

LAUNCH CANADA 2024 CHALLENGE



Metropolitan Aerospace & Combustion Hub

LC2024 Design Report NEW GAR-E (GAROLITE ABLATIVE ROCKET ENGINE)

Competing Team [11]

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ABSTRACT

Metropolitan Aerospace and Combustion Hub (MACH) is a design team based out of Toronto Metropolitan University (TMU). MACH is participating in the technology development category for Launch Canada 2024 with the newest version of GAR-E, a garlolite ablative rocket engine previously featured at LC2023. 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 newest version of GAR-E contains a redesigned thrust chamber assembly that has been modified according to test results of the previous design iteration. The goal for Launch Canada 2024 is to perform two hot-fire tests of the new GAR-E engine in a live demonstration of the team's reusable SRAD liquid propulsion system.

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ABBREVIATIONS & NOMENCLATURE

AIAA	American Institute of Aeronautics and Astronautics	MFV	Main Fuel Valve
APCP	Ammonium Perchlorate Composite Propellant	MOV	Main Oxidizer Valve
BB	Beaglebone Black	MOSFET	Metal Oxide Semiconductor Field Effect Transistor
BizDev	Business Development	MPV	Main Pressurant Valve
BPVC	Boiler and Pressure Vessel Code	N ₂	Nitrogen
CAN	Controller Area Network	N ₂ O	Nitrous Oxide
CEA	Chemical Equilibrium with Applications	OS	Operating System
CONOPS	Concept of Operations	P&ID	Piping & Instrumentation Diagram
COTS	Commercial Off-The-Shelf	PM	Propellant Management
CD	Combustion Dynamics	PCB	Printed Circuit Board
Cv	Valve Flow Coefficient	PPE	Personal Protective Equipment
DIO	Digital Input Output	PRA	Probabilistic Risk Assessment
DAQ	Data Acquisition Unit	PSR	Probable Severity Rating
EthaNOS	Ethanol & Nitrous Oxide	PSU	Power Supply Unit
FEA	Finite Element Analysis	R#	Revision # (of this report)
GAR-E	Garolite Ablative Rocket-Engine	RF	Radio Frequency
GNSS	Global Navigation Satellite System	RMS	Risk Management System
GSE	Ground Support Equipment	RPG	Ryerson Propulsion Group
GUI	Graphical User Interface	SBC	Single Board Computer
I _{sp}	Specific Impulse	SERM	Safety & Emergency Response Manual
Li-Po	Lithium Polymer (Battery)	SOP	Standard Operating Procedure
LOV	Loss of Vehicle	SRAD	Student Researched And Developed
LRE	Liquid Rocket Engine	SSR	Solid State Relay
MACH	Metropolitan Aerospace Combustion Hub	T&C	Transfer & Control
MCU	Microcontroller Unit	TMU	Toronto Metropolitan University
MEOP	Maximum Expected Operating Pressure	UTS	Ultimate Tensile Strength

UNITS

<i>ft</i>	Feet
<i>kg</i>	Kilograms
<i>lbm</i>	Pounds (mass)
<i>m</i>	Meters
<i>N</i>	Newtons
<i>lbf</i>	Pounds (force)
<i>s</i>	Seconds

1.0 INTRODUCTION



Figure 1.0: MACH New GAR-E Injector Coldflow Test

MACH currently has two development cycles progressing in parallel. The first is Day-Glo, the team's first liquid rocket. Day-Glo is a two-year project spanning every subteam and takes up most of the team's time and funding.

The second development cycle is a continuation of the GAR-E program. A hot fire test in November illuminated several issues with the design which are being remedied in anticipation of another hot fire attempt at the end of July. A full redesign of the engine, now dubbed "New GAR-E", has been completed. The new injector, along with the majority of the new thrust chamber assembly were coldflow tested on July 14th, 2024. New GAR-E will use the same test stand developed for GAR-E, freeing up the rest of the team for the progression of the Day-Glo project.

Day-Glo is a 1500 lbf, ethanol-nitrous oxide rocket. The fuel side is pressurized by nitrogen gas. The nitrous oxide is self-pressurized. Development of Day-Glo has centered around three main areas: the airframe, propulsion, and avionics. Day-Glo will be developed over two years. In the first year, all of the major subsystems will be built and tested. The entire assembly (sans-skin, fins, or nose cone) will undergo static testing a year before flight. In the final year of development, all the aerodynamic and recovery components (skin, fins, parachute, and nosecone) will be added. Changes will be made to the existing system once test data has been collected.

The airframe will be constructed of 6061 T6 aluminum rings and stringers, which take the bulk of the axial loads. The airframe is divided into several subsections, used for ease of assembly as well as analysis. Each subsection bolts together with additional

short stringers. The design of the airframe is very modular, allowing changes to be made far into the development cycle.

The propulsion system makes up the bulk of Day-Glo, both in terms of mass and budget. The design of the propulsion system is complete, and a full CAD model has been made. It has been designed for safety and flexibility in testing, and includes isolation valves, vent valves, burst discs and relief valves where needed.

The avionics system runs valve sequences, collects and relays live data from the vehicle during testing. The avionics on Day-Glo will use a series of microcontrollers operating through CANbus. This is a departure from the system used for GAR-E, which relies on a Labjack T7 Pro to conduct valve actuation and data acquisition, all running via USB to a PC. CANbus will give modularity and redundancy to the flightweight avionics.

MACH is well into the development of an SRAD bipropellant liquid rocket. The development of Day-Glo's engine ('Fat GAR-E') depends on the success of New GAR-E, which will prove out much of the engine's manufacturing, design, and assembly process. While a portion of the team develops New GAR-E, the rest of MACH is full-steam ahead on the development and testing of Day-Glo. However, due to manufacturing and budgetary constraints, the team has decided to compete with the New GAR-E engine in the technology demonstration category for Launch Canada 2024. As a result, this report will focus largely on the key technical aspects of the new GAR-E engine and the associated propellant system hardware.

1.1 SUMMARY OF CHANGES

Following the submission of the PDR, MACH has accomplished several key milestones for the Day-Glo project. This includes the acquisition of key hardware, such as burst discs, high pressure solenoid vent valves, most fittings and mounting hardware, pressure regulators, all high-flow ball valves, and key structural hardware. The team has also completed the development of the previously discussed SRAD fuel tank, which was successfully hydrostatically proofed to 1.5X MEOP. While the Day-Glo design has matured significantly over the past few months, these changes will not be covered in this report as the Day-Glo system will be excluded from the team's technology demonstration at LC2024.

MACH has also completed the detailed design of the new GAR-E thrust chamber assembly. In-house manufacturing for the engine casing and retaining rings has been completed. Additionally, the new GAR-E injector has been successfully manufactured and coldflow tested. MACH aims to perform a successful hotfire test of the complete new GAR-E engine prior to competing at LC2024.

2.0 INITIAL REQUIREMENTS AND DESIGN GOALS

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 [1].

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.	Manufacturer's 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 ₂ O 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.

2.2.3.1.1	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).

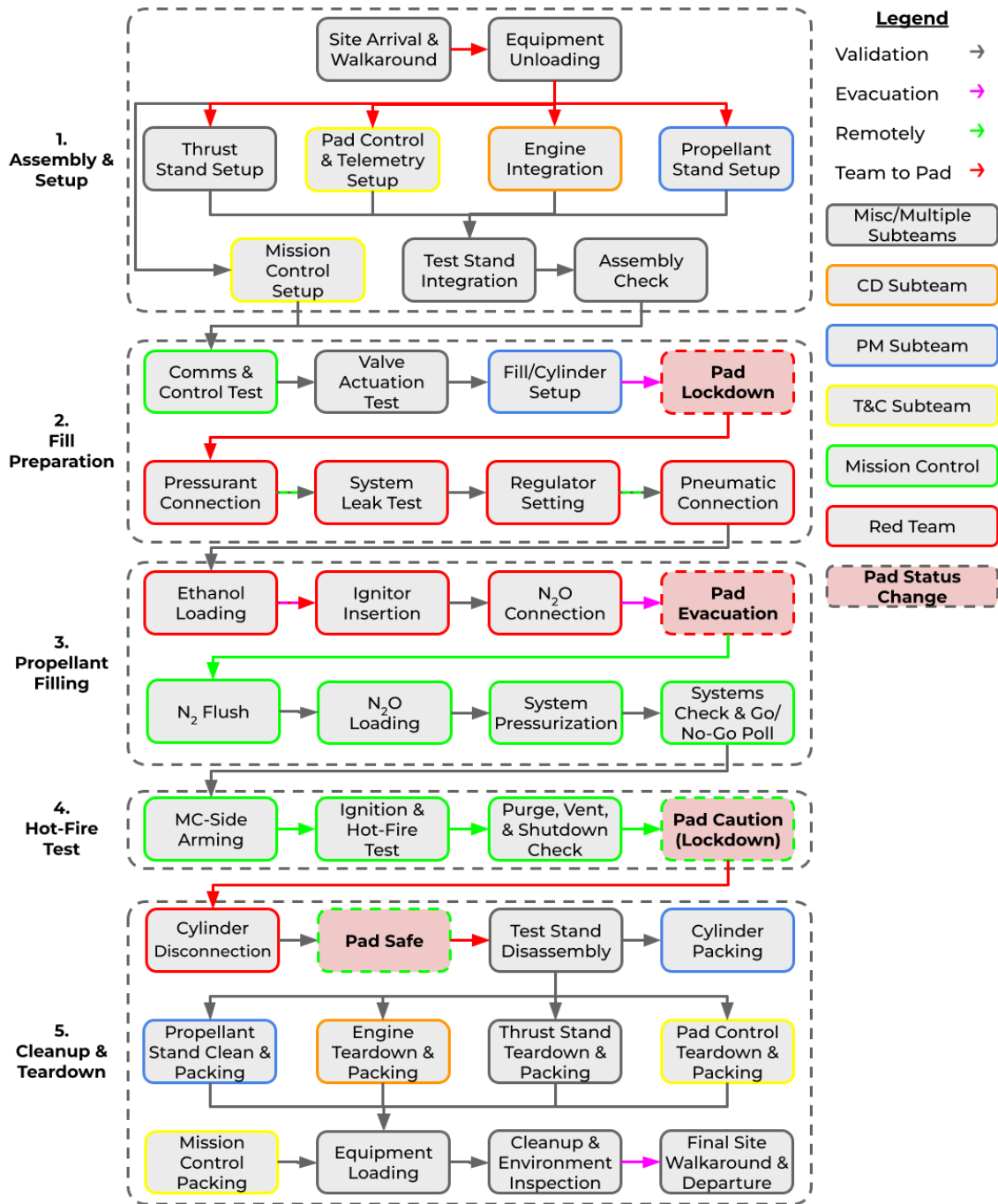


Figure 3.0.1: Nominal CONOPS for Hot-Fire Testing (V2.2).

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 N₂ pressurant and N₂O oxidizer cylinders, prepare ethanol fill setup.
- Pad “Lockdown” declared and off limits except to Red Team personnel.
- Connect N₂ pressurant cylinder and perform pneumatic leak testing.
- N₂ 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 N₂O 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 N₂O loading and propellant pressurization procedures*.
- Perform final systems check and go/no-go poll.

*See Section 4.4.3 for fill procedure overview.

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 4.5 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 N₂ & N₂O 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 [2].
- Perform final site walkaround before departure.

4.0 NEW GAR-E THRUST CHAMBER ASSEMBLY

In November 2023, MACH attempted a hot fire of the first version of GAR-E to some success. The propellant system experienced a regulator clog which prevented nitrous oxide from filling the run tank. The regulator in question was only ever used in the fully closed or fully open position, and discussion of removing it had occurred several times during the development of the test stand. When the regulator failed on the pad, it was removed from the system.

Two tests were conducted: one ignition test, where the injector was installed without a chamber and the hot fire sequence ran, and one hot-fire attempt with the chamber installed. All indications were that the igniter would successfully light the propellants, which was the primary cause of failure at Launch Canada 2023.

The design of New GAR-E is directly applicable to Day-Glo, as the development of the flightweight engine (Fat GAR-E) will not progress until a successful hot fire is conducted at this smaller scale (~300 lbf). New GAR-E is designed to be a one-to-one replacement for GAR-E, allowing us to use the same test stand, while making several design changes to address ignition, injection, combustion, and manufacturing concerns.

4.1 NOVEMBER HOT FIRE RESULTS

During the hot-fire attempt, the pyrotechnic gerb used for ignition successfully lit the propellants at the throat, where it was placed. The gerb appears to have piloted the flame until it fell away from its mount. The flame subsequently moved downstream and anchored somewhere between the concrete blocks. A sequence of stills shows the behavior of the engine during the test.

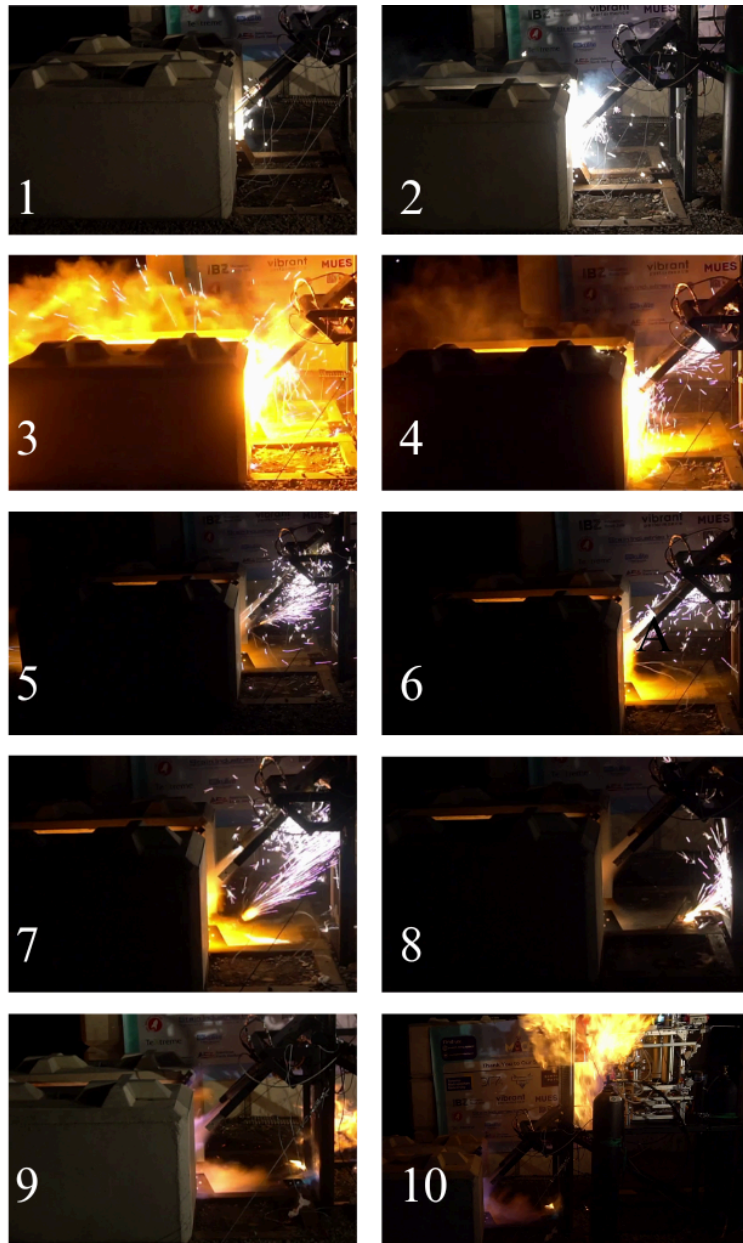


Figure 4.1.1: Breakdown of November Hot Fire Events

- 1 & 2** - Igniter begins to burn with a white flame.
- 3** - Propellant ignition
- 4** - Igniter shown piloting flame at the nozzle.
- 5** - Igniter begins to fall away. Flame front propagates downstream.
- 6** - Igniter springs back for a short time. Propellants reignite at the nozzle.
- 7** - Igniter falls away completely. Flame begins moving downstream.
- 8** - Flame anchors between the concrete blocks.
- 9** - MOV closes. Fuel blowdown. Igniter continues to burn.
- 10** - Engine shutdown. Fuel fireball is lit by the igniter at the base of the blast shield.

