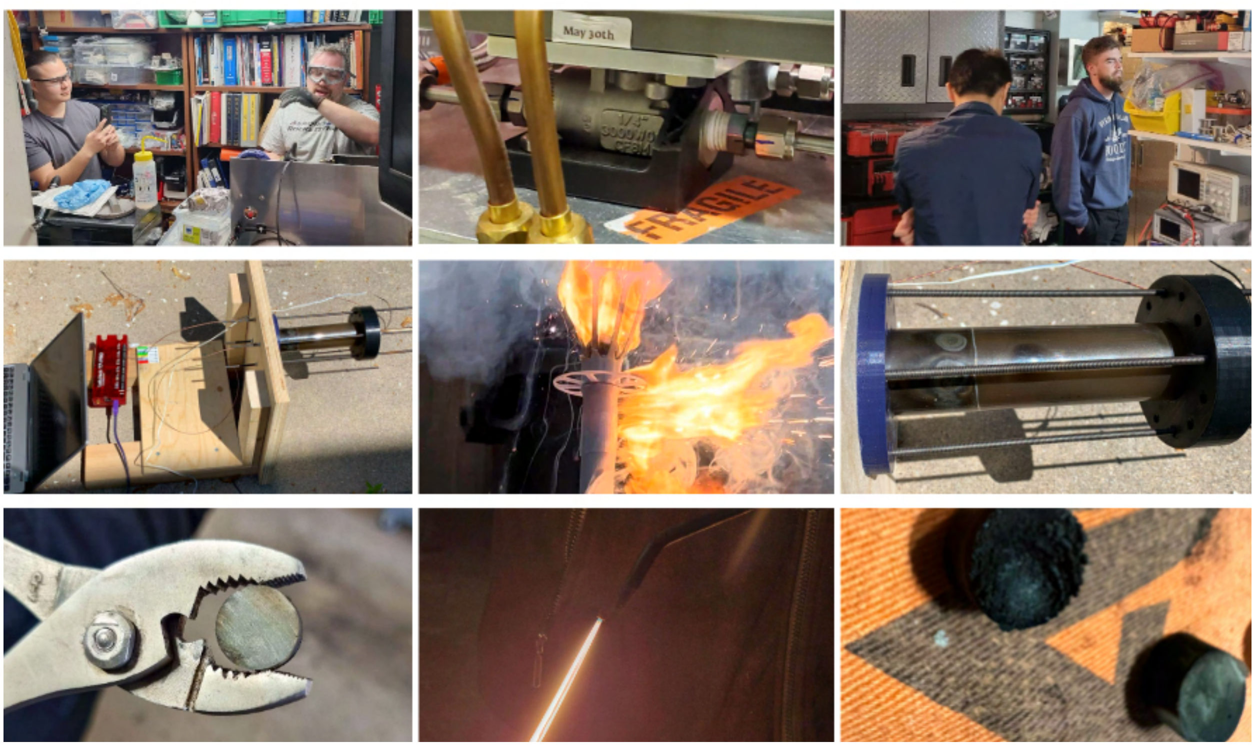


Figure 1.4.6: MACH's various testing events **a:** Component level valve pressure testing **b:** Igniter prototype testing **c:** Garolite FR-4 ablation testing

Since February 2023, the outreach team has secured several new sponsors. In March, a partnership was established with American Earth Anchors. Hex head anchors were required by the team to fasten and stabilize the propellant system. Hence, a sponsorship agreement was procured, providing our team with eight PE26 hex head anchors without charge. This sponsorship goes hand in hand with that of Automation Direct. It is only thanks to their generous support and in-kind donation of parts totalling up to $8000+ that the team has been able to get to the point where we are currently. Some of these components include pressure transmitters, enclosures, conduit cabling, and many many more items.

Over the past three weeks, our team achieved an amazing milestone of a new injector, thanks to support from Dishon Limited, a supplier in the aerospace industry specializing in complex precision machine components and assemblies. Additionally, earlier this July MACH had the opportunity to help out the Design Fabrication Zone in bringing back a time-honoured tradition to the TMU Kerr Quad: Model Rocket Launches! The event was a resounding success with five total rockets being launched and a total of seven launches (two of the rockets re-launched)! Additionally, in order to prep the general TMU engineering student body MACH also held a two-parter "Rocketry101" seminar to go over the basics of rocketry as well as our own designs. The team also had the opportunity to participate in TMU's Open House where members interacted with prospective students and informed them of the leaps we were taking within the student rocketry world!

Figure 1.4.7: Various outreach events **a:** MACHxDFZ model rocket launch **b:** Rocketry101 presentation **c:** TMU FEAS Open House

Finally, none of this would be possible without the team members themselves so the BizDev subteam actively goes above and beyond to document the fun we all have. Rocketry is all about the community after all! Therefore, enjoy a few more images of our team. As well as the pets that help it all happen!

Figure 1.4.8: MACH members at various points through the summer.

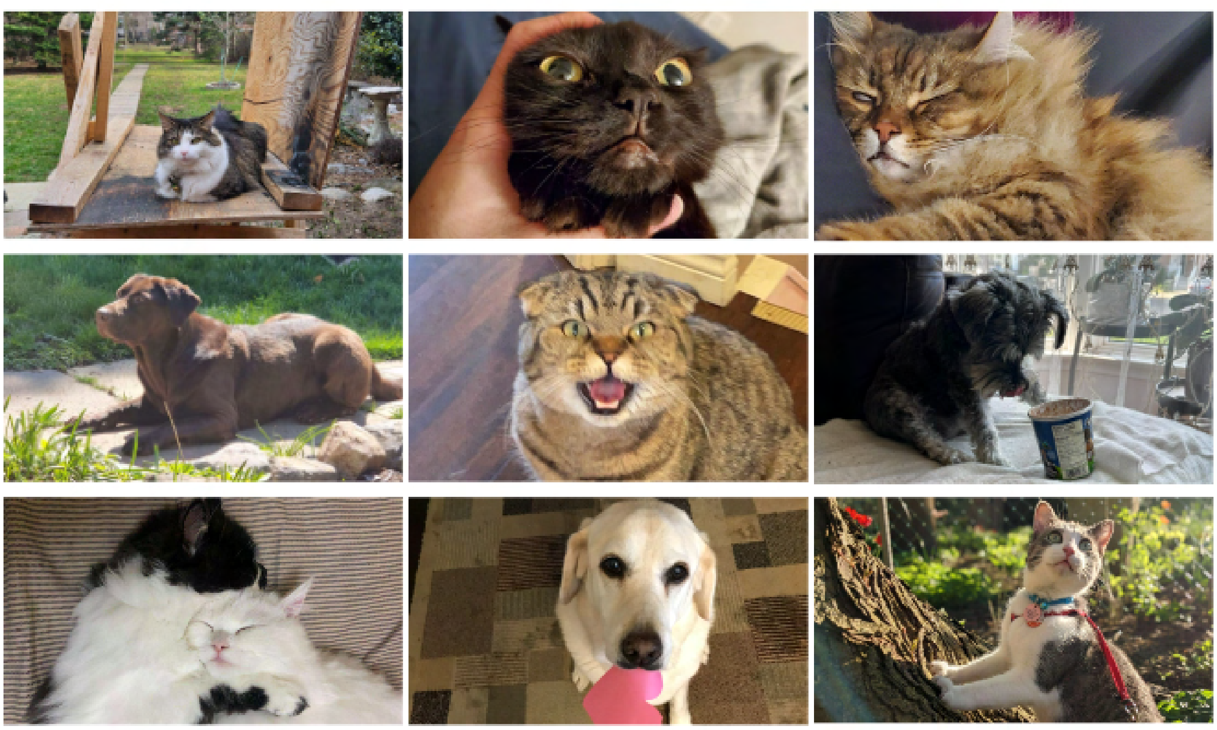


Figure 1.4.9: MACH's rocketry pets.

1.5 SPECIAL REQUIREMENTS

As this is an unconventional project with limited overlap with the majority of COTS test-flight projects at Launch Canada 2023, MACH has a number of special requirements for the demonstration. These requirements are as follows:

- Testing site (or "pad") clear of large obstructions and with vehicle access.
- Sufficient pre-allocated time for pad survey, vegetation clearing, and other preparations prior to testing.
    - Approval to clear hazardous vegetation and other potentially flammable materials within the expected flame path and an ember radius of 15m.
- Liquid N_2O cylinder with dip tube (~700psi); 2x (2200 psig) AT gaseous N_2 cylinders; 5kg ethanol (95%+ concentration).
    - Pressurized containers must have pre-communicated standard interfaces (ie CGA-580, CGA-320, etc).
    - Pressurized containers must have manual shut-off valves and other appropriate safety features (i.e. burst disks for N_2O cylinders)
- 10' x 10' flattened sand, gravel, concrete, or pre-communicated surface
- Physical barrier to allow between no less than 52 meters (safe distance for overpressure) and no greater than 60 meters equivalent of separation between mission control and Pad Control. Where barrier placement shields all known Mission Controls within 539m (safe distance for line of sight). More information can be found in Appendix III.
- This barrier must be comparable to those in Welland, which were used for the LR-101 hotfire.
- Standard safety precautions such as standby firefighters & first-aid.
- For site plan proposals at the Timmins test site, see Appendix III.

2.0 DESIGN REQUIREMENTS

The primary goal of the GAR-E engine, propellant, control, and telemetry systems is demonstration of a safe and economical SRAD bipropellant LRE. The longer term goals of the entire system after this initial demonstration will be the development of a flightweight system, and concurrently conduct novel combustion research using the Borealis engine. Compliance to the following requirements from Launch Canada will be demonstrated [4].

Table 2.0.1: Launch Canada Compliance Requirements

No	Description	Specification	Design Explanation	Compliance
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.	
2.1.4.1	**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.
2.2.1.1.1	**Pressurized Design Standards**	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	COTS parts with a rated pressure exceeding the MEOP of the system will be used wherever possible. Where SRAD parts are required, the part will be designed according to specifications laid out in BPVC or ASME B31.3 and flow testing at or above the MEOP.	The manufacturer's data for COTS parts and appropriate static & flow testing for SRAD parts.

2.2.1.2.1	**Wetted Materials**	All wetted materials employed in a rocket's fluid systems shall be compatible with the fluids and conditions to which they will be exposed.	Parts and materials will be verified to be compatible with all fluids.	Manufacturers' data for all COTS components.
2.2.1.3.1	**General Cleanliness**	All fluid systems shall incorporate provisions in design, assembly, and operation to prevent any contamination that would impede the operation and safety of the system.	SOPs for assembly, operation, storage, and cleaning will be drafted with provisions for cleanliness in mind with particular attention to the N_2O side. Caps and covers will be used for any exposed ports.	SOP and procedural validation for thorough cleaning of all parts immediately before testing with volatile fluids.
2.2.2.1.1	**Burst Pressure**	Vehicle propellant tanks shall not have a burst pressure of less than 1.5 times the MEOP. Other pressure vessels shall not have a burst pressure of less than 2.0 times the MEOP.	All propellant tanks will be COTS and used within the manufacturer's listed operating pressure. The combustion chamber shall be designed with sufficient wall thickness to allow for a safety factor of 3.0+. This safety factor will include yield strength decrease due to elevated chamber temperature.	The manufacturer's data will be used to verify this requirement. Combustion chamber stress shall be analyzed mathematically and with FEA in Solidworks and Ansys to confirm the safety factor.

2.2.2.3	**Proof Pressure**	Prior to use, pressure vessels intended for static testing or flight shall be proof-tested	Propellant tanks will be proof-tested at 1.1x MEOP, which will be less than 75% of UTS. The combustion chamber will also be proof tested at 1.1x propellant tank MEOP. Testing fluid will be water or similar incompressible fluid.	Bulkheads for the chamber will be machined and used for hydrostatic testing. Manufacturer's data for COTS tanks.
2.2.3.1.1	**Remote Pressurization**	Any pressure vessel, system, or component thereof with a burst pressure less than 4x MEOP shall only be pressurized and unpressurized remotely.	All SOPs for pressurizing and depressurizing systems shall do so remotely.	SOPs will be provided for review.
2.2.3.2.1	**Overpressure Protection**	Pressure relief devices shall be incorporated into all systems having a pressure source that can exceed the maximum allowable pressure of the system.	All pressure vessels shall be connected to a pressure relief valve in a way that cannot be obstructed by valves.	P&ID will show compliance
2.2.3.2.3	**Relief Devices**	Relief valves shall be selected to ensure the pressure does not exceed 110% of the maximum expected operating pressure of the system	Relief devices shall be selected to operate at, above and below the maximum expected pressure.	Manufacturer's data will be used to verify this requirement

2.2.3.3.1	**Propellant Fill**	Propellant tanks shall be filled and drained from the bottom of the tank.	Both propellant tanks will be filled from the bottom. Nitrous oxide will be filled using an upstream vent to create a pressure differential, and ethanol will be filled using a detachable hose and pump	P&ID & filling SOPs will show compliance
2.2.3.3.5	**Fuel and Oxidizer Venting**	Fuel and Oxidizer vents shall be kept separate to preclude the potential mixing of vented propellant.	Vents will be designed directionally to minimize the potential for mixing vented propellants.	Test stand plans and/or images will show compliance
2.2.3.4.1	**Failsafe Remote Venting**	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.	The worst-case control failures (loss of communications, power, or pneumatics) will be designed for automatic venting of pressurized systems.	System design will be provided for compliance.
2.2.3.4.2	**Propellant Mixing**	Bipropellant systems shall be designed such that a single malfunction cannot result in the mixing of fuel and oxidizer.	Propellant feed systems shall be distinct, discrete, and downstream of the pressurant run tank. Mitigations against backflow shall be implemented.	P&ID will show compliance

2.2.3.4.3	**Check Valves**	A single check valve shall never be used in a situation where leakage would expose personnel to danger.	Pair of check valves, or check valves in conjunction with actuated valves are used to mitigate risk of check valve failure.	P&ID will show compliance
2.5.2	**Leak Testing**	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.	Leak testing will be conducted on tanks and plumbing after each assembly. N_2 will be used for testing and soap solution will be used for spot leak detection.	SOPs will be provided for review.
2.5.3	**Tanking Test**	SRAD Launch vehicles using liquid propellant(s) shall successfully complete a propellant loading and off-loading test in "launch configuration"	Procedures for loading and off-loading shall be included in SOPs. Loading and off-loading capabilities shall be tested before cold-flow.	SOPs and test results will be provided for review.
2.5.4	**Cold-Flow Testing**	During development of a SRAD propulsion system employing hybrid or liquid propellants, cold-flow testing shall be performed prior to progressing to hot-fire testing.	Multiple cold-flow tests will be performed. Water and liquid carbon dioxide shall be used as inert propellant stand-ins. Tanks, plumbing, injector and chamber shall be flushed and thoroughly cleaned before testing with volatile propellants.	SOPs and test results will be provided for review.

3.0 MISSION CONCEPT OF OPERATIONS OVERVIEW

An overview of the nominal Mission Concept of Operations (CONOPS) is shown in Figure 3.0.1, followed by detailed descriptions for each phase. Contingency procedures and precautions are described in subsequent sections and MACH's Risk Management System (RMS).

Figure 3.0.1: Nominal CONOPS for Hot-Fire Testing (V2.2).

1. Assembly & Setup

Start: Equipment & personnel arrive at the test site.

End: All equipment fully assembled and ready for testing.

- Perform initial inspection of site & unload equipment.
- Set up mission control & support equipment to pad (power, comms, etc).
- Set up and secure thrust stand, prepare site (flame trench, defoliation, etc).
- Assemble propellant stand, engine & thrust assembly, electronics at pad.
- Integrate all subsystems into test stand & perform assembly checks.

2. Fill Preparation

Start: System testing begins.

End: All testing passed and system ready for propellant loading.

- Perform communications, control, E-stop, and valve actuation testing.
- Set up N_2 pressurant and N_2O oxidizer cylinders, prepare ethanol fill setup.
- Pad “Lockdown” declared and off limits except to Red Team personnel.
- Connect N_2 pressurant cylinder and perform pneumatic leak testing.
- N_2 inert gas flush performed & system depressurized after passing leak tests.
- Main pressurant & propellant valves disarmed at pad.

3. Propellant Filling

Start: Ethanol filling begins.

End: Final systems checks completed and go/no-go poll passed.

- Perform Ethanol filling procedure*.
- Switch Red Team personnel and perform N_2O connection procedure.
- Arm main pressurant, propellant, & fill valves.
- Connect ignitor power. Arm ignitor and evacuate pad**.
- Pad “Evacuation” status declared and off limits to all personnel.
- Perform remote N_2O loading and propellant pressurization procedures*.
- Perform final systems check and go/no-go poll.

*See Section 4.2.3 for fill procedure overview.

**See Section 4.1.3 for ignitor safety & arming.

4. Hot-Fire Test

Start: Mission control side arming procedure.

End: No oxidizer and/or fuel remains in the system, “Caution” pad state declared.

- Perform mission control side arming procedure.
- Send ignition command (engine computer automatic control initiated).
- *Engine control system ignition, hot-fire, shutdown, & purge operations*:*
    - Initiate E-match, await detection of APCP ignition.
        - Return to standby if APCP ignition is not detected.
    - Open propellant valves, await detection of propellant ignition.
        - Abort and purge if main ignition is not detected.
    - Perform abort if any preset parameters are exceeded during firing*.
        - Controlled (automatic or manual) abort shuts down fuel and oxidizer main & isolation valves in sequence, initiates purge sequence, and opens all vent valves.
        - Emergency manual abort cuts power to valve control, returning the system to safe state & initiating uncontrolled shutdown.
            - Vents open, depressurizing all lines & venting oxidizer.
    - After 5s, initiate nominal shutdown, purge, and vent sequence.
        - Close fuel line isolation valves and open purge bypass valve.
        - Initiate purge sequence with remaining pressurant, flushing residual fuel via bypass line & oxidizer directly through run tank.
        - Close all isolation valves and open all vents.
- Monitor hot-fire & perform manual or emergency abort if necessary.
- Follow appropriate contingency procedures if necessary.

*See section 4.3.2 for engine control software overview & abort modes.

5. Cleanup & Teardown

Start: “Safe” pad state declared after a five-minute fire watch.

End: All equipment & personnel leave the site.

- Red Team returns to the pad to disconnect N_2 & N_2O cylinders.
- Fully disarm both mission control and pad side systems.
- Drain remaining ethanol & perform field-clean of sensitive systems.
- Disassemble test stand into component systems, remove & check cylinders.
- Teardown & pack propellant stand, engine & thrust assembly, & electronics.
- Teardown & pack mission control & support equipment.
- Inventory & load equipment for transportation.
- Perform site cleanup & inspection; take soil samples for analysis [5].
- Perform final site walkaround before departure.

4.0 SYSTEM ARCHITECTURE & DESIGN

The overall system architecture of the test setup is arranged by groupings of physical assemblies and subassemblies. These are pre-assembled and designed to be separately transported and easily reintegrated for testing to minimal setup time. The "pad" side of the system includes the engine, propellant, telemetry & control, and supporting systems to enable static-fire testing. Mission control is separated by distance and physical barriers for safety. A simplified interface diagram of the entire system is shown in Figure 4.0.2.

The major assemblies are the engine & thrust assembly, propellant stand & propellant enclosure, and the engine enclosure, all of which are physically integrated into the thrust stand to form the complete test stand. All systems on the test stand incorporate water resistant connectors and enclosures, while the Engine Computer, Pad Arming Enclosure, and rest of Pad Control is set up in a weather-proof shelter.

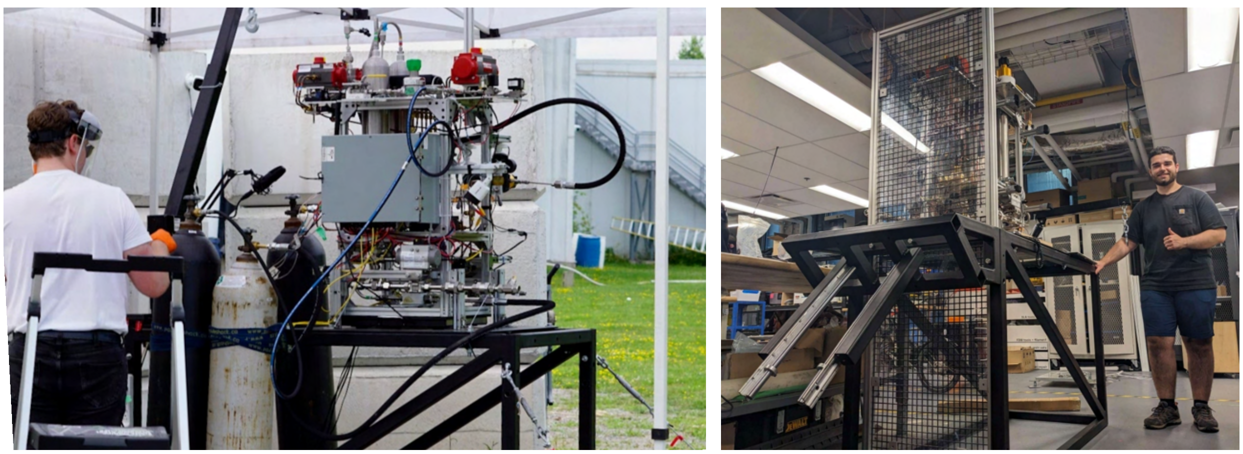


Figure 4.0.1: Partially stacked configurations of the pad-side system.

The Engine is assembled with the ignitor and injector, then mounted onto the load cell and thrust plate. This is the thrust assembly, which can be mounted onto the thrust stand as a complete unit. The ignitor and sensors for engine telemetry are connected to the Engine Enclosure on the thrust stand.

The propellant stand contains the pressurant, fuel, oxidizer, and pneumatic systems and associated sensors. The electronics required for telemetry & control are contained within the propellant enclosure, pre-assembled onto the propellant stand. Additionally, a weight scale is secured to the bottom of the propellant stand, as well as most monitoring cameras. These are transportable as a single unit, and can be integrated onto the thrust stand via Crane upon unloading. Additional details on test stand assembly are provided in section 4.4.1.

On-pad wiring consists of four cables with weather-resistant connectors: a set of USB cables and a set of power cables for each enclosure. All wiring from Pad to Mission control are weather-resistant or run through conduit.

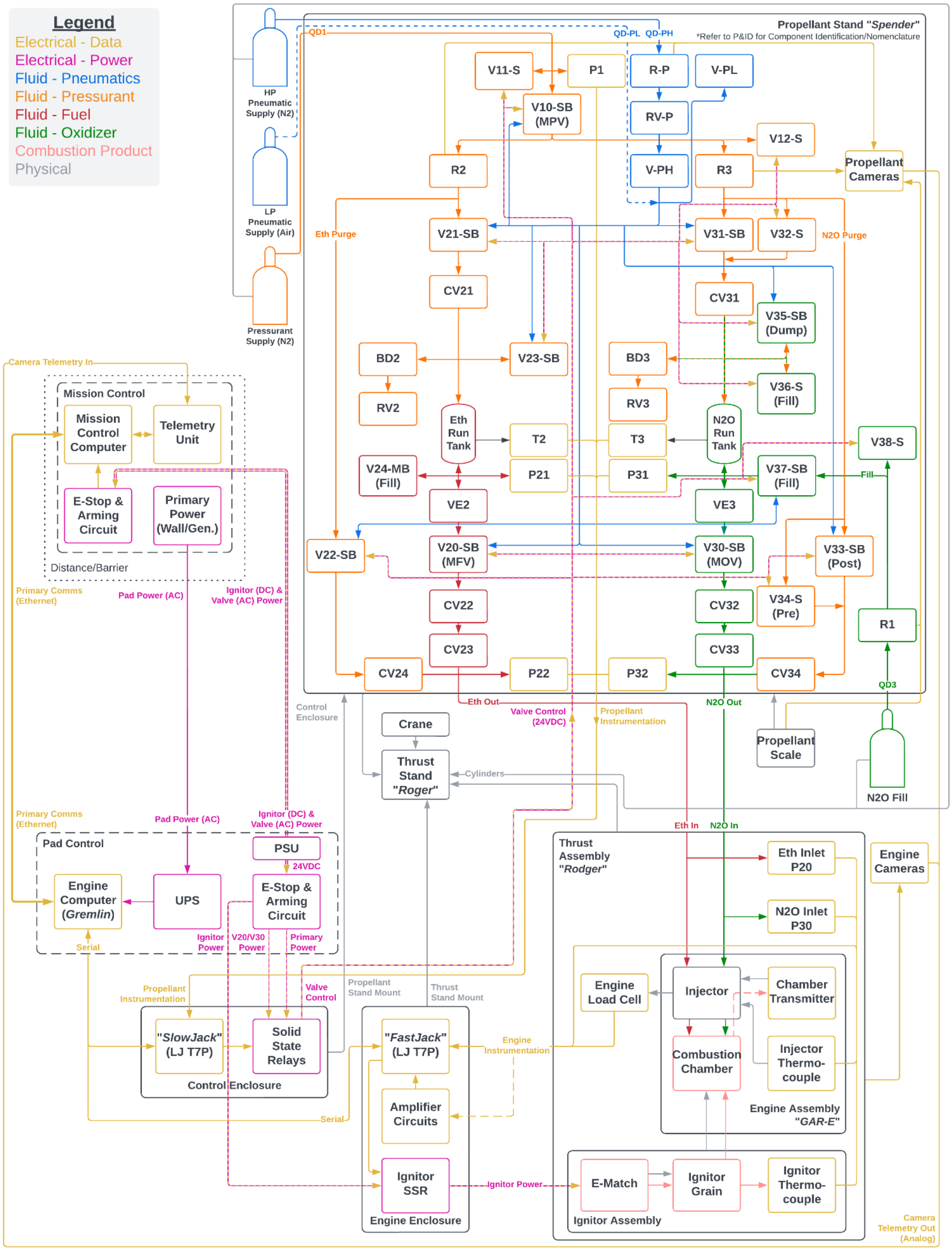


Figure 4.0.2: System Architecture & Interface Diagram (V2.6.1).

4.1 ENGINE

The Garolite Ablative Rocket-Engine is a proof-of-concept for MACH to rapidly develop flightweight designs. The rationale and design goals of GAR-E are detailed earlier in Section 1. The internal geometry of GAR-E is identical to the Borealis engine with minor modifications to improve ease of manufacturing, hence the targeted performance characteristics and supporting requirements are also identical. The Borealis design can be found in previous documentation [2] [6].

The design of the engine continues the high modularity for comparative testing of specific components, with particular interest around the study of injector and nozzle variations of geometry, materials, and manufacturing methods. General properties of the engine are listed in Table 4.1.1 and the engine assembly is shown in Figures 4.1.1 and 4.1.2.

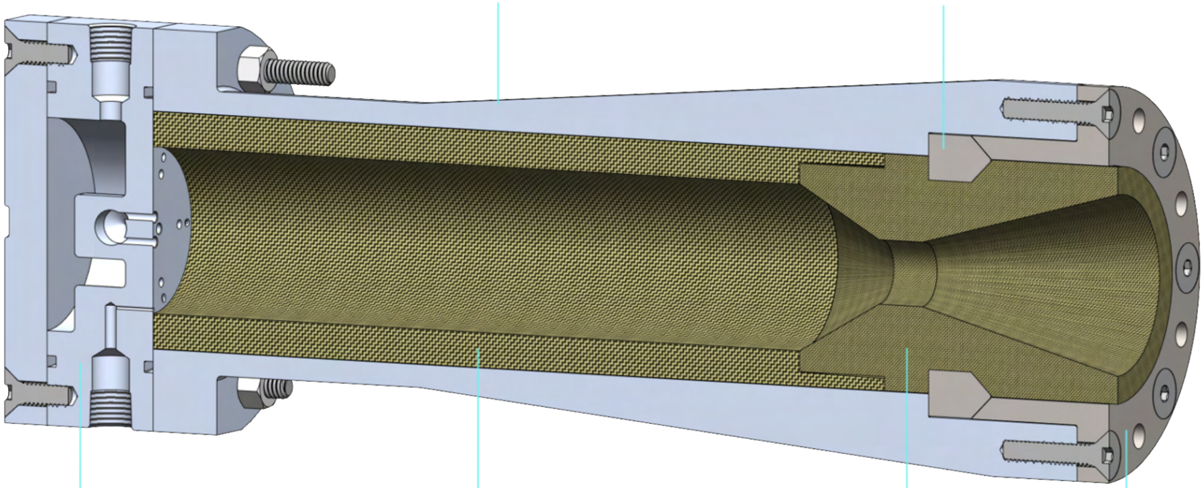


Figure 4.1.1: Labeled engine assembly cross-section.

Figure 4.1.2: Manufactured GAR-E components to date.

Table 4.1.1: Garolite Ablative Rocket-Engine Properties

Parameter	Value
Propellants	Ethanol (0.95 kg), N_2O (3.02 kg)
Total Impulse	6050 Ns
Specific Impulse	152 s
Nominal Burn Duration	5 s
Designed Thrust	1186 N (267 lbf)
Mass Flow Rate	0.190 kg/s Ethanol 0.604 kg/s N_2O
O/F Ratio	3.18
Propellant Tank Pressures	8.80 MPa (1277 psig) Ethanol 7.40 MPa (1073 psig) N_2O
Propellant Injection Pressures	5.79 MPa (840 psig) Ethanol 5.79 MPa (840 psig) N_2O
Chamber Pressure	4.83MPa (700 psig)
Chamber Temperature	2791 K
Cooling System	Silica Phenolic Ablative
Maximum Heat Flux	23.2 MW/m^2
Chamber & Nozzle Material	FR-4 Glass Fiber Reinforced Composite
Outer Jacket Material	6061 Aluminum
Injector Material	6061 Aluminum
Retainer Material	1018 Steel

The simplification of the design into an ablative prototype engine resulted in the removal of the liquid cooling system, drastically reduced instrumentation requirements, and greater safety margins. Consequently, the estimated total cost of materials and manufacturing (excluding the injector) have been reduced from over $6000 to less than $500 per engine, with the non-reusable ablative components expected to cost around $150 to replace after each hot-fire test [7].

4.1.1 Construction

GAR-E uses ablative FR-4 Garolite for its combustion chamber and nozzle. These are inserted into a thick-walled aluminum jacket for structural strength, held in place by the injector seal and nozzle-end retainer.

Similar to other silica-phenolic ablatives, FR-4 was chosen for its excellent machinability, cost, and flame retardant properties even compared to other types of Garolite. The phenolic matrix chars under pyrolysis to form an insulating carbon layer as well as a transient gas boundary layer, and the gradual ejection of material aids in the cooling process. The glass fiber reinforcement also provides excellent thermal insulation for the jacket, enabling the use of lower cost and easier to machine aluminum [8]. There is a very large margin of additional ablation thickness for the expected 5 second burn duration.

The FR-4 liner and nozzle are made as two separate pieces for ease of manufacturing, and grease is used at the stepped interface. A graphite nozzle insert is not required for the low-abrasion combustion products. Double high temperature silicone -036 o-rings (grooves not pictured) seal the nozzle to the casing.

The aluminum jacket is designed with a very high factor of safety for both hoop and axial stresses. It also contains the mechanical features for assembly with the injector, thrust stand, and testing procedures. For assembly, the liner end of the chamber is lightly compressed against the injector seal, and the nozzle is held by a 3-piece steel retainer. Steel was chosen for its higher strength under the higher thermal loads at the nozzle. A tapered split ring design is used to increase the contact surface area and provide a steel-on-steel interface. The end retainer is secured to the jacket with eight ¼”-20 screws. An additional four ¼”-20 screws are used to mount L-brackets for mounting the the thrust stand, and four more are used to mount the igniter assembly.

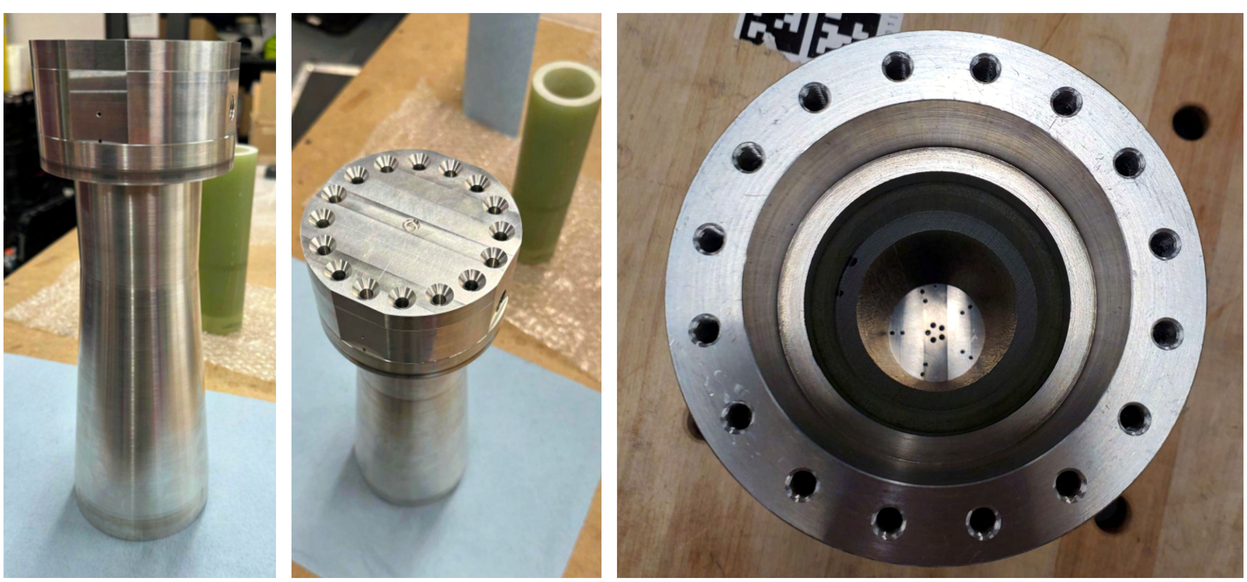


Figure 4.1.3: Test-fit of some GAR-E components.

4.1.2 Impinging Injector

Since the R3 report, the injector has been redesigned into a like-like doublet impinging injector. The impinging injector was chosen due to their long heritage, readily available literature, and scalability to larger engines. Additionally, a generous sponsorship from Dishon Limited allowed the manufacturing of this design within our tight timelines. The injector is machined from 6061 T6 aluminum. From the favorable thermal properties of ethanol, high flow rate, and large volume, thermal issues are not expected for a 5 second hot-fire test. Future injectors for larger engines and longer burns will be made from stainless steel.

Five pairs of Like-impinging doublet ethanol holes surround a central nitrous oxide showerhead. The outer jet of each ethanol pair is angled inwards at 22.5° while the inner jets are straight. This configuration improves fuel-oxidizer intermixing with the central showerhead and simplified manufacturing. A large ethanol volume serves to distribute the inlet pressure and cool the assembly. Protruding into the ethanol volume are ports for nitrous oxide and chamber pressure. This single-piece, side-inlet design has no interpropellant seals.

