Rocket Propulsion Laboratory

Static Fire Test Rig Design Packet

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Contents

1 Documents

1.1 Executive Summary

Rocket Propulsion Laboratory at UCSB was founded to provide educational opportunities to students interested in aerospace. To accomplish this mission statement, RPL at UCSB is competing in the FAR/Mars competition, a yearly amateur rocketry competition hosted by Friends of Amateur Rocketry (FAR) and The Mars Society. The goal of this competition is to build a liquid-fueled rocket capable of a 45,000 ft apogee, with a total impulse below 9,208 lb-s.

Before a rocket can be entered into the competition, the propulsion system must be tested separately to verify the desired performance of all the components in the propulsion system, and to collect data and study phenomena which are exceedingly difficult to simulate or evaluate analytically. These tests include, but are not limited to: leak tests, component functionality tests, thermal tests, liquid nitrogen flow tests, and the final static fire test. Proof of a successful static fire test and thorough documentation of the engine performance and the safety of the system must be demonstrated and submitted to the competition organizers.

Although completing all testing through the liquid nitrogen flow test will demonstrate the functionality of the feed system, signifying a successful capstone project, the propulsion system will not be completely finished until the static test fire of the engine with combustibles is accomplished. This must be done before December 2020.

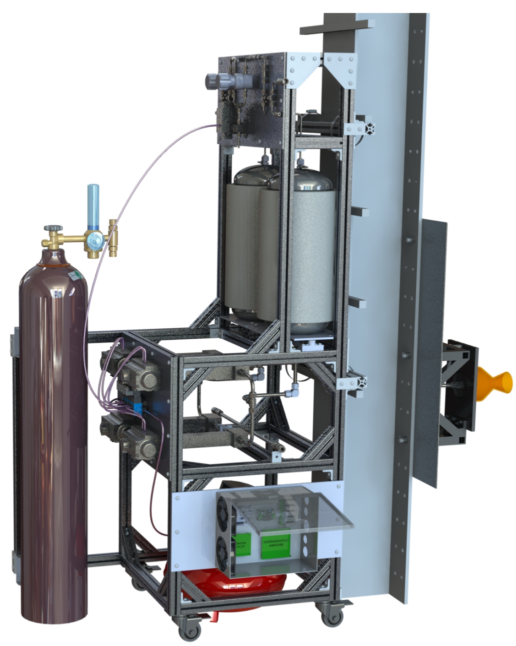


Figure 1: Rendering of the static fire test stand, Player One.

1.2 Introduction and Target Specifications

A rocket engine converts the chemical potential energy of the propellants into thermal and kinetic energy. Liquid methane (LCH4) and liquid oxygen (LOx) enter through the injector as an atomized mist, then into the combustion chamber in the presence of an ignition source, such as a sustained spark or flame. The propellants then combust, releasing immense heat and rapidly expanding the gaseous products, which accelerate through the nozzle of the rocket engine. The nozzle and combustion chamber are designed such that the gas exceeds the speed of sound when leaving the engine, producing the thrust force needed for the rocket to fly.

The liquid propellants are initially stored in the propellant tanks, then are delivered through the bottom feed system to the injector by pressurizing the tanks with gaseous helium, which is delivered to the tanks by the top feed system. The valves throughout the feed system are actuated using a pneumatic system, and the entire test rig is controlled and monitored by the electrical ground systems. Lastly, the static test structure holds all components in place, enabling safe operation of the test rig and allowing for reliable data acquisition.

1.2.1 Engine

Baby Come Back's engine is composed of a carbon fiber overwrap, a silica phenolic ablative layer, and a mounting flange for attaching the engine to the injector and the rest of the structure. The engine thus has well-defined structural requirements, as well as strict performance requirements. While many facets of the engine will be designed and manufactured by Compositex, a professional rocket engine manufacturer, the following characteristics are required:

1. The combustion chamber shall interface with the injector
2. The engine shall deliver a thrust force of 700 lbf (+50 lbf -100lbf)
3. The combustion chamber shall operate at chamber pressure 350 psi (+70 psi -50 psi)
4. The Mixture Ratio (Oxidizer/Fuel) will be 2.8 ± 0.2
5. The Nozzle Exit inner Diameter shall be 2.82 in $\pm$ 0.03 in
6. The Throat Inner Diameter shall be 1.34 in $\pm$ 0.01 in
7. The combustion chamber shall provide a stable environment for the mixing and combustion of liquid oxygen and liquid methane
8. The geometry should have an L* (characteristic length) of 3.28 ft $\pm$ 0.2 ft
9. The combustion chamber shall be structurally stable through the burn time
10. The combustion chamber shall have an inner coating of ablative material
11. The combustion chamber shall be pressure rated to 1.5 times the chamber pressure