Pressure data from the hot fire attempt has been presented below. Note PINJ (chamber pressure, brown line) doesn't get above approximately 80 psi.

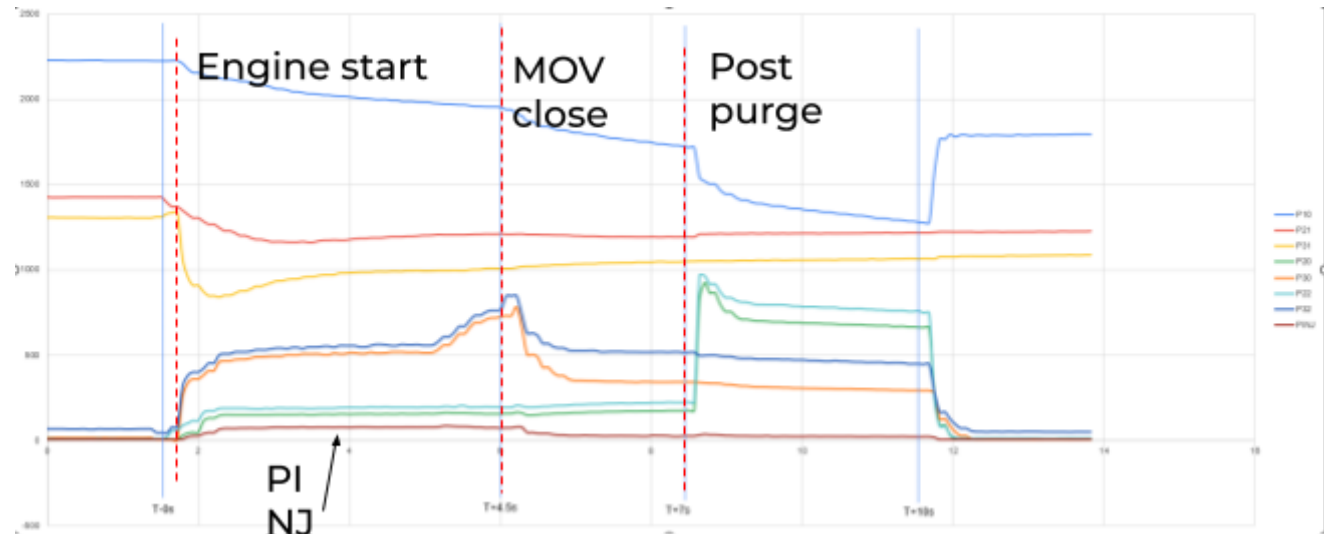


Figure 4.1.2: Pressure data from November 17th Hotfire Attempt

As demonstrated from the data presented in Figure 4.1.2, a negligible rise in chamber pressure was observed throughout the test duration. The 80 psi rise in the chamber pressure can be attributed to the flow of cold nitrous vapor through the chamber and nozzle and not sustained combustion. The liquid nitrous vaporizes as it exits the injector and chokes at the nozzle throat before expanding downstream. The fixed flow rate from the injector and choked flow at the nozzle allowed for a rise in the measured chamber stagnation pressure. Analytical proof of this phenomenon has been presented in Appendix _.

It is likely that the choked sonic flow at the nozzle throat prevented the flame front from propagating upstream into the chamber. The results of the test indicated a need to expand the nozzle throat to allow for superior placement of the ignitor, and decrease the chamber mach number through dimensional changes to the injector and chamber. A summary of the finalized changes has been provided in the proceeding section.

4.2 GAR-E DESIGN CHANGES

From video and pressure data, we concluded that the igniter failed to light the propellants in the chamber. To remedy this, several changes are being made to GAR-E in preparation for another hot fire attempt in March. A summary of the changes is given below.

Table 4.2.1: New GAR-E Design Parameter Changes

Parameter	Current	New
Chamber Diameter	1.76"	2.23"
Chamber Length	8.62"	7.65"
L^*	1.5	1.8
Throat Diameter	0.68"	0.908"
Target Chamber Pressure	700 psi	400 psi
Jet Impingement Angle	21 degrees	60 degrees
Fan Impingement Angle	N/A	15 degrees

The placement of the gerb in GAR-E was limited by the prohibitively small throat diameter. As such, the gerb was placed downstream of the throat, inside the nozzle, firing a stream of sparks into the chamber. This stream of sparks failed to ignite the propellants in the chamber. To address this, the throat diameter is being increased and the chamber pressure decreased to allow the gerb to fit through the throat. The gerb will be installed just downstream of the impinging point, near the injector face.



Figure 4.2.2: Open-air gerb test from November

The dimensions of GAR-E were taken directly from the design of Borealis - the team's previous rocket engine - for which many design criteria were no longer valid. For example, the diameter of Borealis was limited to 1.76" to facilitate effective regenerative cooling at such a small scale; this was no longer a factor for GAR-E, which was ablatively cooled. Nonetheless, the chamber diameter was borrowed from Borealis without checking. In a similar vein, the contraction ratio could have been increased to lower the mass flux. GAR-E's L^* was also comparatively low. While this wasn't confirmed to be a source of failure (since combustion in the chamber was never achieved), we are taking the opportunity to address these concerns and "question everything". This kind of "technical debt" will be avoided in the future by documenting our process in updates like this final report.

Another concern surrounds the injector design: on GAR-E, the 1.76" diameter of the injector face severely limited the impingement angle of the fuel streams. The result was an impingement angle of 21 degrees, far below the 60 degree rule of thumb. After careful consideration, the injector has been redesigned from scratch, and in such a way that it can be easily scaled up with additional elements

4.3 "NEW GAR-E" DESIGN

In addition to the issues already mentioned, New GAR-E will explore different manufacturing techniques to speed up the development cycle and reduce costs.

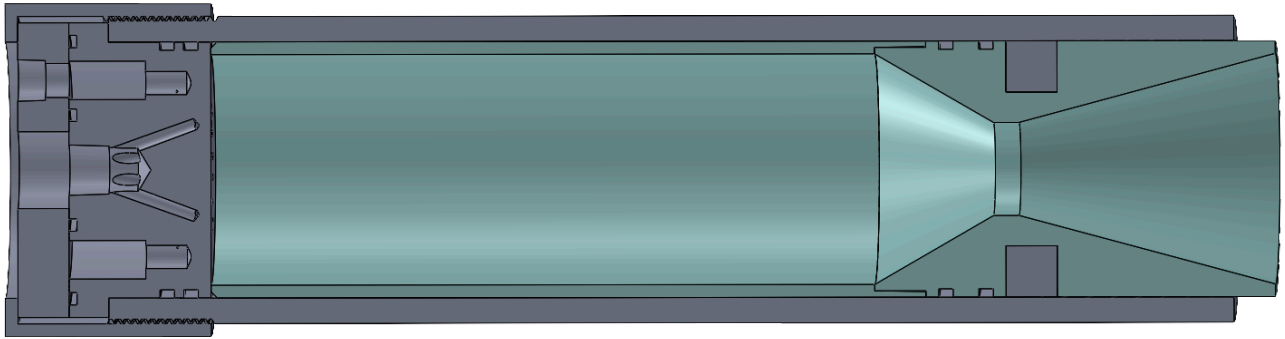


Figure 4.3.1: New GAR-E cross-section

Figure 4.3.1: New GAR-E Manufacturing Breakdown

Component	Material	Manufacturing technique
Injector	6061 T6 aluminum round stock	5-axis CNC (off-campus)
Engine case	T6 aluminum tube, 3" OD, 2.5" ID	Lathe (on-campus)
Chamber lining	G10 (silica phenolic) tube, 2.5" OD, 2.25" ID	Lathe (on-campus)
Nozzle	G10 rod	Lathe (on-campus)
Split ring	6061 T6	3-axis CNC (on-campus)
Retaining ring	6061 T6	3-axis CNC (on-campus)

Most of the time savings come from using tubes where possible, rather than boring out round stock or rod. The design changes highlighted in Table 4.2.1 resulted in a slight shift in target engine performance. The new engine performance parameters have been highlighted in Table 4.2.2.

Table 4.3.2: Revised Engine Performance Parameters

Parameter	Value
Propellants	Ethanol (1.2 kg), N ₂ O (2.5 kg)
Specific Impulse	190 s
Nominal Burn Duration	4.5 s
Initial Thrust	294 lbf
Mass Flow Rate	0.16 kg/s Ethanol 0.604 kg/s N ₂ O
O/F Ratio	3.77
Initial Chamber Pressure	414 psia
Chamber Temperature	3100 K
Cooling System	Silica Phenolic Ablative
Injector	Like-like impinging

4.3.1 COMBUSTION CHAMBER

New GAR-E's combustion chamber uses the same lining material and a similar assembly process as GAR-E. The chamber is assembled like a pressure vessel with bulkheads and double temperature-resistant o-ring seals at each end. Here, the injector and nozzle function as the bulkheads, in a similar method as Half Cat designs [3].

During assembly, the nozzle is bolted first using a split ring. The chamber liner is then slid in, followed by the injector. The entire injector sub-assembly is held in place by a retaining ring, which allows for play in the first steps of the engine assembly. The nozzle and liner are thoroughly greased for ease of assembly. A lack of adhesives ensures static pressure between the liner and the engine case, preventing the liner from cracking. Two high-temperature silicone o-rings (a design choice consistent with GAR-E) form a tight seal between the injector and the engine case. Likewise, two o-rings form a tight seal at the nozzle.

4.3.2 INJECTOR

Choosing to redesign the injector was not done lightly; a lot of time and energy went into the design used on GAR-E. However, many of the constraints on the previous design were lifted; namely, the chamber diameter and inlet positions. As such, MACH is taking the opportunity to model an engine which is designed from the beginning to be scaled up for Day-Glo. All of the manufacturing and assembly techniques *should* be directly applicable to Fat GAR-E.

A six-element, like-like doublet injector was chosen with a jet impingement angle of 60 degrees and a fan impingement angle of 15 degrees. The like-like impingement configuration was selected based on NASA's documented studies of gas-liquid injectors that highlighted the selected configuration as optimal [4]. The selected orifice pattern for the injector has been presented in Figure 4.3.2.1. The central ring of 12 0.063" orifices are used for nitrous injection while the outer ring of 12 0.047" orifices are used for ethanol injection. Orifice sizing was kept as similar as possible to GAR-E as cold flow testing indicated that a sufficient injector stiffness was obtained with the original injector orifice sizing. This was not possible for the fuel orifices due to manufacturing constraints. However, experimental testing revealed that the injector assembly is able to achieve the desired level of stiffness with the selected 3/64" holes.

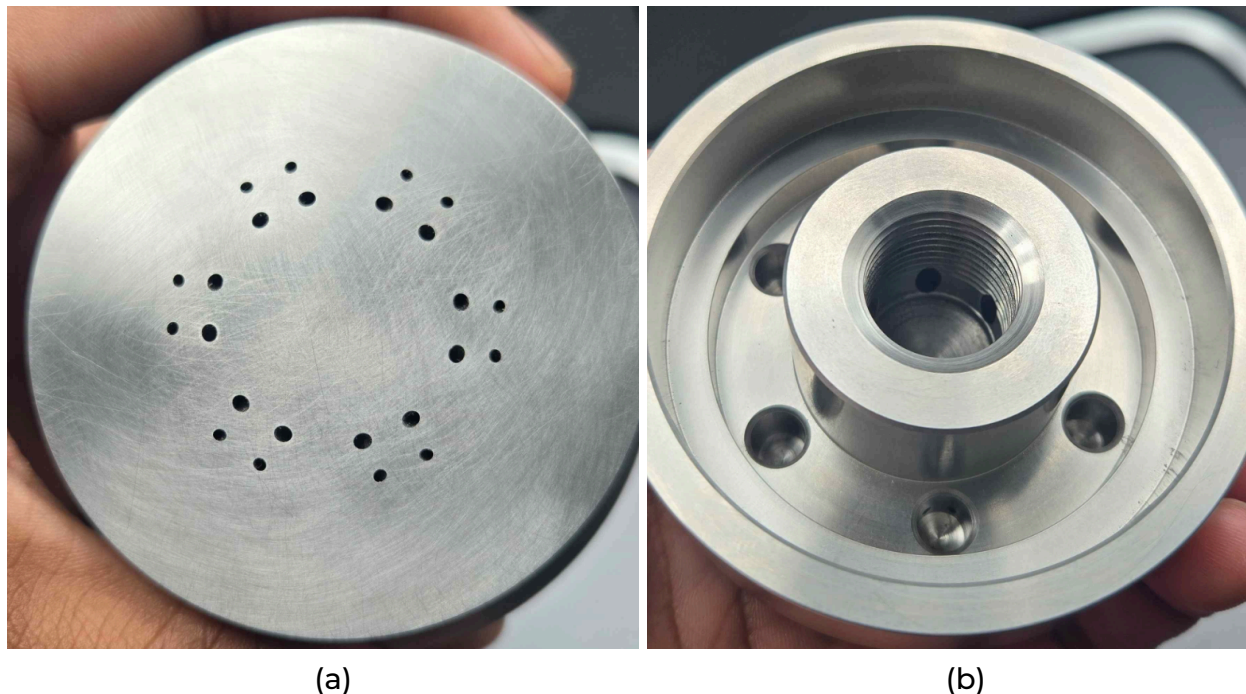


Figure 4.3.2.1: (a) New GAR-E injector orifice pattern & (b) New GAR-E injector volute

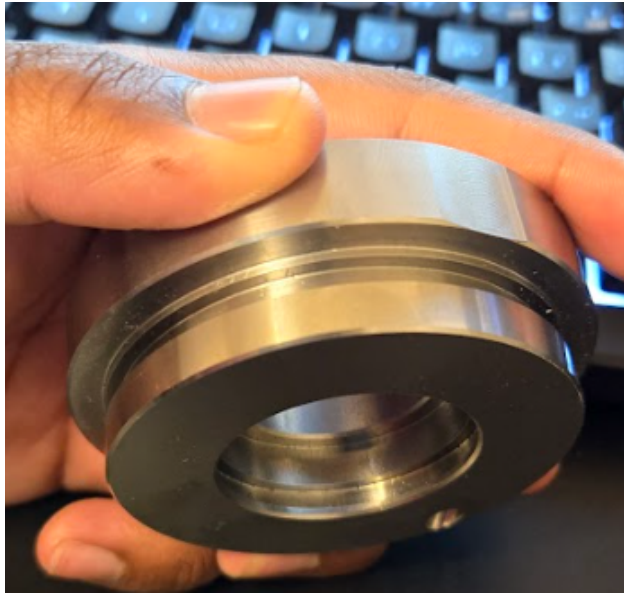
To manifold the injector, inspiration was taken from GAR-E. A central nitrous inlet, this time at the top of the injector (in anticipation of a 1" line on Fat GAR-E), is split off into six feed passages. Each feed passage then splits into two orifices. The flow from two adjacent nitrous orifices are intended to impinge on each other, creating a resultant fan of effervescent nitrous. The nitrous fan is intended to impinge on a similar fan created by adjacent ethanol orifices. Unlike the nitrous volute, the fuel is fed axially into a large annular volute, containing pilot holes to pairs of the ethanol injection orifices.