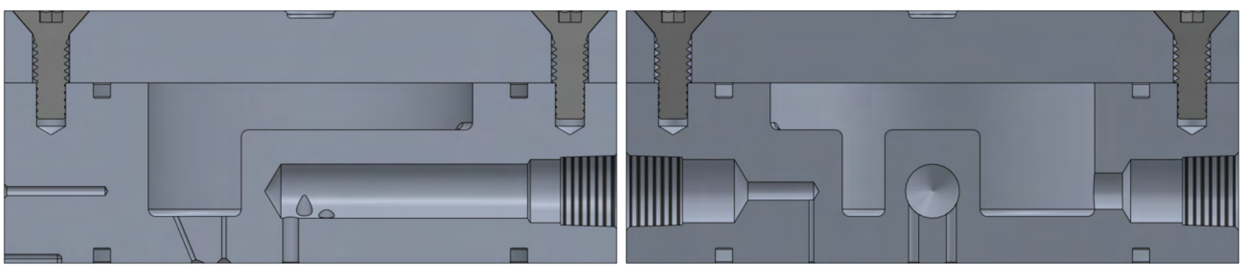


Figure 4.1.4: Sections of **a:** N_2O & thermocouple ports **b:** Eth & transducer ports

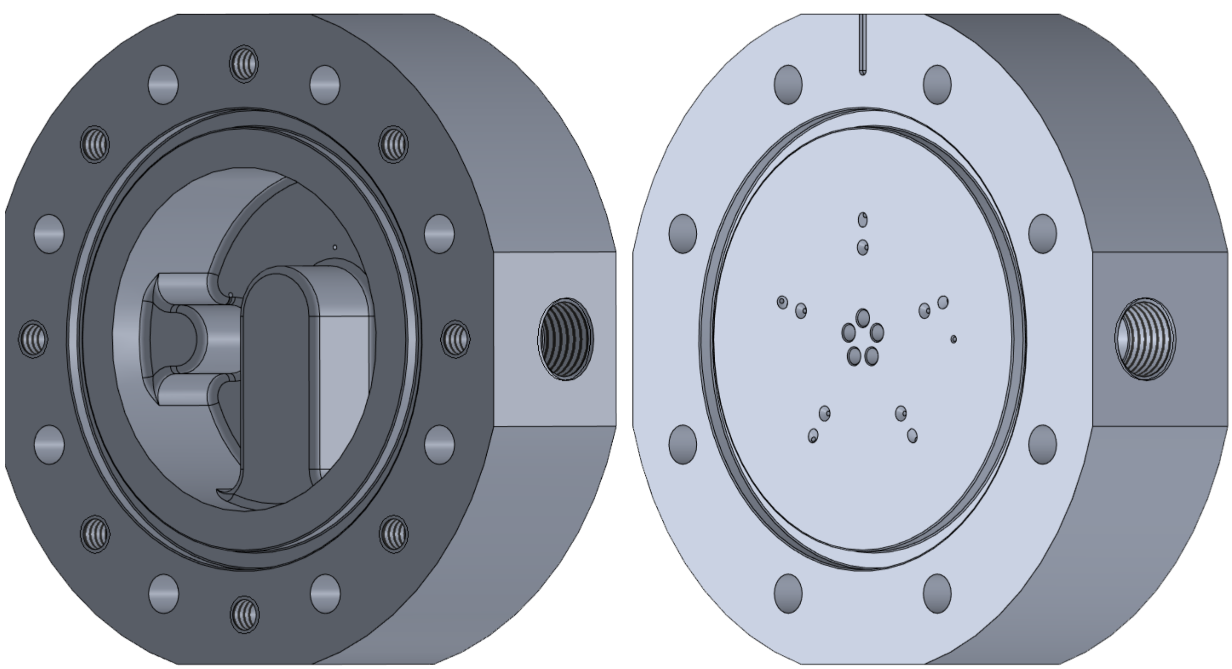


Figure 4.1.5: Views of the injector **a:** Inlet side **b:** Injector face.

-232 high temperature silicone o-rings are used to form seals on the ethanol volute as well as on the chamber. These were selected for their relatively high temperature resistance, compatibility with the grease selected for the engine assembly (Molykote 112), and low cost. Two sets of four ¼"-20 countersunk bolts secure the top cover of the injector, tapped to different depths due to space constraints. Eight 1/4"-20 countersunk bolts secure the injector to the engine.

Propellants enter the injector through aluminum AN to ¼ NPT fittings. The pressure transmitter port is isolated from the high chamber temperatures using thermal grease. Two thermocouples are installed in the injector: one halfway through the injector wall, and another between the FR-4 chamber lining and the aluminum engine case. An indented feature on the forward face allows it to interface with a load cell.

Figure 4.1.6: The manufactured injector.

4.1.3 Ignitor Assembly & Safety

Ignition of the rocket engine is achieved by using a pyrotechnic igniter. This consists of a primary and secondary ignition charge, a thermocouple, housing, and independent power, safety & continuity circuit. Every component of the ignitor assembly is designed to be single-use, with an economical and easily iterable system the second highest priority after safety.

E-matches are used as the primary ignition source. This in turn lights the secondary charge, a grain of APCP (aluminum perchlorate composite propellant, the fuel in solid rocket motors) which burns intensely for ~3 seconds. The E-matches are in contact with the APCP grain, which is in turn surrounded by a resin enclosure with perforations to direct an even, high intensity flame. A thermocouple port is placed immediately before the flame exit holes. This thermocouple provides the initial timing for ignition, only opening the propellant valves after detecting a rapid temperature spike indicative of successful APCP ignition. Two E-matches are used to mitigate a common case of ignition failure (E-match fails to light APCP) due to the complex procedures required to safe pad and replace a faulty ignitor.

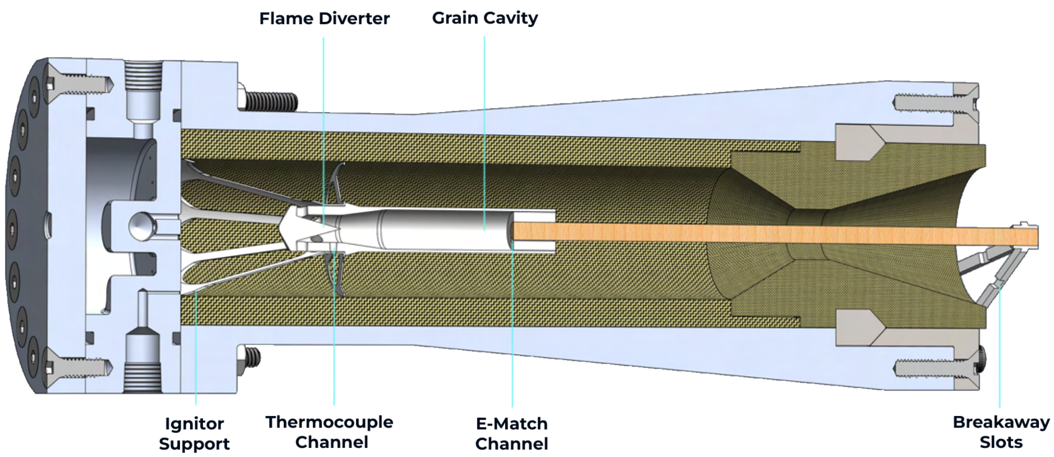


Figure 4.1.7: Labeled ignitor housing cross-section

A disposable SLA-printed resin housing is used to support the grain, ignition charges, and thermocouple. An additional thin support structure is inserted within the chamber during engine assembly for centering. The resin housing is supported by a 6 mm dowel which extends out of the nozzle. The dowel is mounted using a FDM-printed support structure, the legs of which are then secured to the engine case using dedicated ¼”-20 bolts. The legs are designed with weak points to enable controlled rapid failure, breakaway, and ejection of the main structure upon engine ignition, while the support structure breaks up without obstructing the nozzle.

Several rounds of testing on various designs have been carried out, allowing the team to converge on the current design. In particular, the arrangement and size of the holes were varied to direct an even spread of flame while maintaining the structural integrity of the grain housing over the course of the burn.

Figure 4.1.8: Ignitor prototypes undergoing testing.

A diagram of the ignitor safety circuit is shown in Figure 4.1.9. The electrical leads of the initial charge are run through the ignitor assembly to outside the engine and into a normally-open solid state relay (SSR). This is connected in series to an arming switch at pad, then to another keyed arming switch in series at mission control. The separate 24VDC power for the ignitor's is located at the pad side and disconnected until the final arming procedure.

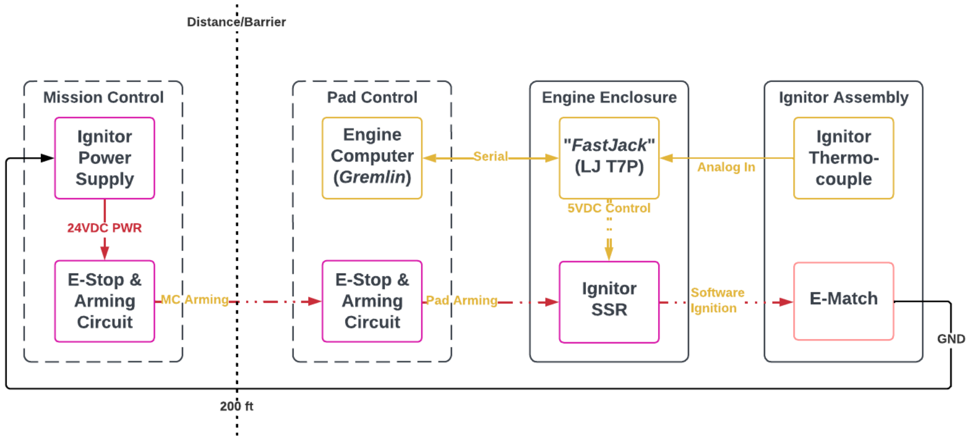


Figure 4.1.9: Ignitor Safety Circuit (V3.0).

The ignitor SSR is actuated by the engine computer through a LabJack unit, which also acquires data from the thermocouple. After the initiation signal for the automatic ignition sequence is received, the engine computer commands FastJack to close the ignitor relay and light the E-match, then waits for a thermocouple threshold to confirm successful propellant grain ignition. Once secondary ignition is detected, the main fuel and oxidizer valves are opened in short sequence, and the main burn of the rocket is initiated. The exhaust and significantly more hostile chamber conditions break the supporting structures of the housing and eject the main ignitor assembly out of the nozzle.

4.2 PROPELLANT SYSTEM

The propellant system is designed with an abundance of safety as the primary focus. The pressurant, fuel, oxidizer, and oxidizer fill lines are separated by isolation valves and check valves. Each isolated part of the system has fail-safe vents and relief mechanisms. Additionally, critical valves such as the main propellant valves, N_2O dump vent, and high-pressure vent valves fail into safe states with triple redundancy through solenoid or spring return even in the event of simultaneous failure of communications, power, and pneumatics. All other valves fail into a safe state with at least two of the above critical failures. The entire propellant system, along with the supporting pneumatics and electronics, is integrated onto a single compact propellant stand (nicknamed “Spender”). The propellant stand has been fully rebuilt using most of the same components and design since R3 of this report.

All pressurant and propellant connections are made with high-pressure Swagelok, AN, or NPT connections and stainless steel tubing. Connections to the injector are made with aluminum fittings to mitigate galvanic corrosion. The low pressure pneumatic system uses copper tubing with Yor-Lok, AN, BSPP, or NPT connections. Due to unanimous dissatisfaction with NPT connections within the team, as well as recommended reassembly practices (do not) [12], efforts have been made to adapt all NPT connections to reusable fittings.

The pressurant system uses directly connected commercial-off-the-shelf high-pressure nitrogen gas canisters to pressure feed both the fuel and oxidizer systems. The ethanol and nitrous oxide run tanks are pressurized to 1277 psig and 1073 psig, respectively. Estimations of the run tank pressures have been derived through computations of the theoretical pressure loss in the plumbing system between each run tank and the injector [11]. The computations were verified and compared with CFD simulations performed in Flownex and experimentally tested in cold-flows. The approach for managing the two-phase flow of nitrous oxide is supercharging, which involves both cooling and pressurizing of N_2O with inert N_2 to maximize the difference between the operating and vapor pressures. An integration diagram and P&ID of the propellant system are provided in Figures 4.2.1 and 4.2.2, respectively, and Table 4.2.1 lists the properties of major components.

The intended burn duration is 5 seconds. The run tanks for both ethanol and N_2O were selected to be 3.785L Swagelok sampling cylinders. Swagelok sampling cylinders were chosen due to their availability, cost, and volume relative to other manufacturers. The computations of the run tank volumes are outlined in Appendix I. It is important to note that the assumed N_2O density was 818 kg/m^3 as cooling of the N_2O fill tank is to be performed prior to, and during, the fill procedure. After computing the required pressures for various pressurant tank configurations, it was determined that the N_2 supply cylinder would serve as the pressurant run tank. The large volume of the industrial N_2 cylinder allows for low pressure reduction over the entire flush, fill, run, and purge sequence.

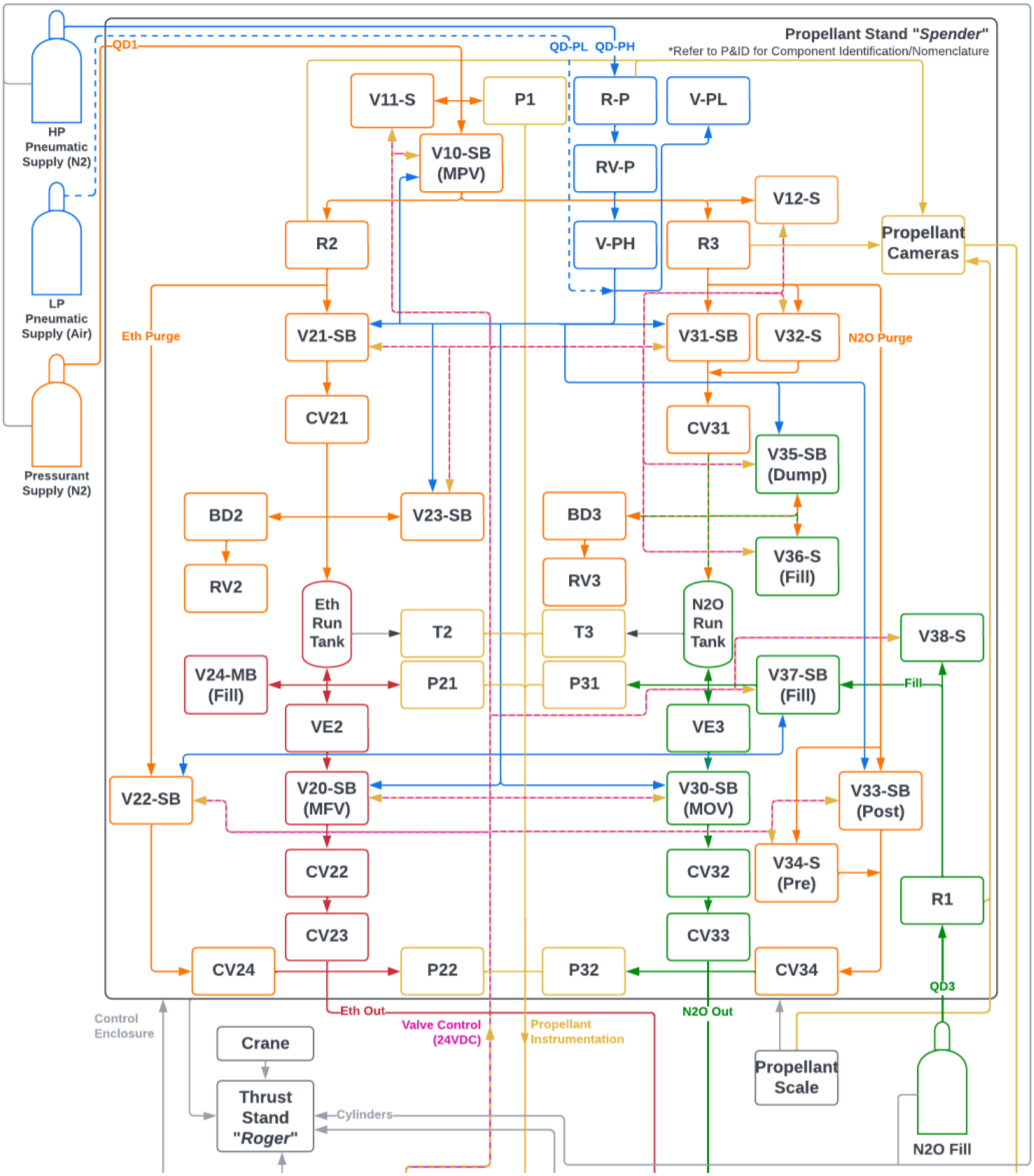


Figure 4.2.1: Propellant system integration diagram (V2.6.2).

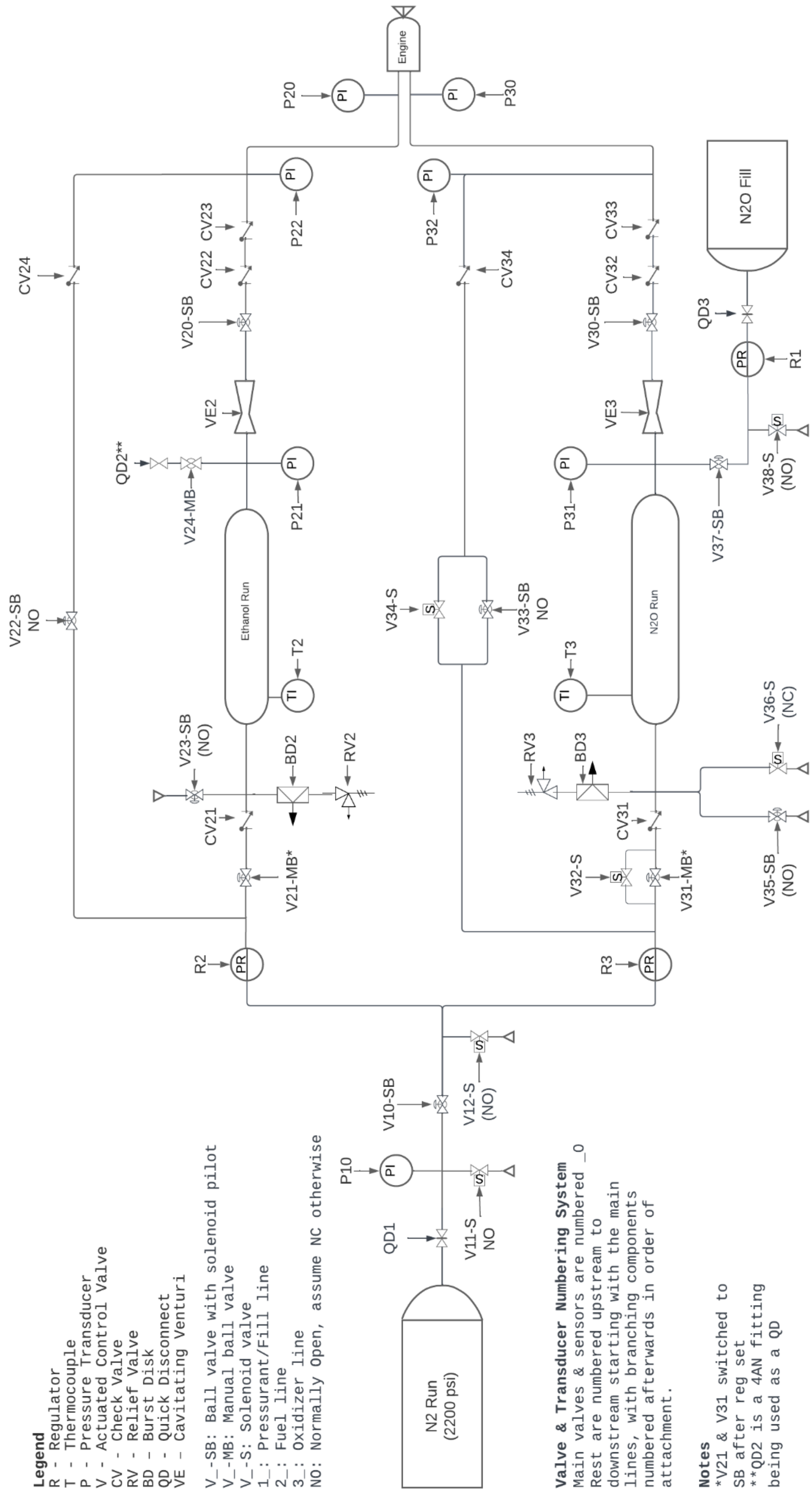


Figure 4.2.2: Propellant System P&ID (V5.1).

Table 4.2.1: Details of Selected Plumbing Components

Description	Type	MAWP	Characteristics	Material
Eth Main Ball Valve	COTS	17.2 MPa	3.0 Cv ¼" FNPT	316 SS PTFE
N_2O Main Ball Valve	COTS	15.2 MPa	12.0 Cv ¼" FNPT	316 SS PTFE
N_2O Fill Ball Valve	COTS	20.7 MPa	¼" FNPT	316 SS
Pressurant Isolation & Control Valves	COTS	20.7 MPa	7 Cv ¼" FNPT	303 SS CTFE
High Pressure (NO) Solenoid Vent Valves	COTS	25 MPa	0.022 Cv G1/4	303 SS
High Pressure (NC) Solenoid Vent Valves	COTS	34.5 MPa	0.01 C_V ⅛ " FNPT	303 SS Acetal Plastic
Relief Valves	COTS	41.4 MPa	11.7 MPa Set ½" FNPT	316 SS FKM
Burst Disks	COTS	19.2 MPa	¼" NPT	316L SS
Check Valves	COTS	41.4 MPa	0.67Cv 6.9 Kpa Cracking ¼" Swagelok	316 SS FKM
Ethanol & N_2O Run Tanks	COTS	12.4 MPa	3.785L ½" FNPT	304L SS
N_2O Fill Regulator	COTS	41.4 MPa	0.08 Cv 4" FNPT	Aluminum Polyimide
N_2O Run Regulator	COTS	41.4 MPa	1.1 Cv ½" FNPT	316 SS PEEK
Eth Run Regulator	COTS	34.5 MPa	0.8 Cv ¼" FNPT, ½" FNPT	Al, Brass, SS Kel-F, Viton
Ethanol Flex Hose	COTS	27.6 MPa	-4AN SS Braided	SS & PTFE
N2O Flex Hose	COTS	17.2 MPa	-8AN SS Braided	SS & PTFE
Ethanol Cavitating Venturi	SRAD	20.7 MPa	1.434 mm Throat Diameter	6061-T6 Aluminum
N_2O Cavitating Venturi	SRAD	20.7 MPa	3.346 mm Throat Diameter	6061-T6 Aluminum
Eth & N_2 Feed Tubing	COTS	35.2 MPa	¼" OD	316 SS
N_2O Feed Tubing	COTS	20 MPa	¾" OD	316 SS
N_2O Fill Tubing	COTS	15.9 MPa	½" OD	316 SS

4.2.1 Valve Selection

The propellant system uses fail-safe valves to manage pressures, control propellant & pressurant flow, and quickly vent pressurant & oxidizer. Parameters considered during the selection process of each valve included: flow coefficient, fail-safe capabilities, actuation method, actuation time, pressure ratings, fluid compatibility, mounting, and cost.

The main valves of the propellant feed systems required a normally closed configuration with minimal pressure drop. Swagelok pneumatically actuated ball valves were selected as the main fuel valve (MFV: V20-SB) and main oxidizer valve (MOV: V30-SB) due to their high flow coefficients, spring-return, and in-valve vent.

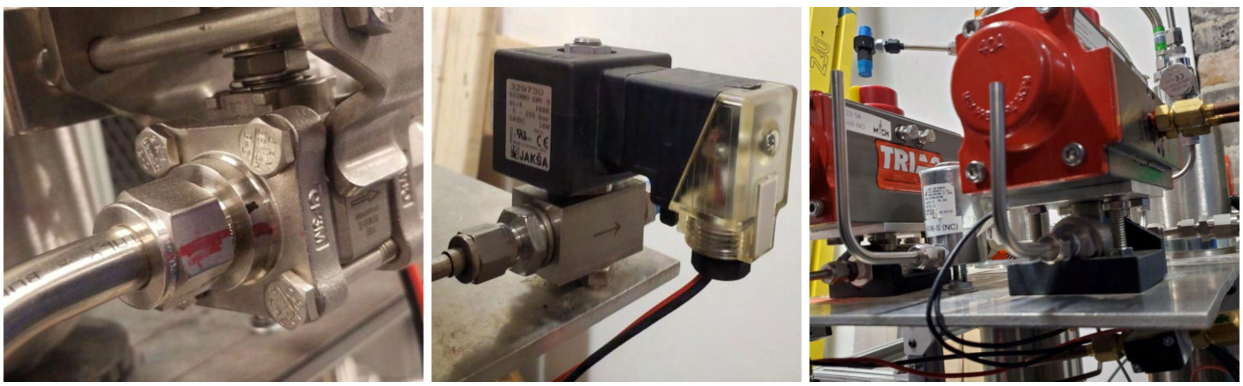


Figure 4.2.3: a: Ball MOV (V30-SB) **b:** Solenoid Vent (V12-S) **c:** Ball Vent (V35-SB).

The flow of N_2 is also controlled using pneumatically actuated ball valves for the Main Pressurant Valve (MPV: V10-SB), ethanol & N_2O isolation valves (V21-SB & V31-SB), dump vents (V23-SB & V35-SB), and purge bypass valves (V22-SB & V33-SB). Ball valves were used for N_2 isolation valves for their high flow coefficients. COTS valves and pneumatic actuators with SRAD couplers were used for pressurant valves due to the cost of COTS combined units. The MPV uses a spring-return actuator while all other valves use double-acting actuators. The pneumatic pilot solenoid valves are configured to fail into safe states in the event of power loss. The use of spring-return actuators on all critical valves (V10-SB, V20-SB, V30-SB, V37-SB) ensures safe abort in the event of complete pneumatic loss. Computations for valve sizing are provided in Appendix I.

Vent valves were added to each isolated subsection to allow the system to return to safe conditions in the event of an automatic, manual, or emergency abort. The no-power fail-safe state of the system is a critical safety feature which enables the use of an emergency-stop (E-stop) system in case all electronic control is lost. The vent valves were selected to be normally open to allow for automatic venting in the event of power failure. For three vents , it was calculated that the maximum flow of the valves was not an important factor for valve selection as pressure relief could be sufficiently performed by other relief mechanisms in the event of regulator failure. Relief system sizing calculations are provided in Appendix I. High-pressure, normally-open solenoid valves were selected for the critical V11-S, V12-S, & V-38 valves. Jaksa Solenoid Valves were selected due to their positions upstream of the regulator and on the fill line, low actuation time, and generous sponsorship discount. Ball valves were used for the main dump vents to handle failure cases of the high flow coefficient Eth and N_2O regulators (R2 & R3). On the N_2O side of the system, three normally closed Peter Paul solenoid valves are also used in parallel with ball valves as the fill vent (V36-S), slow pressurization valve (V32-S), and N_2O pre-purge (V34-S).

For remotely monitoring valve status, flow direction indicators are used on all ball valves. DIN solenoid connectors with LED indicators are used for all high-pressure solenoid valves as well as pneumatic pilot valves. The valve states are also monitored through software described in section 4.3.3.

Relief valves and burst disks are used to prevent over-pressurization and manage regulator creep. The set pressure of the relief valve is to be 16% above the maximum expected operating pressure to account for cracking below the set point. In the event of regulator failure, both relief valves (RV2 & RV3) have been sized to handle the maximum possible flow with an acceptable increase in upstream pressure. Severe overpressurization events in both propellant lines & tanks are also mitigated by burst disks (BD2 & BD3). All high pressure relief and vent valves are terminated by Tee fittings to mitigate venting forces.

Check valves are present in the propellant, pressurant, and purge lines to prevent backflow. The main propellant lines after the MFV and MOV use two check valves in series. Poppet valves with 1 psi (6.89kPa) cracking pressure were selected.

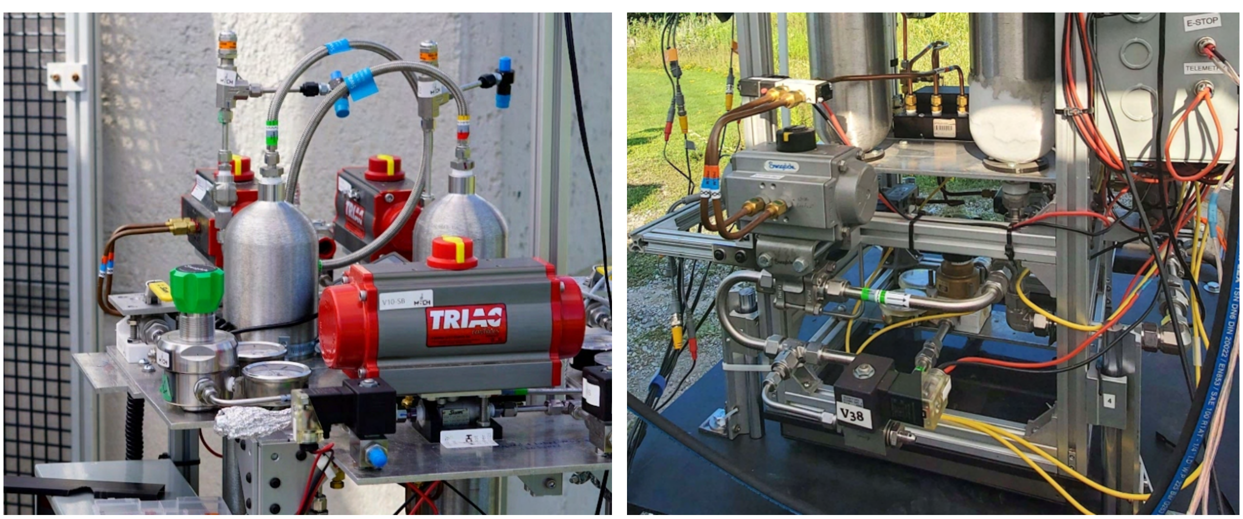


Figure 4.2.4: The upper & lower components of Spender during cold-flows.

4.2.2 Cavitating Venturi Flow Control

The flow control mechanism for each feed line is a SRAD cavitating venturi. Cavitating venturis were selected due their ability to act as both a flow controller and a flowmeter [13]. Since the flow rate through a cavitating venturi is only a function of the upstream pressure, readings from an upstream transducer will be sufficient to compute the flow rates in real time after tuning and calibration [14].

The geometries of the ethanol and N_2O cavitating venturis were calculated with reference equations and verified using system-based CFD simulations in Flownex SE [13]. The results indicate that the theoretical design process can yield accurate geometries able to choke the flow to <0.5% of simulated results. The simplified flow simulation setup with the ethanol venturi and the corresponding injector orifice is presented in Figure 4.2.5. The boundary conditions and results of the flow simulations are presented in Table 4.2.2.

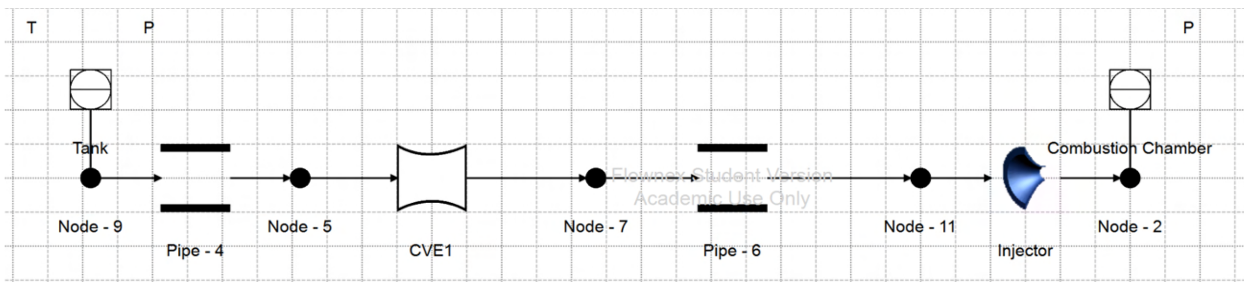


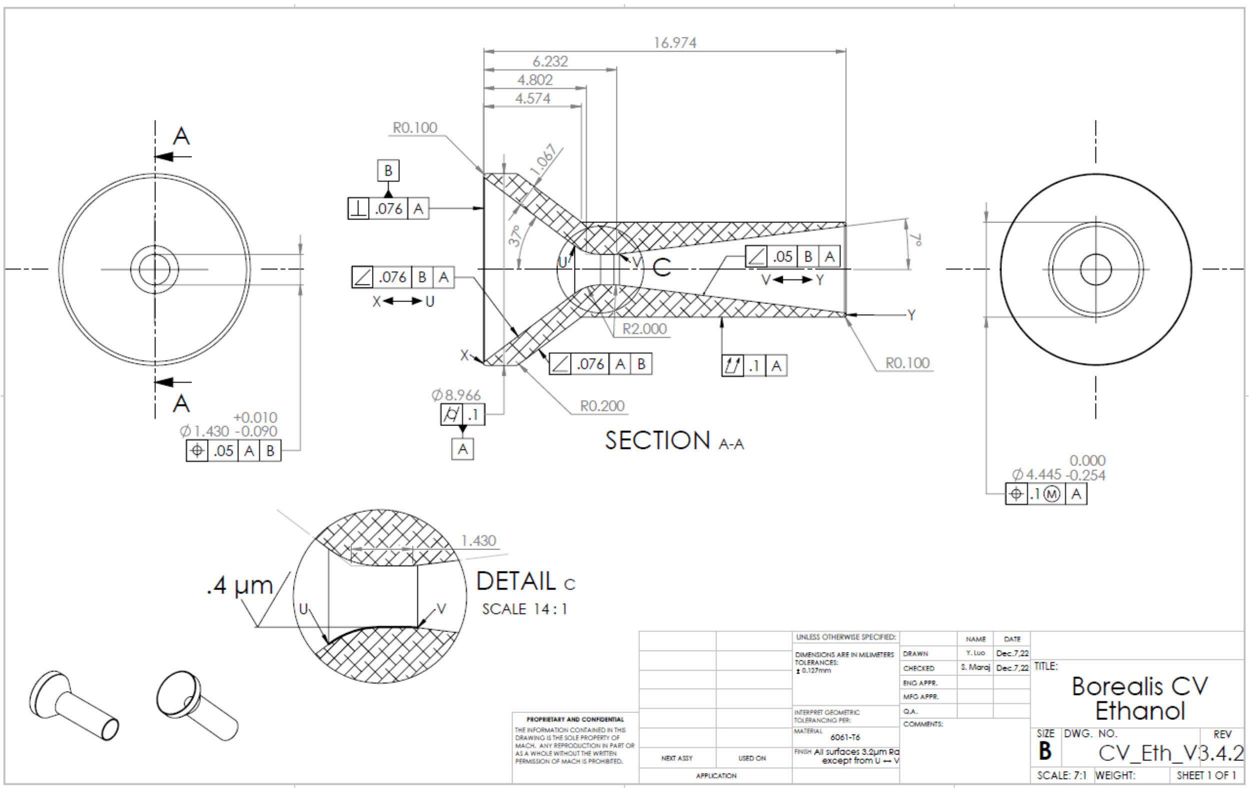
Figure 4.2.5: Simplified Eth cavitating venturi and injector model in Flownex SE.

Table 4.2.2: Boundary Conditions and Results from Simplified Flow Simulation

Property	Value
Upstream Stagnation Pressure	8.80 MPa (1277 psia)
Upstream Temperature	21°C
Downstream Injector Pressure	4.83 MPa (700 psi)
Choked Mass Flow Rate	0.1893 kg/s
Injector Pressure Drop	1.03 MPa (152.51 psi)

The discharge coefficient (C_d) is experimentally determined through inert cold-flow testing with propellant stand-ins, and cold-flows with non-reactive propellant combinations. These tests will first be conducted with water and CO_2 as stand-in propellants with somewhat similar fluid properties, followed by separate testing of N_2O and potentially ethanol for validation.