1.2.2 Injector

The injector is designed to deliver an atomized spray of fuel and oxidizer to the engine. It must meet the following requirements:

1. The injector must deliver an atomized mixture of the fuels at a oxidizer-to-fuel mixture ratio of 2.8 ± 0.2 and a total mass flow rate of $2.7 \pm 0.4 \frac{\text{lbm}}{\text{s}}$.
2. The injector material must be compatible with both liquid oxygen and liquid methane and be ductile at temperatures of $-315°$F.
3. The injector will be designed to have a pressure drop of 70 ± 25 psi and survive pressure drops of up to 240 psi.
4. The spray of the injector should have an angle from normal of around $45°$ as a rule of thumb for pintle injectors.
5. The injector must fit inside the 4 inch inner diameter of the combustion chamber and mount to the thrust plate as well as the engine.
6. All structural components of the injector are designed to have a factor of safety of above 2.0
7. A water test must be performed on the final injector to determine discharge coefficient.

1.2.3 Feed System

The main purpose of the feed system is to provide flow of the fuel and oxidizer towards the injector in order to successfully static fire the engine. The second goal is to consider designing the feed system with rocket flight requirements such as mass and size. The requirements of the feed system must include both performance and safety needs. It must meet the following specifications:

1. All components of the feed system must be designed or sourced with a safety factor of at least 2.0 on all maximum operating pressures.
2. The fuel, oxidizer, and helium tanks must have relief valves rated for 1.25 times operating pressure.
3. The tanks must have vent valves rated at 1.5 times operating pressure. The vent valves must be remotely activated by manual switch at the control box.
4. The helium must have normally closed isolation valves while the propellant and oxidizer must have normally open vent valves valves. The vent valve must be at the top of the propellant and oxidizer tanks.
5. The feed system must prove remote controlled main valve open and close, remote controlled vents, and remote controlled pressurant on and off valve.
6. The feed system must have a pressurant tank pressure regulator and check valve.
7. The feed system must have propellant and oxidizer check valves upstream and downstream of the tanks.

8. The fuel/oxidizer tanks must be proof-tested to 1.5 times max operating pressure.
9. All components shall be tested for compatibility with cryogenic fluids before fire.
10. There must be a fill/drain port at the low point of the feed system.
11. There must be pressure transducers on the fuel tank, oxidizer tank, and the helium tank.
12. The feed system must deliver flow rate and mixture ratios as laid out in Section 1.2.2
13. Both propellant tanks must withstand operating pressures of 600 psi.
14. The lower feed system must withstand operating pressures of 600 psi.
15. The upper feed system must withstand operating pressures of 2200 psi.
16. All parts in the lower feed system must operate at temperatures as low as -320 °F.
17. All wetted components must be cleaned to the specifications laid out in ASTM G93.
18. All valves must be able to be activated remotely and be tested for functionality before fire.
19. All sensors must be able to transmit data to a safe location and be tested for functionality before fire.

1.2.4 Propellant Tanks

The propellant tanks safely hold the fuel and oxidizer for the static fire test both at atmospheric and operating pressure. The tanks are insulated to minimize boil-off of propellants prior to the test fire.
The propellant tanks must meet the following specifications:

1. The propellant tanks must withstand operating pressures of 600 psi at temperatures as low as -320 °F.
2. The oxidizer tank must be compatible with liquid oxygen.
3. The fuel tank must be compatible with liquid methane.
4. The propellant tanks must be compliant with ASME Boiler & Pressure Vessel Code Section VIII Division 1.
5. The propellant tanks must be manufactured by an ASME Boiler & Pressure Vessel Code certified manufacturer.
6. The propellant tanks will have minimum safety factors of 4.0 against yield, 8.0 against ultimate tensile failure, and 10.0 against leak-before-break.
7. The propellant tanks will be proof tested to 1.5 times maximum operating pressure.
8. The propellant tanks will be leak tested before installation into the static fire test stand and integration with the feed system.

1.2.5 Structure

The structure of the test rig must withstand the forces of the firing engine and securely hold the feed system during the firing and transportation to the test site. It must meet the following requirements:

1. All structural components must have a minimum safety factor of 3.0.
2. The welded thrust frame must withstand a 1000 lbf maximum force from the engine.
3. The test rig must be able to fit in a 10' x 10' x 8' U-Haul ® box truck.
4. The test rig shall have a load cell to measure the engine's thrust over time.
5. The structure shall securely mount all elements of the propulsion system to the I-beam provided at the test site.
6. The test rig shall have a blast plate wide enough to shield the rest of the rig from an explosion of the engine.
7. The structure shall provide easy access to all of the feed system components and sensors.
8. The test rig shall be easy to transport.