A "lid" forms a seal against the ethanol volute with two silicone o-rings and has a large centered hole to allow for the nitrous inlet to pass through. The lid contains a $\frac{1}{8}$ " NPT fitting and an angled hole that leads to the ethanol volute. The angled ethanol flow passage in the lid was implemented as a measure to prevent injector maldistribution. While this has not been demonstrated analytically, the success of this countermeasure will be evaluated by analysis of hotfire test results. The ethanol inlet and nitrous pass-through hole have both been presented in Figure 4.3.2.2.

The injector and lid were both manufactured using 303 stainless steel to ensure that the injector subassembly possesses the sufficient heat resistance required to survive the 5 second burn duration. While the team may consider returning to a 6061-T6 aluminum injector for subsequent engine designs, the current engine design does not consider mass to be a limiting factor, hence the safest and most conservative material was selected.



(a)



(b)

Figure 4.3.2.2: (a) Injector lid top view & (b) injector lid side view

4.4 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, N₂O 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”).

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) [5], 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 cylinders 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. The computations were verified and compared with 1D flow 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 4.4.1 and 4.4.2, respectively, and Table 4.4.1 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.

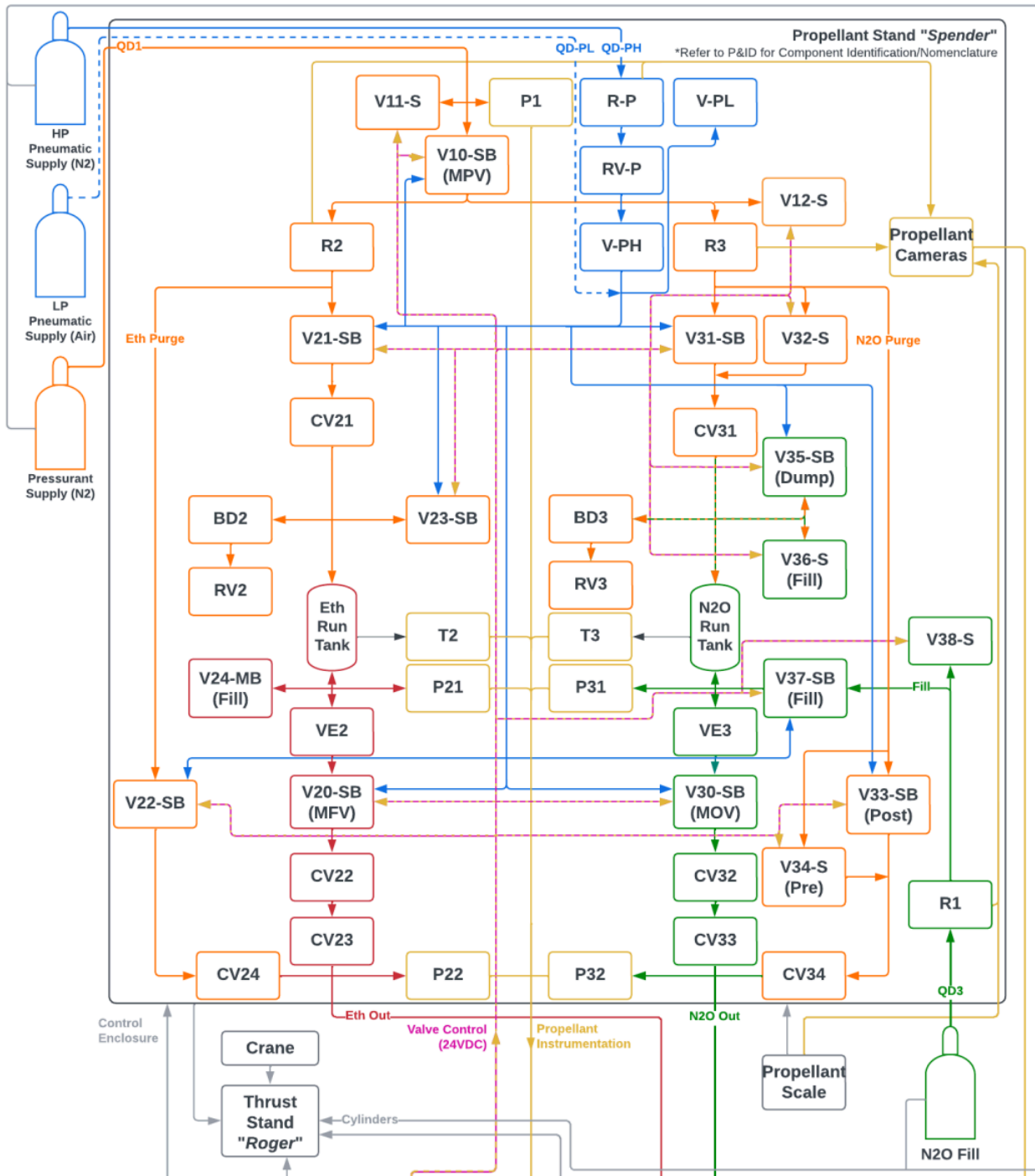


Figure 4.4.1: Propellant system integration diagram (V2.6.2).

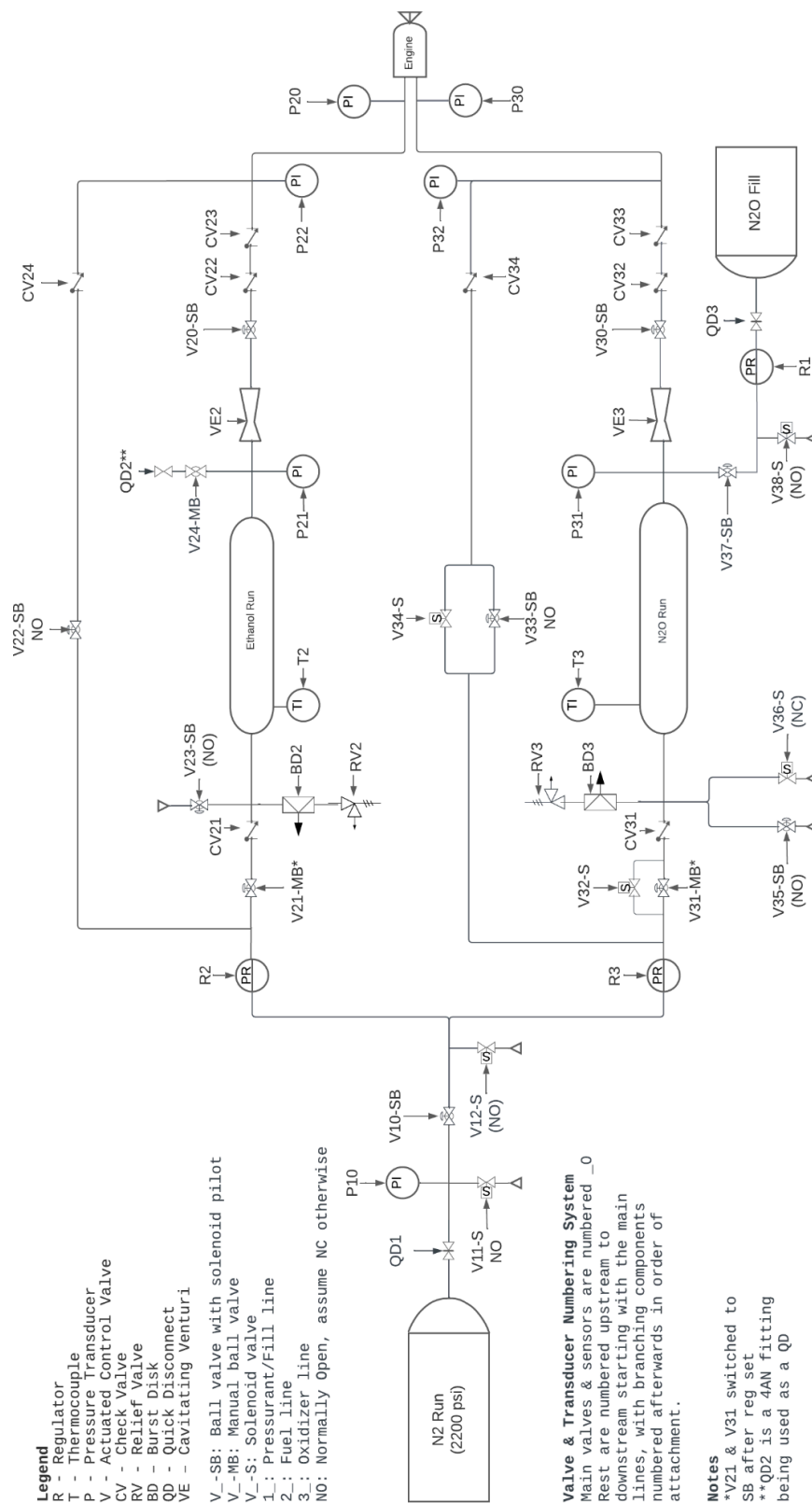


Figure 4.4.2: Propellant System P&ID (V5.1).

Table 4.4.1: Details of Selected Plumbing Components

Description	Type	MAWP	Characteristics	Material
Eth Main Ball Valve	COTS	17.2 MPa	3.0 Cv 1/4" FNPT	316 SS PTFE
N₂O Main Ball Valve	COTS	15.2 MPa	12.0 Cv 1/4" FNPT	316 SS PTFE
N₂O Fill Ball Valve	COTS	20.7 MPa	1/4" FNPT	316 SS
Pressurant Isolation & Control Valves	COTS	20.7 MPa	7 Cv 1/4" 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 1/8 " FNPT	303 SS Acetal Plastic
Relief Valves	COTS	41.4 MPa	11.7 MPa Set 1/2" FNPT	316 SS FKM
Burst Disks	COTS	19.2 MPa	1/4" NPT	316L SS
Check Valves	COTS	41.4 MPa	0.67Cv 6.9 Kpa Cracking 1/4" Swagelok	316 SS FKM
Ethanol & N₂O Run Tanks	COTS	12.4 MPa	3.785L 1/2" FNPT	304L SS
N₂O Fill Regulator	COTS	41.4 MPa	0.08 Cv 4" FNPT	Aluminum Polyimide
N₂O Run Regulator	COTS	41.4 MPa	1.1 Cv 1/2" FNPT	316 SS PEEK
Eth Run Regulator	COTS	34.5 MPa	0.8 Cv 1/4" FNPT, 1/2" 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
N₂O Cavitating Venturi	SRAD	20.7 MPa	3.346 mm Throat Diameter	6061-T6 Aluminum
Eth & N₂ Feed Tubing	COTS	35.2 MPa	1/4" OD	316 SS
N₂O Feed Tubing	COTS	20 MPa	3/4" OD	316 SS
N₂O Fill Tubing	COTS	15.9 MPa	1/2" OD	316 SS

4.4.1 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.

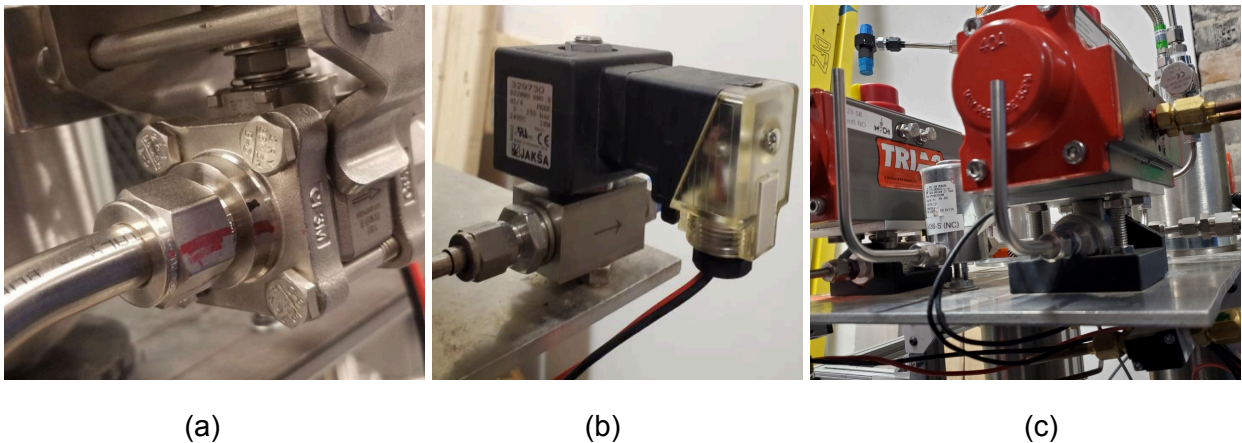


Figure 4.4.1.1: (a) Ball MOV (V30-SB) (b) Solenoid Vent (V12-S) (c) Ball Vent (V35-SB).

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 N₂O regulators (R2 & R3). On the N₂O 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 N₂O 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 4.5.

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.

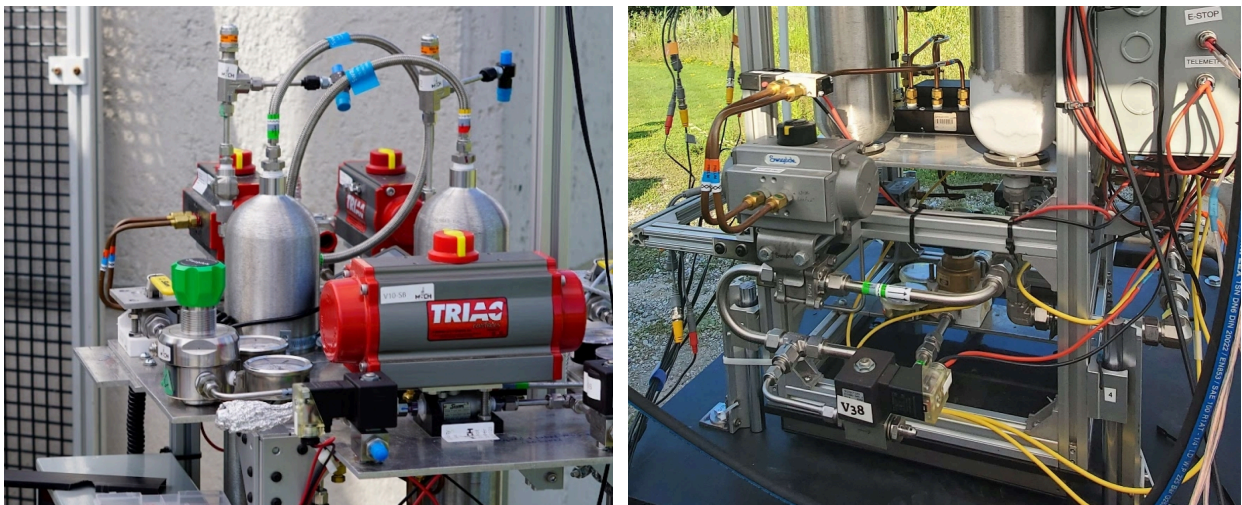


Figure 4.4.1.2: The upper & lower components of Spender during cold-flows.

4.4.2 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 [6]. 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 [7].