The cavitating venturis are designed to fit into AN fittings for their respective propellant run lines. Their dimensions and geometries are shown in Figure 4.2.6.



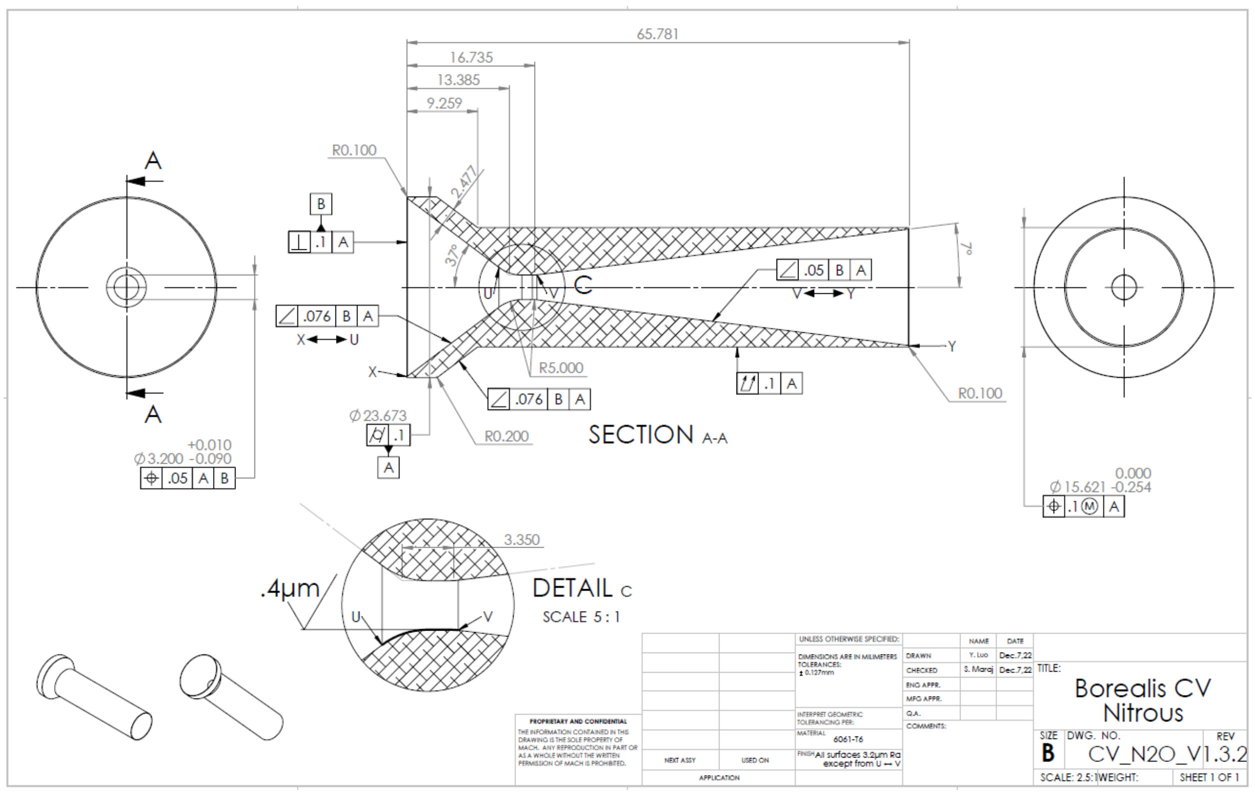


Figure 4.2.6: Production drawings for the **a:** Ethanol & **b:** N_2O cavitating venturis.

They are initially manufactured in 6061 aluminum due to cost considerations. As manufactured, the throats are sized exactly to the theoretical designs, leaving expected efficiency losses as excess material for tuning. Increasing the radius of the throat inlet (and to lesser effect, outlet) and smoothing the surface finish can be used for fine adjustment. The throat diameter can be increased by precision boring followed by radiusing and polishing for more drastic adjustment.

Figure 4.2.7 Manufactured cavitating venturis.

As manufactured, results from inert cold-flow tests have found C_d of 0.83 and 0.76 for the N_2O and Eth cavitating venturis, respectively. While this is within expected margins, the resulting mass flow rate with propellant stand-ins are ~25% below the theoretical values. After evaluating the new performance and safety factors, the cavitating venturis were deemed to be acceptable for a first hot-fire test without adjustment. Subsequent hot-fire tests will be performed after tuning to evaluate the performance difference and tuning process. After validation of the process, future cavitating venturis will be made using stainless steel.

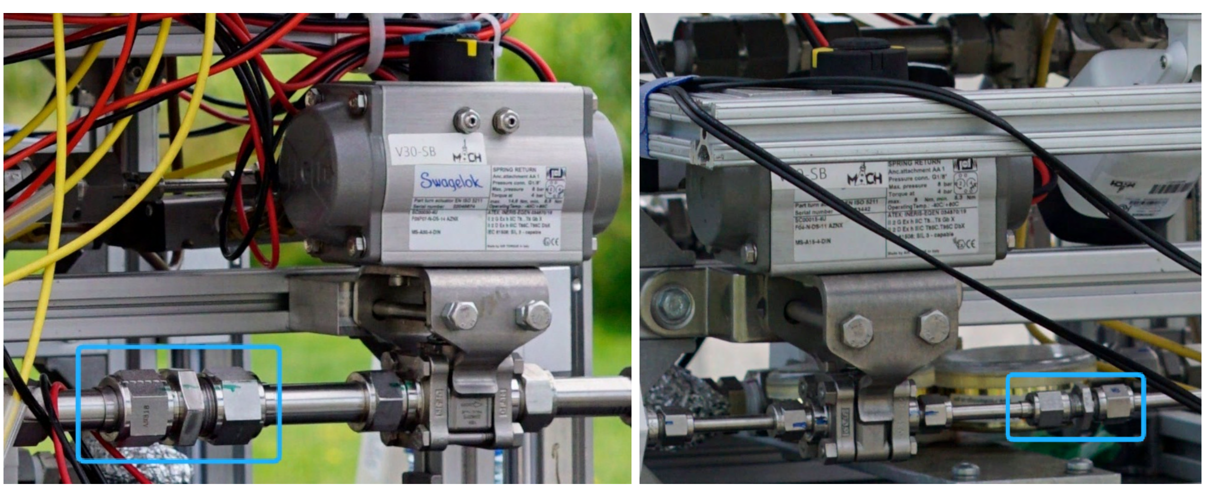


Figure 4.2.8: Cavitating venturis installed into **a:** N_2O & **b:** ethanol lines.

4.2.3 Propellant Loading & Unloading

Both propellants are loaded into the run tanks through the bottom of the tank, in compliance with LC requirement 2.2.3.3.1 [4]. Before the fill procedure can be conducted, a pneumatic leak test of the system must be performed with the pressurant cylinder after each assembly. This test also serves as an inert gas flush to displace any contaminants and oxidizing air from the propellant lines and tanks. The MPV (V10-SB), V21-SB, & V31-SB are then disarmed (closed) for safety, as are the MFV (V-20SB) and MOV (V-30SB) previously.

A pre-measured volume of ethanol is first loaded manually using a flex hose line with a quick disconnect fitting (QD2) that also acts as a manual drain port. Gravity filling was found to be inadequate for a multitude of reasons; therefore a hand operated pump fill procedure is used. The safety procedures require a change in “Red Team” pad personnel before continuing fill. The two Red Teams alternate to remotely monitor the pad from mission control; this ensures the most experienced personnel available are always at both ends during high-risk procedures.

Nitrous oxide is first pre-chilled to increase the density, liquid ratio, and minimize two-phase flow during operation. A dip tube will also be used to increase the fraction of liquid loaded into the tank. The N_2O fill tank is manually connected through a quick-disconnect fitting (QD3) into a fill line consisting of a regulator (R1), pneumatically actuated spring-return ball fill valve (V34-SB), and vent valve (V35-S). All arming procedures are then conducted for the control, propellant, and ignitor systems. The pad is then evacuated and locked down until a safe state is redeclared.

The N_2O is then remotely loaded by opening the low-flow fill vent (V33-S) and fill valves, creating a pressure differential to draw the N_2O into the tank. The fill vent orifice size was selected to be as small as possible (0.6mm) to minimize pressure drop in the tank, thereby minimizing the amount of N_2O wasted during the filling procedure. Filling is monitored through the propellant scale, and visually confirmed when liquid reaches the vent valve and the plume changes color and thickens. The fill valves are then closed remotely for testing to proceed. This process has been tested with inert propellants to take around 2 minutes.

After a test, the nominal purge sequence will bypass the ethanol run tank to purge the fuel lines, and purge through the N_2O run tank to flush any remaining oxidizer from the system. During aborts, the N_2O dump valve (V32-SB) can rapidly vent the oxidizer tank and lines. In cases of controlled aborts, the partial fuel purge & oxidizer dump or full purge sequence can be run automatically or manually depending on urgency and recoverability of the test. With loss of communications and/or control, the E-stop returns the system to a fully isolated and venting state. With the worst-case possibility of simultaneous loss of communications, power, and pneumatics, the valve configuration still initiates N_2O dump & full depressurization (pad “safe” state) without backflow to the pressurant lines. Any remaining ethanol can be manually drained after the pad is safed.

4.2.4 Propellant Stand

The propellant stand ("Spender V2") is a modular, mobile structure which secures the propellant run tanks and all associated plumbing, valves, and other components. The stand is constructed from 3030 series (30 mm square profile) 6061 aluminum extrusions, along with ¼" thick 6061 aluminum plates as platforms. All structural members are reinforced with a combination of corner rails, L brackets, and gusset plates. Additionally, all corner members were milled to within 0.010" of each other, further contributing to a frame with substantial rigidity. Some legacy 1010 (1" square profile) extrusions are used as nonstructural members, such as legs and camera mounts. The stand is designed to be compact due to the team's mobile testing needs, easily transported horizontally in any station wagon or SUV. The new construction since R3 of the report was deemed necessary after significant issues were identified with the previous iteration of the test stand ("Spender V1") [1].

The main propellant tanks are mounted to extrusion-reinforced plates, with worm clamps providing additional horizontal and lateral rigidity during transport. All plumbing components are securely mounted to the stand using removable fasteners, with FDM printed mounting brackets on some for alignment and fitment. A weight scale is also secured to the bottom of the stand for measuring propellant mass during testing. Additionally, linear rail sliders are mounted to each bottom corner for securing Spender to the thrust stand, which is detailed in Section 4.4.1. The propellant enclosure for control and data acquisition is physically integrated into the propellant stand as well, which is further described in Section 4.3.3.

The stand is physically divided into upper and lower portions by the height of the tanks, as can be seen in Figures 4.2.4 & 2.4.9. The upper platforms mount the common pressurant line, with the majority of the fuel and oxidizer fill and run lines on the lower platforms. All fluid lines are identified per MIL-STD-1247D [15].

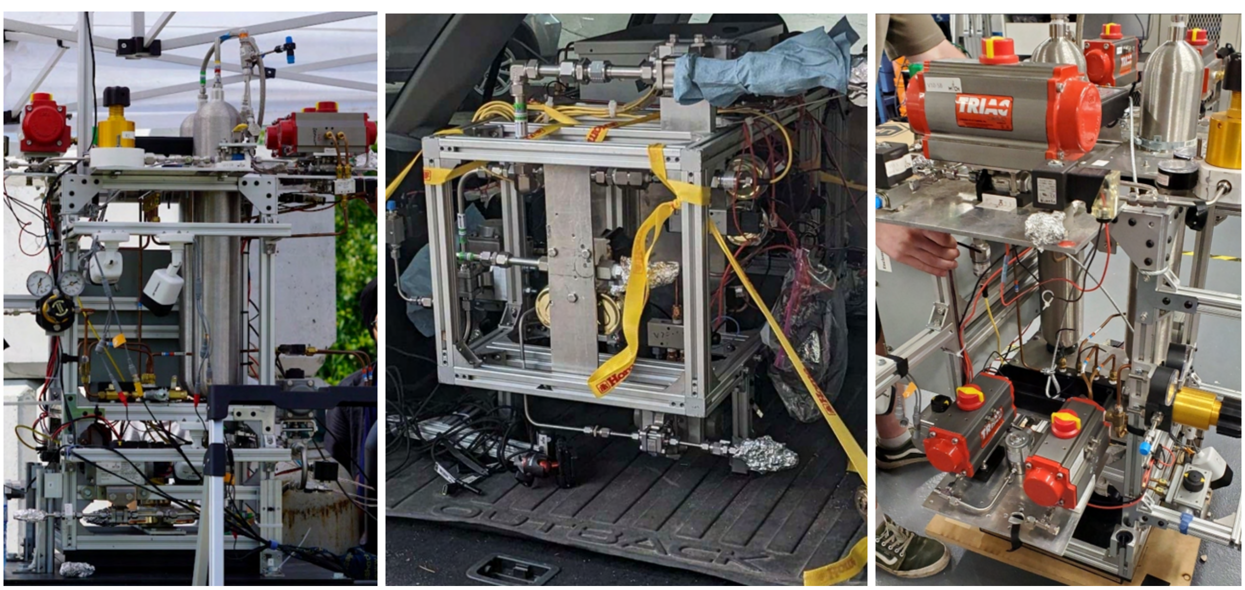


Figure 4.2.9: Spender **a:** integrated **b:** in transport **c:** w/ partially installed purge.

4.2.5 Pneumatic System

A hard-line pneumatic system using copper tubing was built with Spender V2. This eliminated issues with the previous iteration of the pneumatic system detailed in Appendix A2.2, and greatly improved transportability and reliability.

¼” OD copper tubing was used for the pneumatic lines for their cost and availability. All tubing connections are made using brass Yor-Lok or JIC fittings. The inlet is located on the lower platform for accessibility in the stacked configuration. A lower and upper manifold distributes the air to the various pilot solenoid valves, and a vertical length of copper tubing connects the manifolds.

A pneumatic feed line runs to each of the pilot solenoids, which splits off into two lines into the corresponding ports on the pneumatic actuators. All pilot valves are installed with attention to power fail-safe default states. In the event of control or power loss, pneumatic pressure alone can return the valve to a safe state.

The pneumatic system has a nominal operating pressure of 100 psi. There are two inlets that can be configured to suit testing needs. The high-pressure inlet is used with compressed air or N_2 cylinders up to 6000 psi, and connects through a reducing regulator (R-P). Compressed gas cylinders are used during major testing for their high gas mass and reliable operation. A low-pressure standard air hose QD can be used with any standard air compressor for convenience of low-risk testing where compressed cylinders are not available. Air compressors are not used during testing due to their low tank size, spark risk from motors, and start-stop operation.

During testing, the low pressure QD (QD-PL) is removed and closed with a -6 JIC cap to prevent QD leaks. The high pressure inlet connects to stainless steel tubing with a 4AN fitting, and can be closed with a manual ball valve (V-PH) when not in use. The regulator is self-venting and a 150 psi relief valve is immediately downstream for redundancy. A manual ball bleed valve (V-PL) is also present.

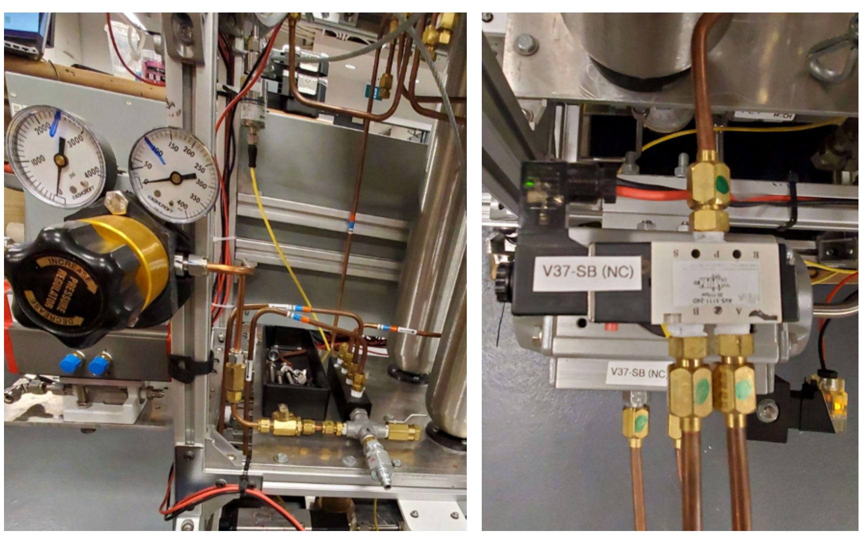


Figure 4.2.10: a: Pneumatic inlet manifold **b:** Pneumatic pilot solenoid.

4.3 TELEMETRY & CONTROL

The telemetry & control system is designed to enable the successful hot-fire testing of the engine while providing the maximum possible safety. The system is designed around an extensive instrumentation suite driving a seamless and reliable engine control system, backed up by telemetry for monitoring, and provisions for manual procedures and intervention. Though the control system is designed to be primarily operated on software, many electronic hardware safety features are used in conjunction with the propellant system design described in Section 4.2 to ensure fail-safe operation in contingencies.

There are 5 major subsystems: mission control, engine computer & pad control, propellant enclosure, engine enclosure, and communications systems. A simplified block diagram of these subsystems is provided in Figure 4.3.1 and key components of each subsystem are listed in Table 4.3.1.

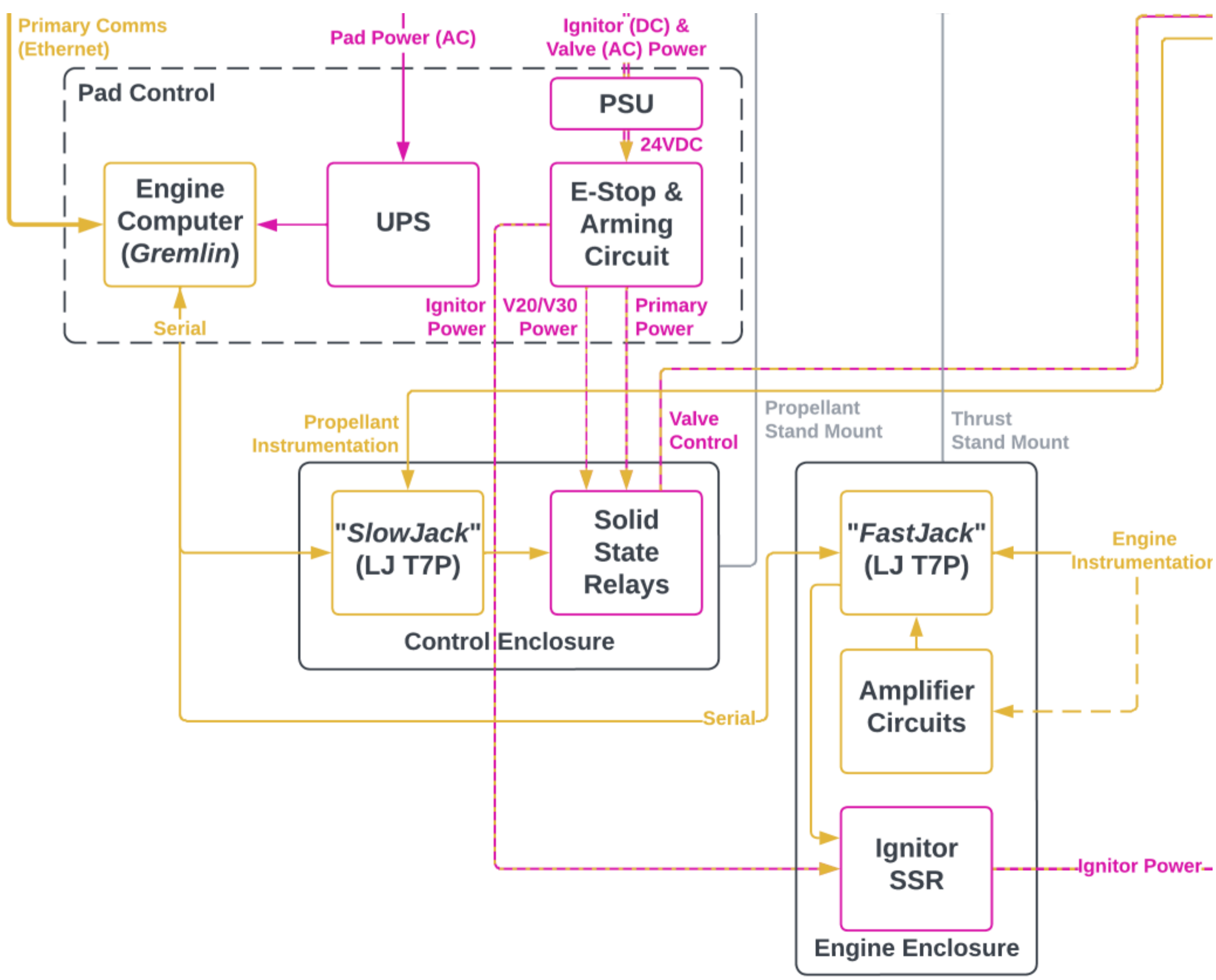


Figure 4.3.1 Engine side telemetry & control system integration diagram (V2.6.2).

Table 4.3.1: Transfer and Control Subsystems Overview

Subsystem	Key Components
Mission Control	Laptop Computers, Displays, Power, Ignitor Power MC Arming & E-Stop Enclosure
Pad Control	Pad Arming & E-Stop Enclosure, 24VDC Valve PSU, UPS, **Engine Computer**
Propellant Enclosure	LabJack T7 Pro, DB37 & DB15 Expansions, Valve SSRs
Engine Enclosure	LabJack T7 Pro, CB37 Expansion Board, Signal Conditioner, Ignitor SSR
Communications Systems	Ethernet, Network Switches, Wired Cameras, Conduit

All system control, ignition and data acquisition is done using two Labjack T7 Pro units. A fully integrated software-hardware relationship allows for immediate and reliable actuation of each valve, as well as initiation of pre-programmed sequences. Using digital input-output labjack functions, the state of each valve can be reliably read and updated on the graphical user interface. All control with the exception of ignition control and a small portion of low priority DAQ is done with a labjack unit dubbed “SlowJack”. All high priority engine data acquisition and ignition control is done using “FastJack”, a Labjack unit that is completely dedicated to high speed data acquisition and transmission. Ignition is actuated through a singular digital pin on FastJack which is paired with an SSR and a mechanical safety interlock.

FastJack also processes the telemetry for transmission to mission control, and saves the large quantity of data to the engine computer’s onboard storage for later analysis. The full instrumentation stream is downsampled to reduce transmission bandwidth and processing required to provide live telemetry data to mission control, thereby increasing reliability.

Two-way communications between mission control and the pad enables monitoring and controlling nominal operations such as filling, as well as manual intervention in contingencies. Primary communications is accomplished over a wired ethernet connection (over short distances with barriers). Fiber optic transmission was planned but was scrapped due to team budget and the excessive speeds for the safe distance requirement for the testing of GAR-E. A constant parallel wireless connection is used for redundancy. Visual telemetry from pad cameras are routed through separate connections for redundancy and bandwidth considerations. The physical compartmentalization of critical parts into separate enclosures allows for easy integration and mitigates risk of total system loss. The enclosures provide protection from environmental hazards, and are interfaced with a minimal number of sealed connectors.

4.3.1 Sensors & Data Acquisition

Data acquisition is distributed through the two Labjack units. The data of interest during testing are temperatures and pressures throughout the system, propellant mass, and engine thrust. To safely control the engine through a hot-fire test, sensors in the propellant system, engine, and test stand provide crucial data for the function and operational status of the engine. These are outlined in Table 4.3.2 .

Table 4.3.2: Sensors Overview

Sensor(s)	Location(s)	Purpose(s)
Ignitor Thermocouple (1)	Embedded within ignitor assembly	- Verify successful ignition of solid rocket propellant grain - Initiate timing for ignition valve actuation sequence
Injector Thermocouples (2)	Thermocouples at the injector volute & chamber seal	- Detect injector & chamber over-temperature events
In-Chamber Transducer (1)	Within injector, pressure port filled with thermal isolation media	- Detect chamber overpressure events and initiate abort - Detect propellant ignition failure - Measure chamber pressure data
Injector Inlet Transducers (2)	Immediately before injector inlet ports on fuel and oxidizer lines, connected to respective lines via T-fittings	- Detect potential combustion backflow events in conjunction with in-chamber transducer - Detect suboptimal injection pressures (due to leaks, malfunctions, etc) downstream of main propellant valves
Piezoresistive Load Cell (1)	On the thrust assembly contacting the engine thrust adapter	- Measure thrust data for validation & research - Detect propellant ignition failure - Detect catastrophic RUDs
Propellant System Transmitters (5) **& Gauges** (6)	In isolated lines for pressurant, fuel, oxidizer, and fill. T-fittings to transducers & gauges on regulators	- Detect propellant system anomalies (overpressure, reg failures, leaks, etc.) - Monitor pressurization and vent state of propellant system - Indirect flow rate data for Venturis
Run Tank Thermocouples (2)	On the exterior surface of run tanks.	- Detect over/under temperature events - Validate N_2O filling - Indirect flow rate data for Venturis
Propellant Scale (1)	Integrated below the propellant stand	- Measure propellant mass during fill, drain, run, and vent - Validate safe condition for venting

The LabJack units have built in analog-to-digital-converters (ADCs) and microcontrollers to obtain analog telemetry signals and convert them into digital communications, which are then sent to Gremlin through USB. A high-low configuration is used to accommodate the large number of sensors without sacrificing data quality. The “SlowJack” unit on the propellant system handles the majority of sensors, while the “FastJack” unit only reads a small number of sensors for engine instrumentation at a significantly higher polling rate. for the purpose of data acquisition greatly increases sampling rates and quality of data due to the absence of control and state communications constantly using bandwidth.

Although the T7 Pro can distinguish voltage variations of 316 uV from each sensor, an amplifier will be used to increase the voltage from the sensors. This ensures that accurate data is acquired and minute voltage changes from the sensors are detected. For the voltage resolution setting of 316 uV, the T7 Pro has a sensor sample rate of 0.04 ms/sample [16]. A single Labjack T7 Pro unit is capable of reading 100k samples per second from a singular sensor. Using Table 4.3.2, it can be found that SlowJack will be able to read its 9 sensors at 11.111k samples per second. Similarly, FastJack’s 5 sensors are able to poll at 20k samples per second. The digital data acquired by the T7 is sent to the engine computer over a serial connection and LabJack’s LJM cross-platform library, where it is processed for control, sent for telemetry, and stored for later analysis.

The engine enclosure is outfitted with dedicated panel mount connectors for thermocouples, pressure transmitters and the load cell. These are in place to minimize environmental risks, and allow for quick disconnect and rearrangement of telemetry. Due to the fragile nature of most telemetry, power is routed to this enclosure directly from the Propellant Enclosure, a 1 amp fuse will be connected in series with the main power distribution block within this enclosure. This will ensure no telemetry suffers from overvoltages.

The switch to pressure transmitters generously provided by Automation Direct eliminated the need for additional signal conditioning or amplification. Thermocouples are reliable and relatively simple analog devices so they also do not require any extra circuitry. The load cell is the only sensor requiring conditioning and amplification circuitry, using an Absolute Process Instruments (API) 4059 G.

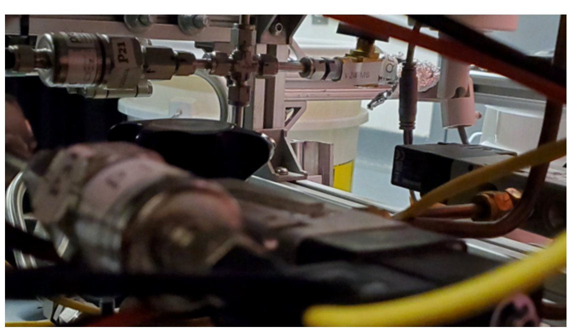


Figure 4.3.2: Pressure transmitters P31 and P21 installed

4.3.2 Engine Computer & Software

The engine computer, nicknamed "Gremlin", is the primary method of data collection, communications, and control. During hot-fire testing, it uses real-time instrumentation data from the DAQ to run an automatic safety algorithm, then outputs the appropriate commands to the control unit for actuation. The software is responsible for monitoring the engine state and performing safe ignition, hot-fire, and shutdown, as well as abort sequences with minimal intervention from mission control. This design aims to greatly reduce the control response time in reaction to the complex and rapidly changing conditions of the test, as well as mitigate failures or delays in communications.

Desktop computing hardware was selected for Gremlin for its processing power, expandability, and relative low cost. It interfaces with both the DAQ and control unit with a USB connection, and uses onboard ethernet for communication.

Figure 4.3.3: a: Engine Computer *Gremlin V2*. **b:** Pad Control Setup with *Gremlin*.

The control software runs entirely on the engine computer and can function independently without mission control (though a loss of communication triggers automatic abort). An interface for control & monitoring of the propellant system is provided at the pad to allow full control of valve actuation and sequences. The GUI is based on the P&ID and system architecture diagrams, and uses a mouse & keyboard for input. This interface is mirrored on the mission control computer. The GUI is programmed in such a way that infinite clients can connect to the GUI and run a fully functional and identical system on virtually any PC.

The software contains a number of preprogrammed actuation sequences for the valves and ignitor, which are executed upon receiving actuation commands from the GUI. Valve states are preprogrammed and are simple single actuations or short sequences with predetermined order and timing fine-tuned during the various cold-flow tests. Once commands are received, the control software sets specific digital input/output (DIO) pins on the SlowJack to either a high or low state. The state of each DIO pin characterizes whether a valves corresponding SSR has a large enough voltage difference to actuate. Sensor data is displayed on the GUI using linear gauges with predefined off-nominal color ranges.

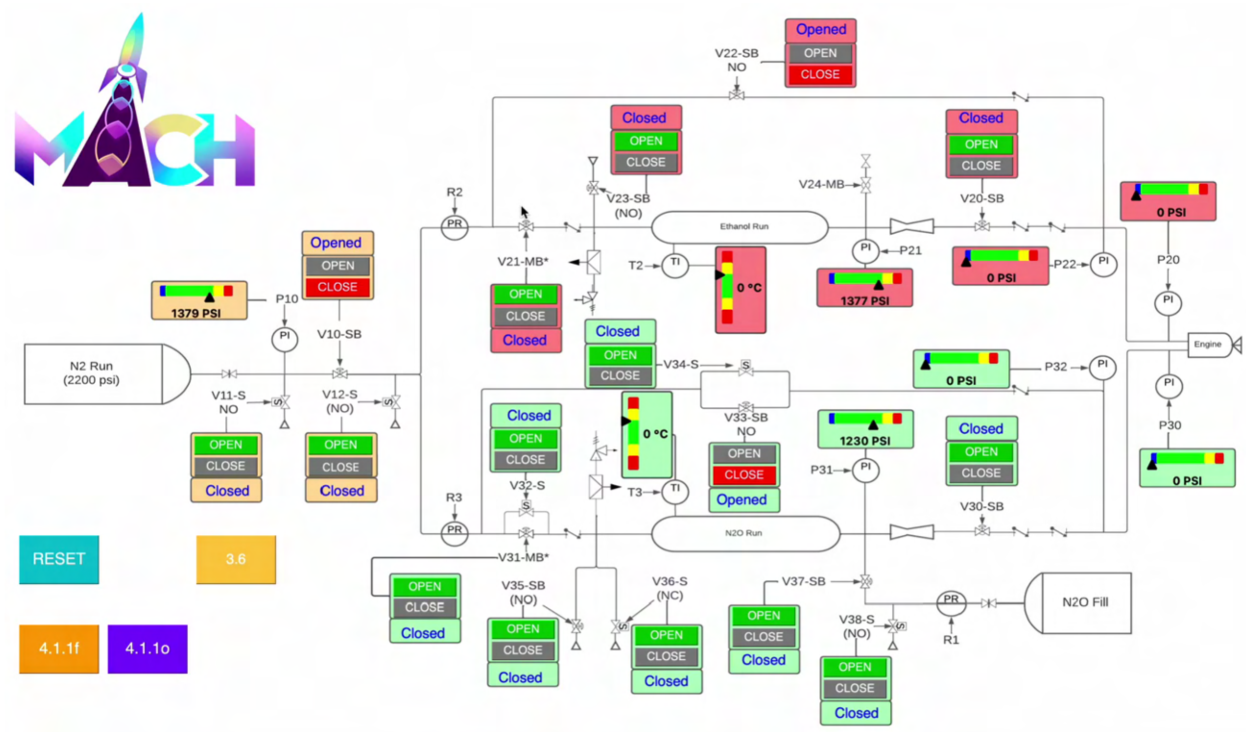


Figure 4.3.4: A screenshot of the GUI during a cold-flow.

The control software operates on a state machine model. Sensor inputs and manual commands from the communications system are used to determine the state of the engine and test at any time. These are continually monitored for any conditions that may trigger a state change or desired state. Required changes in state are used to determine the control outputs, and appropriate commands are sent to trigger pre-programmed ignition and valve actuation sequences. The engine state is continually validated to ensure commands are successful or initiate contingency cases. Table 4.3.3 and Figure 4.3.5 illustrate the major states and transitions in the engine's operation, the RMS contains a more comprehensive list of identified scenarios to trigger abort or purge commands, from which the control algorithm is developed.

The engine computer software also downsamples telemetry data to send to mission control, as well as writing the full data stream to storage in a convenient format for later analysis.

Table 4.3.3: Major Engine States

Engine State	Description/Conditions	Triggers
Inert Safe	- No combination of fuel and oxidizer in system - No pressurization detected in system - No armed ignitor in system - No power to valve actuation or ignitor, all valves in default state	- Initial condition after assembly & setup - Final state after nominal hot-fire - Manually triggered after abort & safing
Fill & Test States (includes separate sub-states for pressurant testing & loading of fuel and oxidizer)	- Used while connecting pressurant, fuel, or oxidizer fill line during pneumatic leak testing & fill procedures - All isolation & vent valves closed during pressurant/fill tank connection and disconnection - Vent of pressurized fill lines for nitrous oxide and nitrogen actuated remotely	- Manually triggered from mission control or pad according to appropriate procedures
Standby	- Pressurant tanks connected, fuel and oxidizer run tanks filled - Tanks are NOT pressurized - Ignitor is NOT armed	- Manually triggered by mission control - Automatically triggered by some abort (ie ignitor failure) cases
Armed	- Pressurant tanks connected, fuel and oxidizer run tanks filled and pressurized - Ignitor is inserted and armed	- Manually triggered by arming of all safety switches at pad & mission control
Igniting*	- Ignitor sequence initiated - Valve actuation sequence for engine startup after validating successful ignitor - Internal control system takes over engine operations after this state	- Manually triggered by mission control after procedural checks passed
Firing	- Main propellant valves open, Nominal operation state during hot-fire	- Automatically triggered by successful ignition
Shutdown*	- Nominal shutdown & purge sequence initiated	- Automatically triggered 5s after fuel valve opening & nominal operation

Abort*	- Premature shutdown sequence initiated - Purge, vent, or hold sequence depending on specific trigger	- Automatically triggered by out-of-bounds sensor readings - Manually triggered from mission control
Emergency Abort	- Valve actuation power disconnected, all valves returned to default safe state & venting	- Triggered by manual emergency abort button from mission control
Caution	- Valves in safe state, system not fully emptied of propellants or pressurant	- Triggered by most abort cases

* A series of sequences, states, & logic in short order.