1.2.6 Ground Systems

The ground systems serve to provide essential data for the safety of the rig as well as relay information gathered by sensors on the rig. The following specifications must be met:

1. The ground systems shall measure pressure in the helium/fuel/oxidizer tanks remotely.
2. The ground systems shall measure pressure in the combustion chamber.
3. The ground systems shall monitor the quantity of propellants in each propellant tank during the fill procedure.
4. The ground system must have a Rocket Emergency Depressurization System (REDS) equipped to each tank and a separately wired REDS control box to depressurize the system in case of an emergency.
5. The values of the load cell will be read remotely at a frequency of 10kHz and with a resolution of 1 lbf.
6. Thrust sensing shall have an upper limit of 1000 lbf.
7. All temperature and pressure data shall be read at a rate of 10 kHz during the test fire, with resolutions of 1 °F and 5 psi respectively.
8. The ground systems shall transmit the required sensor data to the control bunker and store a backup copy onboard.
9. The ground systems shall display live sensor data on multiple GUIs for the operators in the bunker.
10. The ground systems shall control the actuation of valves in precise timed sequences, as well as allow for remote human operation.

1.3 Assembly drawing

All of the drawings are located in Appendix D and E.

1.4 List of sub-assembly drawings

1. Assembly Without Plumbing
2. 8020 Frame
3. Tank Assembly
4. Weldment Assembly
5. Injector
6. Bottom Plumbing
7. Upper Plumbing

1.5 List of detail working drawings

1. Assembly Without Plumbing Parts
    - Avionics Mounting Plate
    - Pneumatic Mounting Plate
    - Tank Mounting Plate
    - Level Sensor Mount
2. 8020 Frame Parts
    - Extrusion Framing
3. Tank Assembly Parts
    - Propellant Tank Cylinder Body
    - Tank Head
    - Foam Insulation
4. Weldment Assembly Parts
    - Weldment Tube (6)
    - Hinge Half
    - Thrust Plate Extension
    - Extension Extender
    - Tubing Solid Injector (2)
5. Injector Parts

- Thrust Plate
- Pintle Body
- Pintle Tip
- Reservoir

6. Bottom Plumbing Parts

   - Tube - Fill Valve to Out
   - Tube - Fill Valve to Tee
   - Tube - Main Valve to Out
   - Tube - Main Valve to Tee
   - Tube - Short
   - Tube - Tank to Tee Curved
   - Tube - Tank to Tee Straight

7. Upper Plumbing Parts

   - Top Mounting Sheet
   - 2 in Elbow
   - 2 in Straight
   - 4 in Straight
   - Tubing Into Tank

1.6 Ground systems functional block diagram

In the diagram below, the orange blocks are sensor subsystems, green is the control subsystems, and blue is data transmission and processing. Additionally, a key for the different types of interconnections is shown on the left side of the diagram. The sensors, top left, are all mounted on-board the engine, and relay their data through an op-amp filter to the microcontroller.

The control systems in the center of the diagram displays the various required on-board circuit components for valve actuation and ignition, as well as the software to control them. Additionally, the far right green box displays the capabilities of the bunker control box, used to control the valves remotely and monitor the their status. Lastly, the subsystems required to process and display the sensor data in the bunker are shown in the bottom box, connected to the various systems through ethernet.