The geometries of the ethanol and N₂O cavitating venturis were calculated with reference equations and verified using system-based CFD simulations in Flownex SE [6]. 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 4.4.2.1. The boundary conditions and results of the flow simulations are presented in Table 4.4.2.2.

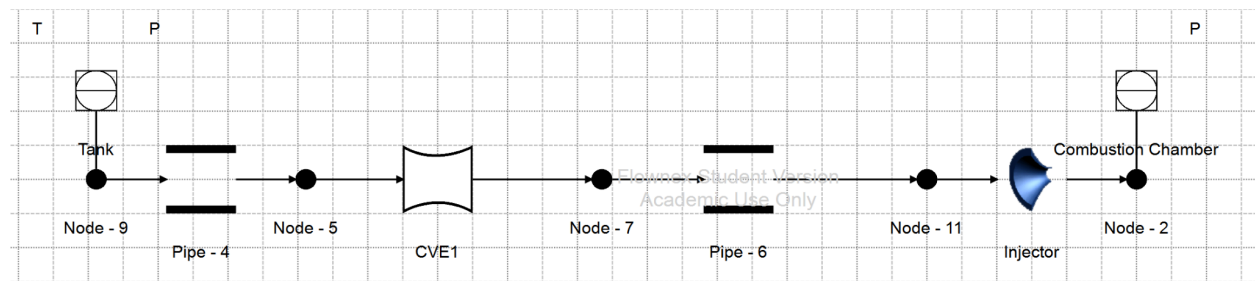


Figure 4.4.2.1: Simplified Eth cavitating venturi and injector model in Flownex SE.

Table 4.4.2.2: 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	2.76 MPa (400 psi)
Choked Mass Flow Rate	0.1893 kg/s
Injector Pressure Drop	0.34 MPa (49.4 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 CO₂ as stand-in propellants with somewhat similar fluid properties, followed by separate testing of N₂O and potentially ethanol for validation.

The cavitating venturis are designed to fit into AN fittings for their respective

[illegible]

SECTION A-A

DETAIL C
SCALE 5:1

PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF BOREALIS. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF BOREALIS IS PROHIBITED.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
± 0.125mm

INTERPRET GEOMETRIC TOLERANCES PER:
MATERIAL: 6061-T6
FINISH: All surfaces 3.2µm Ra except from U → V

NAME DATE

DESIGN: Y. LIO Dec 7, 20
CHECKED: S. MANG Dec 7, 20
ENG APPR:
MFG APPR:
D.A.:
COMMENTS:

TITLE:
Borealis CV Nitrous

SIZE DWG. NO. REV
B CV_N2O_V1.3.2

SCALE: 2.5:1 WEIGHT: SHEET 1 OF 1

Figure 4.4.2.2: 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 4.4.2.3 Manufactured cavitating venturis.

As manufactured, results from inert cold-flow tests have found C_d of 0.86 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 hot-fire tests without adjustment.

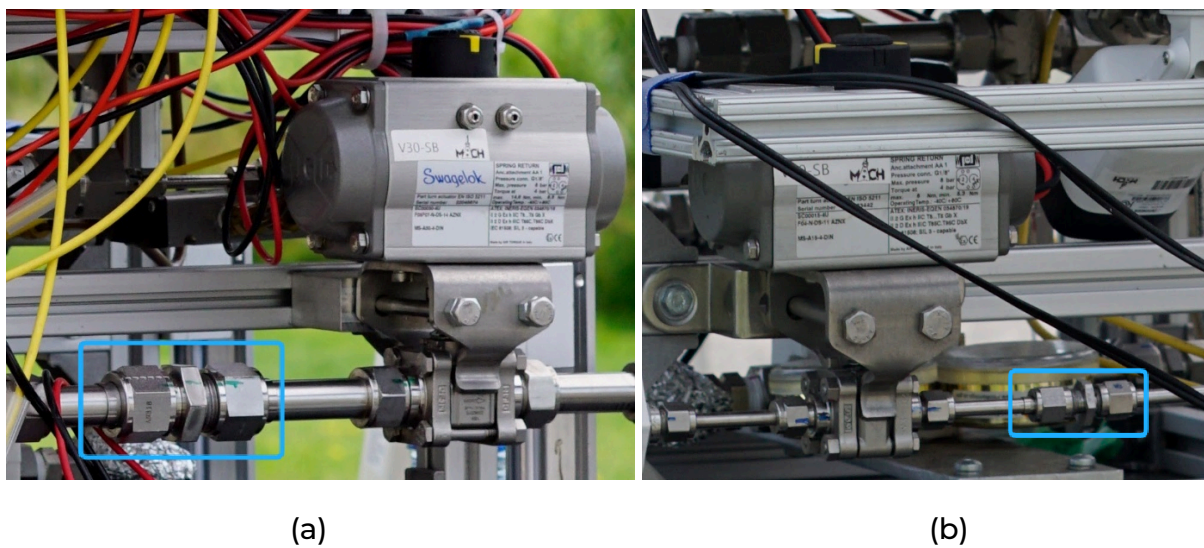


Figure 4.4.2.4: Cavitating venturis installed into **a:** N_2O & **b:** ethanol lines.

4.4.3 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 [1]. 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 N₂O 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 N₂O is then remotely loaded by opening the low-flow fill vent (V33-S) and fill valves, creating a pressure differential to draw the N₂O 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 N₂O 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 both inert propellants and nitrous oxide and has been found 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 N₂O run tank to flush any remaining oxidizer from the system. During aborts, the N₂O 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 N₂O dump & full depressurization (pad “safe” state) without backflow to the pressurant lines. Any remaining ethanol can be manually drained after

the pad is safed.

4.4.4 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 $\frac{1}{4}$ ” 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”) [8].

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. The propellant enclosure for control and data acquisition is physically integrated into the propellant stand as well, which is further described in Section 4.5.3.

The stand is physically divided into upper and lower portions by the height of the tanks, as can be seen in Figure 4.4.4.1. 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 [9].

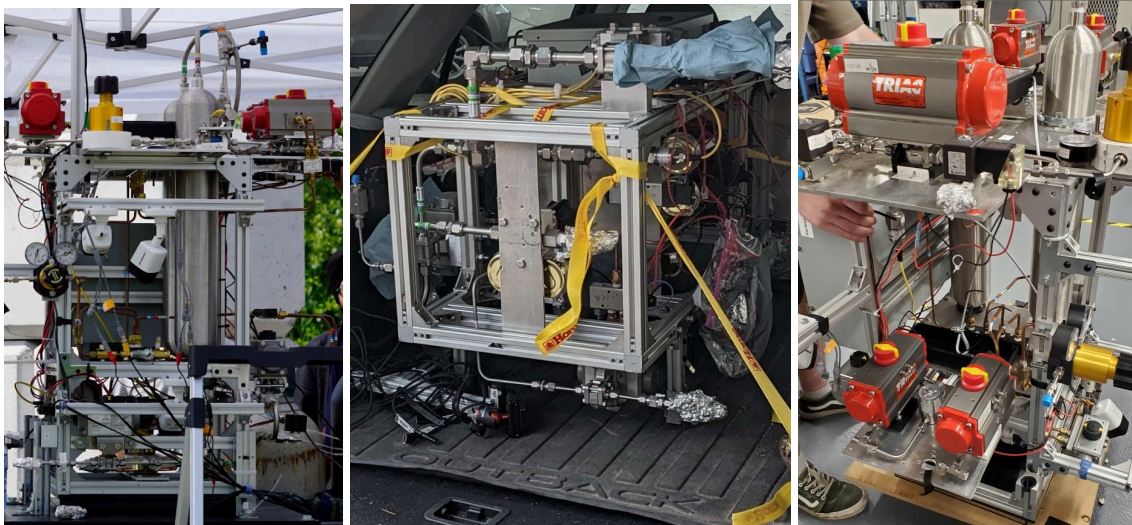


Figure 4.4.4.1: Spender (a) integrated (b) in transport (c) w/ partially installed purge.

4.4.5 Pneumatic System

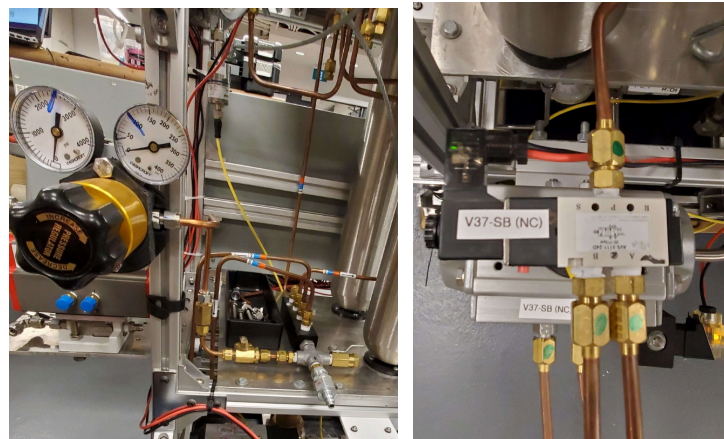
A hard-line pneumatic system using copper tubing was built with Spender V2. This eliminated issues with the previous iteration of the pneumatic system detailed in Appendix A2.2, and greatly improved transportability and reliability.

$\frac{1}{4}$ " 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.



(a)

(b)

Figure 4.4.5.1: (a) Pneumatic inlet manifold (b) Pneumatic pilot solenoid

4.4.6 July 14th 2024 Coldflow Results

Two inert coldflows of the propellant system and new GAR-E injector were conducted on July 14th, 2024. The first primary objective of the test was to collect pressure drop data from both the fuel and oxidizer orifices to verify that sufficient stiffness has been achieved with the new design. Additionally, mass flow and pressure drops were intended to be measured and used to ensure that the new injector would be compatible with the existing propellant system. Camera footage was intended to be collected to characterize the atomization and mixing of the fuel and oxidizer.

The telemetry and control subsystem functioned adequately, allowing for the acquisition of the required data. To evaluate the injector stiffness, the pressure reading directly upstream of the injector (P20) was used to determine the injector pressure drop. This value was also used to calculate the combined discharge coefficient of the injector orifices to sanity check the validity of the measurement. The pressure plot used for this analysis has been presented in Figure 4.4.6.1.

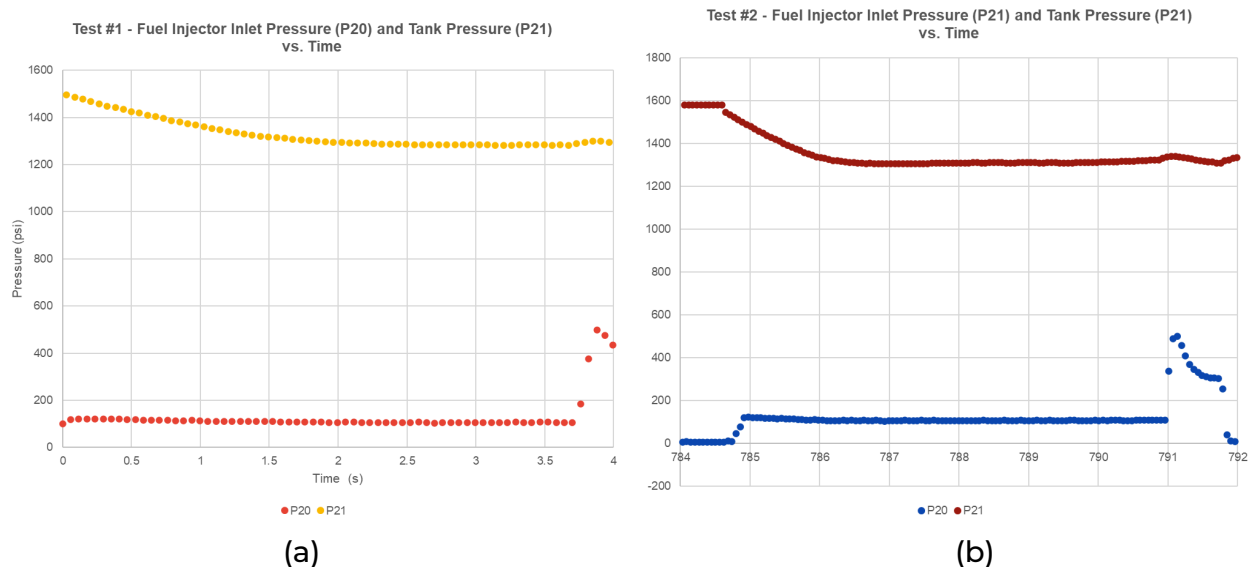


Figure 4.4.6.1: Fuel injector pressure drop (P20) and venturi inlet pressure (P21) for (a) first coldflow and (b) second coldflow

As demonstrated in Figure 4.4.6.1, the pressure drop results were repeatable between both coldflow attempts. The experimentally measured pressure drop varied between 106 psi and 108 psi. This value was used to calculate the experimental discharge coefficient. This value was calculated to be 0.367. This abnormally low value indicated that there was likely an excessive pressure drop from the transition passageway between the injector lid and volute. This pressure drop will be fixed by slight modifications to the volute geometry of the current injector assembly. This

pressure drop will be re-measured prior to the team's hotfire attempt in the coming weeks.

The average mass flow rate of the fuel system was computed using the discharge mass and time. Due to load cell issues during the first test, an accurate initial fill mass was not obtained. However, for the second test, the discharge time was determined to be 6.364s, resulting in an average mass flow rate of 0.189 kg/s. This mass flow rate was used to calculate the experimental cavitating venturi discharge coefficient. This value was calculated to be 0.856, whereas the previously established discharge coefficient from previous tests was 0.860. The small percent difference demonstrated that the fuel-side cavitating venturi was not affected by the presence of the new injector, thus demonstrating compatibility between the two subsystems.

The pressure reading directly upstream of the oxidizer injector orifices was used to evaluate the stiffness of the corresponding oxidizer portion of the injector. As demonstrated in Figure 4.4.6.2, a pressure drop of between 580-650 psi was observed between the two tests. This high pressure drop was an expected outcome, and has been observed in previous tests. The mass flow rate was determined to be 0.53kg/s and is in line with the predictions of calibrated flownex models of the propellant system. The lower-than-desired mass flow rate was a direct result of the high ambient temperature conditions. Observation of the high injector stiffness, and mass flow rates consistent with the predicted values indicated that the injector operated in the critical flow regime with the flow rate metered upstream by the cavitating venturi. This was the desired outcome, resulting in the overall acceptance of the oxidizer pressures and flow rates.