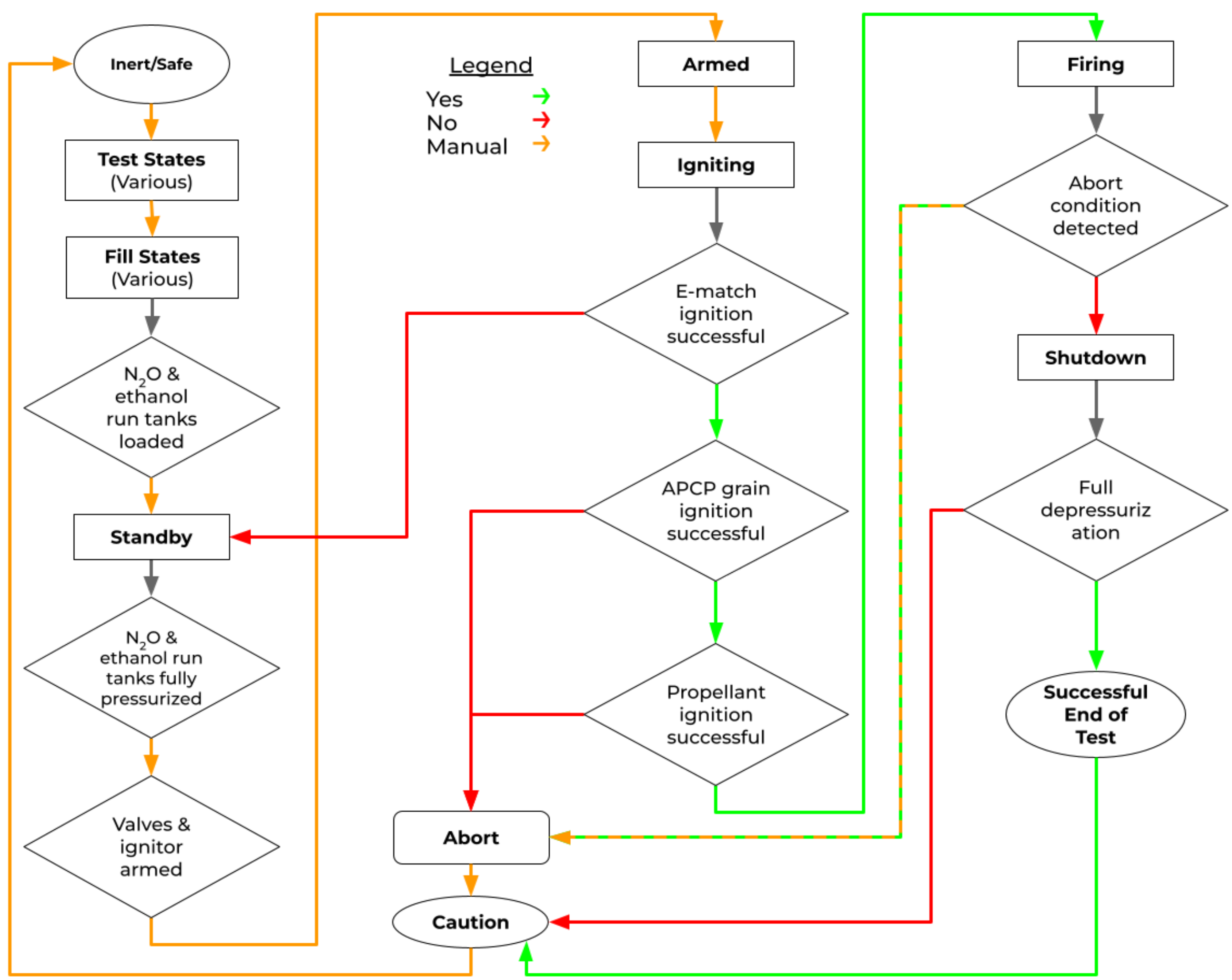


Figure 4.3.5 Simplified Engine State Logic Diagram (V2.1).

If any of the parameters received from instrumentation exceeds acceptable thresholds, the engine computer will commence an automatic abort sequence which will terminate propellant flow, close isolation valves, begin purge or vent, and return the engine to a safe state. Several types of software and hardware abort can be executed depending on the condition of the engine and test. For example, an ignitor failure abort case differs from a mid-firing abort case. Additionally, aborts can be triggered manually both through software (controlled abort) or the use of the E-stop (uncontrolled or emergency abort). The specific cases are as follows:

- **Abort:** Unintended early shutdown. This procedure is initiated with ignition, mid-firing, or shutdown anomalies.
    - **Automatic Abort:** The engine computer detects an error in the sensor data, the propellant & isolation valves are closed in sequence and a purge or vent is initiated if appropriate, without human intervention.
    - **Manual Abort:** Manually-initiated shutdown. This procedure occurs in the event of an error in the engine computer, a failure in the initiation of the automatic abort, or any other anomalous condition detected by personnel at mission control. The valves are closed in sequence and a purge or vent can be initiated if deemed appropriate.
    - **Emergency Abort:** The emergency stop button at mission control cuts off all power to all engine side systems through a separate wired link. This resets the valves to their default safe state, which closes isolation valves and opens vent valves. This specific abort sequence will only be used under severe failure which includes unsuccessful automatic and manual aborts, due to loss of the control and/or communications systems. This abort case is solely controlled by pneumatic or mechanical return of the valves and is not sequenced. It also precludes the initiation of purge sequences, and requires venting of all oxidizer before the pad can be declared safe.
- **Nominal Shutdown:** Intended mode of shutdown at the conclusion of a successful hot-fire. The MFV and ethanol isolation valves are closed and the bypass valve is opened. Any remaining ethanol in the fuel lines and nitrous oxide in the run tank & oxidizer lines are purged with nitrogen.

As Gremlin performs state determination, telemetry & communication, and actuation sequence selection for state transitions, all processing is centralized in the most powerful computing unit available. Hence, the command to initiate the ignitor actuation sequence is sent to the FastJack. This reduces the data sent to the engine computer, enabling greater redundancy. Due to the high traffic of DIO pins on the SlowJack, FastJack is used for a faster and more reliable ignition sequence actuation. Gremlin also asynchronously transmists sensor data to the GUI server. This data is displayed in real time along with visual feeds for any person who has connected successfully to the GUI server with an applicable device.

4.3.3 Control Unit

The Labjack T7 Pro is used as the primary control unit. The original PLC design was reworked due to difficulties with interfacing & programming. The LabJack has the digital input/output capability of interfacing with 23 devices. This number is dropped if a multiplexer is used with multiple expansion boards, as the MIO pins are used to communicate between these terminal boards. All DIO pins are run into DB37 and DB15 screw terminal adapters, which allows each pin on the labjack to be interfaced directly in a more compact form factor. All non-soldered electrical connections are secured with screw terminals or WAGO connectors, and all exterior connections are run through water-resistant connectors or gaskets.

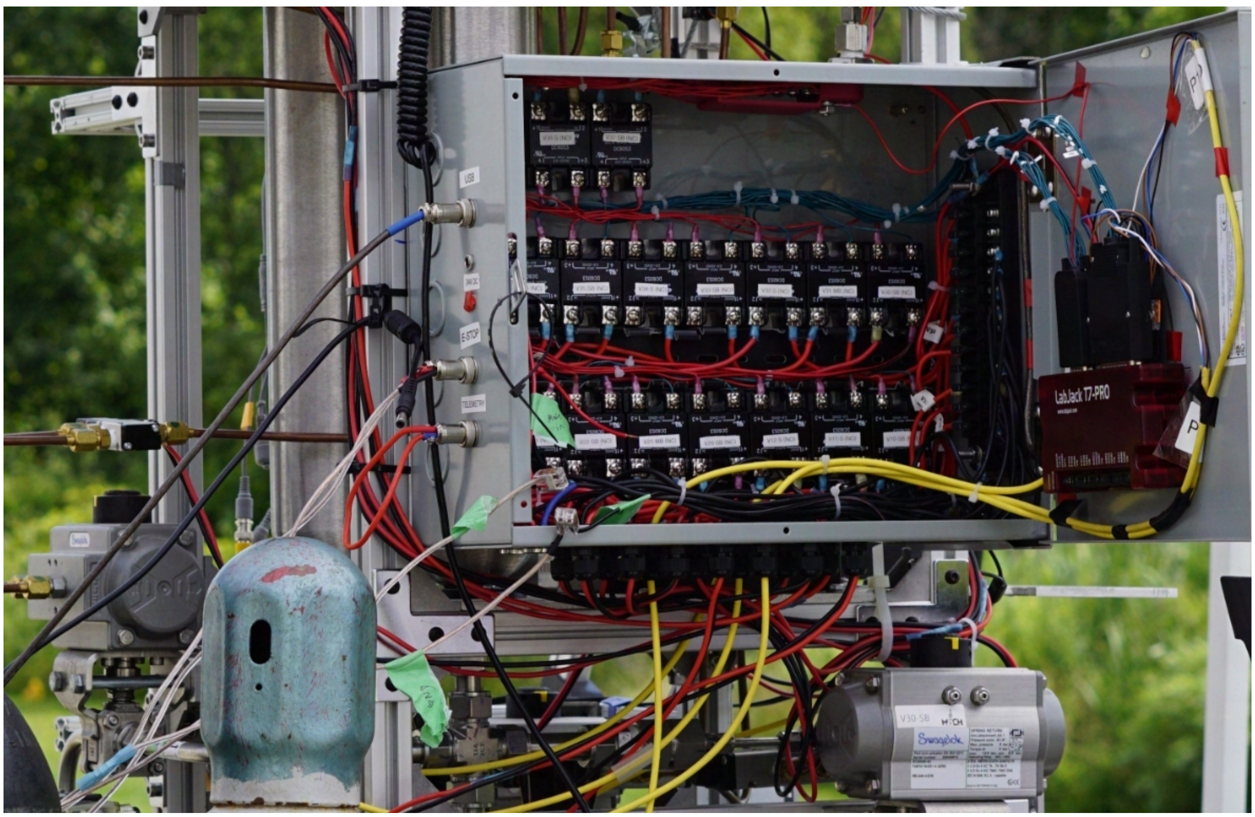


Figure 4.3.6: Interior of the Propellant Enclosure during a cold-flow.

The control enclosure is separated into the “low” and “high” voltage sides by the SSRs. The low voltage or “control” side uses 5VDC USB power supplied by the LabJack, and actuates the SSRs. The high voltage or “power” side uses 24VDC supplied through a pad-side power supply, and actuates all valves. All relays are normally open (power off), and default (flow) state determination of the valve is configured only at the valve; all upstream components (SSRs, pilot solenoids, etc) are set to a common (power) “off” state by default.

Each DIO pin can be set to either input or output mode, and has both a high and a low state. It was experimentally determined that the high output state supplies a voltage of ~4V and the low state supplies ~1V. This high and low state is used to control whether an SSR receives enough voltage difference between its 3rd and 4th pins to actuate. When the SSR actuates, power connected to port 1 will flow freely to port 2, where the valve power will be connected. The Crydom DC60S3 SSR's used in the system shown below in Figure 4.3.6 require a voltage higher than 3.5V to actuate. Using the Labjack's USB supplied 5V VS pin, a power bus routes a constant 5V supply to port 3 of each SSR. The DIO pin is connected to port 4, thus in a high state, the difference across ports 3 and 4 is ~1V, resulting in the normally open position of the SSRs. Changing the DIO pin into a low state creates ~4V, closing the relay and actuating the associated valve. Therefore, low state is for actuating the SSR and allowing it to send power to the valve.

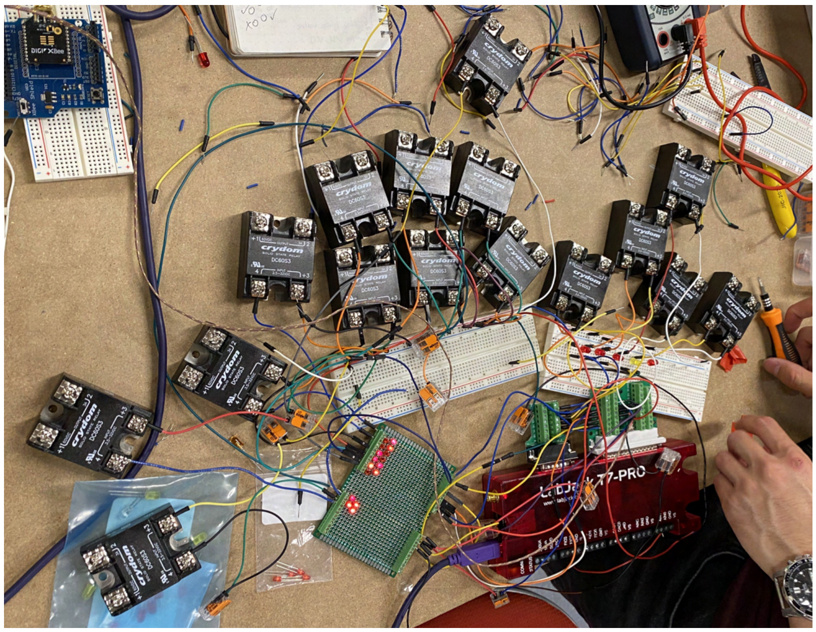


Figure 4.3.7: Testing of the SSRs before integration into the propellant enclosure.

The control system power is distributed across two fuse boxes connected in parallel. The highest current draw of any valve on the system is 0.75A from the Jaksa solenoid valves. For this reason, each slot is outfitted with a standard ATO/ATC 1A fuse. Supplier data sheets for each valve indicate that their overcurrent protections are sufficient with 1A fuses. Both The direct-control and indirect pneumatic pilot solenoid valves are connected to LabJack-controlled SSRs. SSRs are chosen over electro-mechanical relays for actuation to eliminate risk of vibration-induced misactuations. The ignitor is also controlled by a SSR with a separate power source, as outlined in Section 4.1.3.

The states of each valve is received through a function in the LJ library that grabs all DIO pin states and represents them sequentially in a double of 23 numbers. Each SSR is connected to these DIO pins in similar sequential order which simplifies decoding of the state double. State is dependent on the DIO pin status upstream of the SSRs and valves. Confirmation using valve-mounted flow indicators and LED indicators is used in pre-test procedures and continually monitored.

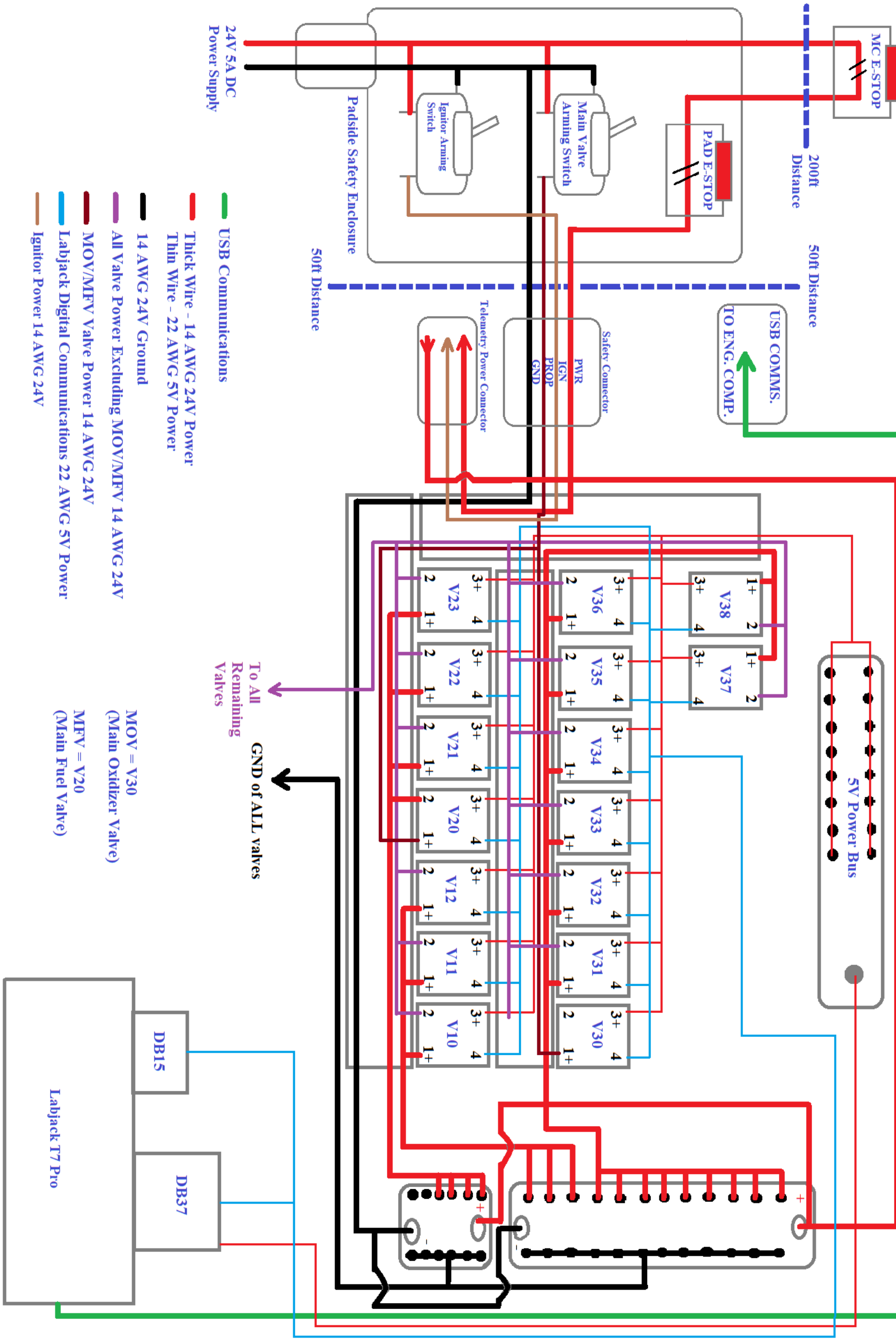


Figure 4.3.8: Propellant Enclosure Wiring Diagram (V1.4)

4.3.4 Arming & E-Stop

The engine-side E-stop & arming circuit is primarily run through two Arming Enclosures, each containing a set of switches and E-stop buttons. The MC Arming Enclosure is located beside the mission control computer, reachable by the same operator. The Pad Arming Enclosure is located at the pad control shelter beside Gremlin, approximately 50 ft away from the test stand and protected by a barrier.

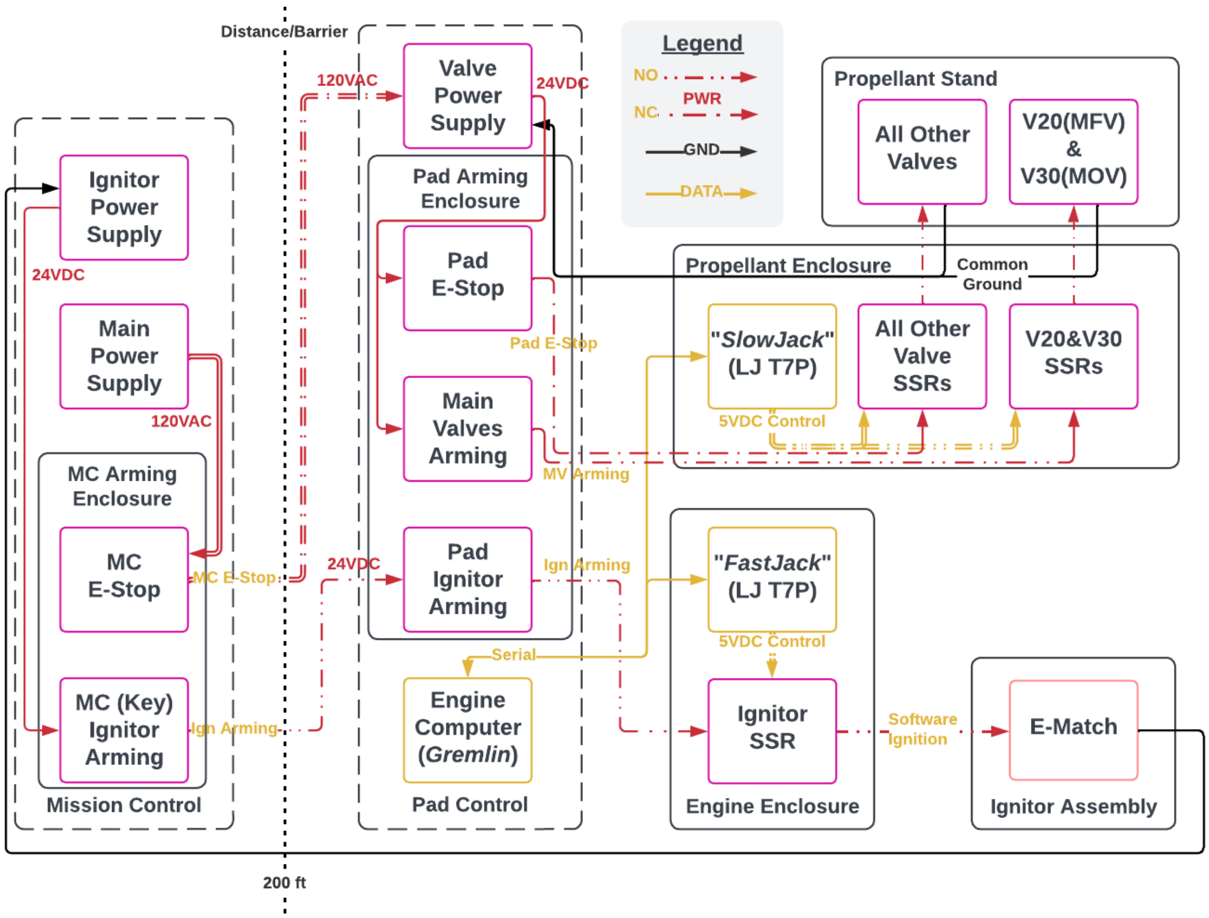


Figure 4.3.9: Arming & E-Stop Circuit (V3.2).

The MC side E-Stop sits between the power source and power to pad; 120VAC is used due to the long wiring distance. The Pad Arming enclosure is where 24VDC power for valves is introduced into the system. Power is routed through both E-stop buttons in series. Both buttons must be in the “up” position for operation, and hitting either will break the circuit and return all valves to safe state. From the pad E-stop, power is wired in parallel to an arming switch for the main propellant valves (V20 & V30), and directly to all other valves. All valves return to a common ground routed through the same custom cable to Pad Control.

As the injector is the only part of the propellant system where the fuel and oxidizer can mix in any valve position, the separate main propellant valves arming switch (green) prevents catastrophic errors in software, control, or procedure during pre-test operations. The arming switch is in series with the valves' corresponding SSRs, so a software signal must still be sent for valve actuation.

As detailed in Section 4.1.3, the pad ignitor arming switch (red) is connected to a separate DC circuit running back to mission control. In the MC arming enclosure, the MC ignitor arming switch is wired in series, along with a shunt. The MC ignitor switch is keyed with the key worn by pad personnel (safety officer or supervisor). Fully arming the system for a hot-fire test can only occur once all personnel return to MC.

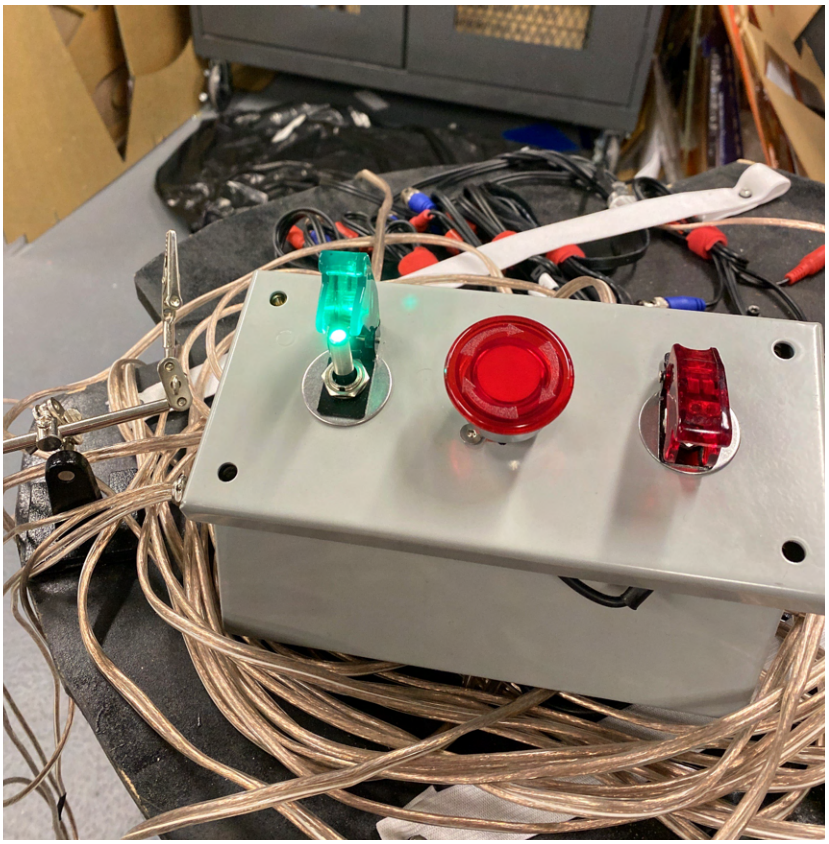


Figure 4.3.10: The Padside Arming Enclosure.

The nominal testing procedure requires a test of all arming systems prior to any pressurization or propellant loading. The ignitor and main propellant arming switches are then disabled until all pre-test procedures are completed. The last step prior to Red Team evacuating pad is fully arming the pad-side enclosure. Once successful propellant loading and the go-poll are confirmed, the keyed ignitor switch at MC is armed. A signal is then sent from the mission control computer GUI, initiating the automatic control software aboard Gremlin and commencing the hot-fire test.

4.3.5 Mission Control

The mission control computer communicates with the engine computer through the ethernet connection. The engine computer sends the state and telemetry from all sensors to MC through this connection, and constantly monitors it for commands. The mission control and engine computers communicate over a local network connection using the TCP/IP protocol in a peer-to-peer connection. The communication is done on custom user-defined ports on both systems, and all telemetry is displayed in a Python application with a custom GUI created using Qt with the PyQt library.

The primary interface at mission control is a GUI which includes telemetry from the pad, mirrored engine computer interface described in section 4.3.2. A second interface is used for live camera feeds. The primary GUI and control is displayed on the mission control computer. Cameras are displayed on a secondary monitor via DVR software, and then displayed using a projector. A Capture card is then used to route the camera feed into the secondary computer. Additional physical interfaces at mission control include the arming switch and the E-stop button.

The status of the pad - Safe (unrestricted), Lockdown (Red Team only), or Evacuated (no access), is represented visually through a stacklight at MC. This allows instant and clear communication of pad states at mission control.

Figure 4.3.11: Mission Control setup during cold-flow attempt #3

4.3.6 Visual & Audio Telemetry

Live camera systems are used for visual observation of analog gauges and valve indicators. These real-time views are streamed to mission control during pre-test procedures, fill, and testing. For bandwidth and reliability, these cameras operate completely separately from the main communications between mission control and Gremlin. Higher quality cameras without live streamed feeds are also at the pad to capture footage for later analysis and enjoyment.

An eight-camera, analog security system is used to remotely monitor pad during all procedures and engine operation. Having eight cameras provides a degree of redundancy to the system.

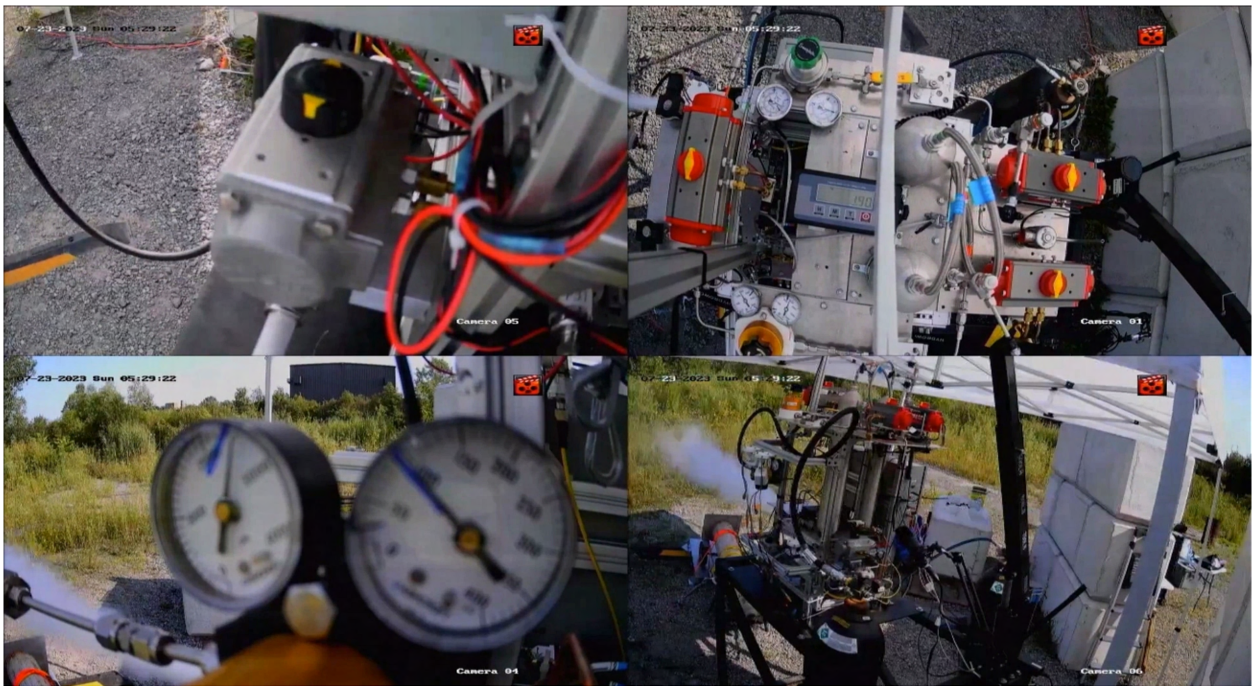


Figure 4.3.12: Camera views during a N_2O cold-flow

All eight camera feeds run through two hundred feet of conduit back to mission control, where the signals are processed and saved on a hard drive in the DVR (Digital Video Recorder). The camera feed is then projected onto a screen at mission control. It is also streamed on Twitch via Starlink.

In addition to the camera feeds, a condenser microphone on pad relays live audio to speakers at mission control. The audio is routed both to the twitch stream and saved in a DAW (Digital Audio Workstation).

4.4 TEST STAND & SUPPORT EQUIPMENT

4.4.1 Thrust Stand

The thrust stand was designed in four major sections, each of which are bolted together to form a robust assembly: box, angled thrust adapter, blast shield, and Crane. Design considerations included ease of transportation, ease of assembly, and rigidity. Earth anchors generously supplied by American Earth Anchors secure the thrust stand to the ground via four steel cables and turnbuckles.

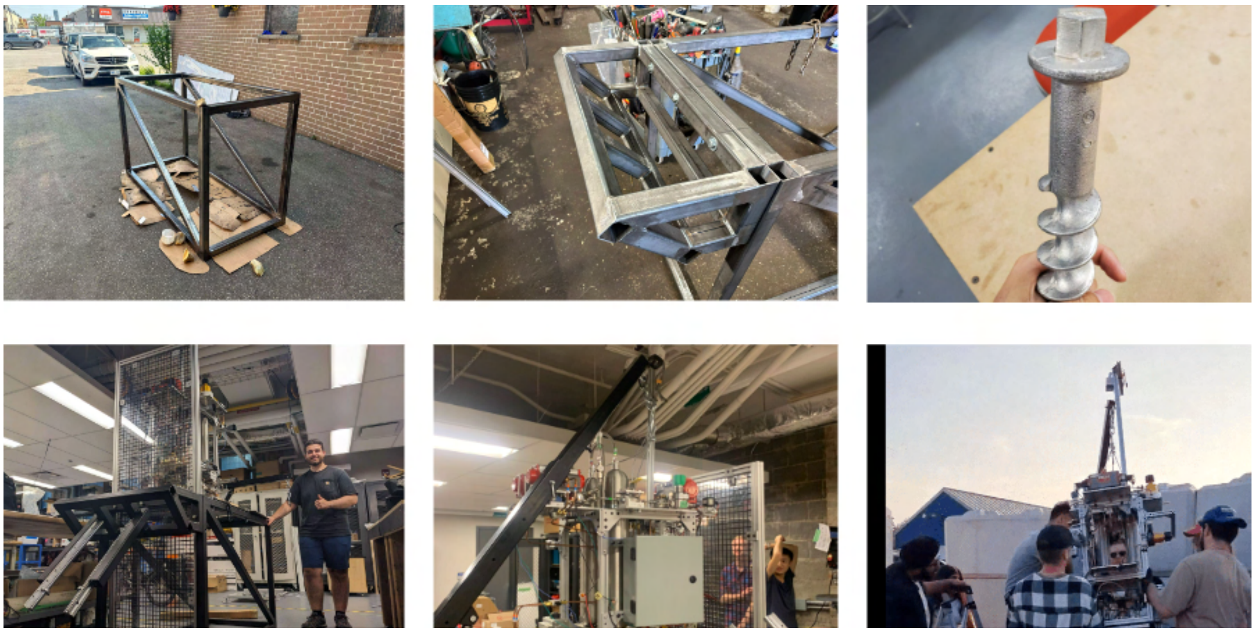


Figure 4.4.1: a: Box **b:** Thrust Adapter **c:** Earth Anchor **d:** Blast Shield **e & f:** Crane

The box and thrust adapter are constructed from 2” x 2” x 0.25” welded mild steel tubing, and bolted together with ½” steel bolts, nuts, and washers. ¼” steel plate is used both for the thrust plate, to which the load cell is mounted, as well as a large steel plate which supports Spender. Four SBR20 linear rails bolted to the thrust stand constrain lateral motion, but leave vertical forces free for propellant measurements with the scale. All pressurized cylinders are also secured to the sides of the thrust stand with straps.

The elevated mounting minimizes hose length between the main propellant valves and the engine, and greatly reduces FOD contamination from dusty ground at the test site. The tradeoff in ergonomics was found to be acceptable during the July 22-23 cold-flow. Crane is used to lift and set down Spender.

On the thrust assembly, two SBR20 linear rails secure the engine assembly and constrain off-axis motion from the thrust vector. Four mild steel L-brackets bolt the engine case to the rails. A set of stop collars are tightened so the injector makes light contact with the compressive load cell but does not move along the rails. The rails are angled at 45° downwards so any unignited propellant can passively drain through the nozzle.