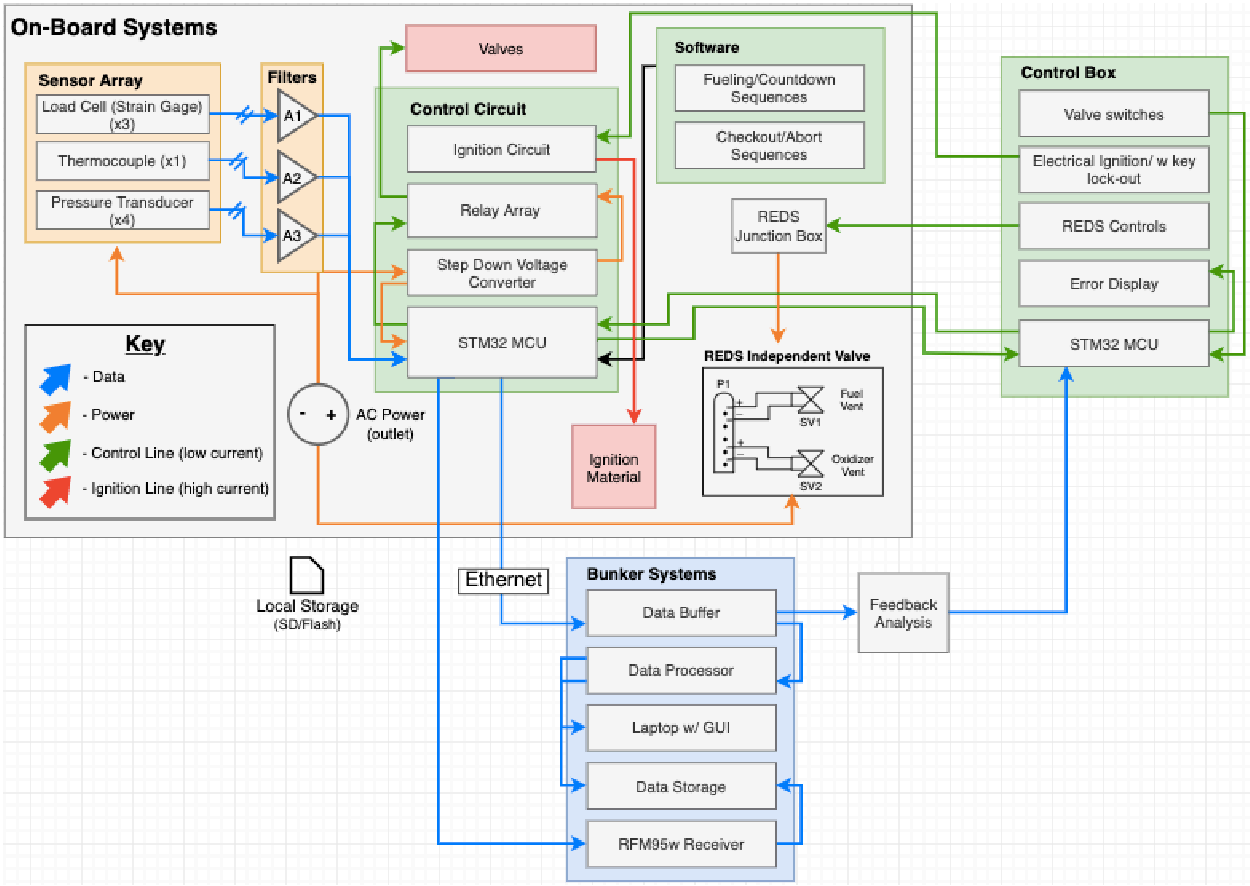


Figure 2: Block diagram detailing the components and interconnections of the ground systems

1.7 Ground Systems Circuit Diagram

The circuit diagram below outlines in more detail the composition of each subsystem and exact connections between each. The central component is the on-board microcontroller, which is connected to the sensors system through multiple ADC channels, and the valve controls system through GPIO. The exact pin names of each connection are given in the diagram. Additionally, the toggle switch and LED circuit on the control box in the bunker are shown in the lower left. Lastly, a functional diagram of the independent REDS system is shown in the bottom right, detailing the connections of each REDS component.