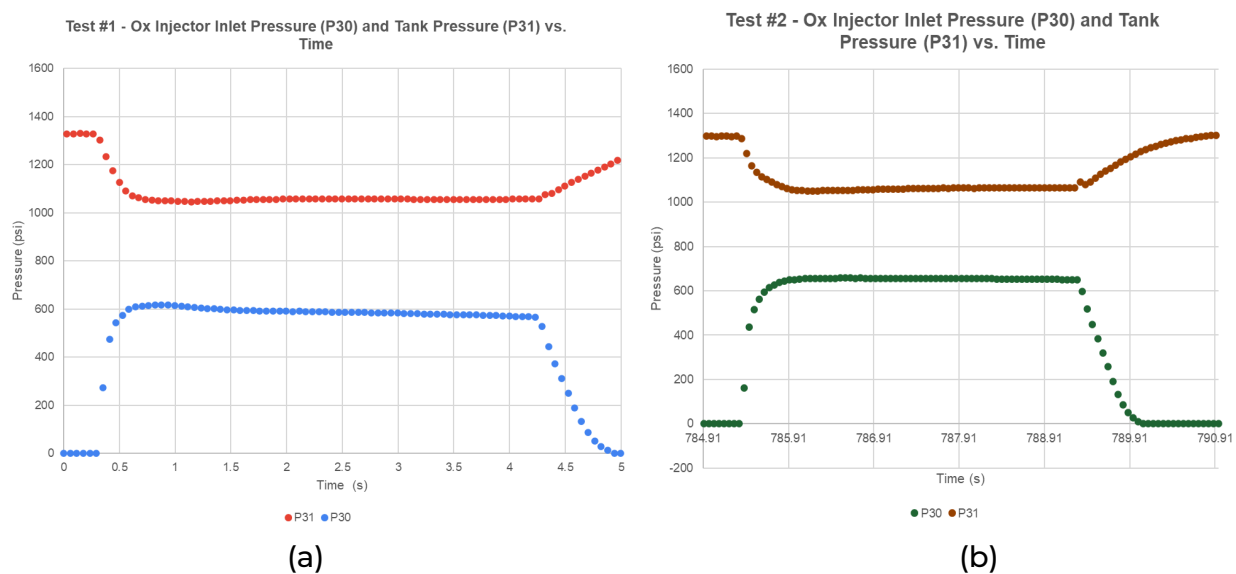
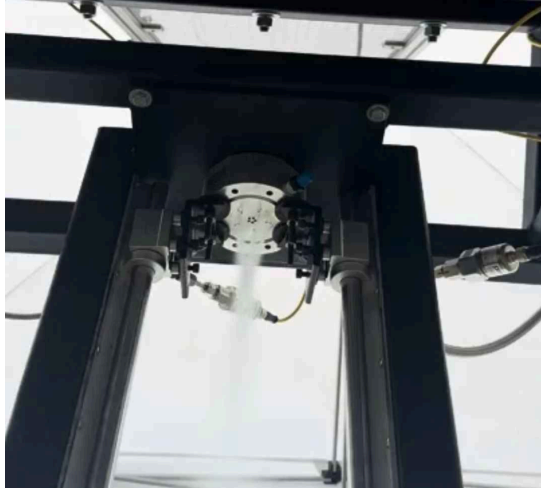


Figure 4.4.6.2: Ox injector pressure drop (P30) and venturi inlet pressure (P31) for (a) first coldflow and (b) second coldflow

Mixing and atomization were evaluated using video footage of the test. The

value timing was intentionally staggered to allow for a 0.5s period of pure fuel self-impingement. A screenshot of this process, along with the comparable results for the original GAR-E injector has been provided in Figure 4.4.6.3.



(a)



(b)

Figure 4.4.6.3: Fuel atomization for (a) original GAR-E injector and (b) new GAR-E injector

As can be observed in Figure 4.4.6.3, droplet formation can be clearly observed for the new GAR-E injector. This was not observed in the initial coldflow test campaign of the original GAR-E injector due to the suboptimal impingement configuration of the fuel orifices. The high axial velocity of the nitrous was also noted as a concern during the redesign process of the new injector. This was addressed by adding like-like impingement of the nitrous orifices. The results of this change can clearly be seen by comparison of the video footage between both coldflows. The nitrous jets can clearly be seen to be slower and more dispersed with the new design.

Overall, the test was deemed to be a success as all primary data collection objectives were met. While slight modifications will be performed for the fuel volute, the re-measurement of the pressure drop will be performed on the same weekend as the hotfire attempt, thus allowing for minimal modifications to the summer's testing timelines.

4.5 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 4.4 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 4.5.1 and key components of each subsystem are listed in Table 4.5.1.

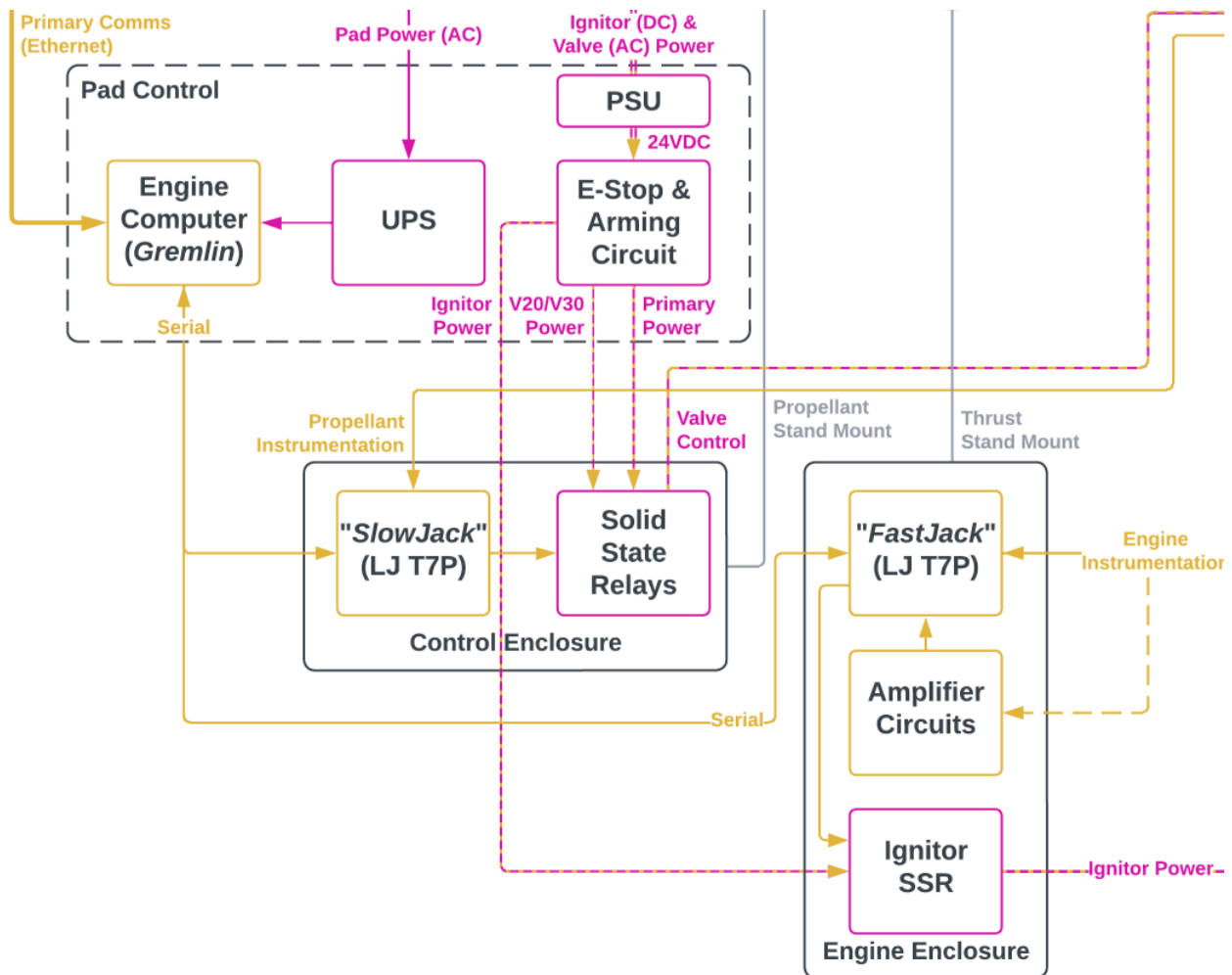


Figure 4.5.1 Engine side telemetry & control system integration diagram (V2.6.2).

Table 4.5.1: 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.

4.5.1 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 4.5.1.1.

Table 4.5.1.1: 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 N₂O 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 μV 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 μV , the T7 Pro has a sensor sample rate of 0.04 ms/sample [10]. A single Labjack T7 Pro unit is capable of reading 100k samples per second from a singular sensor. Using Table 4.5.1.1, 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 4.5.1.1: Pressure transmitters P31 and P21 installed

4.5.2 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.



(a)



(b)

Figure 4.5.2.1: (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.

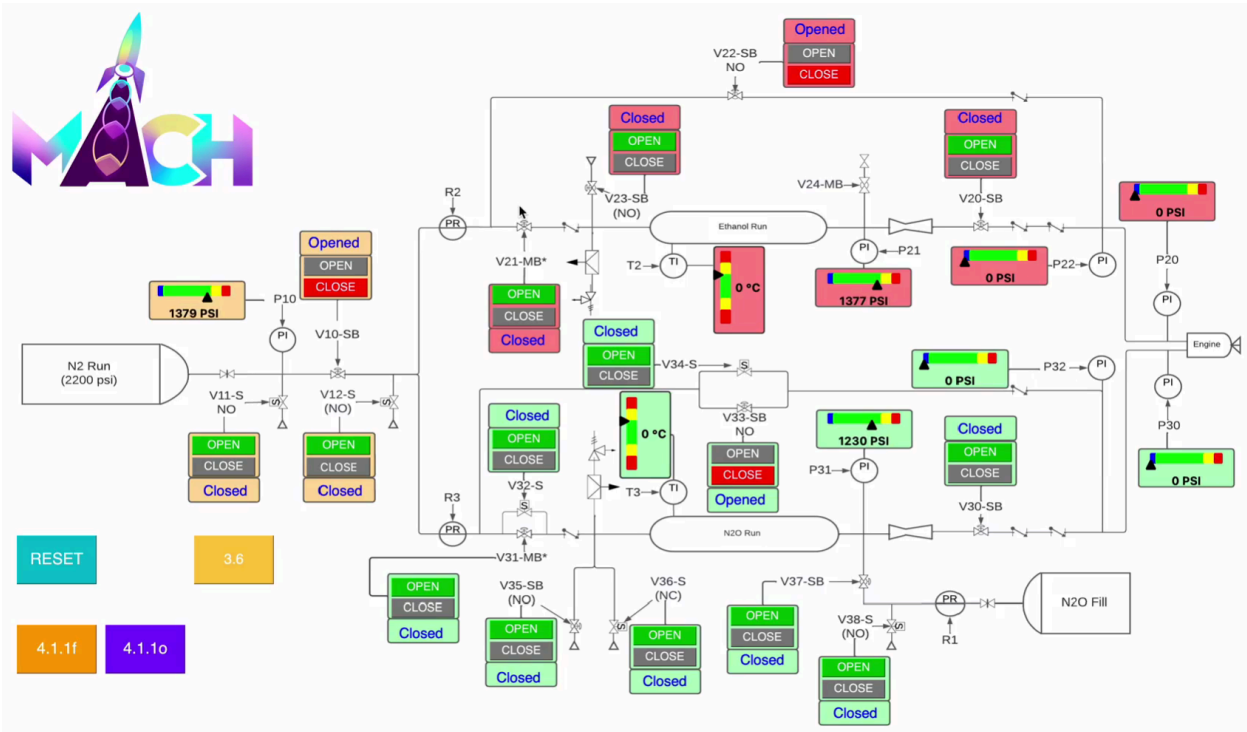


Figure 4.5.2.2: A screenshot of the GUI during a cold-flow.

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 4.5.2.1 and Figure 4.5.2.3 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 4.5.2.1: 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.

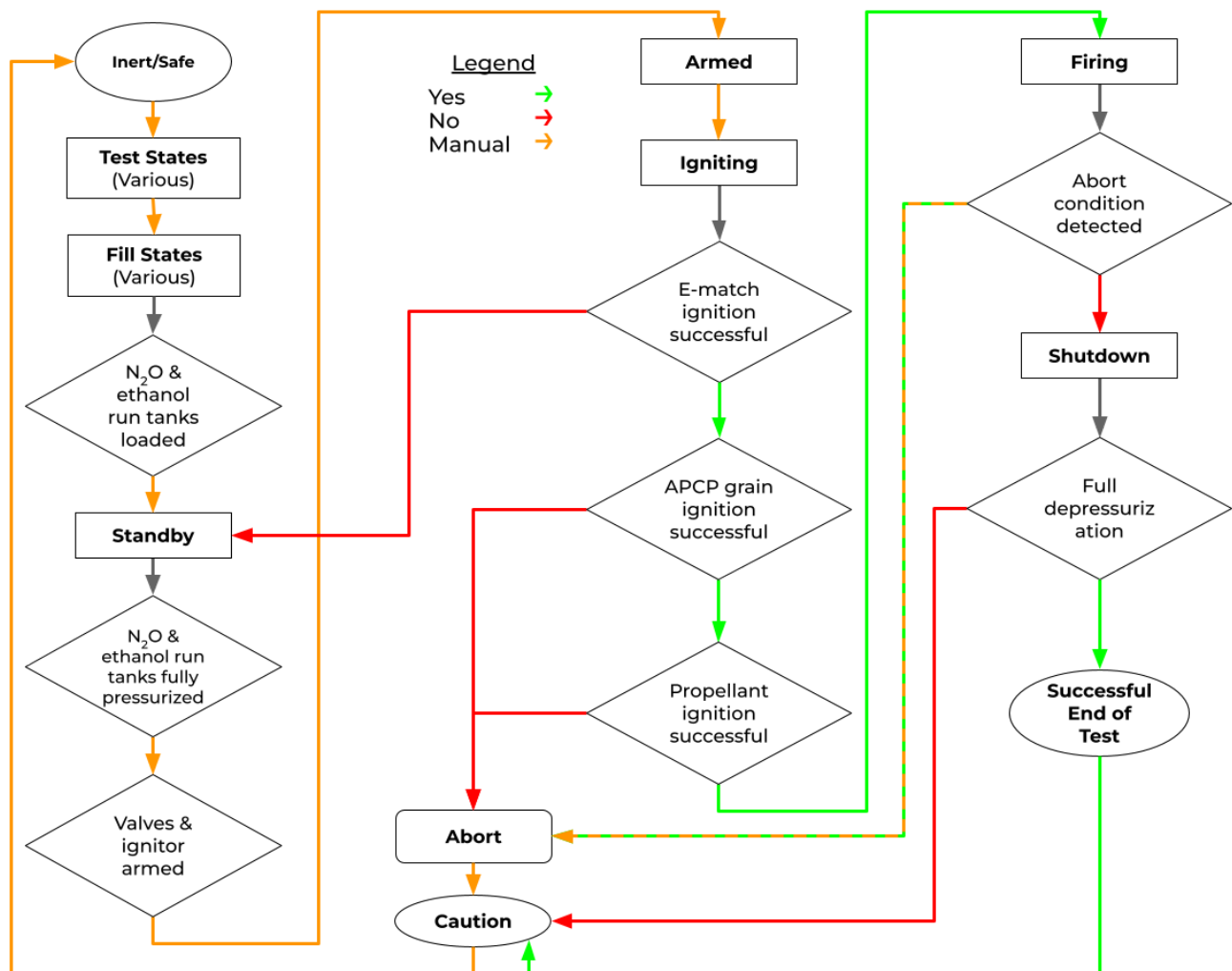


Figure 4.5.2.3 Simplified Engine State Logic Diagram (V2.1).

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 transmits 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.

4.5.3 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.