Figure 4.4.2: CAD view of the thrust stand assembly

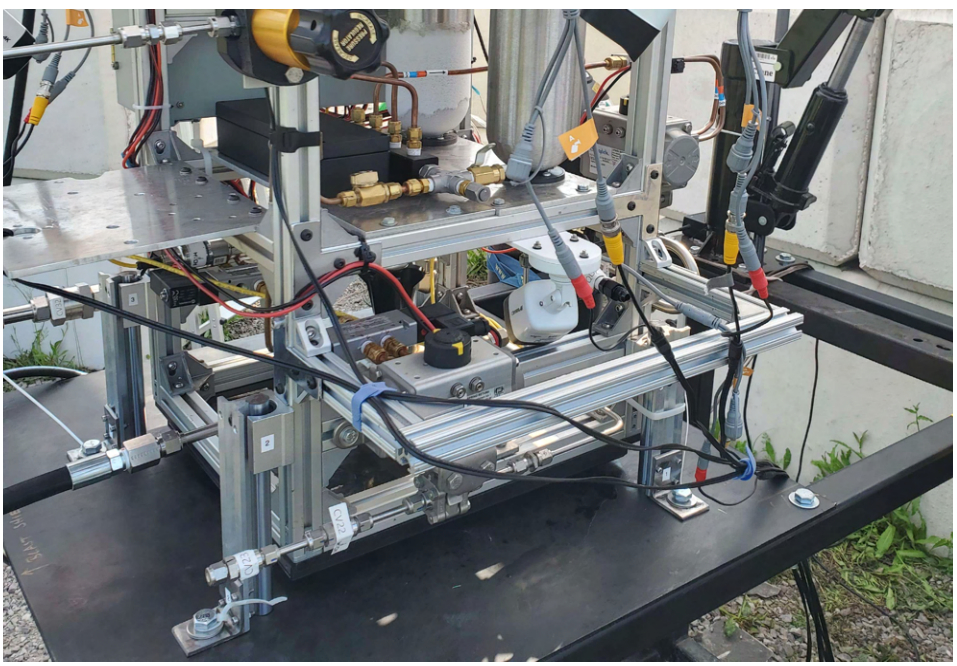


Figure 4.4.3: Spender & weight scale mounted to the thrust stand with linear rails.

The blast shield is composed of a steel mesh and 3/16” Lexan sheet previously used in high-velocity impact testing. As seen in Figure 4.0.1, the shield runs from the ground to above the height of Spender. This provides a clear view of the engine and propellant system and physical protection in case of RUD on either side. The main propellant hoses and engine telemetry wiring are run through holes or routed around the blast shield.

4.4.2 Power & Communications

Several wiring runs to the pad are required for power and communications. Two runs of 120VAC electrical power is provided from wall outlets or a generator through 200 ft of weather-resistant extension cords. From MC to the engine computer, ethernet is used for communications. One 120VAC line is dedicated to valve power and is connected to the MC E-stop, while the other provides primary power to the engine computer and other pad equipment through a line-interactive uninterruptible power supply (UPS). The non weather-resistant camera cables, ignitor wiring, and ethernet are run through a cable conduit generously provided by Automation Direct. All wiring is managed using cable spools.

4.4.3 Additional Equipment

Additional equipment required for testing include the pad canopy tent, pad control tent, modular storage systems, Starlink, and miscellaneous equipment.

The 10’ x 10’ pad canopy tent shelters pad personnel from sun and rain, and has walls for use during winter testing. The pad control tent is a high-ceiling tent with full walls, providing a waterproof space for vulnerable components such as the engine computer and power outlets.

Starlink provides outside communications and internet access during testing in remote locations where cell service is poor or non-existent. The router is located at mission control and does not require

MACH’s new inventory and logistics system is built around modular storage solutions (colloquially termed “pack-outs”). These tool boxes are used as regular storage in the workshop, and transported to pad during testing days, greatly reducing time spent packing and unpacking.

Figure 4.4.4: Cold-flow setup of **a:** Pad Control tent **b:** Pad Toolkits

5.0 TESTING & PROGRESS

In addition to significant progress, drastic improvements have been made in the past few months since the R3 report. This has essentially resulted in rebuilt or new hardware for every single subsystem, most of which have undergone extensive testing throughout various cold-flows and minor tests. An updated testing overview is provided in Table 5.0.1. A complete rework of procedures and logistics has also been implemented and is further detailed in Section 5.1.

Currently, the GAR-E design is in the final stages of manufacturing, awaiting completion of four machined parts. The thrust stand is complete, and several minor components for the thrust adapter are currently being manufactured.

The propellant system is nearly complete pending the installation of a purge line and bypass line. After completion, a full system tear-down and cleaning is to be conducted in preparation for oxidizer service. All parts for the propellant lines to engine connection have been acquired, and are being assembled.

The hardware for the control system has been completed and tested, as has the new visual telemetry system. The Engine Enclosure is awaiting assembly, and the arming circuit is undergoing improvements from testing experience. The basic GUI and software for manual valve actuation and pre-programmed sequences have proven to be reliable. The software control loop and improving data acquisition are currently in progress.

Table 5.0.1: Testing Overview.

Test Name (Subsystems)	**Description**	**Objectives**
Control & Actuation Tests (Propellant, Control)	Iterated actuation tests for refinement of valve sequencing	- Determine and validate the proper valve sequencing for ignition, shutdown, abort, and purge scenarios. - Validate proper valve sequencing using the pyrotechnic ignitor feedback loop.
Instrumentation & Safety Device Calibration (All subsystems)	Testing & calibration of all thermocouples, transducers, relief valves, etc.	- Validate accurate functioning of all sensors & safety equipment - Calibration tests will be repeated as needed per guidelines from manufacturers/published references
Cavitating Venturi Tuning & **Validation** (Propellant)	Tuning of cavitating venturi geometry for both propellants Performed with cold-flow tests.	- Use water and carbon dioxide as propellant stand-ins to conduct iterative flow testing on cavitating venturis - Repeat and iterate as required, may be conducted again after cold-flows

Inert Cold-Flow #1-3 (Propellant, Control, Telemetry)	Venturi calibration, flow rate characterization, and system verification using inert propellant stand-ins and flow meters at outlets.	- Conduct full test sequence using inert propellant stand-ins, validating valve sequencing - Verify proper operation of the system and validate cavitating venturi design with inert propellant stand-ins - Collect flow rate, pressure, temperature, and other system data for validation and baselines for future comparison - Validate performance of mission control to engine communications, ensure proper functioning of emergency stop sequence - Validate and refine setup, fill, flow test, shutdown, and cleanup procedure - Validate proper valve sequencing for nominal ignition, fire, and shutdown - Validate proper valve sequencing for abort, emergency shutdown, and purge scenarios with inert propellant stand-ins
Ignitor Tests #1-6 (more as required) (Engine, Control)	Testing of ignitor assembly and electronic ignition system. Expected to be performed concurrently with inert cold-flow tests to validate integration, software, & procedure.	- Validate ignitor assembly design and electronic ignition - Test ignition sequence and validate safeties in the automatic control system - Characterize ignitor burn time, determine grain size and shape required to develop ignition timing sequence - Analyze viability of ignitor refurbishment and reuse
Low-Pressure Pneumatic Leak Tests (Propellant)	Verifies the sealing and design of the propellent feed system.	- Verify the assembly of the propellant feed system (gas leak detection and extended-time pressure test) - Validate and refine pressurant handling & pressurization procedure
GAR-E Hydrostatic Test (Engine)	Hydrostatic test of full engine assembly	- Verify mechanical properties of combustion chamber - Satisfy LC competition and internal safety requirements

Non-Reactive Cold-Flows #1-2 (Propellant, Control, Telemetry)	Venturi calibration, flow rate characterization, and system verification using separately conducted cold-flows with one propellant and one inert stand-in at a time. Cold-flows with injector integration for atomization & mixing analysis.	- Verify proper operation of the system and validate cavitating venturi design with active propellants (in separate non-reactive tests) - Collect flow rate, pressure, temperature, and other system data on actual propellants for validation - Validate and refine setup, fill, flow test, shutdown, and cleanup procedure - Refine procedure and develop experience for full thrust stand assembly & active propellant handling for ignition and hot-fire testing - Test injector & collect high-speed footage for qualitative analysis
Thrust Stand & Integration Testing (All subsystems)	Mechanical testing of thrust stand to validate structural design.	- Validate structural design of thrust stand - Develop and refine assembly and teardown procedure of thrust stand - Develop & refine integration procedure of propellant, telemetry, & engine subsystems - Simulated loading of 7.5x+ expected GAR-E thrust to validate stand for future engines
Ignition Tests #1-2 (more as required) (All subsystems)	Short open-air hot-fire tests through the injector without a combustion chamber attached.	- Iterate precise igniter and valve timings to minimize probability and severity of hard starts - Validate and refine control system with gradual additions of control-critical instrumentation and abort conditions - Test shutdown, abort, purge, and cleanup procedures in a hot-fire scenario with live propellants
GAR-E Static Fire #1 (All subsystems)	First hot-fire test of GAR-E engine at Launch Canada 2023.	- Hot-fire test for full system evaluation & performance validation - Full test & validation of procedures - Characterize ablation rate
GAR-E Static Fire #2 (All subsystems)	Second hot-fire of the GAR-E engine.	- Develop refurbishment procedure for ablative engine liners - Test varying chamber geometry/materials - Validate reusability of support systems

* Bolded tests are considered major and conducted at the Welland or LC2023 test site with full procedures and documentation.

5.1 PROCEDURES & OPERATIONS

In addition to improvements to our physical systems, the team has gained a significant amount of operational experience from the various major and minor testing campaigns over the past few months.

Operations & Logistics

A focus on teaching and training has resulted in a higher level of base expertise among all members. The multiple low-risk testing campaigns with inerts were used to develop pad experience and a strong roster of Red Team personnel.

The team's mobile testing requirements and limited storage space originally presented a massive challenge in transportation and logistics. The reorganization of the Safety & Logistics team was an effort to address this. A new barcode inventory system was implemented which greatly improved workflow on pad as well as during regular worksessions. Setup and packing checklists were also iterated over multiple tests, culminating in ~1 hour setup and cleanup times during the July test.

The team attitude prior to major testing campaigns have also seen gradual improvements. Testing goals and timelines remain ambitious, but room for slip and postponements to address inadequate preparation are now the standard. Most importantly, a curfew prior to and during major testing has been implemented with moderate success, ensuring critical members are well-rested.

Procedures

During the January cold-flow attempt, a lack of procedure was identified as one of the most significant failings. Over subsequent tests and full dry-runs of draft procedures, the iterative improvements resulted in a well-practiced and relatively problem-free procedure stack by the July cold-flow. The major procedures used during that test are attached in Appendix VIII; minor procedures such as setup and control tests have been excluded. The recorded improvements and impromptu procedures from that test have not yet been incorporated into the version attached.

The system familiarity and team dynamic, particularly among Red Team personnel, resulted in efficient and safe problem-solving under stress. A supplier issue with the CO_2 supply during the July cold-flow required an inversion of the cylinder before filling could commence. A cold-flow was executed with the water already loaded. Then the team safed pad, performed the cylinder inversion, and returned to mission control to perform a successful CO_2 loading and cold-flow within 1 hour. Red Team safed pad again, returned to re-fill water, swap N_2 cylinders, and discharge excess pressure using a mix of prepared and Sharpied procedures. This process again took 1 hour, resulting in a second successful cold-flow.

5.2 INERT COLD-FLOWS SUMMARY

The first cold-flow test was attempted on January 21-22, 2023, marking the first major system test since the team's founding. A second cold-flow attempt was made on Jun 3-4. A third test was carried out over the weekend of July 22-23, resulting in two successful inert cold-flows.

This section is an abbreviated summary of all three tests to date, and their respective impacts on our systems and procedures. The test objectives are shown in Table 5.2.1 along with a summary of results for all three cold-flows.

Table 5.2.1: Summary of Inert Cold-Flow Test Objectives

Objective		Description	Jan	Jun	Jul
Inert Fill	**1**	Validate & iterate general testing procedures.	Yes	Yes	Yes
	2	Validate & iterate propellant fill procedures.	No	No	Yes
	3	Validate & iterate leak testing procedure.	Part	Yes	Yes
	4	Determine N2O fill time & efficiency using CO2 stand-in.	No	No	Yes
	5	Validate remote telemetry & control setup.	Yes	Part	Yes
	A	Validate & iterate setup procedure & weather resistance.	Part	Part	Part
	B	Validate visual telemetry & mission control setup	Yes	Part	Yes
Cold-Flow	**6**	Validate & iterate cold-flow procedures.	No	Yes	Yes
	7	Validate pressurization & plumbing system performance.	No	No	Yes
	8	Validate purge & vent sequence.	No	No	Yes
	9	Validate engine computer data processing & storage.	No	No	Part
	C	Perform abort & E-stop test.	No	Part	Yes
	D	Determine tanked "propellant" mass after cold-flow.	No	No	Yes
	E	Produce media assets for outreach.	Part	Part	Yes

* Primary objectives are numbered & secondary objectives are lettered.

Figure 5.2.1: Cold-flow setups during **a:** January. **b:** June. **c:** July.

5.2.1 Inert Cold-Flow 1 (Jan. 21-22)

The team's first cold-flow attempt in late January was in large part a total failure. Extenuating circumstances prior to the test combined with tight deadlines resulted in severe problems with logistics, operations, and procedures. The first day at the test site was on systems integration. The second day resulted in a failure at the first valve in the pressurant system, precluding testing of other components.

The subsequent failure analysis of this test found many shortcomings of the existing systems at that point. The months after the January cold-flow were spent overhauling all existing hardware and focusing on system robustness during design and construction of new components. A detailed breakdown can be found in the R3 revision (Section 5.1), and the full failure analysis is still included as Appendix II of this revision due to its significance to the team's designs and operations.

5.2.2 Inert Cold-Flow 2 (Jun. 3-4)

The second cold-flow attempt in early June saw the testing of a fully rebuilt propellant system and reworked control system. The control system was being rebuilt at the time and a last-minute reversion to the previous iteration using an Arduino as the controller. Some leaks were also detected and corrected on the pad. This caused considerable delays and time constraints prevented a cold-flow test.

5.2.3 Inert Cold-Flow 3 (Jul 22-23)

A third cold-flow was attempted July 22-23. Two cold-flows were successfully achieved - first with the propellants run separately, then again simultaneously. The stacking, functionality of the propellant, control, telemetry, and procedures were all validated. Data from this cold-flow is detailed in Appendix VII and successfully verified the function of our systems. The data and experience gathered from these tests allows us to move on from inert propellants.

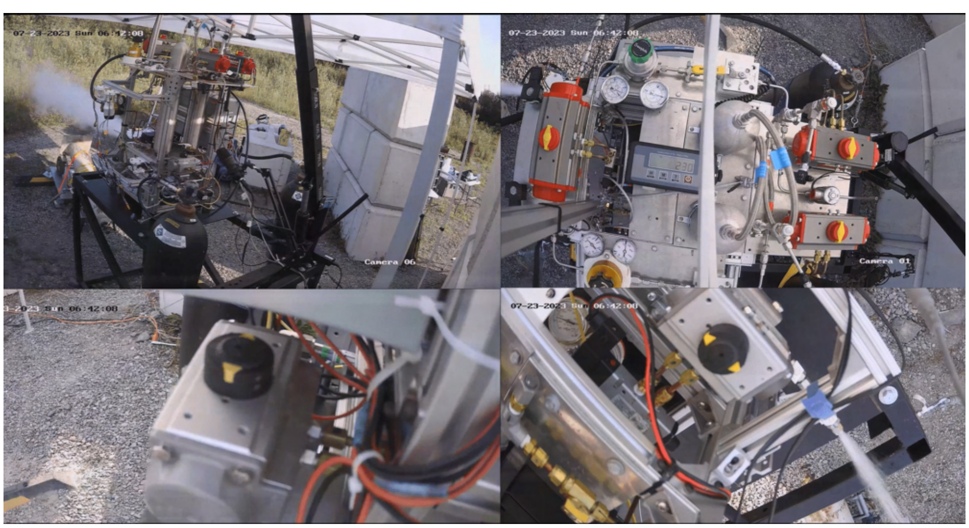


Figure 5.2.2: Screenshot of camera feeds during the simultaneous cold-flow.

6.0 PROPOSED TIMELINE

Due to time spent on improvements previously described and programmatic challenges, the timeline from R3 was delayed. However, the state of our current systems, operations, and personnel inspire great confidence in our ability to achieve a successful hot-fire by the end of Summer 2023..

The revised timeline presented in Table 6.0.1. A limitation on MACH's testing schedule is the availability of our testing site. With the information provided in this report, the team hopes to demonstrate the readiness of our systems and operations for a hot-fire test. MACH still aims to perform our ignition tests and attempt our first hot-fire at Launch Canada 2023.

Table 6.0.1: Targeted Testing Timeline For Major Tests

Test Name	Expected Date of Completion
Inert Cold-Flow #1-3 (Propellants, Control, Telemetry)	January - July, 2023 (completed)
Non-Reactive Cold-Flow #1 (Propellants, T&C, Engine)	Mid August, 2023
Ignition Tests #1-2 (All subsystems)	Launch Canada 2023
GAR-E Static Fire (All subsystems)	Launch Canada 2023

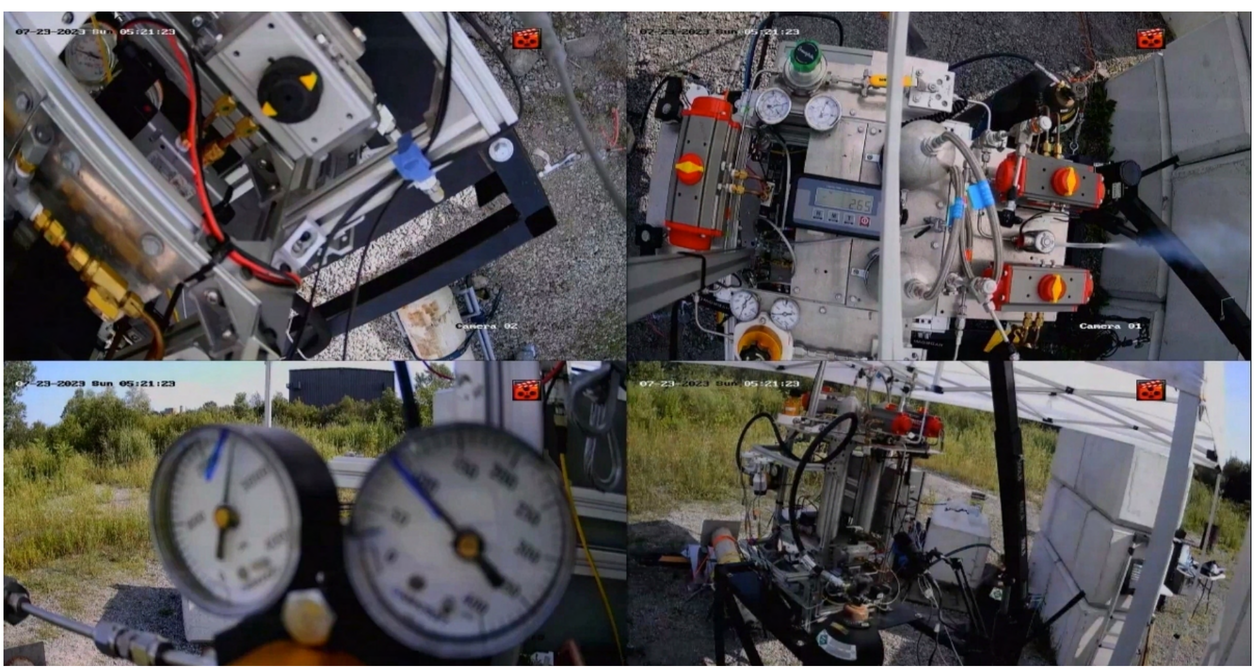


Figure 6.0.1: CO_2 tank venting during a cold-flow test.

6.1 PLANNED FUTURE DEVELOPMENT

The GAR-E design being demonstrated at LC2023 is only a first step towards MACH's goal of flying a liquid rocket engine. With its design performance identical to that of the Borealis, this first iteration does not produce sufficient thrust to achieve any significant altitude after accounting for mass estimations for propellant and dry weight of an appropriately sized sounding rocket.

The goal of GAR-E is to demonstrate the versatility of the static test system, and quickly iterate towards flightweight engine designs with minimal changes to system design and hardware. The medium-term end goal of the GAR-E design is to produce a 6.7kN (1500 lbf) static test engine of similar construction, dubbed "FAT GAR-E", to validate combustion geometry, propellant delivery, and performance. The results would be used to optimize the design for flightweight engines, and potentially pursue improved materials and construction techniques.

These higher thrust engines necessitate larger run tanks for the same 5 second burn duration, which was also targeted for extension. Any liquid propulsion system, especially pressure-fed designs, is heavily integrated into the flight vehicle, most notably in the form of structural tanks. This presented an opportunity to develop techniques & experience for SRAD propellant tank construction alongside engine development, as well as a fully integrated flight vehicle design currently in the early design stages. Testing could be conducted with the same propellant and electronics systems, with minor modifications such as new cavitating venturis and regulators to accommodate higher flow rates.

The ambitious timeline for this project was to begin FAT GAR-E & SRAD tank development over the summer of 2023. Then MACH received its funding allocation. Despite recurring financial and new programmatic setbacks covered in Section 7.1, this roadmap for future development has only been lengthened, not de-scoped in ambition. The team hopes that successful hot-fire tests of the GAR-E engine and a strong demonstration of our capabilities at LC2023 could assist in securing funding and support necessary for our future projects.

Development of the Borealis engine has been sidelined indefinitely as we progress towards a flightweight, 1500 lbf engine. The largest, most ambitious goal for the team is to be the first student team in Canada to fly a liquid bipropellant rocket from Canadian soil.

7.0 RISKS & MITIGATION STRATEGIES

SRAD LREs significantly increase expected programmatic and technical risks due to the inherent added complexity in design relative to COTS solid and SRAD hybrid projects. Thus it is vital that appropriate risk management is undertaken to understand and minimize the likelihood and impact of failures on any level. Alongside this brief overview, MACH's in-progress Risk Management System (RMS) contains the full list of currently identified technical failure modes and mitigation strategies [17]. The Hazard identification section for each sub-system has been updated to include the recent hazards identified leading up to and during cold-flow testing. In addition, MACH's Environmental Report has been updated to include hazardous combustion products of GAR-E's ablative G10-FR4 [5].

Cold-flow and hot-fire testing cannot proceed unless the respective risk assessment section of the RMS is complete. There are three main categories of technical risks during testing: Health, Mission, and Vehicle Risks.

Health risks are of the utmost importance. It is vital that all systems that carry high health severity, assuming for any reason that mitigation does not withstand, are designed without the requirement of personnel physically present. The severities listed in the RMS take that into account and as a result, only hazards that do require a member be present have a corresponding health severity rating. Steps to lockdown the site, site inspection, and radio communication are vital to ensure that assumption remains correct during testing. First-aid training, Safety & Emergency Response Manual (SERM), and Standard Operating Procedures (SOP), are mandatory prior to conducting hazardous testing to limit potential health risks.

Mission risks entail the jeopardization of learning objectives, data collection, or significant loss of equipment which may impede future operation of the team. It is important to distinguish these risks from vehicle risks, as experimental rocketry is an extremely high-risk endeavor and failures are an expected part of the process. An unsuccessful test resulting in damage to the vehicle is not a wasted test, as long as data is gathered on the failure mode and lessons learned to prevent future failures. However, if significant damage results from a vehicle-loss incident, such as major loss of the propellant or electronic system components, it puts the continued mission of the team at major risk due to tightly constrained budgets. Therefore, MACH weighs the risk of significant damage to non-engine systems heavily over engine components or even total loss of the engine itself.

However, vehicle risks are still a significant consideration for any test. Due to the aforementioned reasons, the "vehicle" risks are heavily biased towards the engine itself. This is particularly the case with the extremely low-cost GAR-E design, again driven heavily by budget consideration.

In order to compensate for MACH's limited funding, risk reduction through design, testing, redundancy in every system, and physical isolation between major subsystems are all steps taken to mitigate potential risks in all categories. These mitigation options are more thoroughly described in the Risk Management System and reflected through the stated design process.

MACH utilizes three techniques as part of its overall RMS: Possible Severity Ratings (PSR), Probabilistic Risk Assessment (PRA), and Risk Mitigation Analysis. PSR is a pre-risk assessment tool that lists all hazards with each type of severity (health, mission, and vehicle) assigned by the relevant leads. PRA specifies scenarios made up of one or more hazards, along with their component level initializing and pivotal events. PRA also combines and determines failure rates of scenarios, which are extrapolated from many sources including US military handbooks [18] [19]. Risk Mitigation Analysis evaluates the severities and probabilities of new mitigation options presented by decision makers after risks outside of MACH's risk tolerances were identified. Feedback from Launch Canada on acceptable risk tolerances was greatly appreciated. MACH's RMS, which contains the foundation of these tools, have been provided alongside this document [17].

Over this summer considerable strides have been made to improve procedure, both in presentation and in practice. Efforts have been made to conduct dry runs prior to and when coldflows were scrubbed, and the team has made great progress in communications and procedure since the first coldflow. This can no doubt be attributed to lengthy internal debriefs that saw honest criticism.

While these subteams have separate sections on hazards, it is important to identify that each system is still interconnected with the others and that system specific failures can and will lead to other failures, and conversely mitigation strategies are often integrated across subsystems. Therefore, it is imperative to MACH's risk mitigation that each subteam is familiar with the hazards of other systems. All team members should consider, and stay informed on, the most pertinent risks and scenarios that could, and must be assumed to, occur, then implement effective mitigation strategies through design or procedure.

7.1 PROGRAMMATIC RISKS

MACH continues to face many external challenges concerning funding & sponsorships, resources, workspace access, and administrative support. Internally, delays from external causes, member time commitment, cross-subsystem training, transference of knowledge, technical debt, and organizational sustainability are also programmatic risks that must be continually mitigated and worked around.

7.1.1 External Programmatic Risks

MACH’s limited funding from TMU for the scale of the project affects all subteams and has a direct impact on the overall scope of mission and risk mitigation strategies MACH can employ. The team's received funding for the year is significantly less than requested, forcing serious reconsiderations in technical focus and project scope. There are also issues with funding access, with direct purchases using the team’s account possibly taking up to 6 months, or alternatively burdening individual members with months-long waits for reimbursement.

Access to on-campus resources is very limited, which presents major challenges especially in manufacturing and prototyping. Though MACH has gained the gracious support of several resources on campus to assist with manufacturing, the lack of directly accessible machine shops and other precision fabrication tools is a limitation. The GAR-E design is a direct response to the lack of advanced manufacturing access required for the Borealis and similar regenerative engines.

Though MACH has had great success with in-kind sponsorships of tools and equipment, external monetary funding is difficult to come by, as is the case with most Canadian rocketry teams. Gaining administrative approval and sign-offs on secured sponsorships has been more challenging than initially expected, which has delayed access to sponsored materials and required additional spending.

As TMU is located in downtown Toronto, real estate is always a scarce resource. The shortage in space for engineering teams resulted in MACH moving to a separately managed space for startups on campus. Unfortunately, the large size of the team, technical requirements, and working differences has become an issue since the R2 report. This has resulted in severe access restrictions to our usual workspace, causing significant delays to our testing schedule, systems integration, recruitment efforts, and general operations. The weeks leading up to the first inert cold-flow was one of the most difficult, and extensive worksessions and testing planned for the winter break had to be pushed back. Temporary workarounds and compromises are currently in place, but a long term solution is still in the works.

7.1.2 Internal Programmatic Risks

The largest internal programmatic risk faced by the team is severe impacts to schedules due to delays beyond the control of the team. As mentioned, TMU's internal structures for purchasing and reimbursements. Testing delays also prolong uncertainty with the design, and greatly slows the team's progress if any component needs to be remanufactured and retested. Leading upto the third coldflow attempt, weather was the cause of more than one scrub. The effects of these delays cascade over school semesters, which require increasing time commitment from students over the course of weeks. These issues are however, expected and universal to all student teams, particularly ones with heavy concentrations of engineering students. MACH's mitigation strategies have centered around distributing subsystem-level testing and prioritizing purchases where possible, then focusing major testing events like cold-flows and hot-fires into large blocks such as holidays to work around school schedules.

As a student team, MACH also faces challenges and risks in the transference of knowledge and technical debt. MACH was in a fortunate position regarding the former especially considering the impact of the pandemic on many other design teams. Several previous leads stayed on as active members of the team and advisors, greatly soothing the transition process for the current year's leads. Technical debt and vision was a larger issue, with the current system bearing little resemblance to the initial designs from the team's inception. This was in large part from a lack of systems engineering during the design process, and led to continual iterations and eventual clean-sheet redesigns of most major subsystems [20] [21]. These were difficult processes due to poor documentation of original design justifications, but ultimately resulted in much more practical, economical, better documented, and safe designs. Additionally, the original long-term technical goals of the team were poorly defined, which was reflected in the original design and purpose of the Borealis project. Organizational shortfalls inherited by the team also hampered intra-team communications and resulted in challenges with system integration as the team moved into manufacturing and testing after the pandemic.

These were all significant issues, some common to most other design teams and others more unique to the longer-term projects of MACH, and required several different mitigation strategies. Internal and external design documentation is now held to a much higher standard within the team to mitigate many of the issues above, for current, new, and all future members. A current organizational goal of the team is that documentation at several levels of detail should be accessible to students with varying backgrounds, prior experience, and time on the team. Additionally, as mentioned in Section 1.3, several highly prepared, interactive workshops have been and will continue to be hosted. These workshops aim to increase the knowledge depth of current members, inspire interest in rocketry in the wider student body, as well as serve as future reference material in recorded form. With the issues of technical aim, a more goal-oriented approach to all our projects has been adopted, with clearly defined short, medium, and long-term goals, documented justifications and discussions over goal changes, and realistic timelines for getting there.

With the successful mitigation of many internal problems, Some new risks could be identified. Many of the current Leads felt unprepared for their tasks at the beginning of their tenures, and the Lead-in-training roles were created to address this. The very high level of complexity in MACH's project requires significant dedication and time commitment, which could be intimidating for new members. While handing out hundred page documents detailing systems design to first year recruits is comedic, there are limitations to what can be digested through technical reading material. MACH has been organizing more interactive workshops, testing events, and other activities in an effort to raise engagement and retention.

Onboarding presentations are a work in progress, but have been delayed due to testing and the Leads' other commitments, which has led to delays in general recruitment. While interactive introductory material could alleviate knowledge gaps, they are a high effort commitment from everyone involved and cannot be run with regularity. In addition to the large amount of theoretical knowledge inadequate training and improper assembly has resulted in the loss of several components and tools spanning every technical subteam. New training efforts and requirements have been organized and recorded as reference material to address these issues.

The rapid progress of the team also means bringing returning members back up to speed requires significant effort from both parties. So far, MACH has operated around a core of extremely dedicated Leads, delegating compartmentalizable tasks to general members through thorough task guides. However, there are limitations to this system both in reliance on individual Leads and keeping general members engaged. The sustainability of this system needs to be reevaluated, and additional strategies for temporarily or permanently filling in critical lead roles are required.

Over MACH's history inventory has been an issue plaguing the team. Tools, parts, and equipment have been misplaced, stolen, or damaged due to improper storage. The Safety & Logistics subteam has been working on an inventory system to help alleviate this problem. A barcode system has been in place for the two previous coldflows however this system has been underwhelming in terms of fixes to these long standing issues. Namely, the barcode system is limited to a digital footprint of all items and is only as good as it is maintained. Without additional solutions to lost items, damage, and theft, the barcode system is only the start of the inventory solution at large and needs considerable work to bring to standard operation.

7.2 TECHNICAL SUBTEAM RISKS OVERVIEW

The following is a brief overview of the technical risks faced by each subteam. These are very high level overviews of the most severe risks and general mitigation strategies for them. Again for the full list of technical risks, refer to MACH's RMS.

7.2.1 Propellant Management Risks

The most pressing health hazard is a leak in the nitrous oxide fill line. This is most likely to occur during the connection and opening of the N_2O fill tank to the run tank, and the disconnection procedure. Methods to mitigate this hazard include visually inspecting quick disconnect fittings before pressurization, fill, and disconnection procedures. Vents are also assembled to face away from any potential personnel, and as much of the fill procedure is conducted remotely as possible. Mandatory PPE includes full-face respirators, fire-retardant coveralls, a lab apron, and a team member on standby with an ABC class fire extinguisher.

The Propellent Management subteam has applied multiple check valves and isolation valves to reduce the possibility of combustion backflow and uncontrollable leaks. In worst-case scenarios, emergency stops disconnect the valve actuator from power, and mechanical return closes all isolation valves and opens all vents to depressurize all fluid systems and initiates venting of the N_2 and N_2O lines. Emergency stops are less desirable than an electronic stop due to the loss of purge, and potential ice buildup in the N_2O system [22]. All fluids will depressurize and vent. The system can be considered safe once the nitrogen and nitrous oxide have completely vented and boiled off into the atmosphere. Other common potential issues such as regulator failures and loss of the pneumatic system have passive mechanical and active electronic safety features. These are detailed in subsections 4.2 and 4.3, as well as the RMS.

Volatile Exothermic Oxidizer Decomposition is another major hazard that has received additional focus. Nitrous Oxide contamination greatly reduces its stability, and decomposition results in a rapid and violent release of energy and the release of Nitrogen and Oxygen. This process can also lead to thermal runaway & cascading decomposition, which would cause rapid and extreme spikes in pressure and temperature. This failure mode is of considerable concern to the propellant system and could possibly damage tanks, tubes, valves, and other components beyond safe reuse. Therefore, deep cleaning procedures of the N_2O lines and pressurant lines are being carefully written and conducted before the use of non inert propellants in subsequent coldflows and hotfires. A highly clean assembly, transport, and setup environment is also challenging with the aforementioned programmatic risks, and a solution is being worked towards. The temperature and pressure of the N_2O run tank will also be closely monitored.

7.2.2 Combustion Dynamics Risks

All high severity hazards contribute to Loss of Vehicle under the considerations detailed in 7.2. Excess pressure in the combustion chamber or insufficient injector pressure can lead to backflow of hot combustion gasses, potentially damaging the inlet lines and propellant tanks. This could lead to further system failures. Mitigation strategies involve applying two check valves along each propellant line immediately upstream of the injector. Additionally, in this and many other predictable failure cases, the control system will automatically stop testing and begin the purge sequence. To minimize collateral damage and mission risk in cases of rapid unscheduled disassembly, the propellant and electronic systems in close proximity are isolated by a blast shield.

A mechanical failure in the throat of the nozzle is caused by melting, weakening, or burn through of the chamber. This particular risk has increased with the two-piece construction of the chamber liner and nozzle. However, previous mitigations requirements required for Borealis' reusable copper chamber are less necessary for GAR-E, as the ablative liner is entirely disposable and the evaluation of a FR-4 nozzle with no graphite insert is one of the test objectives of the engine. In the case of catastrophic structural failure at the throat, the nozzle is expected to break apart and be ejected, limiting damage to the injector and all upstream components.

A propellant ignition failure or hard start can produce a catastrophic explosion as a result of the fuel-oxidizer mix being built up within the combustion chamber, and/or a delay in ignition. To avoid hard starts, several checks are incorporated into the automatic ignition sequence in the electronic control system. The main propellant valves will not open if the ignitor's thermocouple does not reach the necessary temperatures, and additionally will quickly shut down if an increase in chamber temperature and pressure indicative of successful propellant ignition is not detected.

7.2.3 Transfer & Control Risks

The control and telemetry system onboard GAR-E and supporting systems is subject to software and hardware risk factors. These risks can be caused by power failures, communication failures, or equipment failures between distance-isolated subsystems or locally between components.

Any communication error detected within the primary communications link will result in the initiation of an abort sequence. If a communication error arises between any of the four major components on the engine side (DAQ, Engine Computer, or either Labjack units), automatic shutdown sequences and fail-safes will be attempted to be initiated. Should this not work or should mission control lose telemetry, remote visuals, or detect any other anomalous conditions, an emergency abort sequence will be initiated through the separate E-stop circuit.

As the software control system is the first line of mitigation strategy for many failure cases within other subsystems, in case of software failure, the independent emergency stop system combined with power-off valve states serves as the primary last-resort abort procedure.

Additional risks were identified during the cold-flow test, primarily that of inadequate physical and environmental protection. This resulted in the design of the physically separated, enclosure-based telemetry and control system. The addition of separate groups of arming switches was also a direct response to identified risks of accidental valve actuation through electronic or human error. Better insulation of all connectors and better managed wiring in general are also being implemented to improve subsystem durability and general safety.

Running the arming circuit over long distances potentially requiring fiber optics is another challenge in active search of a solution. The increased complexity of the pad-side ignitor safety is to address the risks associated with running a direct electrical safety across such long distances for the electrically sensitive E-match. Feedback on our arming system design as presented in Sections 4.1.3 and 4.3.3 is greatly appreciated.

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Toronto Metropolitan University	Metropolitan University Engineering Society	Design Fabrication Zone	Innovation Boost Zone	Stein Industries Inc
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Figure 8.0.1: MACH's Current Sponsors

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Appendix I: Preliminary Calculations and Design Trade-offs

A1.1 Tank Sizing

The ethanol and nitrous oxide flow rates are to be 0.19 kg/s and 0.604 kg/s respectively. The nominal burn duration is 5 seconds and the assumed operating temperature is 15°C. In the assumed operating conditions, the densities of ethanol and nitrous oxide are 786.9 kg/m³ and 818 kg/m³ respectively. It is assumed that there will be a trapped propellant volume of 1%. The propellant volume can therefore be calculated as follows [11]:

$$V_{EtOH} = \frac{(\dot{m} * \Delta t)}{\rho * 0.99} = 1.219L \quad \text{(A1)}$$

$$V_{N2O} = \frac{(\dot{m} * \Delta t)}{\rho * 0.99} = 3.489L \quad \text{(A2)}$$

Under the assumed operating conditions, vaporization of the propellants and inert gas occupies space above the free surface of the propellants. It can be assumed that the ullage volume is 2.5% [11]. Accounting for the ullage volume results in the required pressure vessel volume. The computation can be performed as follows:

$$V_{EtOH, req} = V_{EtOH} + V_{EtOH} * 0.025 = 1.250L \quad \text{(A3)}$$

$$V_{N2O, req} = V_{N2O} + V_{N2O} * 0.025 = 3.576L \quad \text{(A4)}$$

The selected COTS tanks satisfy the minimum volume requirements.

A1.2 Cavitating Venturi Dimensions

The assumed inlet pressures of the venturis are equivalent to the theoretical tank pressures. The throat area of each cavitating venturi is to be calculated according to the following [13]:

$$A_{th} = \frac{\dot{m}}{0.9 * \sqrt{2 * \rho * (P_{inlet} - P_{throat})}} \quad \text{(A5)}$$

With an assumed circular throat profile, application of the previous equation yields throat diameters of 1.434 mm and 3.346 mm for the ethanol and nitrous oxide venturis respectively.

A1.3 Control Valve Sizing

To compute the absolute minimum flow coefficient for the gas system valves, the estimated volumetric flow rates were first calculated. The volumetric flow rate of the compressed N_2 into each tank was computed using the volumetric flow rates of each propellant exiting from the bottom of each run tank. In order to maintain pressure in the tanks, the volumetric flow rate of the propellants exiting the run tank must be equal to the volumetric flow rate of the N_2 entering the tanks.

The mass flow rates of the fuel and oxidizer have been presented in Table 4.1.1. Using the densities of each propellant, the volumetric flow rates have been computed and are also presented in Table A1-1.

Table A1-1: Propellant Mass and Volumetric Flow Rates

Properties	N2O	Ethanol
Density (kg/m^3)	818	789.6
Mass Flow Rate (kg/s)	0.604 kg/s	0.1904 kg/s
Volumetric Flow (m^3/s)	0.0007384	0.0002406

With a known temperature of 21℃ and pressures approximately equal to the tank stagnation pressures, the density of N_2 entering each tank was computed. The mass flow rate was computed using the known densities. Using the conservation of mass principle, the mass flow rate of N_2 entering the manifold was computed. The volumetric flow rates at each point in SCFH were used to calculate the absolute minimum flow coefficient for valves and regulators in each of the respective subsystems. Equation (A6) is representative of the relationship between the flow coefficient, critical flow rate, inlet pressure, specific gravity and temperature of a choked compressible flow through a component.

$$C_V = \frac{Q}{816P}\sqrt{SG * T} \tag{A6}$$

Application of (A6) yields the absolute minimum required flow coefficient for any valve or regulator in each portion of the pressurization system. The results of the flow coefficient calculations have been summarized in Table A1-2.

Table A1-2: Absolute Minimum Flow Coefficients

	N_2O Pressurization System	Ethanol Pressurization System	Common Manifold
Minimum **Flow Coefficient**	0.1783	0.0583	0.1224

The selected control valves have a flow coefficient of 7. Since the selected valves have a flow coefficient that is much larger than the required flow coefficient, it can be concluded that the selected control valves are sufficient for use in the current propellant system.

A1.4 Relief Valve Sizing

Relief mechanisms have been sized to handle the flow of N_2 in the event of a complete regulator failure. Flow coefficients for the regulators have been provided for each regulator. It is important to note that the flow coefficient of a regulator is representative of the regulator flow behavior when it acts as an open orifice. Therefore, the critical flow through each of the choked regulators was computed using (A7).

$$Q = Cv * \frac{816 * P1}{\sqrt{SG * T}} \tag{A7}$$

The absolute maximum flow of the ethanol and N_2O pressurant regulators (R1 and R2) was computed to be 103.5 SCFM and 1423.8 SCFM. By analysis of the flow curve of the selected R3A relief valve, at a flow of 100 SCFM, the upstream pressure of the relief valve will increase by 1.38 MPa (200 psi). Since this is within the operating pressure of all system components, it was concluded that the ethanol pressure relief valve was sufficiently sized.

According to the analyzed flow curves provided by Swagelok, the R3A relief valve was undersized for pressure relief in the event of the N_2O regulator failure (R2) and therefore only serves to manage regulator creep in the stagnant flow condition. The dump N_2O dump valve (V32-SB) has a flow coefficient of 7. Since the flow coefficient of the dump valve is significantly larger than the regulator flow coefficient, it can be concluded that pressure relief can be sufficiently achieved with the current relief system configuration.

It is important to note that while the relief systems have been sized, burst disks were implemented in the event of a high pressure surge and serves as a redundant pressure relief mechanism.

Appendix II: Inert Cold-Flow 1 Failure Analysis

In the days after the test, debrief sessions at varying levels and scopes were conducted to dissect the test and make technical and procedural improvements. This report goes through the major and minor failure events, their causes, and mitigation strategies developed.

A2.1 Preparation & Setup

The first and by far largest issue was the lack of adequate preparation. Unfortunately, this was not a circumstance that could have been resolved at the time, and a long-term solution is still a work in progress at the writing of this report. In debriefing meetings, the team overwhelmingly agreed that going forward with the test regardless was the correct decision. The majority of the issues described in this section, and ways to prevent them, could not have been highlighted without the practical testing experience. To work around this and other potential external setbacks in the future, the team will strive for more flexible testing windows and improve logistics for preparation.

The system assembly took significantly longer than the process laid out in MACH's cold-flow CONOPS (similar to Section 3.0 with reduced steps). The majority of this stemmed from the aforementioned unplanned systems integration which had to occur during setup. These additional contributing factors were identified:

- Insufficient tools, parts, and equipment
- Extremely poor inventory management
- Amount of outstanding tasks due to inadequate preparation
- Inadequate training & task briefing
- General fatigue especially among leads
- Low temperatures and insufficient heating/insulation at pad
- Cable management & workspace clutter
- S. Maraj's overabundance of pockets

A2.2 Pneumatic System

One of the most troublesome subsystems was the pneumatic system used for valve actuation, which used push-to-connect fittings and PTFE tubing as a temporary solution before the plumbing system was finalized. Even before testing, the system was too fragile to transport over long distances and had to be disassembled for transportation. The reassembly process was hindered by addition of components without full consideration of affected components. The shortage in tubing and fittings was solved through creative routing, and buying out the entire searchable stock of ¼-⅛" NPT adapters across the Niagara & St. Catharines region.

Even afterwards, there was significant leakage in the pneumatic system as it was pressurized to its operating pressure above 100 psig. The inability to identify and fully seal all leaks in the pneumatics inhibited the performance of the valves and greatly frustrated testing. Though a soap-solution procedure was used and leaks were successfully identified, there were a large number of connections to seal, many difficult to access due to suboptimal adapters, and recurring leaks developed upon pressurization.

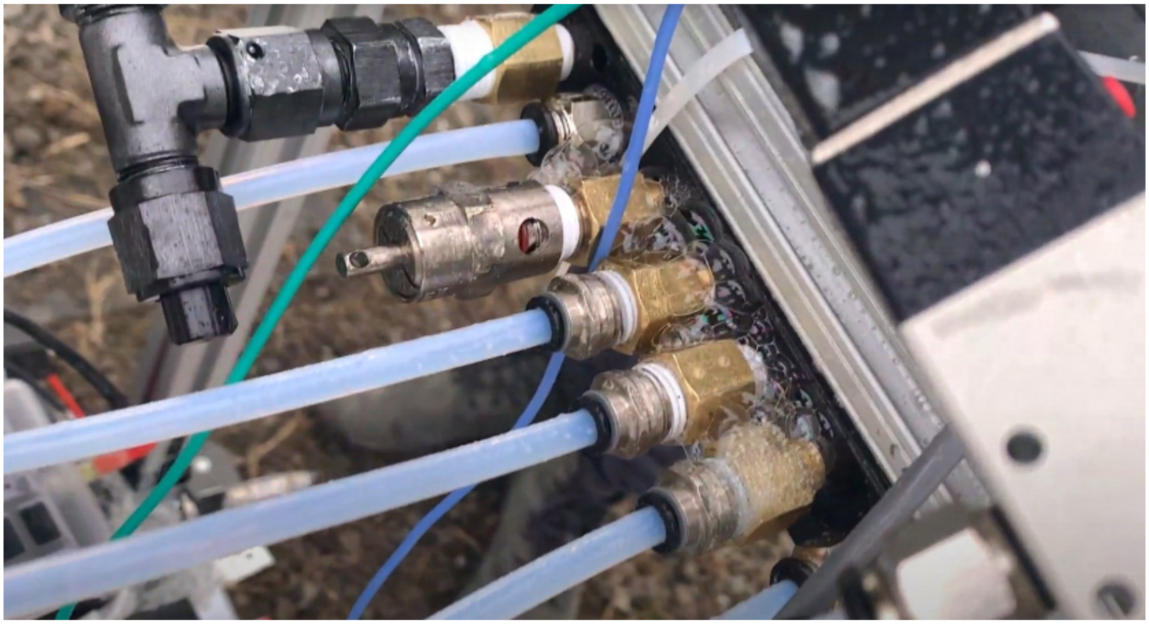


Figure A2-1: Problematic manifold identified during pneumatic leak testing.

To temporarily address this issue, the air compressor used as the supply was to be run continuously throughout the duration of the test and controlled with the regulator and separate wiring run to mission control. As this is not a sustainable solution for subsequent tests involving non-inert propellants, several changes to the pneumatic system have been made.

Firstly, the pressurant supply for the pneumatic system has been changed to a compressed air cylinder. The use of a compressed air cylinder allows for both a larger reservoir volume and higher stagnation pressure. The use of a compressed air cylinder would also eliminate risks pertaining to the operation of a brushed DC motor near non-inert propellants. A pressurant line tap-off before the MPV can also be considered, but is not the preferred option.

In addition to the changes to the supply source, implementation of hard-line pneumatic tubing has been greatly accelerated to replace the push-to-connect fittings and PTFE tubing intended for testing. The new pneumatic design uses copper tubing interfaced with the associated valves, actuators, and regulator using a combination of Yor-Lok, AN, BSPP, and NPT fittings. This implementation of the pneumatic system is intended to be used for hot-fire tests and will not require disassembly for transportation.

A2.3 Main Pressurant Valve

The test was scrubbed directly due to the failure of the main pressurant control valve. Subsequent analysis revealed that the valve failed due to yielding of the stem seal. Upon review of the failed valve assembly, the stem seal failure was caused by procedural oversights during the assembly of the packing nuts and washers. New procedures have since been developed to ensure that the packing installation is performed correctly for subsequent tests.

Figure A2-2: The MPV failure **a:** during pressure testing **b:** effect on the stem seal.

In hindsight, this failure was likely diagnosable and correctable on the pad if there was sufficient time for troubleshooting. In many ways, the failure was a validation of the propellant system's safety-oriented design, as vent and isolation valves downstream of the MPV prevented any other part of the system from suffering potential damage. The assembly oversight also resulted in the stem seal failing so completely that neither it nor the valve appear damaged during the blow-out. The failed valve is set to undergo high-pressure testing and should it pass, be put back into use as a less critical part.

The risks in SRAD components for extremely critical valves such as the MFV, MOV, and N_2O fill valves was identified early on in system design, and no expense was spared on fully integrated Swagelok COTS units for those components. High pressure leak and actuation testing will also be conducted on each individual valve assembly prior to integration with the system.

A secondary issue identified and may have contributed to the failure was in the design of SRAD couplers and coupling plates for the pneumatic actuators. The valve assembly in question, along with several other valves in the system, were high-pressure manual ball valves coupled with universal pneumatic actuators from two different suppliers to save cost. While the universal actuators followed the ISO 5211 mounting standard, the manual ball valve did not. Therefore custom couplers and mounting plates were machined from scrap aluminum stock. The couplers were simple in design and produced from meticulous measurements taken from one of the ball valves. Tolerancing was kept tight with the goal of reducing backlash to compensate for the softer aluminum, and the manufacturer produced the parts accurately. However, an oversight was made during the design process to account for production variations between individual valve units. This caused fitment issues.

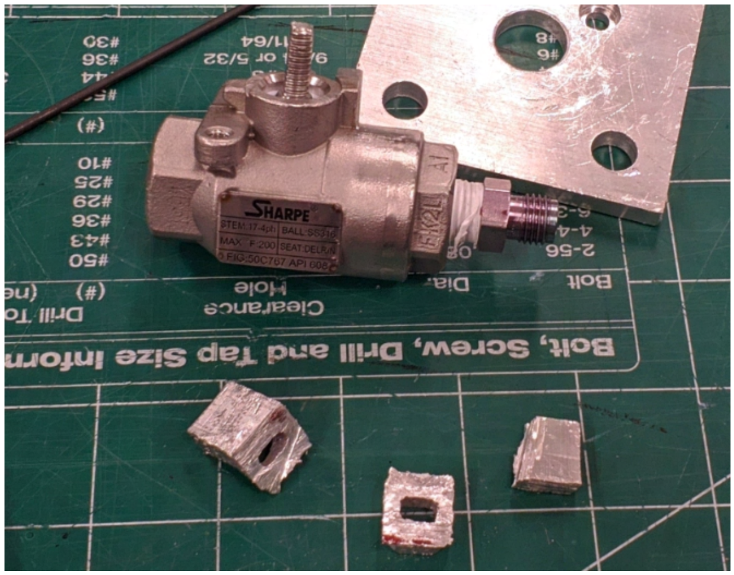


Figure A2-3: The disassembly process for the coupler with the worst fitment.

Under severe time pressure prior to the test date, heavy sanding and light percussive assembly was applied to fully seat some couplers, including that of the MPV. The difficulty of this process likely contributed to the oversight in assembly procedure, as well as weakening the seal during assembly and disassembly. The couplers have since been redesigned and remanufactured with looser tolerances, with interface packing material used to achieve better fitment. All valves assembled with couplers so far will be tested with extra scrutiny before reuse.

A2.4 Procedures

Many general and specific procedural shortcomings were identified for rectification in future testing. The majority of the issues again stemmed from a lack of preparation time and practice runs to develop detailed procedures. Checklists were created for various complex operations as a compromise solution, with the understanding that they would require on-site procedural development and later expansion into full SOPs. At several points during the test, the lack of pre-prepared troubleshooting steps required significant additional time and effort to develop solutions on the spot. For future testing, extensive procedural practice, system preparation and component-level troubleshooting will be carried out before major system testing. Though this concept was not a new insight and knowingly foregone for this test, specific steps were identified for future testing:

- A checklist to procedure to checklist process for complex SOPs
    - Develop initial checklists using theoretical steps
    - Test & iterate checklists into draft procedures with dry run simulations
    - Test & iterate draft procedures during testing
    - Simplify validated common procedures into quick checklists for experienced personnel
- Conduct as much component-level testing as possible before integration
    - Test main fluid system components with recent access to high-pressure pneumatic testing capabilities
    - Electrical components and software with integration testing focused on control subsystems
- Perform full-system pressure testing to identify likely leak points, with particular focus on NPT and high-cycle fittings
- Practice and develop procedures for full system setup and teardown
- Improve cross-subteam technical training for leads and general members
- Improve distribution of general procedures, safety documentation, testing overviews, and SOPs to all members on site
- Prepare clipboards and all necessary reference material in physical form
- Develop and practice cleaning and contamination procedures during assembly, setup, and transportation of Spender

Additionally, the longstanding systematic lack of documenting assembly procedures directly contributed to the MPV failure. These issues had already been identified long before the specific events leading up to the cold-flow, but were not rectified in time due to the amount of dedicated time commitment required and perpetually high number of outstanding tasks. A higher focus has been placed on these tasks in the aftermath of the test.

During testing, a number of procedural shortcomings with serious potential to compromise safety during more volatile testing were also identified. They can be summarized as the following points:

- Inadequate & overly flexible criteria & times of milestones & go/no-go calls
- General fatigue & sleep deprivation
- Objective judgements skewed by personal bias and investment
- Insufficient technical knowledge of all systems among key decision makers
- Explicit assignment of pad team personnel after restriction

The majority of these were a result of MACH's first experience with "launch fever". In debriefings all of MACH leads agreed that significant misjudgments of progress and safe practices lead to the exposure of higher levels of risk then was characterized in the RMS, and that decisionmaking was grossly skewed. While there were no injuries and said testing was a part of the lowest severity testing, this type of experience is something that has to be avoided at all cost. Though launch fever is extremely difficult to mitigate given the personal investment of all members and especially leads, several factors have been identified for improvement and careful reflection in future testing.

Fatigue was a severe issue during testing and serious safety risk in general. Prior to testing, many of the key leads and pad personnel were extremely sleep deprived due to the usual stresses and additional work required by the circumstances. Not only was judgement, reaction time, memory, and dexterity compromised by fatigue at the test site, many also drove 4+ hour round trips with passengers and equipment, including return trips after sunset and in adverse weather. Though mandating sleep among engineering majors is one of the most difficult problems known to humanity, MACH is working to ensure that members are not pushed to extremes and sustainable work practices are employed.

An insufficient level of full-systems technical knowledge to make accurate risk and progress assessments was also identified within the leads team. As a result, critical de-facto decision-making was deferred to select few members with full systems knowledge or extensive subsystem knowledge. The level of detail in this document is one of the steps to addressing this problem, along with improved cross-subteam training.

Finally, a lack of explicit role definition led to several problems with pad access control, mission control operators, and Red Team operations. The following policies will be implemented for testing going forward:

- Explicitly defined Red Team personnel
- Mission controllers with extensive experience during high-risk procedures
    - The Red Team swap system outlined in section 4.2.3
- No-questions-asked abort veto for Leads and Red Team members at all times
    - Extremely clear, unmistakable communications of the appropriate abort procedures to be executed

Additionally, issues with radio communications were experienced. These included:

- Inadequate training for radio equipment & etiquette
- Unclear and/or unnecessary communications during critical times
- Insufficient number of radios especially once charging is required
- Lack of dedicated radio operators leading to critical roles being overloaded

A2.5 Inventory & Tools

Extremely poor inventory management was one of the biggest hindrances during and after the test. This was primarily caused by the lack of time to prepare full inventory lists of team and personal equipment. Another contributing factor which greatly complicates inventory management is the lack of team equipment due to funding limitations, requiring members to bring and lend out personal tools.

The main problems can be summarized as follows:

- Chronic lack of accurate team-wide and subteam inventory management
- Shortcomings in BOM and ordering processes resulting in shortage of required components and tools
- Disorganized mixing of team and personal tools & equipment
- Inadequate training in tool operation and storage
- Spread of tools & equipment across mission control/setup area and pad
- Excess of fastener types, tool bits, wrench heads, etc. across systems

A complete team-wide re-inventory and equipment reorganization effort is underway with the goal of building a sustainable inventory management solution. On future testing days, a small inventory team will be created dedicated to that task. Testing day strategies were developed with the expectation of limited time and an abundance of chaos. These include identification of personal equipment with color-coded stickers, creation of inventory lists during unpacking, preparing application-specific and location-designated kits of tools and hardware, and new rolling cleanup procedures.

The lack of practical tool training and experience from many team members was also identified as a key issue due to shortcomings in the typical engineering curriculum, especially over the pandemic. Tool training sessions have already been conducted and will continue to be on an as-needed basis for groups or individuals. More attention will be paid to ensure individuals are familiar or quickly trained with any specific tool required for an assigned task.

A2.6 Miscellaneous

Power failure, while accounted for in the RMS hazard identification section, was of greater probability than previously perceived. The PRA sections are still a work in progress, but an underlying assumption during the development of hazard mitigation was proved incorrect in testing. The probability and effect of losses of power were miscalculated, where several incidents throughout the cold-flow were noted for future testing. The most serious concerns are identified as follows. Simple but critical mitigations have already been developed for these risks and more, many of which are reflected in other sections of this report.

- Insufficient weatherproofing at connections, especially for snow
- Insufficient physical security for critical connections, i.e. engine computer
- Electrical overloading from multiple space heaters
- Insufficient physical and environmental protection for 24V LiPo battery, engine computer, and other electronics systems

The pad-side control interface and valve mapping was always an important part of the system design, but neither could be made ready in time for the test. The problems briefly summarized in Section 5.1.2 highlighted the necessity of a good user interface especially during highly stressful testing procedures. The following steps have been taken to address the identified problems and improve integration.

- P&ID and interface diagram overhauled with integrated valve identification & numbering scheme
    - Separated pressurant, fuel, and oxidizers with 2-digit convention for intuitive valve identification
    - Unified numbering for valves to reduce confusion for -SB assemblies, which are three physical components handled by different subteams
- Overhauled GUI design to incorporate P&ID or interface diagram
- Redesigned arming circuit with individual arming switches for critical actuation groups

Another concern identified was the cleanliness of the work environment at the pad. Particularly when working with N_2O, the system cleanliness will be critical and the surrounding environment must be constantly maintained to reduce contamination risk. A flooring solution will be required at the pad to reduce dirt, and pad access even during assembly must be better controlled.

Finally, the long-distance transportation method was highly inefficient. The majority of causes and solutions have already been covered across the pneumatics section above and Section 4.2.4.

A2.7 Successes & Remarks

While the debriefings and analysis have sharply focused around problem identification and resolution, the long lists of improvements to be made should not be mistaken for a negative sentiment of the test. MACH is highly encouraged by the outcome of the test, and has gained significant confidence in our systems and operational design.

While balancing out a detailed failure analysis with a long list of minor successes would be an entertaining exercise, below is a brief summary of the key positive takeaways to support our optimism:

- Stellar onsite documentation practices to develop analyses and procedures
- Excellent problem-solving, teamwork, and morale under extreme stress
- Validation of overall systems & operational design
    - None of the identified problems are major setbacks requiring significant redesign or reimplementation
    - A high degree of built-in safety at every level limited damage and prevented injury despite the efforts of the operators
- Extensive experience, progress, and areas of focus gained despite the failure of primary objectives

Appendix III: Safe Distances & Site Layouts

Formula 1: Scaled Distance (Used to find Overpressure [Ps])

$$Z = \frac{R}{\sqrt[3]{W}} \quad \text{A8}$$

R = Stand-off distance
W = TNT equivalent
*Note: Z is sometimes used to calculate safe distances, where R is replaced with some factor relating to risk tolerance.

Formula 2: TNT equivalence

$$W = M_c \cdot (\frac{H_c}{1155}) \cdot Y \quad \text{A9}$$

M_{cETH} = Mass Ethanol = 0.95(kg)[1]
M_{cN2O} = Mass Nitrous Oxide = 3.02(kg)
H_{cETH} = Heat of combustion of Ethanol = 7086 [kcal/kg]
H_{cN2O} = Heat of combustion of Ethanol = 445 [kcal/kg]
Y = Yield of combustion[2] = 1

$$W_{ETH} = 0.95 \cdot (\frac{7086}{1155}) \cdot 1 = 5.828[lbs] \quad \text{A10}$$

$$W_{N2O} = 3.02 \cdot (\frac{445}{1155}) \cdot 1 = 1.163[lbs] \quad \text{A11}$$

Formula 1.1: Stand-off Distance from Milestone Scale Distances

$$Z\sqrt[3]{W} = R \quad \text{A11}$$

By using values of Z from Figure A3-1, the non-scaled distances of interest overpressure 0.4psi, 1 psi, and 3.5psi can be calculated. Where, the engine has a TNT equivalent of 6.99(lbs) or 3.17(kg).

A3.1 Calculated Safe Distances

Table A3-1: Calculated Overpressure distances based on TNT_{eqiv}

Overpressure (psi)	Distance from Origin (m)
0.4 (Safe)	52.4
1 (Shatters Glass)	23.3
3.5 (Serious Injury)	10.5

[1] Masses are equal to engine projected flow rate multiplied by 5(s) burn time.
[2] Yield of combustion, where the worst case scenario is assumed, results in a yield factor of 1. Where all the ethanol is reacted with all the Nitrous Oxide and full combustion is achieved.

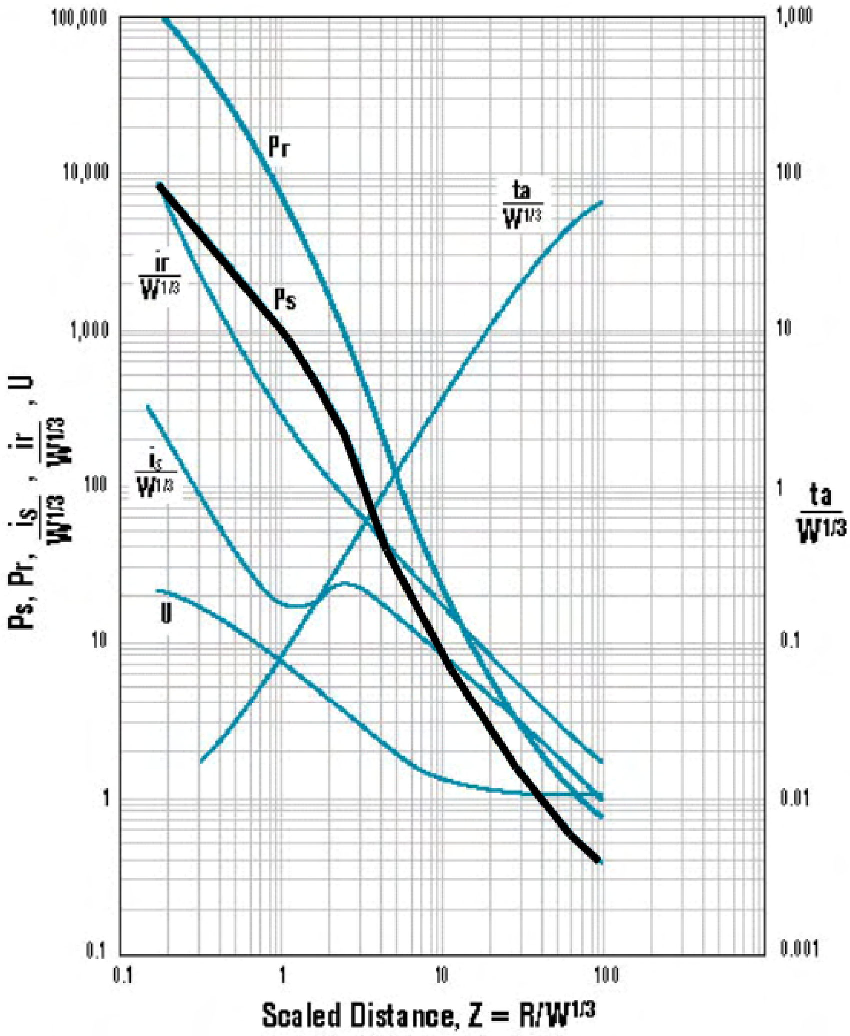


Figure A3-1: Scaled Distance to Peak Positive Incident Overpressure (Ps) Graph [25]

Using the UN Explosion Danger Area Calculator for bare explosives equalling our calculated TNT equivalent, our estimated safe distance with no protective solutions is 539m (1768ft). MACH should request a barricade, human made or natural, or shielding that can contain explosions of MACH's TNT equivalent of 3.17(kg). Providing protection against shrapnel would decrease our safe distance to the overpressure safe distance of 52.4(m) or 172(ft) which is comparable to the conditions of the Simple Path Farms site.

A3.2 Site Distance Considerations

Safety Considerations

Overpressure Safe Distance: The test area must be sectioned off within a range of 52 meters. This distance ensures that our team remains safe from any potential overpressure effects in the event catastrophic failure occurs such that the engine produces an explosion with the energy of expected propellent loads.

Exposed Safe Distance: We have calculated a safe distance of 539 meters from the Pad, considering the possibility of shrapnel and debris. To ensure this safety margin, barriers must be strategically placed around the Pad.

Pad Layout

The Test area will be divided into distinct sections, considering the following critical locations:

- **Mission Control:** Mission Control is a crucial hub for monitoring and control. It must be located within a 52-60 meter range of Pad Control.
- **Pad Control:** Pad Control serves as the interface between Mission Control and Pad and houses control & instrumentation hardware. It must be within 10 meters of the launch pad. This site is evacuated prior to testing.
- **Pad:** The pad is the central point from which the engine is set up and tested. It should be placed at a safe distance from any surrounding structures, with the necessary barriers to protect teams, spectators, and the environment.

Each of these critical locations requires a space of 10x10ft or the size of a standard tent.

Cable Length Limitations

To avoid signal loss and due to budget limitations the maximum cable length for various connections should be carefully considered and adhered to:

- **Mission Control to Pad Control:** The cable length between Mission Control and Pad Control must not exceed 60 meters.
- **Pad to Pad Control:** The cable length between Pad and Pad Control must not exceed 10 meters. This short distance necessitates a barrier.

Barrier Placement and Line of Sight

To ensure the safety of all teams and protect line of sight, barriers need to be strategically placed around the launch area. The placement of barriers will separate the engines and protect the visual observation of all teams involved. There are several locations based on google maps that seem suitable for MACH's placement.

A3.3 Current Site Layout (Welland)

At the current Welland site, the distance from MC to Pad is roughly 52m. The Pad is surrounded by barriers made of large interlocking concrete blocks that shield both MC and the larger facility. Figure A3-2b shows the internal view of the "Blue Barn" and the approximate location of the barrier setup on Pad.

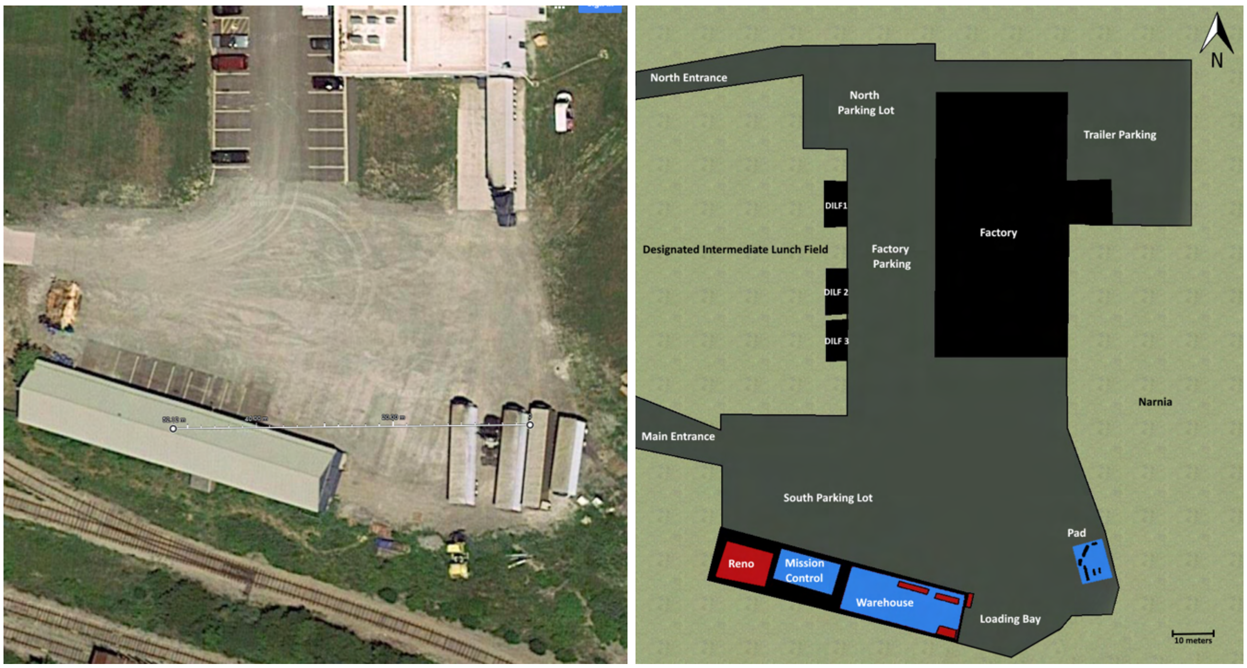


Figure A3-2: The Welland testing site shown in **a:** satellite view **b:** internal view.

Figure A3-3: The barriers at Welland, leftover from the 1100 lbf thrust LR-101 Engine that LC hotfired in late 2021. MC was located roughly 60 meters away.

A3.4 Proposed Site Layouts (Timmins)

Based on the prior parameters and limitations, MACH proposes two layouts that would be best suited for our testing at the Timmins site.

Case 1

In case 1, mission control is next to Space Concordia's MC. While using large barriers to shield MACH's MC, Pad Control, and Space Concordia's MC. Figure A3-4b shows an overview of the most preferable location based on satellite images. This is within the safe distance for overpressure while, in theory, not interfering with Space Concordia and vice versa.