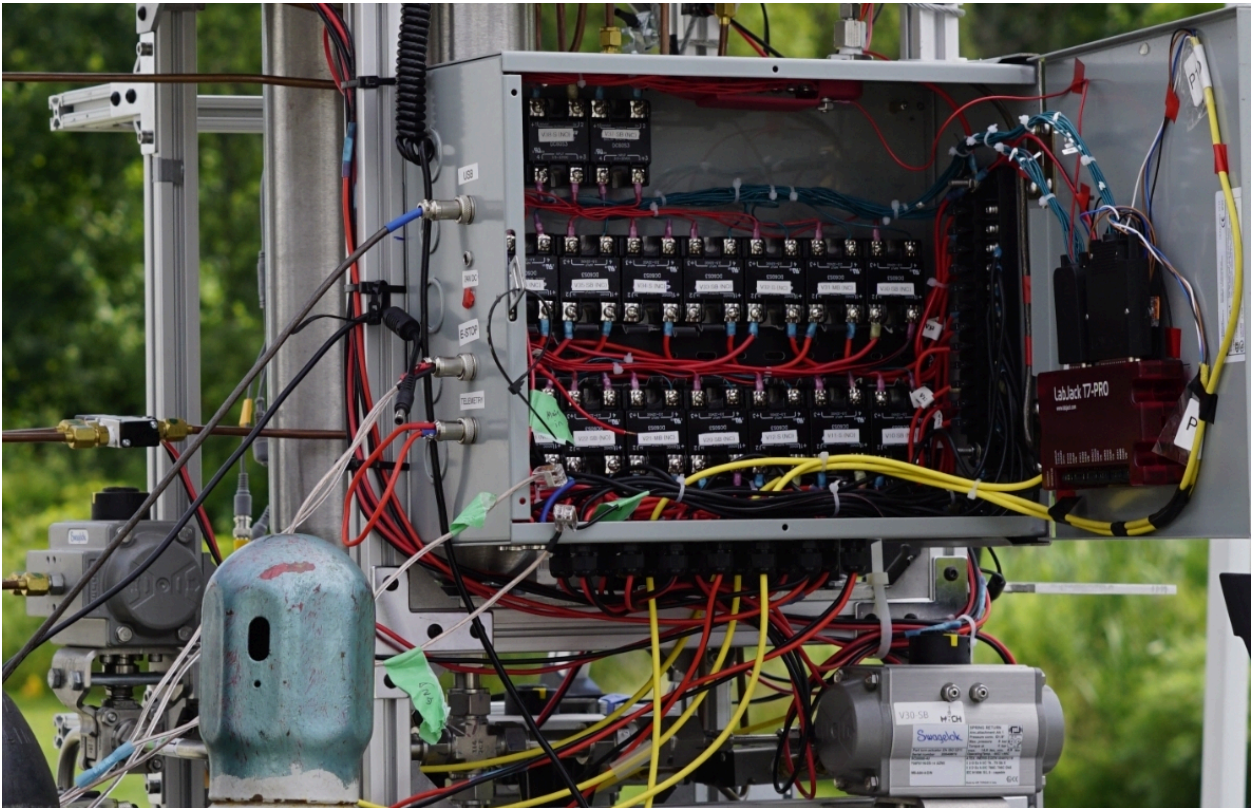


Figure 4.5.3.1: Interior of the Propellant Enclosure during a cold-flow.

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 $\sim 4V$ and the low state supplies $\sim 1V$. 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 4.5.3.2 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 $\sim 1V$, resulting in the normally open position of the SSRs. Changing the DIO pin into a low state creates $\sim 4V$, 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.

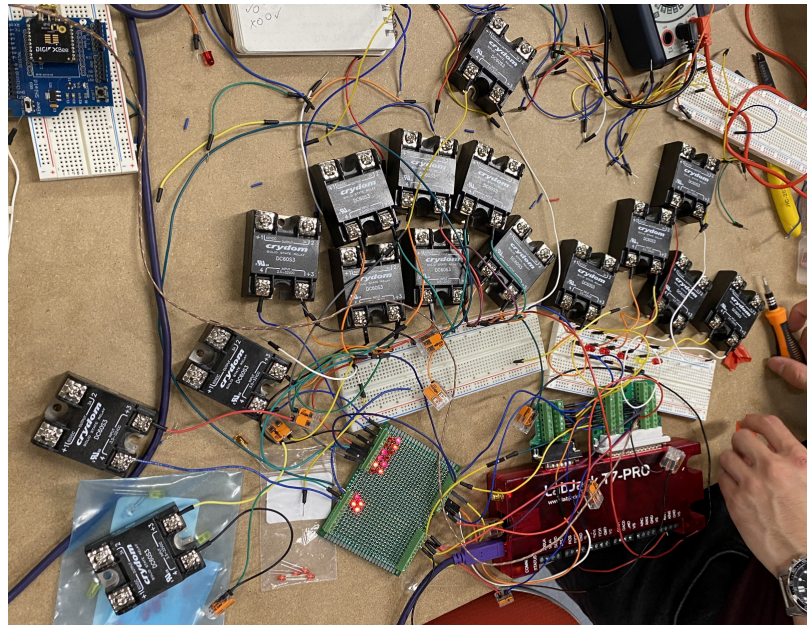


Figure 4.5.3.2: Testing of the SSRs before integration into the propellant enclosure.

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 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.

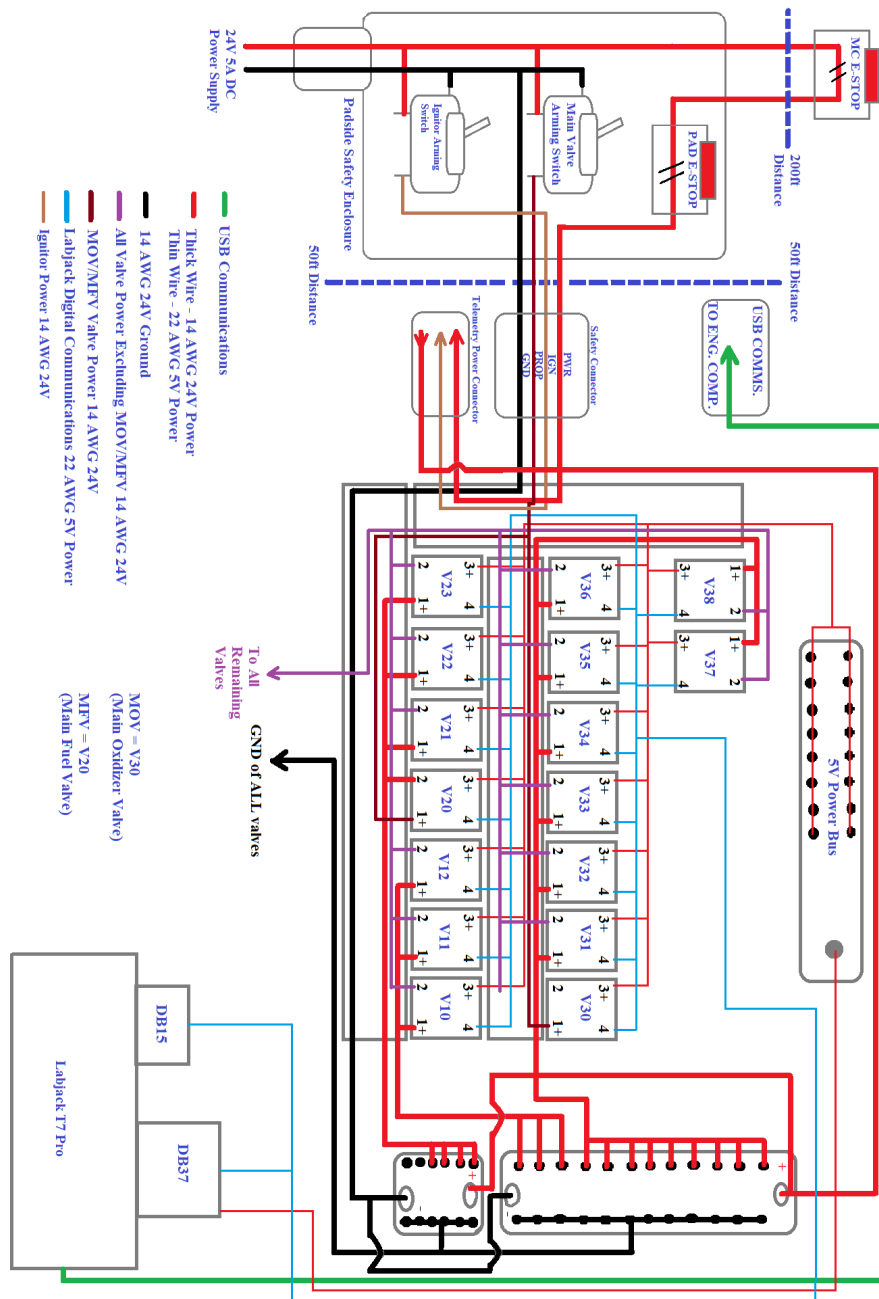


Figure 4.5.3.3: Propellant Enclosure Wiring Diagram (V1.4)

4.5.4 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.

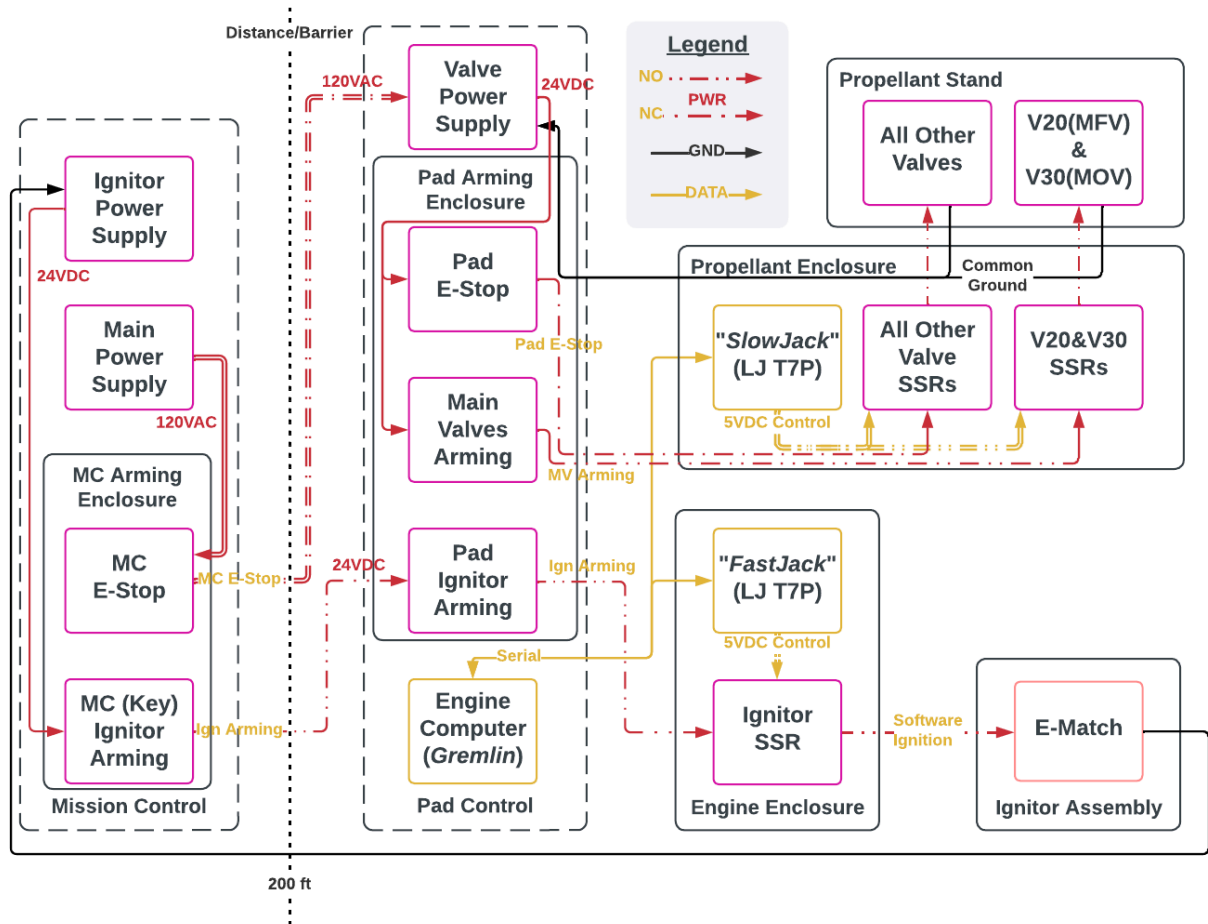


Figure 4.5.4.1: Arming & E-Stop Circuit (V3.2).

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.

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.

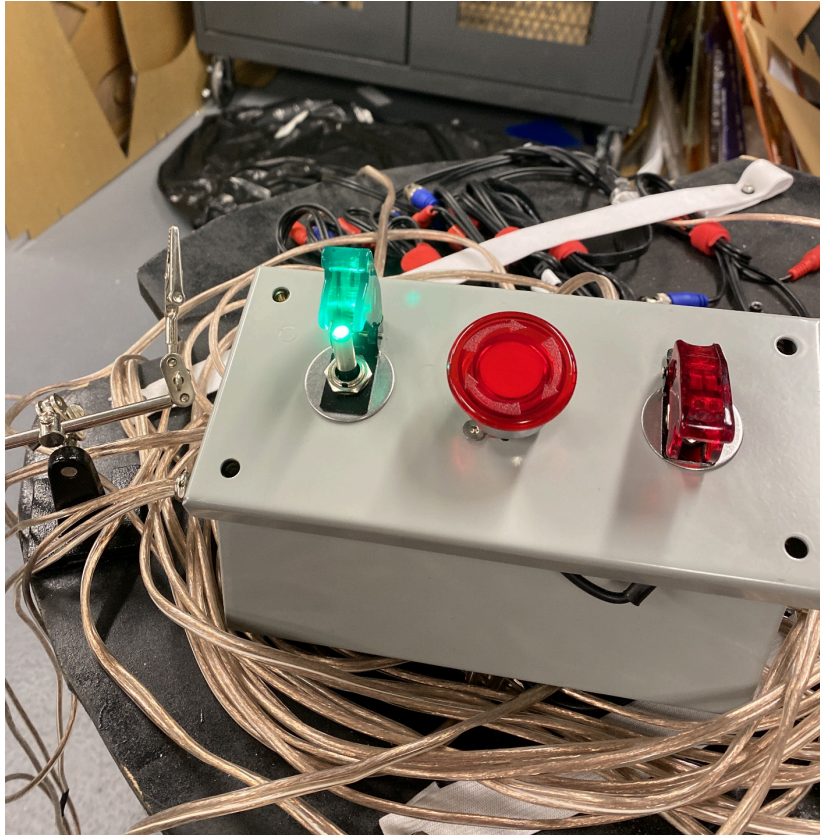


Figure 4.5.4.2: The Padside Arming Enclosure.

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.

4.5.5 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 4.5.2. 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 4.5.5.1: Mission Control setup during cold-flow attempt #3

4.5.6 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.