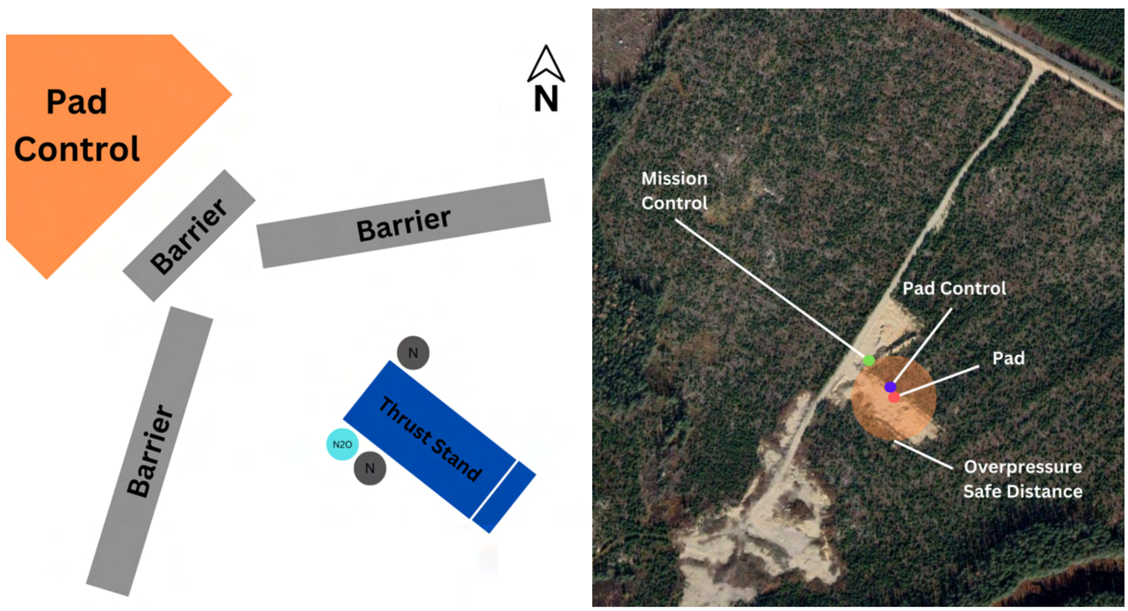


Figure A3-4: Case 1 Pad Layout **a:** Close-up. **b:** Proposed Location

Case 2

In case 2, large barriers are placed in such a manner that Space Concordia and MACH work alongside each other while offering protection for both teams' projects. The downside is that if one team goes on lock down the other team is forced off Pad. There is also the risk with case 2 that should a critical failure occur, then overpressure or debris shot straight up could cause damage to the other team's engine. The upside is less barriers and far more flexible pad placement where the side designated as the common area is always facing Space Concordia's MC. That being said, the location chosen matters significantly for MACH and should be placed in such a way that allows our MC to be straight behind the common area and clear of obstacles.

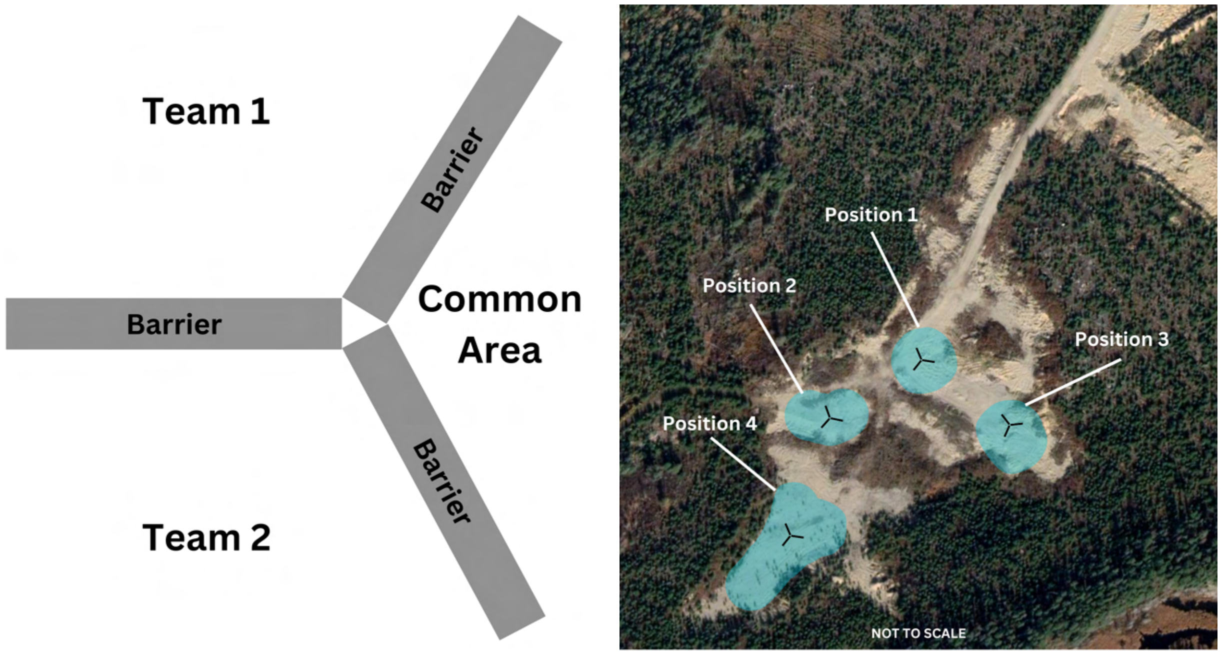


Figure A3-5: Case 2 Pad Layout **a:** Close-up. **b:** Proposed Locations

In conclusion, our team asks that Launch Canada adhere to specific requests for MACH's Site Design based off cable length limitations and Safe distances. The critical points of Mission Control, Pad Control, and Pad must be strategically placed within the specified distance limits. By implementing these requirements, we aim to create a safe and efficient site that fosters successful testing while prioritizing the safety of all team members and spectators.

Appendix IV: Thrust Stand Finite Element Analysis

The Finite Element Method was used to analyze and verify the design of the thrust stand. Static structural analyses were conducted using ANSYS Workbench. Initially, analysis was attempted with a slightly modified version of the CAD model, breaking the model into tetrahedrons. Accurate modeling of stress concentration about the welds proved to be too computationally demanding; as a result, a simplified model of the thrust stand was produced and analyzed with 1D BEAM188 elements. Stress concentrations about welds were approximated with information from [26].

Loads

The thrust stand was subjected to a 2000 lbf load, applied to the portions of the stand in contact with the thrust plate. This load is significantly larger than the thrust that GAR-E can produce, because the thrust stand was designed to accommodate more powerful engines.

Results

BEAM188 Elements provide information about the maximum combined stress experienced by each element. However, due to each element's one dimensional nature, stress concentrations are not taken into account. Consulting [1], a stress concentration factor of 4 was deemed a safe approximation for our most troublesome welds.

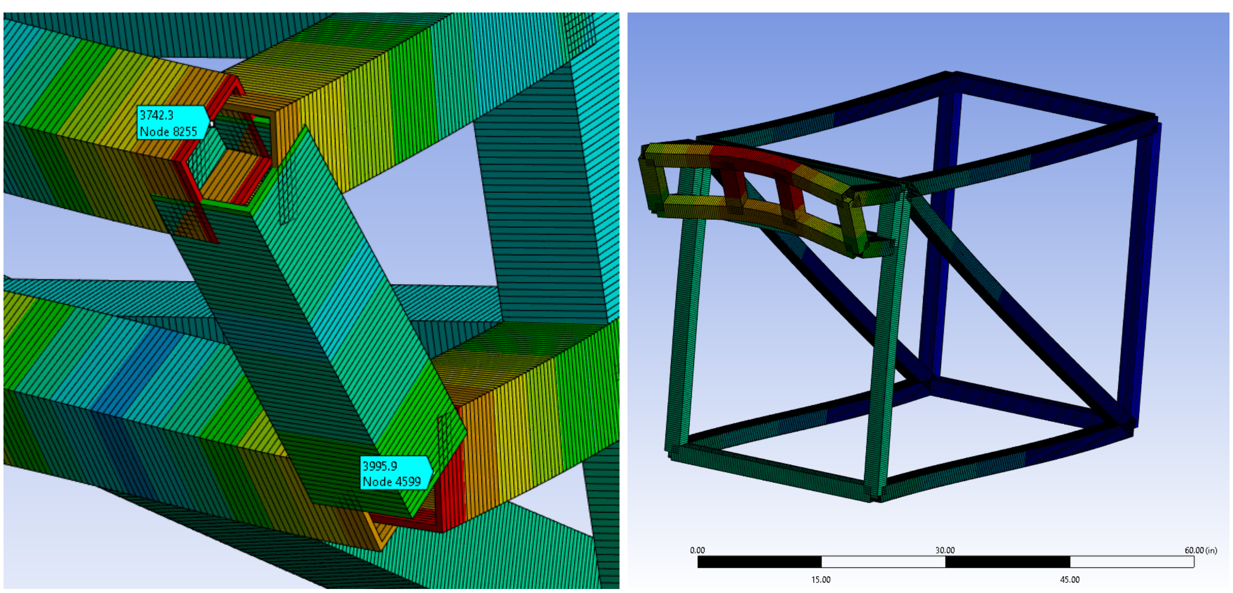


Figure A4-1: a: Maximum Combined Stress **b:** Thrust Stand Deformation (in)

Figure A4-1 details the maximum combined stress at two regions of interest. These areas were assumed to be the failure points of the stand, due to having high combined stress values and unaccounted stress concentrations about the welds. The results of Fig. A4-1a were verified to converge to ~4000 psi with a mesh convergence study.

Assuming a stress concentration factor of 4, and a yield strength of 50800 psi for mild steel, the safety factor of the thrust stand comes to 3.175 for a single 2000 lb load. Due to the high safety factor and low number of expected cycles, a cyclic analysis was not conducted. Further analysis would be somewhat trivial, as a 2000 lbf engine will not be used with the current plate mount, which is the weakest part of the structure.

A maximum total deformation of 0.023” was determined through analysis, seen in Figure A4-1b. This maximum deformation is negligible for a 2000 lbf engine. The team is confident that the thrust stand would not fail.

FEA was conducted again, this time with the ground anchors modeled as fixed remote displacements about the vertical axis. A remote force was used, acting upon the center vertical members, as opposed to line pressures for modeling engine force. The wires will need to provide a total vertical force of 1329.4 lbf (665 lbf each) to stop all vertical displacement of their respective attachment points for a 2000 lbf engine. If attached at 45 degrees, each wire must be rated for $\sqrt{2} * 665 = 940 \approx 1000$ lbs.

Figure A4-2: Crane undergoing structural analysis.

Appendix V: FR-4 Ablation Testing

This report presents the data collected from a FR-4 ablation test conducted by the MACH team and discusses the findings. After recording the initial mass, the test subjected FR-4 samples to a sustained flame from an oxyacetylene torch in order to determine the mass lost due to ablation. Six of these samples were burned for increasing time intervals, in addition to a full burn through test.

The oxyacetylene cutting torch was first run with a balanced flame (~3450K) compared to an expected chamber temperature of ~2800K, as well as an oxygen rich flame for some tests. No notable difference was observed in the mass loss rate.

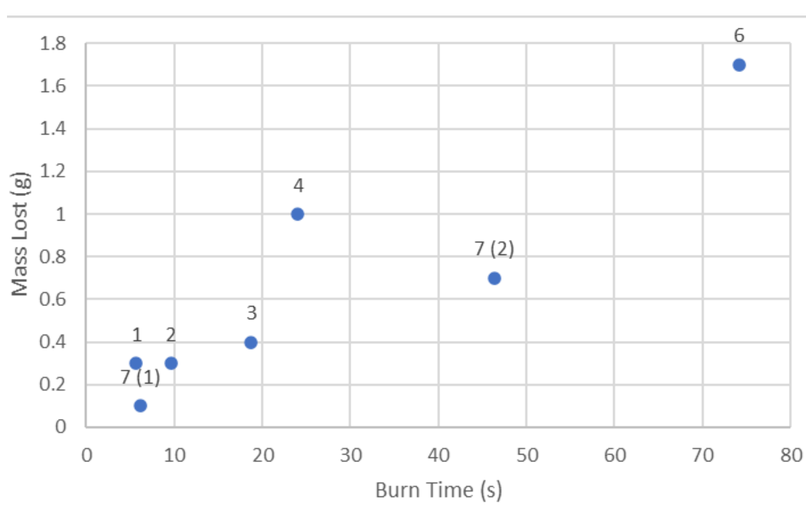
A thermocouple was placed in test piece 6, with 0.703" of material between the testing surface to collect data on insulation properties of FR-4. The results are displayed in Figure A5-2.

Table A5-1: FR-4 Ablation Data

Sample	Initial Mass (g)	Final Mass (g)	Mass Lost (g)	Burn Time (s)
1	5.2	4.9	0.3	5.70
2	4.1	3.8	0.3	9.63
3	5.1	4.7	0.4	18.77
4	5.8	4.8	1	24.07
6	11.6	9.9	1.7	74.17
7 (1)	1.9	1.8	0.1	6.15
7 (2)	1.8	1.1	0.7	46.37
7 (3)	1.1	N/A	N/A	~90

Additional notes:

- Piece 6 embedded a thermocouple which affected weight measurements
- Piece 7 was cut flat to 0.14". 0.13" was measured after test 1.
- Piece 7, test 3 was a burn-through test and timed when flame was observed through the other side



- **Figure A5-1:** Mass lost vs Burn time of FR-4.

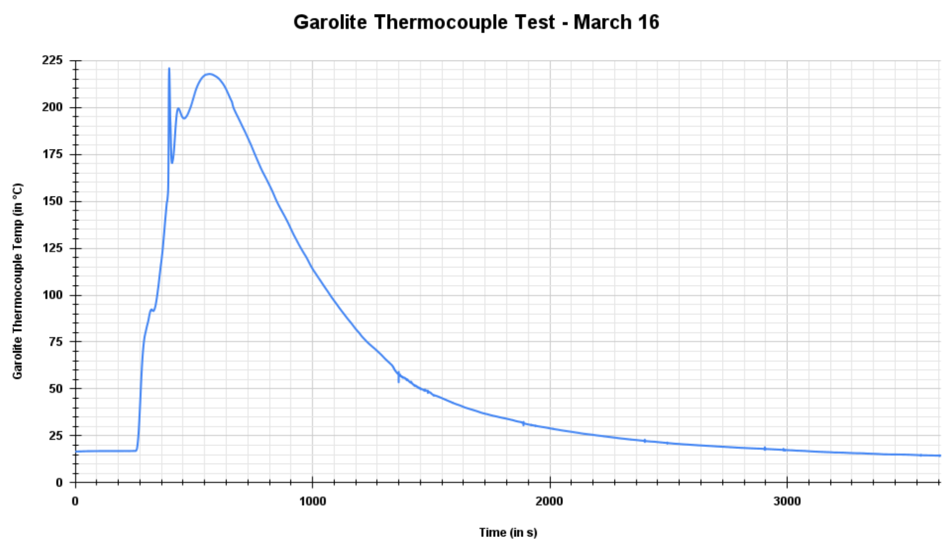


Figure A5-2: Garolite Piece 6 Thermocouple Test

Figure A5-3: Oxyacetylene Torch on FR-4.

Figure A5-4: a: FR-4 Samples after testing. **b:** Sample 7 after burn-through.

Appendix VI: GAR-E Production Drawings

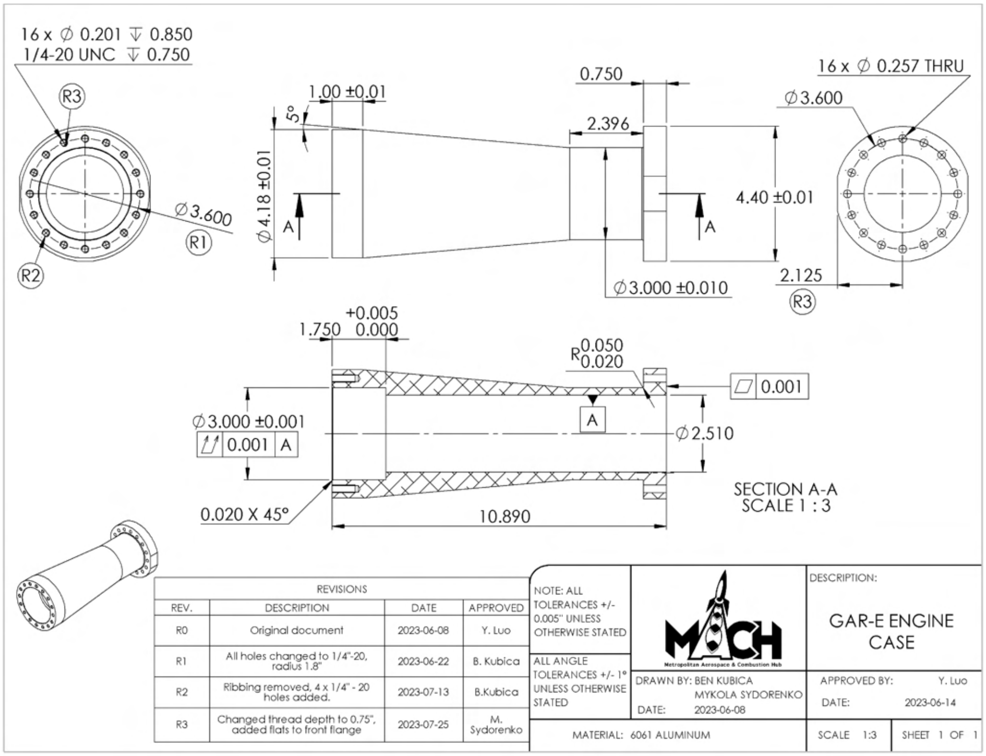


Figure A6-1: GAR-E Engine Case

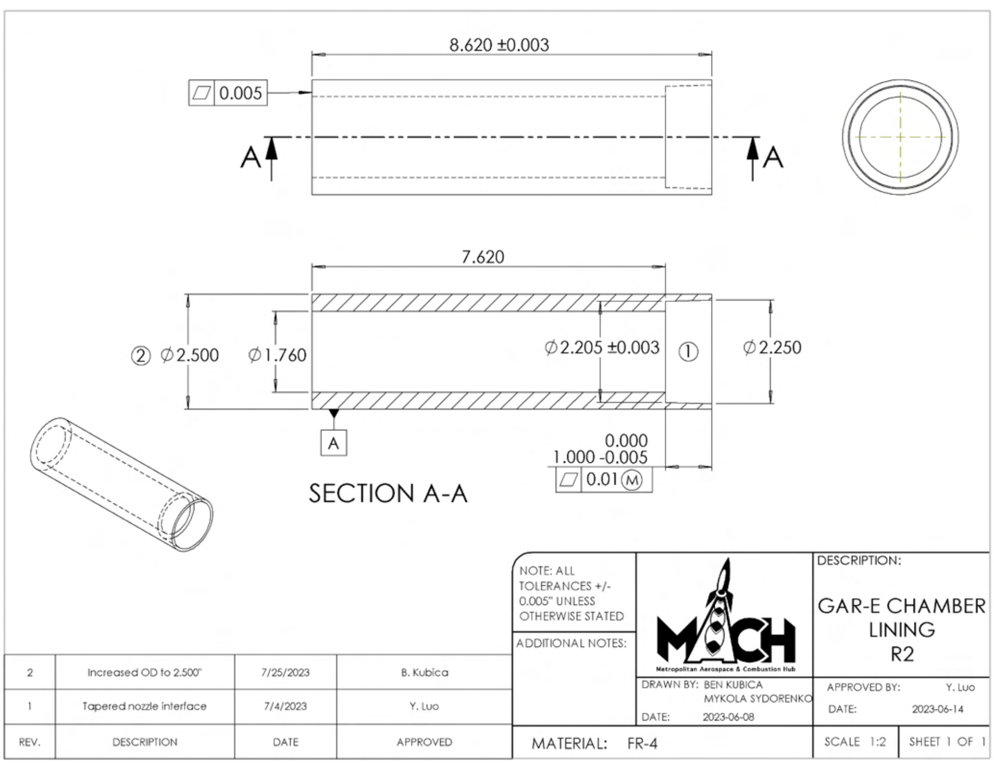


Figure A6-2: GAR-E Chamber Lining

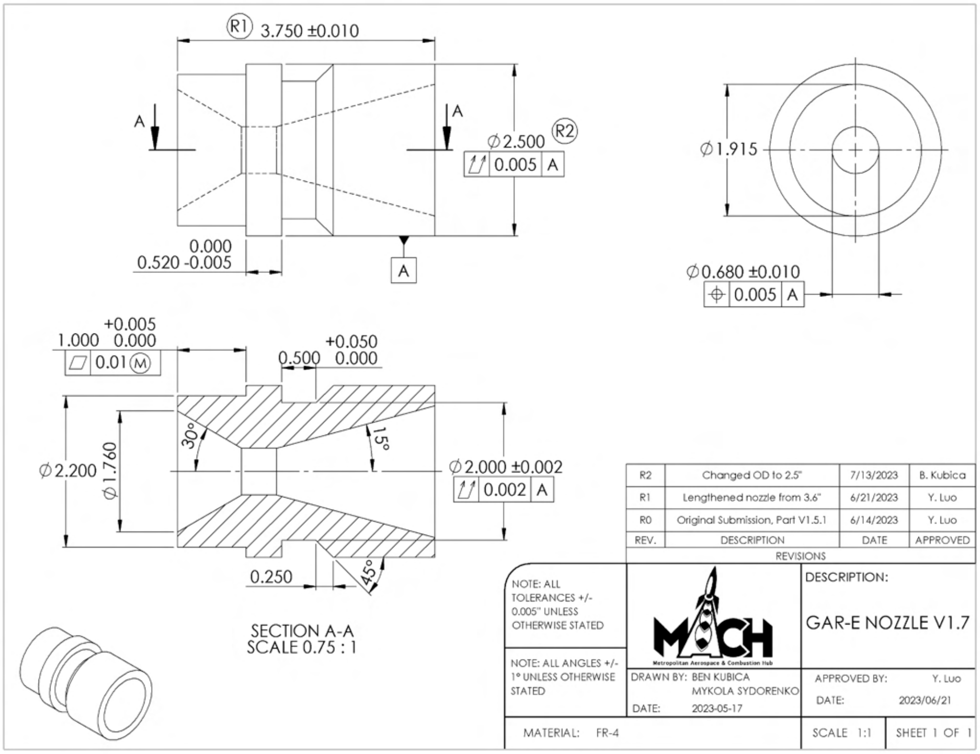


Figure A6-3: GAR-E Nozzle

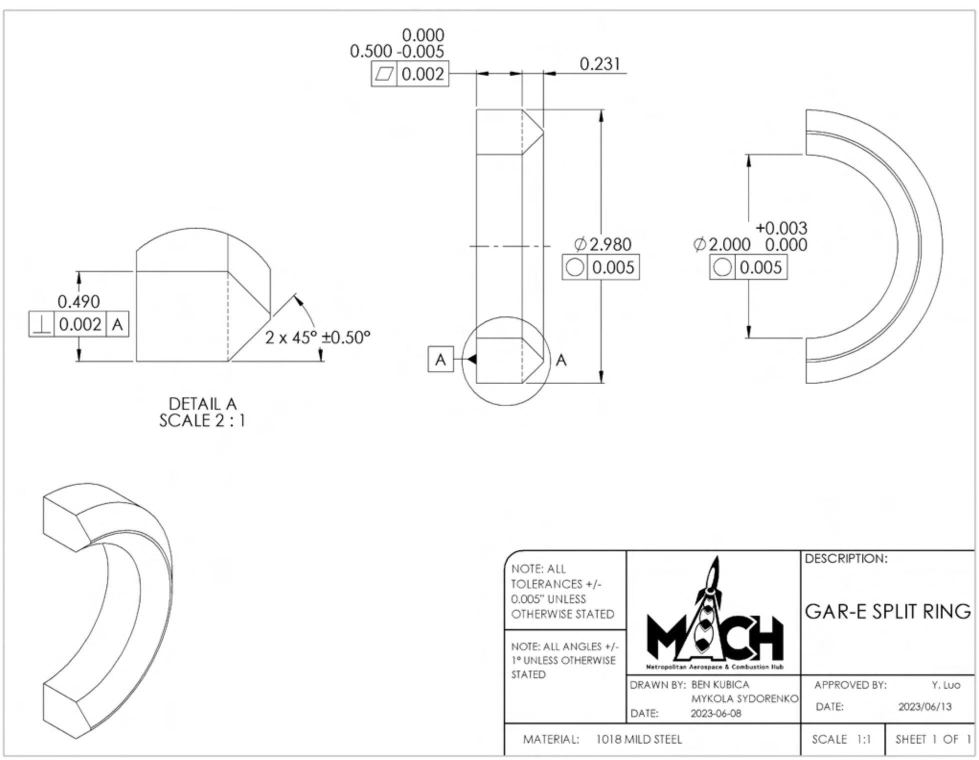


Figure A6-4: GAR-E Split Ring

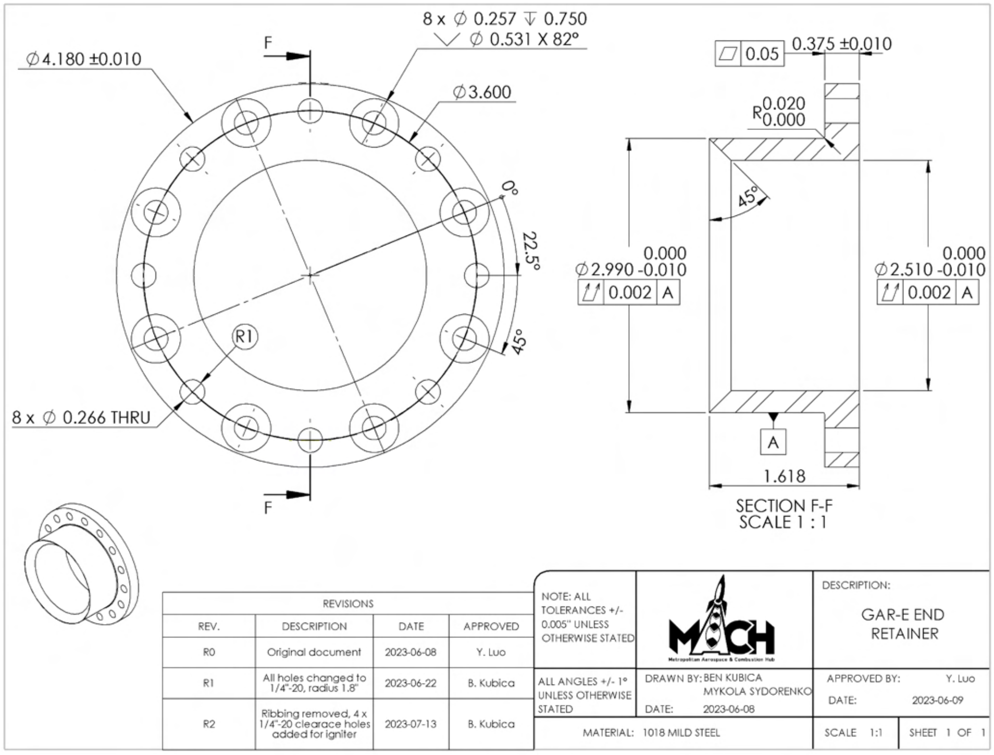


Figure A6-5: GAR-E End Retainer

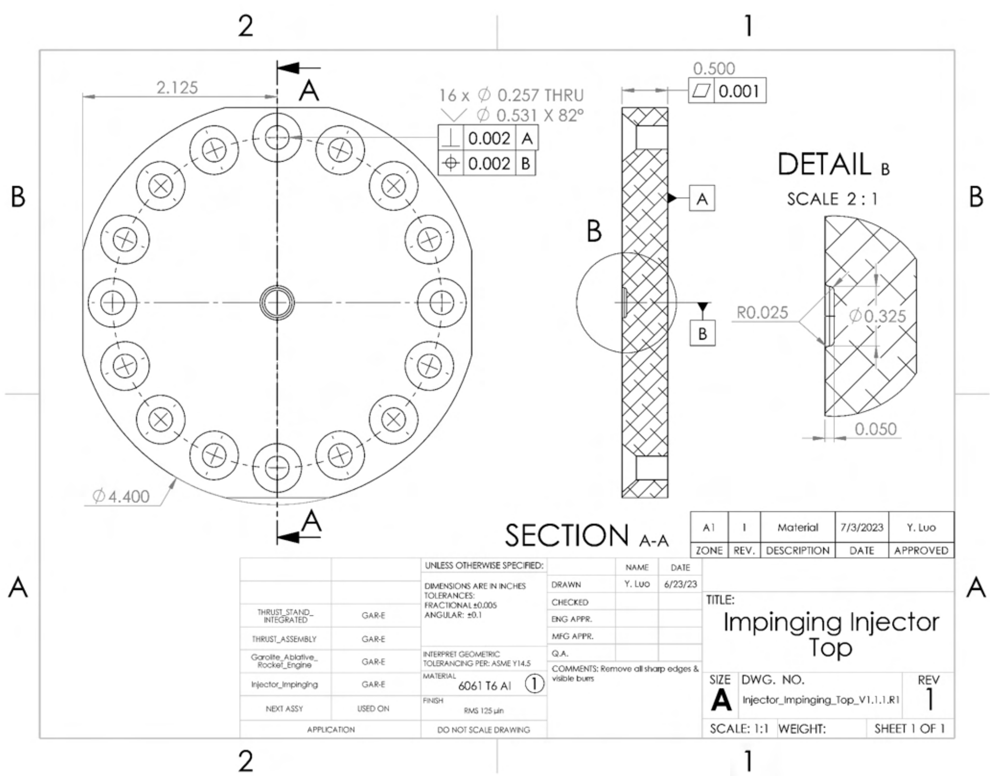


Figure A6-6: Impinging Injector Top

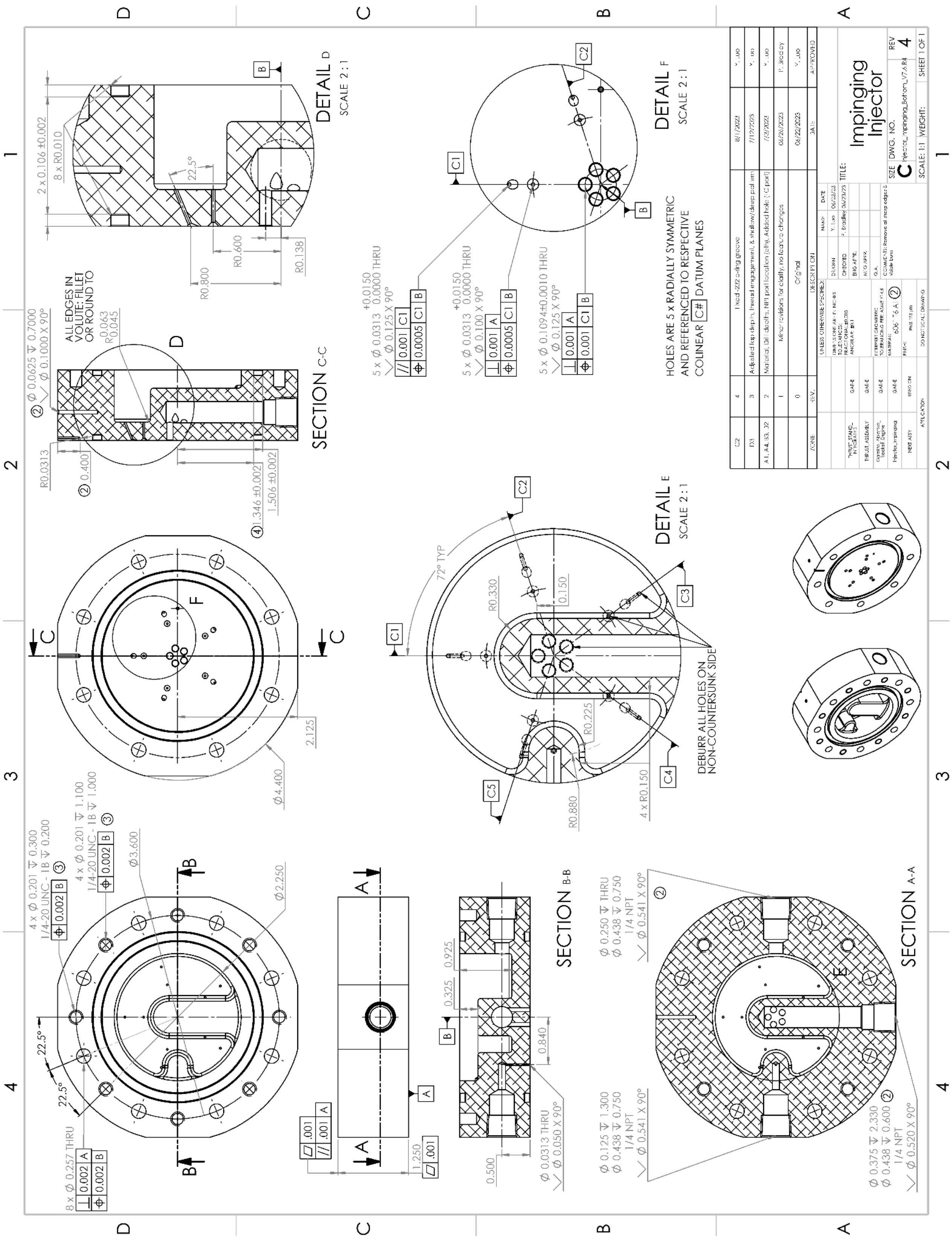


Figure A6-7: Impinging Injector Bottom

Appendix VII: Inert Cold-Flow Data Analysis

The main objective of inert cold-flow testing was to quantify the discharge coefficient of both cavitating venturis. In addition, the droop of both pressurant regulators was to be determined by analysis of pressure data. The pressure data for each coldflow has been presented in Figure A7-1.

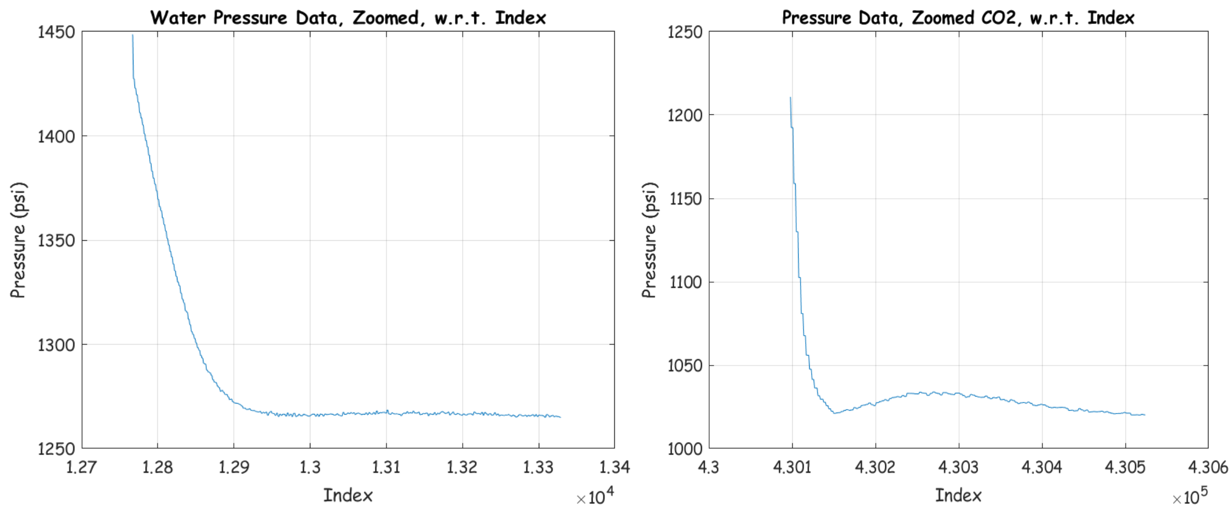


Figure A7-1: Pressure data for water CO_2 cold-flow.

Measurements from Figure A7-1 allowed for computations of the respective droops of each regulator. The Eth Aerocon regulator (R2) experienced a droop of 181.5 psi while the N_2O Swagelok regulator (R3) experienced a droop of 182.5 psi.

The mean value theorem was used to calculate the average mass flow rates for each propellant stand-in. The experimental pressure data was used to calculate the theoretical instantaneous mass flow rates for each stand-in. The theoretical instantaneous mass flow rates were computed using a variation of (A5) in Appendix A1.2 with an assumed discharge coefficient of 1. Plots of the theoretical mass flow rates are presented in Figure A7-2. The computed steady-state instantaneous flow rates and C_d values are recorded in Table A7-1.