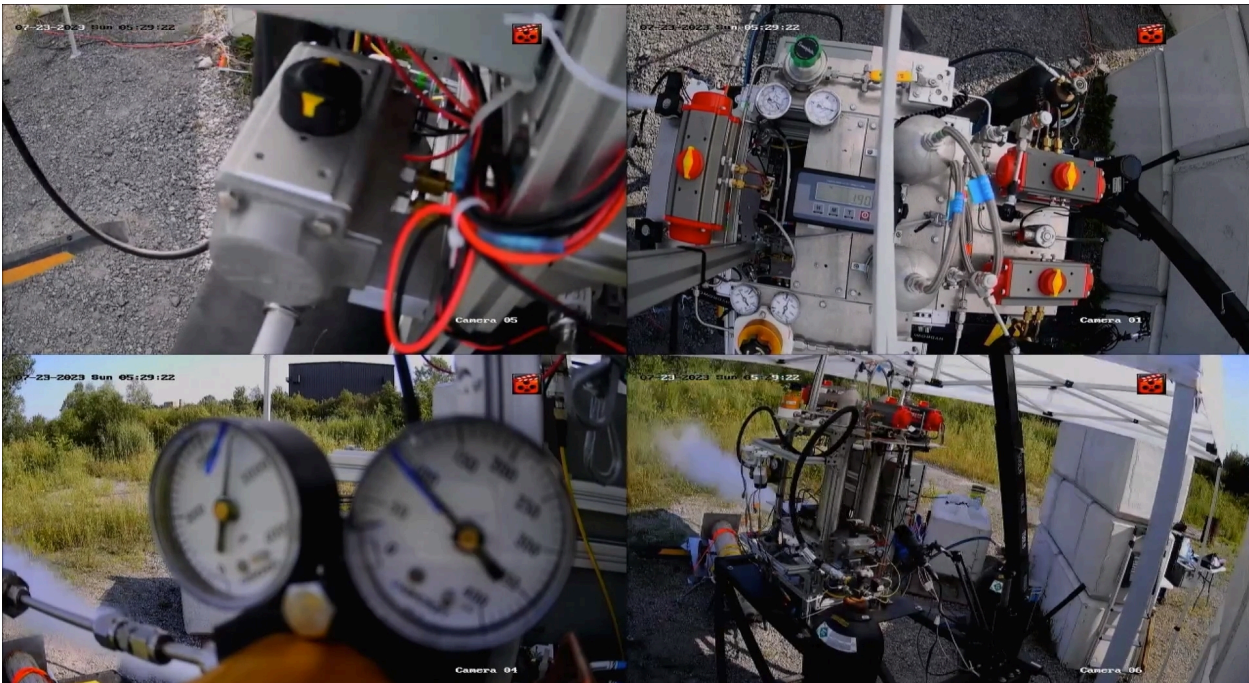


Figure 4.5.6.1: Camera views during a N₂O cold-flow

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).

4.6 TEST STAND & SUPPORT EQUIPMENT

4.6.1 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.

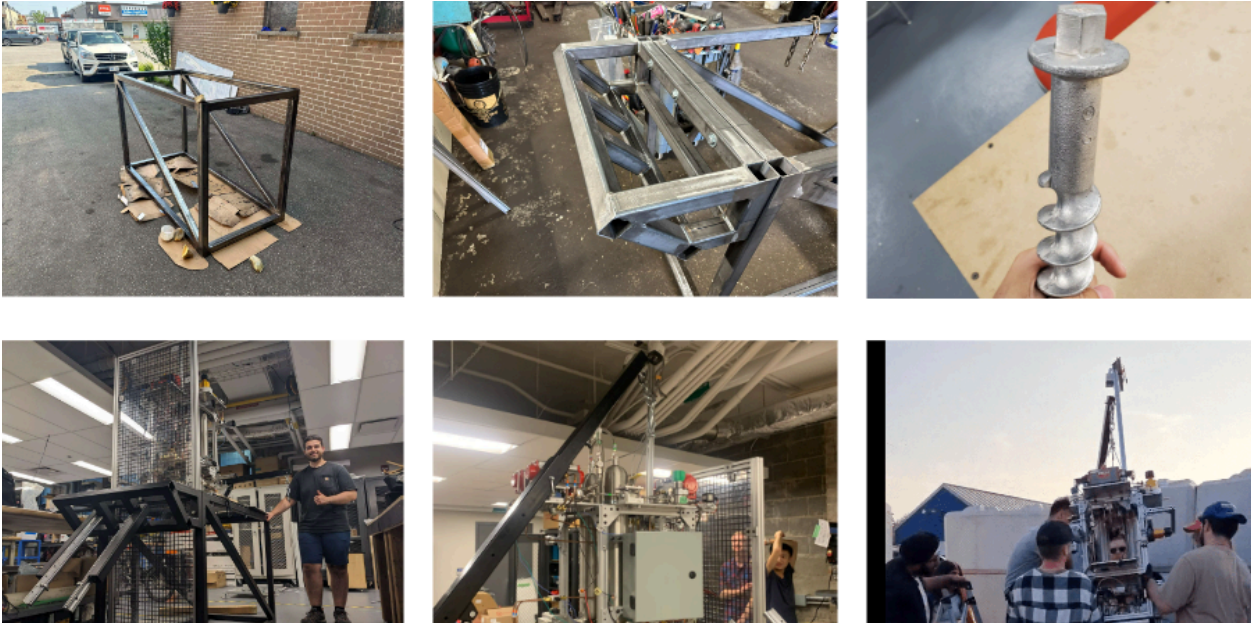


Figure 4.6.1.1: a: Box b: Thrust Adapter c: Earth Anchor d: Blast Shield e & f: Crane

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.

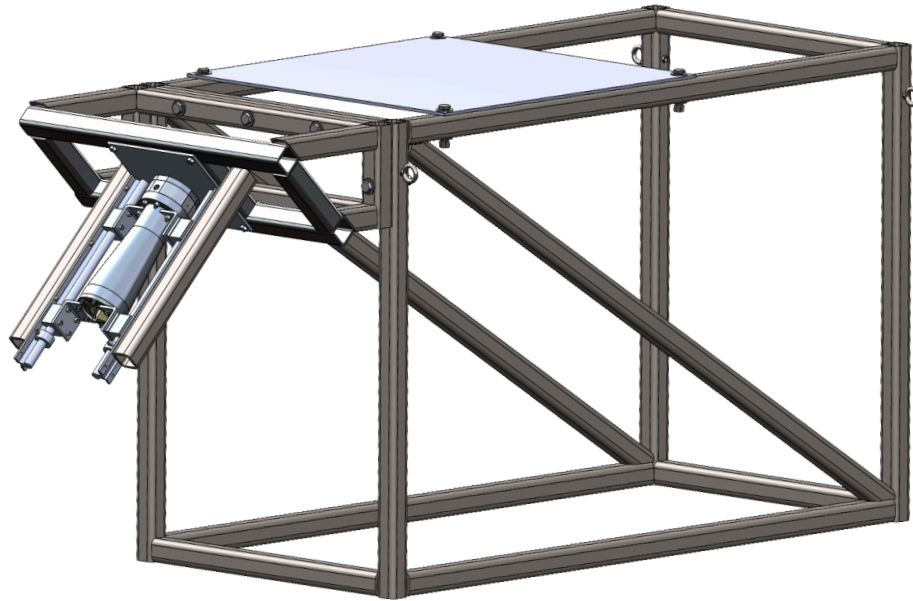


Figure 4.6.1.2: CAD view of the thrust stand assembly

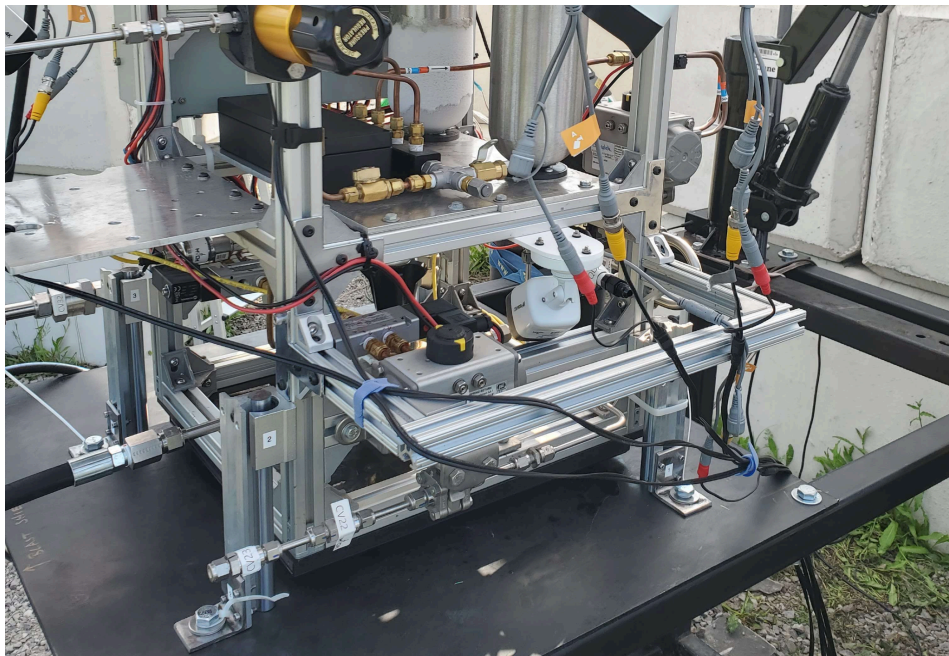


Figure 4.6.1.3: Spender & weight scale mounted to the thrust stand with linear rails.

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 4.6.1.1, 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.

4.6.2 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.

4.6.3 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 4.6.3.1: 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 propellant 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
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* 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 CO₂ 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 CO₂ loading and cold-flow within 1 hour. Red Team safed pad again, returned to re-fill water, swap N₂ 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, 2023, resulting in two successful inert cold-flows. A final inert coldflow of new GAR-E was conducted on July 14, 2024 to test the New GAR-E injector

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	Jul 24
Inert Fill	1	Validate & iterate general testing procedures.	<u>Yes</u>	<u>Yes</u>	<u>Yes</u>	<u>Ye</u>
	2	Validate & iterate propellant fill procedures.	No	No	<u>Yes</u>	<u>Ye</u>
	3	Validate & iterate leak testing procedure.	Part	<u>Yes</u>	<u>Yes</u>	<u>Ye</u>
	4	Determine N2O fill time & efficiency using CO2 stand-in.	No	No	<u>Yes</u>	<u>Yes</u>
	5	Validate remote telemetry & control setup.	<u>Yes</u>	Part	<u>Yes</u>	<u>Yes</u>
	A	Validate & iterate setup procedure & weather resistance.	Part	Part	Part	Part
	B	Validate visual telemetry & mission control setup	<u>Yes</u>	Part	<u>Yes</u>	<u>Yes</u>
Cold-Flow	6	Validate & iterate cold-flow procedures.	No	<u>Yes</u>	<u>Yes</u>	<u>Yes</u>
	7	Validate pressurization & plumbing system performance.	No	No	<u>Yes</u>	<u>Yes</u>
	8	Validate purge & vent sequence.	No	No	<u>Yes</u>	<u>Yes</u>
	9	Validate engine computer data processing & storage.	No	No	Part	<u>Yes</u>
	C	Perform abort & E-stop test.	No	Part	<u>Yes</u>	<u>No</u>
	D	Determine tanked "propellant" mass after cold-flow.	No	No	<u>Yes</u>	<u>Part</u>
	E	Produce media assets for outreach.	Part	Part	<u>Yes</u>	<u>Yes</u>

* 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.

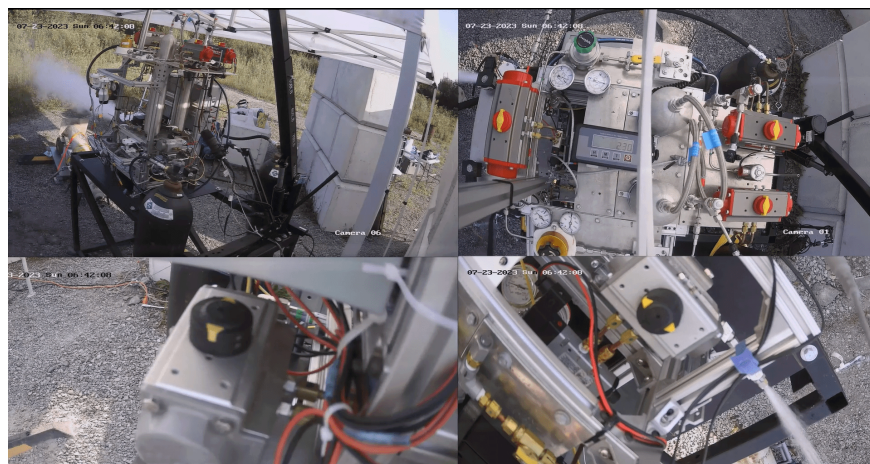
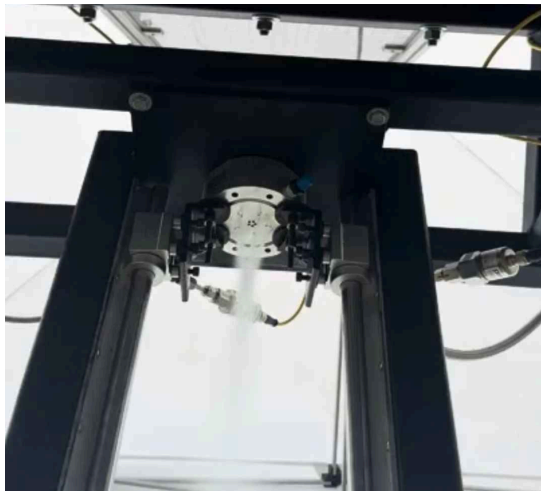


Figure 5.2.3.1: Screenshot of camera feeds during the simultaneous cold-flow

5.2.3 Inert Cold-Flow 4 (Jul 13-14, 2024)

A fourth inert cold-flow was attempted on July 13th and 14th, 2024. Two coldflows were successfully performed on July, 14th. The core objective of the inert coldflow was to collect video footage to characterize the mixing characteristics of the new GAR-E injector. Additionally, the test was performed to measure the injector pressure drops to ensure that the experimental injector stiffness was sufficient for a hotfire. By analysis of the video footage, clear improvements in the atomization and mixing performance were observed. Due to an excessive pressure drop observed across the fuel volute, slight geometric modifications will be made to the injector prior to hotfire testing. This will require a fuel-side insert coldflow test prior to performing the hotfire test. The team's intention is to perform this test on the same weekend as the proceeding hotfire attempt.



(a)



(b)

Figure 5.2.3.1: Fuel atomization for (a) original GAR-E injector and (b) new GAR-E injector

6.0 PROPOSED TIMELINE

MACH aims to complete a hotfire test with the new GAR-E engine prior to competing at Launch Canada 2024. Currently, MACH is on track to accomplish this goal after having performed a successful coldflow on July 14, 2024. Since most engine components have been manufactured, MACH is confident that we will be able to complete engine manufacturing and proceed with hotfire testing within the upcoming weeks. The planned testing for summer 2024 has been presented in Table 6.0.1

Table 6.0.1: Targeted Testing Timeline For Major Tests

Test Name	Expected Date of Completion
Inert Cold-Flow	July 2024 (completed)
New GAR-E Static Fire I	Early August, 2024
New GAR-E Static Fire II	Launch Canada 2024

6.1 PLANNED FUTURE DEVELOPMENT

The new GAR-E design being demonstrated at LC2024 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 LC2024 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 [1]. 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 [2].

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 [12] [13]. 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 [11].

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 up to 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 [14] [15]. 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. 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 N₂O 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 Propellant 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 N₂ and N₂O lines. Emergency stops are less desirable than an electronic stop due to the loss of purge, and potential ice buildup in the N₂O system [16]. 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 4.0 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 N₂O 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 N₂O 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.

8.0 ACKNOWLEDGEMENTS

MACH is reliant on external support to continue what we're doing and take on even bigger projects. We would like to express our sincerest gratitude to Adam Trumpour, Chris Hobbs, Dan Steinhaur, Peter Bradley, and Wintta Ghebreyesus for their invaluable advice, encouragement, and support over the course of our project, as well as all our past leads and members for helping us get this far. Additionally, we would like to acknowledge and thank all our sponsors for making this possible.