Table A7-1: : Calculated cavitating venturi parameters.

Propellant Stand-In	Steady-State Flow Rate (kg/s)	Experimental C_d
CO_2	0.354	0.76
H_2O	0.162	0.83

The C_d values and flow rates are within expectations laid out in Section 4.2.2 for both cavitating venturis. Though tuning of the throat geometry will be required to get the design flow rates, the first hot-fire test can be conducted in the current configuration for an expected performance loss. The expected O/F ratio, thrust, temperature, and pressure with the current cavitating venturis will be analyzed.

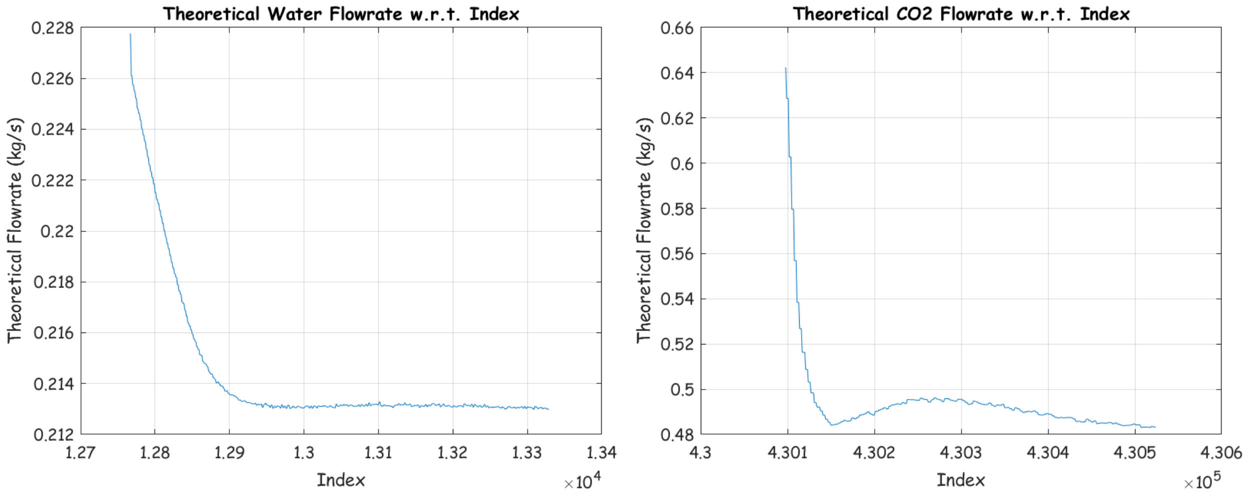


Figure A7-2: Theoretical water and CO2 instantaneous flow rate.

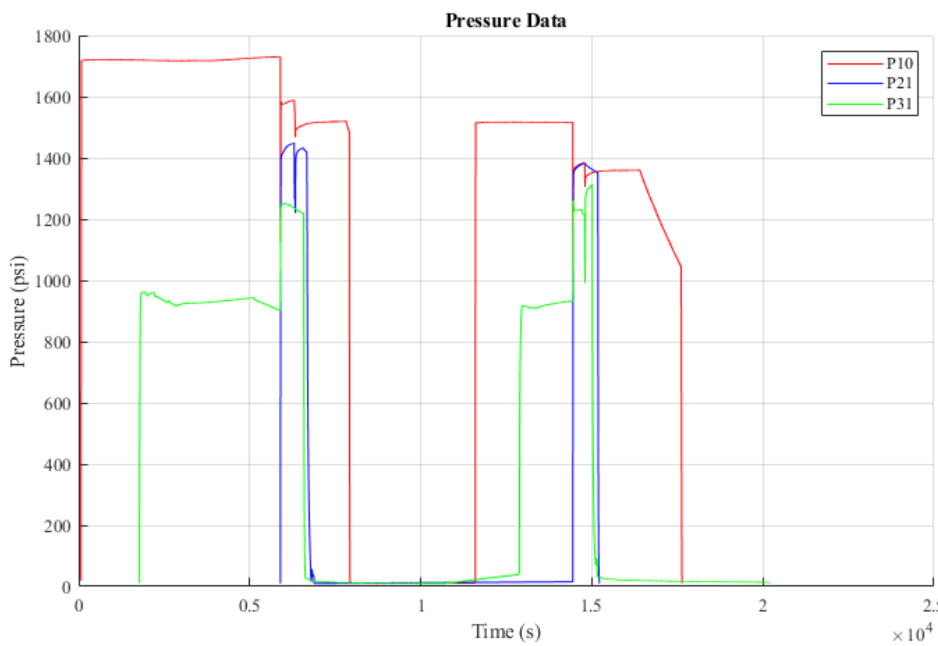


Figure A7-3: Plots from pressure transmitters during 1st cold-flow.

Several issues resulted in significant error margin in the results during the third inert cold-flow. A data acquisition issue with millisecond-scale time measurements resulted in data analysis using the index of each datapoint, which correlates to a ~144 Hz sampling rate. A skill issue with the tank-mounted thermocouples required a temperature approximation from literature [14]. The ±0.050 kg resolution of the COTS scale used also introduced a major error source. Subsequent cold-flows will be performed to verify the values for each discharge coefficient. The accuracy of the results will be improved through superior mass and temperature measurements.

Appendix VIII - Standard Operating Procedures (Modified for Jul. C-F)

Hot-Fire Procedure of Procedures (V2.3)

Procedure				Start	Finish
1.1	**a** Mission Control Setup		**b** Pad Tents Setup		
1.2	Pad Setup				
	a Thrust Stand	**b** Telemetry & Control	**c** Engine Assembly		
2.1	Thrust Stand Integration & Cylinder Setup				
2.2	Communication & Telemetry Test				
2.2A	Control & Actuation Test				
2.2B	Pneumatic Leak Test				
2.3	Pressurant Connection & Leak Test				
2.4	Eth & N2O Regulator Setting				
2.5	V21 & V31 Actuator Swap				
2.5A	Control & Actuation Test				
2.6	Pneumatic Connection & Regulator Setting				
2.6B	Pneumatic Leak Test				
3.1	Ethanol Fill, **RED TEAM SWAP**				
3.2	Engine Connection & Ignitor insertion				
3.3	N2O Connection & Pre-Fill				
3.4	Pad Arming & Evacuation **RED TEAM LEAVES**				
3.5	MC Arming & Data Recording				
3.6	N2O Fill				
3.7	Tank Pressurization				
3.8	Go/No-Go Poll & MC Arming				
4.1	Engine Operation & Hot-Fire Test				
5.1	Cylinder Disconnection & Pad Safing				
5.2	Thrust Stand De-integration & Cylinder Packing				
5.3	Mission Control Teardown				
5.4	Fluid Systems Drying & Cleaning				
5.5	Pad Teardown				
	a Telemetry & Control	**b** Thrust Stand	**c** Engine Assembly		
5.6	Pad Tents Teardown & Cleanup				

SOP 2.3 - Pressurant Connection & Leak Test (V2.2)

#	STEP	TEST ITERATION						
	Op 1.0 - PRESSURANT CYLINDER CONNECTION	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
0	**Roll Call** - Person 1 (Pressurant Hose Operator) - Supervisor - Safety Officer **Tools & Parts** - Main pressurant hose - Pneumatic supply cylinder - Zip ties - Face shields - First aid kit - Fire extinguisher - Medium wrench **Starting Conditions** - All valves default - Pressurant Globe closed - Regs fully closed (backed out)	**Start Time**						
1	(Person 1) Connect pressurant hose to pressurant bottle and **finger-tighten** the **CGA-580 nut**							
2	(Person 1) Use medium wrench and torque the **CGA-580 nut** to **wrench tight**							
3	(Person 1) **Secure hose** to Spender using zip ties							
4	(Person 1) Connect main pressurant hose to Spender via **QD1**							
5	Relay **completion of PRESSURANT CYLINDER CONNECTION** to MC & note down time:							

#	STEP	TEST ITERATION						
	Op 2.0 - LEAK TEST	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Seq 1 - NOMINAL LEAK CHECK PROCEDURE								

0	**Roll Call**
	- Person 1 (Cylinder Operator)
	- Person 2 (Eth Reg Operator)
	- Person 3 (N2O Reg Operator)
	- Supervisor
	- Safety Officer
	- Pad Control
	- MC: CAPCOM, Ground Control, [Tech Support]
	Tools & Parts
	- Face shields
	- Hearing protection
	- Soap & distilled water solution
	- Torque Chart
	- Medium torque wrench & crows feet
	    - ¾”, 9/16”, ⅝” ⅞”, [probably more]
	- Person 2 & 3
	    - Small or medium wrench
	    - Sharpies, [Scriber]
	Starting Conditions
	- All valves default state
	- Pressurant Globe closed
	- Regs fully closed (backed out)
	- Everyone distanced except Person 2 & 3
		Start Time						

1	(Person 2 & 3) **Approach** R2 & R3 while **avoiding any venting pathways** (Person 2 & 3) Remove **FOD Caps** on **V11**-S, **V12**-S, **V23**-SB, **V35**-SB, **V36**-S							
2	(Person 2 & 3) Confirm **R2 & R3** are **fully closed**							
3	([PC]/MC) Confirm **all valves in default state** (Person 2 & 3) **Open V21**-MB & **V31**-MB & relay completion to MC							
4	(Person 2 & 3) **Distance** from Spender							
5	Ensure [air compressor] tank pressure is **> 120 PSI**							
6	(PC/MC) **Close V11**-S, **V12**-S, **V23**-SB, **V35**-SB (PC/MC) **Open V10**-SB							
7	Verbal poll: Ready for pressurization - Persons 1, 2, 3, MC, [Safety], Supervisor							
8	(Person 1) Very **slowly half-open globe valve** (MC) Call out when **P10** rising & stabilizing to 2200 psi							
9	IF AUDIBLE LEAKAGE IS HEARD, **close globe valve** & move to **Seq 1.1**							
10	(Person 1) **Close globe valve** and (MC) **monitor P10** for 30 seconds. IF DROP IS SIGNIFICANT, move to **Seq 1.1**							
11	Once no leaks upstream of regulators, (Person 1) **half-open globe valve** & (Person 2 & 3) **approach** R2 & R3							
12	(Person 2 & 3) Increase downstream pressure of R2 & R3 until a reading of **150 psi** is observed							
13	(Person 2 and 3) IF **MAJOR** AUDIBLE LEAK IS HEARD, **close globe valve** & move to **Seq 1.2**							
14	(Person 2 and 3) IF **MINOR** AUDIBLE LEAK IS HEARD, move to **Seq 1.3**							
15	(Person 1) **Close globe valve**, (Person 2 & 3) **Distance** from Spender, equip **hearing protection**							
16	(PC/MC) **Close V10**-SB, **Open V11**-S (PC/MC) **Monitor P21, & 31** for 30 seconds. IF DROP IS SIGNIFICANT, move to **Seq 1.3**							
17	Once no leaks downstream of regulators (Person 1) **close globe valve**, (Person 2 & 3) **Distance** from Spender, equip **hearing protection**							
18	(PC/MC) **Close V10**-SB (PC/MC) Restore **all valves to default state** (PC/MC) **Monitor P10, P21, P31** & call out <30psi (depressurized)							
19	(Person 2 & 3) **Fully close V21**-MB, **V31**-MB, and **R2**, **R3** (Person 2 & 3) Install **FOD Caps** on **V11**-S, **V12**-S, **V23**-SB, **V35**-SB, **V36**-S							
20	Relay **completion of LEAK TEST** to MC & note down time:							

Seq 1.1 - MAJOR LEAK CORRECTION (Upstream of Regs)								
1	(Person 1) **Close globe valve**, (Person 2 & 3) **Distance** from Spender, equip **hearing protection**							
2	(PC/MC) **Close V10**-SB. (PC/MC) **Open V11**-S, **V12**-S, **V23**-SB, **V35**-SB (PC/MC) **Monitor P10** & call out <30psi (depressurized)							
3	**Retighten every fitting** upstream of regulators - SL to witness marks or slightly past/by feel - AN to midrange of torque spec or higher							
4	Generously **spray soap solution** on every fitting							
5	Repeat **Seq 1** from the **step 4**							
Seq 1.2 - MAJOR LEAK CORRECTION (Downstream of Regs)								
1	(Person 1) **Close globe valve**, (Person 2 & 3) **Distance** from Spender, equip **hearing protection**							
2	(PC/MC) **Close V10**-SB. (PC/MC) **Open V11**-S, **V12**-S, **V23**-SB, **V35**-SB (PC/MC) **Monitor P10, P21, P31**. Call out when all <30psi							
3	**Retighten fittings** near identified leakage - SL to witness marks or slightly past/by feel - AN to midrange of torque spec or higher							
4	Generously **spray soap solution** on tightened fittings							
5	Repeat **Seq 1** from the **step 4**							
Seq 1.3 - MINOR LEAK CORRECTION (Downstream of Regs)								
1	(Person 1) **Close globe valve**							
2	(Person 2 and 3) Approach Spender, **identify leaks** w/ soap solution, **mark leaks** w/ Sharpie							
3	(Person 2 & 3) **Distance** from Spender, equip **hearing protection**							
4	(PC/MC) **Close V10**-SB. (PC/MC) **Open V11**-S, **V12**-S, **V23**-SB, **V35**-SB (PC/MC) **Monitor P10, P21, P31**. Call out when all <30psi							
5	**Retighten fittings** as identified - SL to witness marks or slightly past/by feel - AN to midrange of torque spec or higher							
6	Generously **spray soap solution** on tightened fittings							
7	(PC/MC) **Close V11**-S, **V12**-S, **V23**-SB, **V35**-SB (PC/MC) **Open V10**-SB							
8	(Person 1) **Half-open globe valve** (MC) Call out when **P10, P21, P31** rising & stabilizing							
9	Repeat **Seq 1** from the **step 14**							

SOP 2.4 - Eth & N2O Regulators Setting (V2.0)

#	STEP	TEST ITERATION						
	Op 1.0 - MAIN REGULATORS SETTING	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Seq 1 - ETHANOL REGULATOR (R2) SETTING								
0	**Roll Call** - Person 1 (Pressurant Cylinder Operator) - Person 2 (Eth & N2O Reg Operator) - Supervisor - [Safety Officer] - Pad Control - MC: CAPCOM, Ground Control, [Tech Support] **Tools & Parts** - Face shields - First aid kit - Fire extinguisher **Starting Conditions** - All valves default state - Globe closed - Regs fully closed (backed out) - Everyone distanced	**Start Time**						
1	(Person 2) **Approach R2** while **avoiding any venting pathways** (Person 2) Remove **FOD Caps** on **V11**-S, **V12**-S, **V23**-SB							
2	(Person 2) Confirm **V21**-MB, **V31**-MB, and **R2** are **fully closed**							
3	(Person 2) **Crack open V21**-MB & relay completion to MC							
4	(PC/MC) **Open V10**-SB (PC/MC) **Close V11**-S, **V12**-S							
5	(Person 1) At person 2's discretion, very **slowly half-open globe valve** (PC/MC) Call out when **P10** rising & stabilizing to **2200+ psi**							
6	(Person 2) Increase downstream pressure of R2 until a reading of **1300 psi** is observed (Person 1) At person 2's discretion, **close globe valve** & relay completion to MC (PC/MC) **Monitor P10, P21** & call out <30psi (depressurized)							
7	(PC/MC) **Close V10**-SB (PC/MC) Restore **all valves to default state**							
8	(Person 2) **Fully close V21**-MB (Person 2) Install **FOD Caps** on **V11**-S, **V12**-S, **V23**-SB							
9	Relay **completion of ETH REG SETTING** to MC & note down time:							
Seq 2 - NITROUS REGULATOR (R3) SETTING								
0	**Roll Call** (if necessary) - Refer to Seq 1 if necessary **Tools & Parts** - Face shields - First aid kit - Fire extinguisher **Starting Conditions** - All valves default state - Globe closed - Regs fully closed (backed out) - Everyone distanced	**Start Time**						

1	(Person 2) **Approach R3** while **avoiding any venting pathways** (Person 2) Remove **FOD Caps** on **V11**-S, **V12**-S, **V35**-SB, **V36**-S							
2	(Person 2) Confirm **V21**-MB, **V31**-MB, and **R3** are **fully closed**							
3	(Person 2) **Crack open V31**-MB & relay completion to MC							
4	(PC/MC) **Open V10**-SB (PC/MC) **Close V11**-S, **V12**-S							
5	(Person 1) At person 2's discretion, very **slowly half-open globe valve** (MC) Call out when **P10** rising & stabilizing to **2200+ psi**							
6	(Person 2) Increase downstream pressure of R3 until a reading of **1100 psi** is observed (Person 1) At person 2's discretion, **close globe valve** & relay completion to MC (PC/MC) **Monitor P10, P31** & call out <30psi (depressurized)							
7	(PC/MC) **Close V10**-SB (PC/MC) Restore **all valves to default state**							
8	(Person 2) **Fully close V31**-MB (Person 2) Install **FOD Caps** on **V11**-S, **V12**-S, **V35**-SB, **V36**-S							
9	Relay **completion of N2O REG SETTING** to MC & note down time:							

SOP 2.5 - V21 & V31 Actuator Swap (V1.0)

#	STEP	TEST ITERATION						
	Op 1.0 - ACTUATOR SWAP	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Seq 1 - ETH (V21) ACTUATOR SWAP								

0	**Roll Call**
	- Person 1 (Actuator Swap)
	- Person 2 (Tools Assistant)
	- Supervisor
	- [Safety Officer]
	- Pad Control
	- MC: CAPCOM, Ground Control, [Tech Support]
	Tools & Parts
	- 4x 5/16-18 x ¾" hex bolt
	- 2x couplers
	- V21 & V31 actuator assemblies
	- V21 & V31 pneumatic lines
	- Small torque wrench
	    - ¼" square to 13mm socket
	    - ¼" square to ⅜" square adapter
	    - ⅜" square drive 9/16" crowsfoot
	- Small/Average Wrench
	- First aid kit
	Starting Conditions
	- All valves default state
	- Globe closed
	- Regs set to operating pressure
	- Everyone distanced
		Start Time						

1	(Person 1) **Approach V-21** while **avoiding any venting pathways**							
2	(Person 1) Confirm **V21**-MB is **fully closed**							

3	(Person 1) Open the loose parts box and remove							
4	(Person 1) Using the small wrench, **undo** the **thin 13mm M8 nut** on and **remove the handle** (Person 2) **Store the handle & nut** in the loose parts box.							
5	(Person 1) Using the small wrench - **Loosen all nuts** along the two long 5/16-18 bolts - **Undo** two **thick 5/16-18 nuts** above the coupler plate (Person 2) **Store the nuts** in the loose parts box.							
6	(Person 2) Collect and **hand coupler** to Person 1							
7	(Person 1) Ensure **valve is closed** and **Install coupler** Ensure bottom of coupler is nearly **flush with plate**							
8	(Person 2) **Collect** from the parts boxes and hand to Person 1 - **2x** 5/16-18 x ¾” **bolts** - V21 actuator assembly							
9	(Person 1) **Position and align V21 actuator into the coupler**, ensure flow indicator is in closed position							
10	(Person 1) Using the small wrench - **Tighten** the **two short 5/16-18 bolts** - **Tighten** the **two long 5/16-18 bolts** until bottomed out - **Tighten all nuts** along the two long 5/16-18 bolts							
11	(Person 1) Using the small wrench, **uninstall the V21 cap** (4AN) from the pneumatic manifold							
12	(Person 2) **Store** the 4AN cap (Person 2) Collect and **hand V21 Pneumatic Line** to Person 1							
13	(Person 1) Install V21 Pneumatic line - Ensure flow direction is correct via sticker - Torque 4AN nuts on both ends to **11.3-15.8 Nm**							
Seq 2 - N2O (V31) ACTUATOR SWAP								
0	**Roll Call** Same as Seq 1	**Start Time**						
1	(Person 1) **Approach V-31** while **avoiding any venting pathways**							
2	(Person 1) Confirm **V31**-MB is **fully closed**							
3	(Person 1) Open the loose parts box and remove							
4	(Person 1) Using the small wrench, **undo** the **thin 13mm M8 nut** on and **remove the handle** (Person 2) **Store the handle & nut** in the loose parts box.							
5	(Person 1) Using the small wrench - **Loosen all nuts** along the two long 5/16-18 bolts - **Undo** two **thick 5/16-18 nuts** above the coupler plate (Person 2) **Store the nuts** in the loose parts box.							
6	(Person 2) Collect and **hand coupler** to Person 1							

7	(Person 1) Ensure **valve is closed** and **Install coupler** Ensure bottom of coupler is nearly **flush with plate**							
8	(Person 2) **Collect** from the parts boxes and hand to Person 1 - **2x** 5/16-18 x ¾" **bolts** - V31 actuator assembly							
9	(Person 1) **Position and align V31 actuator into the coupler**, ensure flow indicator is in closed position							
10	(Person 1) Using the small wrench - **Tighten** the **two short 5/16-18 bolts** - **Tighten** the **two long 5/16-18 bolts** until bottomed out - **Tighten all nuts** along the two long 5/16-18 bolts							
11	(Person 1) Using the small wrench, **uninstall the V31 cap** (4AN) from the pneumatic manifold							
12	(Person 2) **Store** the 4AN cap (Person 2) Collect and **hand V31 Pneumatic Line** to Person 1							
13	(Person 1) Install V31 Pneumatic line - Ensure flow direction is correct via sticker - Torque 4AN nuts on both ends to **11.3-15.8 Nm**							

SOP 2.6 - Pneumatic Connection & Regulator Setting (v2.0)

#	STEP	TEST ITERATION						
Op 1.0 - PNEUMATIC CYLINDER CONNECTION		**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
0	**Roll Call** - Person 1 (Pneumatic Cylinder Operator) - Person 2 (Pneumatic Hose Operator) - Supervisor - Safety Officer **Tools & Parts** - Main pneumatic hose - Pneumatic supply cylinder - Zip ties - Face shields - First aid kit - Medium wrench - Medium torque wrench & crows feet - 9/16" ⅝" **Starting Conditions** - All valves default - Pressurant Globe closed - Pneumatic Globe closed - Regs fully closed (backed out)	**Start Time**						
1	(Person 1) Connect pneumatic hose to pneumatic bottle and **finger-tighten** the **CGA-580 nut**							
2	(Person 1) Use medium wrench and torque the **CGA-580 nut** to **wrench tight**							
3	(Person 2) **Secure hose** to Spender using zip ties							
4	(Person 2) Remove Pneumatic **QD-PL** at the **marked fitting**, **install Cap** (6AN), torque to 12.5-16.2 ft-lb (17-22Nm)							
5	(Person 2) Connect pneumatic hose to Spender via the **QD-PH fitting** (4AN), torque to 11.3-15.8 ft-lb (15.3-21.5 Nm)							

6	Relay **completion of PNEUMATIC CYLINDER CONNECTION** to MC & note down time:							

#	**STEP**	**TEST ITERATION**						
	Op 2.0 - PNEUMATIC REGULATOR SETTING	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Seq 1 - Nominal Pneumatic Regulator Setting								
0	**Roll Call** - Person 1 (Pneumatic Cylinder Operator) - Person 2 (Pneumatic Reg Operator) - Supervisor - [Safety Officer] - Pad Control - MC: CAPCOM, Ground Control, [Tech Support] **Tools & Parts** - Face shields - [Cryo Gloves] - Fire extinguisher **Starting Conditions** - All valves default state - V-PH & V-PL closed - QD-PL Cap installed - Pneumatic & Pressurant Globes closed - Pneumatic Reg fully closed (backed out) - Main Regs set to operating pressure - Everyone distanced except Person 2	**Start Time**						
1	(Person 2) **Approach R-P** while **avoiding any venting pathways**							
2	(Person 2) **Crack open V-PH** & relay completion to MC							
3	(Person 2) Open **V-PL** and ensure **R-P** is **fully closed**							
4	(Person 1) At person 2's discretion, very **slowly half-open globe valve** (PC/MC) Call out when **R-P inlet gauge** rising & stabilizing							
5	IF AUDIBLE OR VISUAL LEAKAGE IS OBSERVED, **close globe valve** & move to **Seq 1.1**							
6	(Person 2) Increase downstream pressure of R-P until a reading of **100 psi** is observed (Person 1) At person 2's discretion, **close globe valve** & relay completion to MC							
7	(Person 2) Fully **Open V-PH** (Person 2) **Close V-PL**							
8	Relay **completion of PNEUMATIC REG SETTING** to MC & note down time:							
Seq 1.1 - Pneumatic HP Line Leak Correction								
1	(Person 1) **Close globe valve**							
2	(Person 2) Wait until **R-P inlet gauge reads 0** IF LEAKAGE IS LOW, slightly open R-P to vent							
3	(Person 2) Tighten every fitting from **fill hose** to **R-P**							
4	Repeat **Seq 1** from **step 3**							

SOP 3.1 - Ethanol Fill (V2.1)

#	STEP	TEST ITERATION						
	Op 1.0 - ETHANOL FILL PREPARATION	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Seq 1 - Weight Scale Setup								
0	**Roll Call** - Person 1 (Fill pump, V24-MB, and weight scale operator) - Supervisor - Safety Officer - Pad Control **Tools & Parts** - Propellant scale - Small weight scale - Ethanol fill pump & bucket - Ethanol supply container - Shop towels - Flathead screwdriver - First aid kit - Fire extinguisher **Starting Conditions** - All valves default - Globe closed - Regs set to operating pressure - Everyone distanced except Person 1 **Tools & Parts** - Propellant scale **Starting Conditions** - All valves default - Ensure **V24**-MB is **closed** - Pressurant Globe closed - Main Regs set to operating pressure - Everyone distanced except Person 1 & Supervisor	**Start Time**						
1	Turn on the weight scale monitor.							
2	Verify that weight scale is functional. Confirm that the monitor is visible to MC.							
3	**Zero scale** and ensure that the dry status of Spender corresponds to a weight of 0 lbs.							
Seq 2 - Fill Pump Setup								
1	Remove the remaining pieces of the fill pump from inside the bucket							
2	Ensure the bucket is clean and undamaged from transport							
3	Place the fill bucket on the small scale, and **pour in ~1 kg of ethanol**							
4	Place the pump & lid on the bucket. Tighten fully with thumbscrews							
5	Ensure that the hose fitting on the pump end is properly lubed. Screw it on to the main shaft until **wrench-tight**.							
6	Place the worm clamp onto the **pump-side hose** and push the hose onto the pump-side fitting							

7	Tighten the pump-side worm clamp							
8	**Remove FOD cap** from **QD-2**							
9	Place the worm clamp onto the **fill-side hose** and push the hose onto the **QD-2**.							
10	Tighten the worm clamp on QD-2, **do not overtighten** and dig into threads							
11	Relay **completion of ETHANOL FILL PREP** to MC & note down time:							

#	**STEP**	**TEST ITERATION**						
	Op 2.0 - ETHANOL FILL & CLEANUP	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Seq 1 - Ethanol Fill								
0	**Tools & Parts** - Ethanol fill pump - Shop towels - Flathead screwdriver - First aid kit - Fire extinguisher **Starting Conditions** - All valves default - Pressurant Globe closed - Regs set to operating pressure - Everyone distanced except Person 1 & Supervisor	**Start Time**						
1	Verify that **V23**-SB is in the open position. Cross-reference with MC.							
2	**Open V24-MB**							
3	Operate pump per provided supplier instructions							
4	Monitor **propellant scale** & callout weight **every 10 seconds**							
5	Slow pumping when **0.8 kg** is approached. **Close V24-MB** when **propellant scale reads 0.95 kg**							
Seq 2 - Ethanol Cleanup								
1	Raise the handle on the ethanol pump							
2	Loosen worm clamp from **QD-2** and remove hose. **Reinstall FOD cap.**							
3	Insert hose into hole in the bucket lid, and pump any remaining ethanol into the bucket							
4	Move bucket & hose behind barrier							
5	Wipe any ethanol from Spender using shop towels							
6	Relay **completion of ETHANOL FILL** to MC & note down time:							

SOP 3.3 - N2O Connection & Pre-Fill

#	STEP	TEST ITERATION						
	Op 1.0 - N2O CYLINDER CONNECTION	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
0	**Roll Call** - Person 1 (Fill Hose Operator) - Supervisor - Safety Officer **Tools & Parts** - N2O hose - N2O fill cylinder - Zip ties - Face shields - First aid kit - Fire extinguisher - Medium wrench **Starting Conditions** - All valves default - N2O globe valve closed - R1 (N2O Fill Reg) closed (fully back out) - Everyone distanced except Person 1 and Person 2	**Start Time**						
1	(Person 1) **Ensure plastic gasket is present.** Connect N2O hose to N2O bottle and **finger-tighten** the **CGA-320 nut.**							
2	(Person 1) Use medium wrench and torque the **CGA-320 nut** to **wrench tight**							
3	(Person 1) **Secure hose** to Spender using zip ties							
4	Relay **completion of N2O CYLINDER CONNECTION** to MC & note down time:							

#	STEP	TEST ITERATION						
	Op 2.0 - N2O FILL LINE CONNECTION	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Seq 1 - N2O Pre-Fill and Leak Check								
0	**Roll Call** - Person 1 (N2O Cylinder Operation) - Person 2 (N2O Fill Reg Operation) - Supervisor - Safety Officer - Pad Control - MC: CAPCOM, Ground Control, [Tech Support] **Tools & Parts** - N2O hose - Zip Ties - Face shields - First aid kit - Fire extinguisher - Medium wrench - Medium torque wrench - Cryo gloves **Starting Conditions** - All valves in default state - N2O globe valve closed - R1 (N2O Fill Reg) closed (fully back out) - Main Regs set to operating pressure - Everyone distanced except Person 2	**Start Time**						
1	(Person 2) Connect N2O hose to **QD-3**							
2	(Person 2) Fully open **R1** (N2O Fill Reg) (screw in)							

3	(Person 2) **Distance** from Spender							
4	(PC/MC) Close **V38-S**							
5	Verbal poll: Ready for pressurization - Persons 1, 2, MC, [Safety], Supervisor							
6	(Person 1) Very **slowly half-open globe valve** (MC) Call out when **R1 gauges** rising & stabilizing to ~700 psi							
7	IF AUDIBLE OR VISUAL LEAKAGE IS OBSERVED, **close globe valve** & move to **Seq 1.1**							
8	All personnel **move behind barrier** **Visually monitor** N2O line & R1 pressure for 2 minutes							
9	Relay **completion of N2O PRE-FILL** to MC & note down time:							
Seq 1.1 - N2O Fill Line Leak Correction								
1	(Person 1) **Close globe valve** (Person 2) **Distance** from Spender, equip **hearing protection**							
2	(PC/MC) Open **V38-S**							
3	(Person 2) Tighten every fitting from **fill hose** to **V38-S**							
4	Repeat **Seq 1** from **step 3**							

#	**STEP**	**TEST ITERATION**						
Op 3.0 - SYSTEM PRE-PRESSURIZATION		**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**

0	**Roll Call**
	- Person 1 (Pressurant Cylinder Operation)
	- Supervisor
	- Safety Officer
	- Pad Control
	- MC: CAPCOM, Ground Control
	Tools & Parts
	- Face shields
	- First aid kit
	- Fire extinguisher
	Starting Conditions
	- All valves in default state except:
	  - **V38**-S **Closed**
	  - **N2O Globe** valve **Open**
	- Pressurant Globe valve closed
	- Everyone distanced
		Start Time						

1	Ensure that **V10-SB** is closed.							
4	Ensure that all personnel are **behind barrier**							
5	(Person 1) Very **slowly half-open globe valve** (MC) Call out when **P10** rising & stabilizing to 2200 psi							
6	Relay **completion of SYSTEM PRE-PRESSURIZATION** to MC & note down time: Note down **P10 reading**:							

SOP 3.4 - Pad Arming & Evacuation (V2.1)

#	STEP	TEST ITERATION						
	Op 1.0 - PAD-SIDE ARMING & EVACUATION	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**

0	**Roll Call**
	- Supervisor
	- Safety Officer
	- MC: CAPCOM, Ground Control
	Tools & Parts
	- First aid kit
	- Fire extinguisher
	Starting Conditions
	- All valves in default state except:
	    - **V38**-S **Closed**
	    - **N2O Globe** valve **Open**
	    - **Pressurant Globe** valve **Open**
	- **Everyone evacuated** except:
	    - **Supervisor & Safety behind barrier**
		Start Time						

1	Final **visually check** for test assembly, obstacles, fire hazards, etc in test area							
2	Ensure pad-side cameras are recording (not including the security cameras)							
3	Verbal poll: Ready for pad-side arming - MC, Launch Director, [Safety], Supervisor							
4	[Connect ignitor battery and check continuity]							
5	Ensure pad-side E-Stop is up **Arm main valves** **Arm ignitor**							
6	**Evacuate** to Mission Control and note down time:							

SOP 5.1 - Cylinder Disconnection & Pad Safing (V1.0)

#	STEP	TEST ITERATION						
	Op 1.0 - CYLINDER DISCONNECTION	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Seq 1 - N2O Disconnection								
0	**Roll Call** - Person 1 (Cylinder Operation) - Person 2 (Hose Operation) - Supervisor - Safety Officer - Pad Control - MC: CAPCOM, Ground Control, [Tech Support] **Tools & Parts** - Cutters/Knife - Face shields - First aid kit - Fire extinguisher - Medium wrench - Cryo gloves **Starting Conditions** - All valves are in caution state - All transducers except P10 read ~0 psi - N2O globe valve open	**Start Time**						

	- R1 (N2O Fill Reg) open - Main Regs set to operating pressure **- Everyone distanced w/ hearing protection**							
1	(Person 1) **Close N2O globe valve**							
2	(PC/MC) Open **V38-S** (MC) Call out when **R1 gauges** read ~0 psi							
3	(Person 2) **Approach** Spender while **avoiding any venting pathways**							
4	(Person 2) Disconnect N2O hose from QD-3							
5	(Person 2) Remove zip ties from N2O hose and hand the end to Person 1							
6	(Person 2) Add FOD caps on that line.							
7	(Person 1) Disconnect the N2O hose from the cylinder end. Ensure that the teflon gasket is stored away safely.							
Seq 2 - Pressurant Cylinder Disconnection								
1	Ensure everyone distanced with hearing protection							
2	(Person 1) Close pressurant globe valve							
3	(PC/MC) Close V10 (PC/MC) Open V11-S, V12-S, V23-SB, V35-SB (PC/MC) Ensure P10, P21, P31 reading ~ 0 psi.							
4	(Person 2) Approach Spender and disconnect pressurant hose. Hand off the Spender end of the hose to person 1.							
5	(Person 2) Add FOD caps on that line.							
6	(Person 1) Disconnect the pressurant hose from the cylinder end.							
Seq 3 - Pneumatic Cylinder Disconnection								
1	(PC/MC) Reset all valves							
2	(Person 1) Close pneumatic globe valve.							
3	(Person 2) Equip hearing protection and open V-PH and V-PL. Wait until R-P inlet & outlet reads ~ 0 psi.							
4	(Person 2) Disconnect pressurant hose from QD-PH. Pass the loose end to Person 1.							
5	(Person 2) Add FOD caps on that line.							
6	(Person 1) Disconnect the pneumatic hose from the cylinder end.							
7	Relay completion of all cylinder disconnections to MC.							