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Figure 8.0.1: MACH's Current Sponsors

9.0 REFERENCES

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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 [7]:

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

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% [7]. Accounting for the ullage volume results in the required pressure vessel volume for the fuel tank. The computation can be performed as follows:

$$V_{EtOH, req} = V_{EtOH} + V_{EtOH} * 0.025 = 1.250L \quad (A2)$$

As per AIGA safe practices for handling of nitrous oxide, local regulations in North America permit an admissible filling ratio of 0.68 kg/L. Therefore, the required tank volume can be completed as follows:

$$V_{N2O, tank} = \frac{2.5}{0.68} \quad (A.3)$$

$$V_{N2O, tank} = 3.67L \quad (A4)$$

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]:

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

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 N₂ 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 N₂ 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°C and pressures approximately equal to the tank stagnation pressures, the density of N₂ 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 N₂ 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.

$$C_v = \frac{Q}{816P} \sqrt{SG * T} \quad (A6)$$

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

	N₂O 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 N₂ 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).

$$Q = Cv * \frac{816 * P_1}{\sqrt{SG * T}} \quad (A7)$$

The absolute maximum flow of the ethanol and N₂O 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 N₂O regulator failure (R2) and therefore only serves to manage regulator creep in the stagnant flow condition. The dump N₂O 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: Safe Distances & Site Layouts

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

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

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

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

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 combustion² = 1

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

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

Formula 1.1: Stand-off Distance from Milestone Scale Distances

$$Z\sqrt[3]{W} = R \quad (A12)$$

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).

A2.1 Calculated Safe Distances

Table A2-1: Calculated Overpressure distances based on TNT_{equiv}

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.

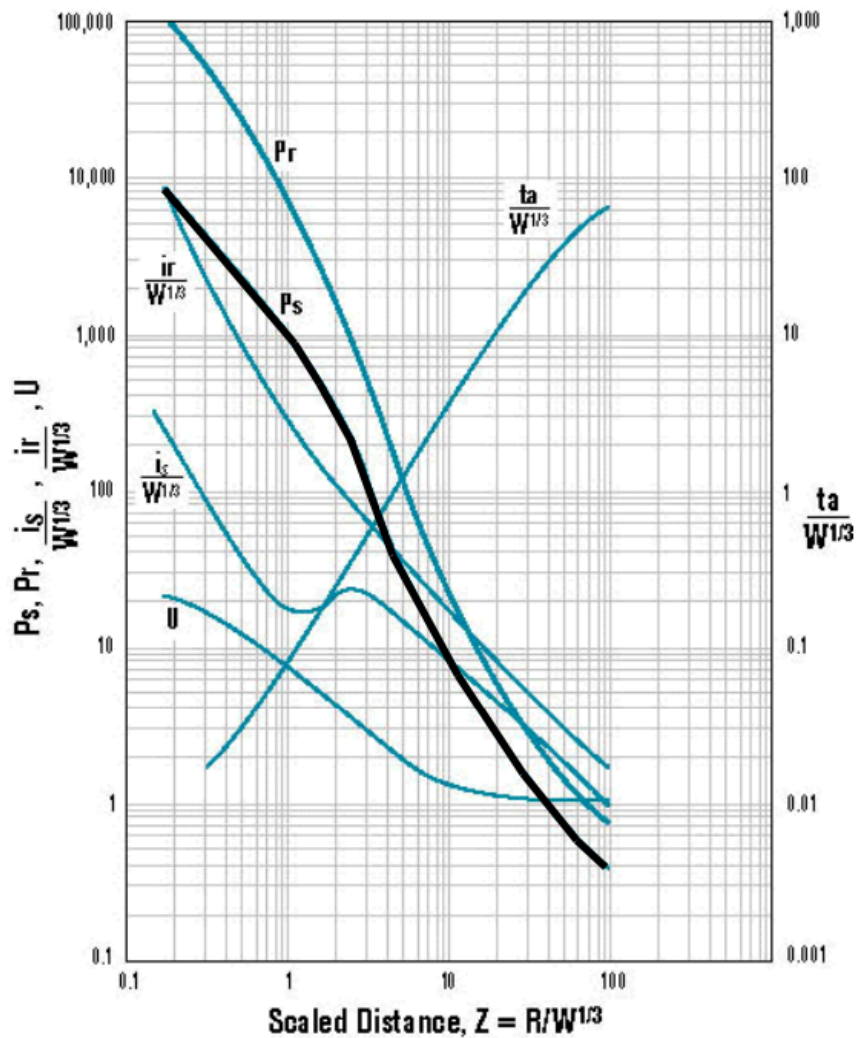


Figure A2-1: Scaled Distance to Peak Positive Incident Overpressure (P_s) Graph
[17]

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.

Appendix III: 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 [18].

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.

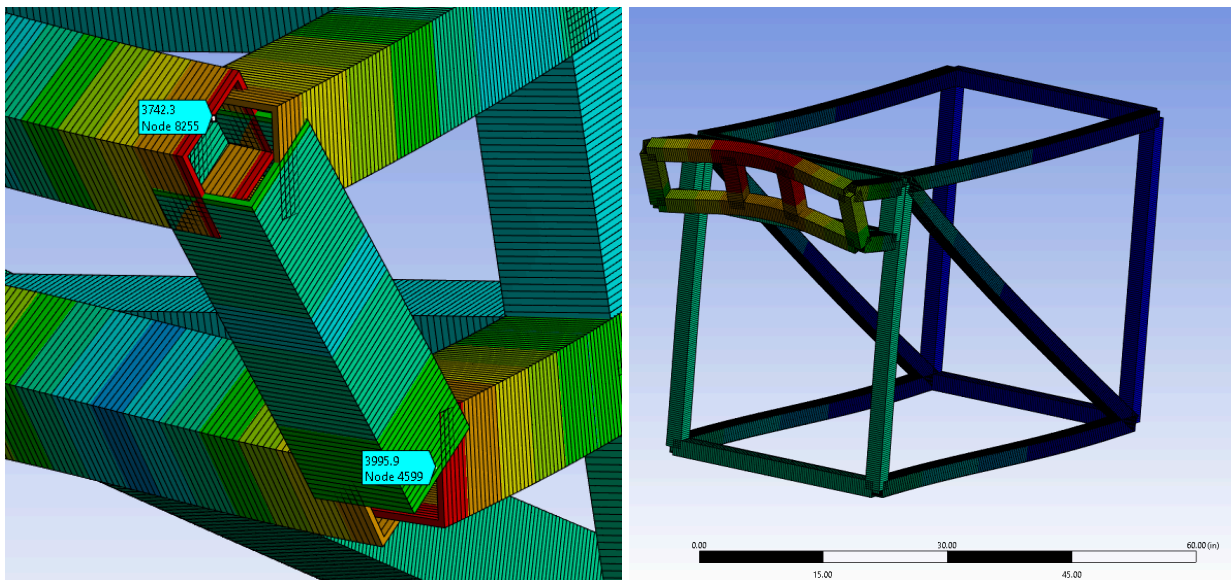


Figure A3-1: a: Maximum Combined Stress b: Thrust Stand Deformation (in)

Figure A3-1 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. A3-1a 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 A3-1b. 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 A3-2: Crane undergoing structural analysis

Appendix IV: New GAR-E Production Drawings

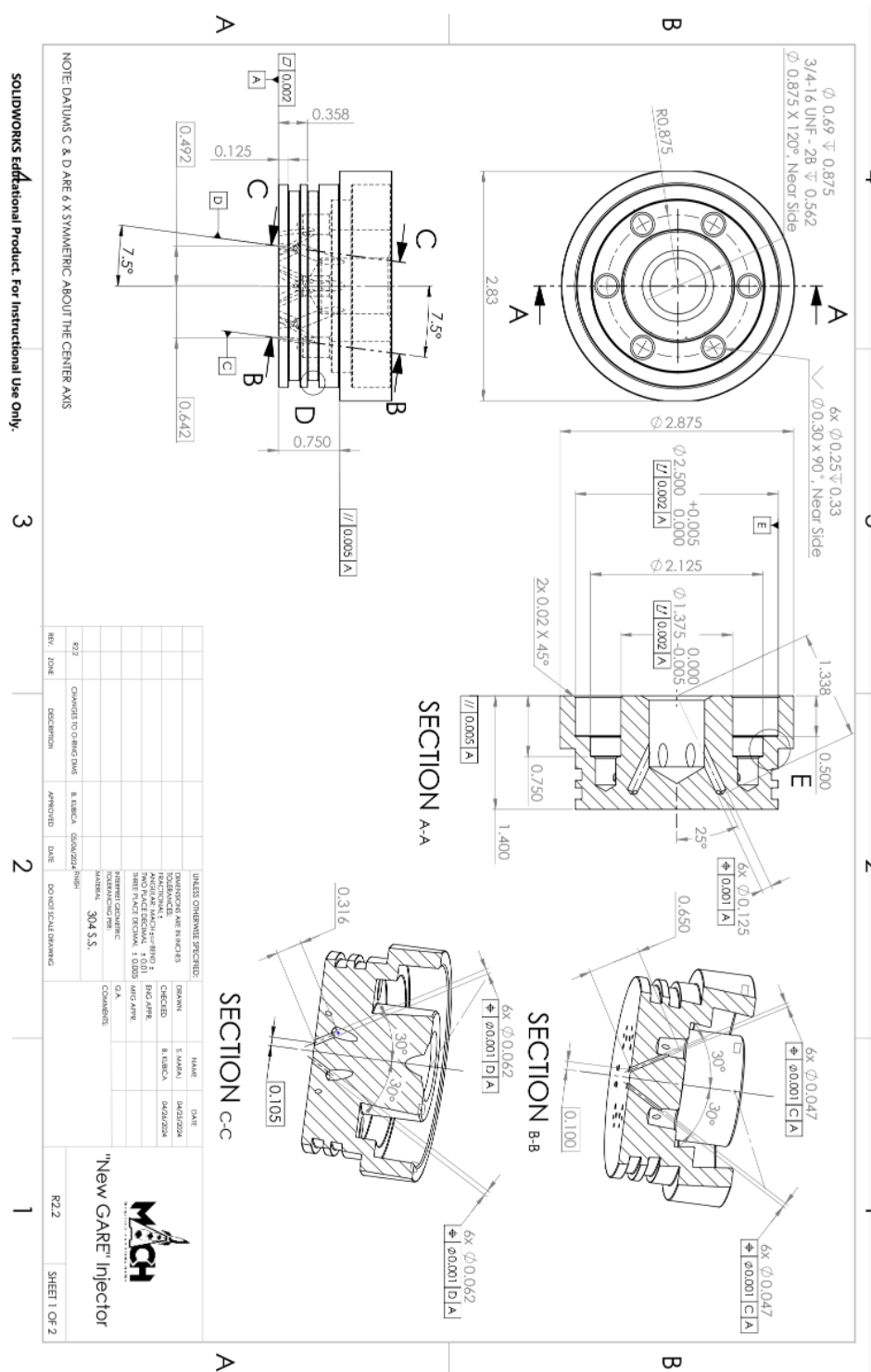


Figure A4-1: New GAR-E Injector Body



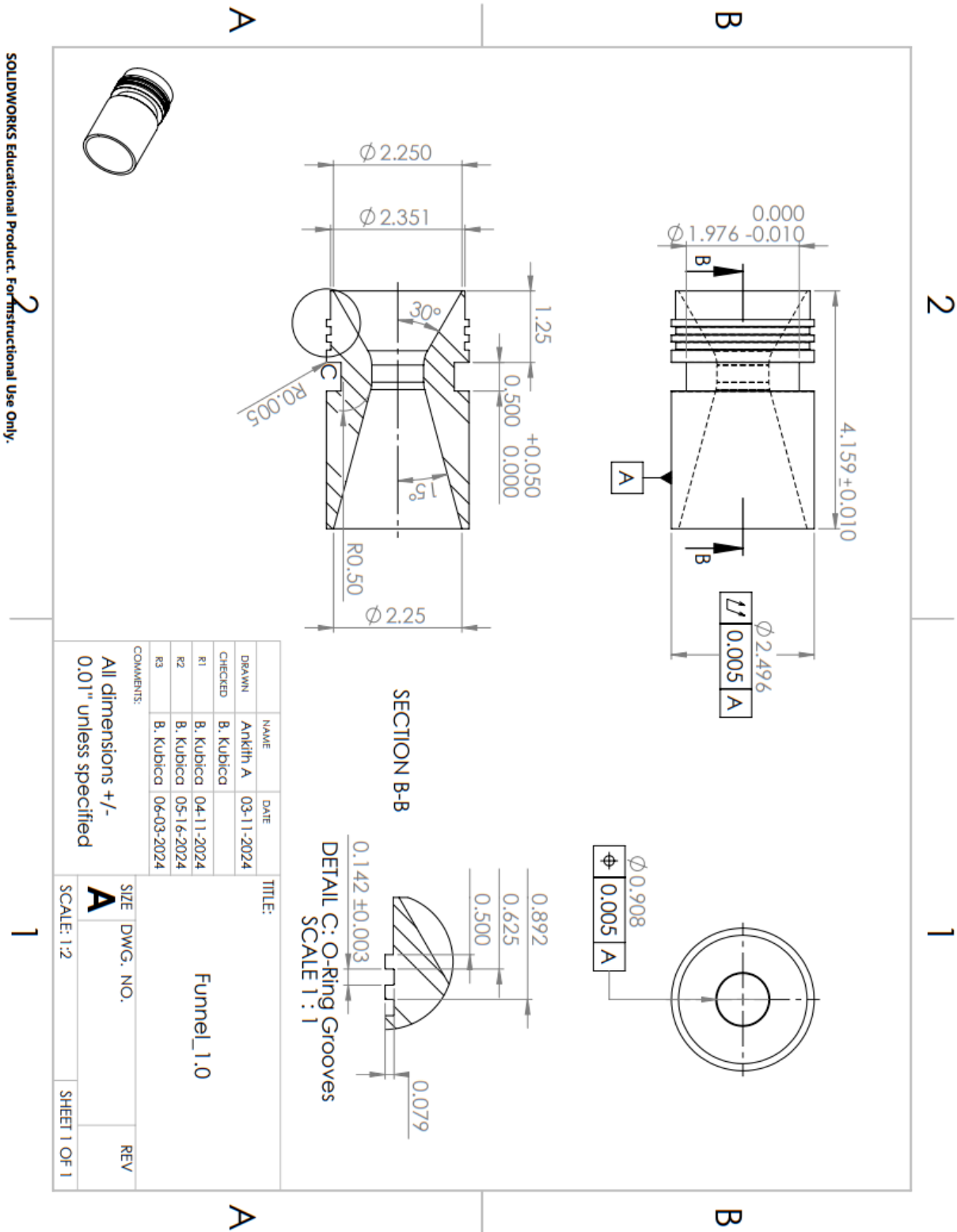


Figure A4-3: New GAR-E Nozzle

Appendix V - 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 QDI							
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 - 3/4", 9/16", 5/8" 7/8", [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 3/4" hex bolt - 2x couplers - V21 & V31 actuator assemblies - V21 & V31 pneumatic lines - Small torque wrench - 1/4" square to 13mm socket - 1/4" square to 3/8" square adapter - 3/8" 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 3/4" 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 3/4" 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" 5/8" 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	Start Time						
	- 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							
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 - R1 (N2O Fill Reg) open - Main Regs set to operating pressure - Everyone distanced w/ hearing protection	Start Time						
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.							