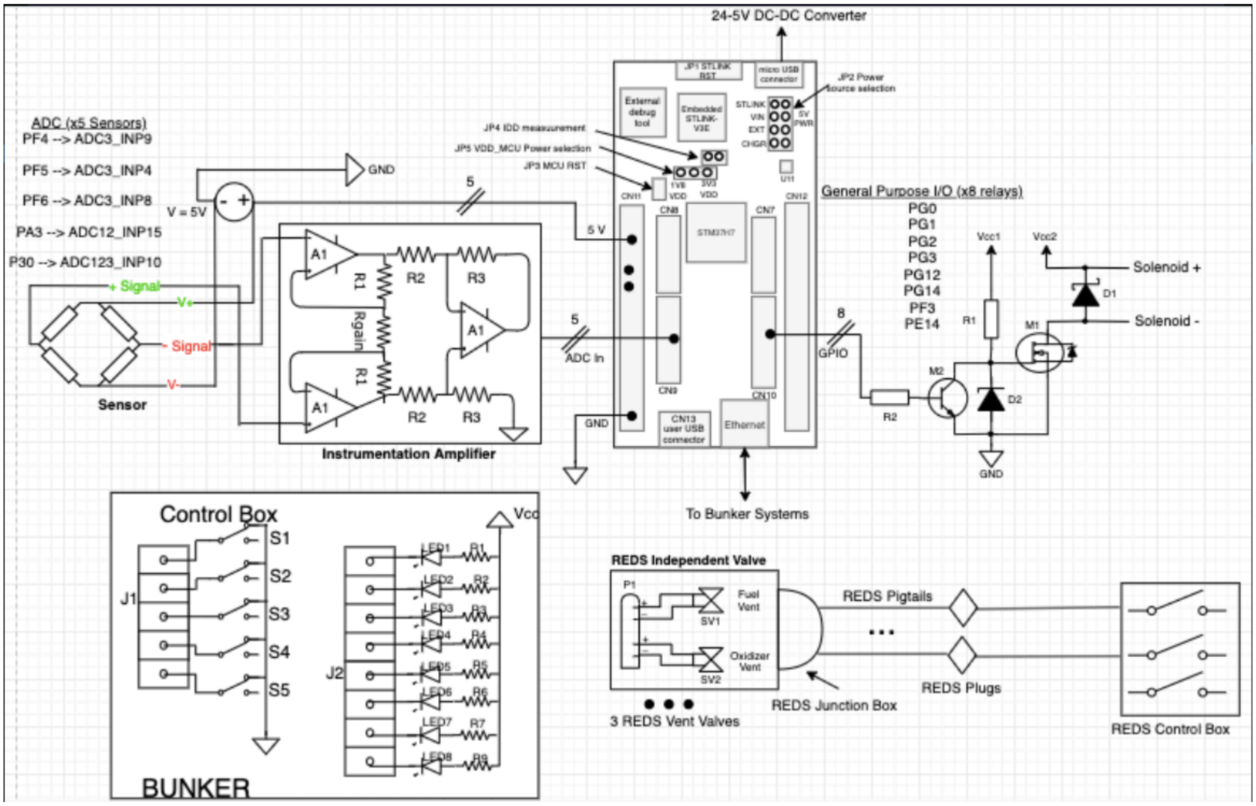


Figure 3: Circuit diagram of the complete ground system

1.8 Static fire operational flowcharts

The hot fire test will occur in five different phases, after the test rig has been installed and interfaced with ground systems in and around the bunker. These phases are as follows:

- **Chill**: using liquid nitrogen to cool down the components in preparation for the cryogenic propellants, then removing the liquid nitrogen
- **Fill**: loading propellants in tanks and feed system
- **Pressurize**: preparing the system for a test fire and releasing helium into the top plumbing
- **Fire**: feeding propellants through injector into the engine to ignite, generating thrust
- **Post-fire**: removing propellants and depressurizing the feed system, allowing for team members to approach the test rig and dismantle the assembly

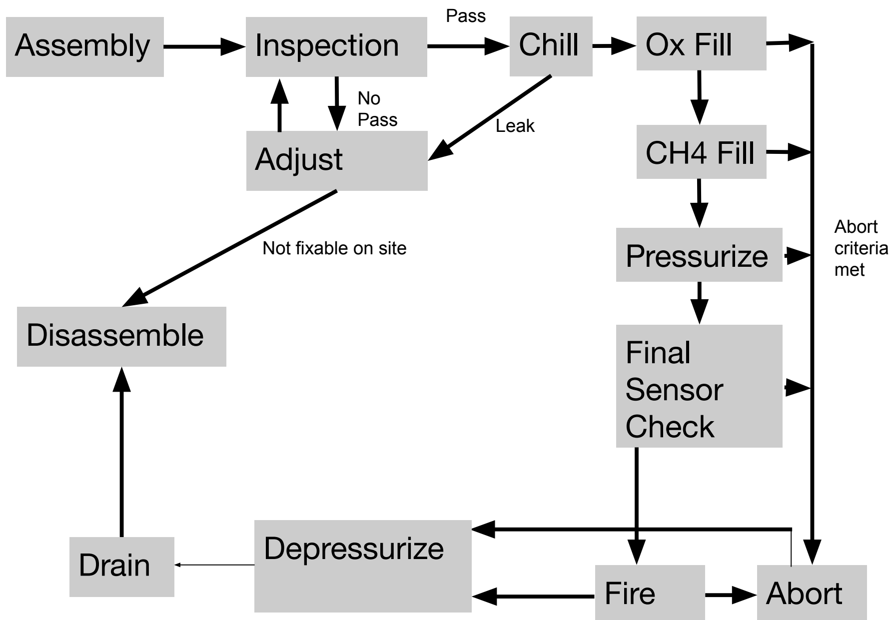


Figure 4: Block diagram showing test fire sequence

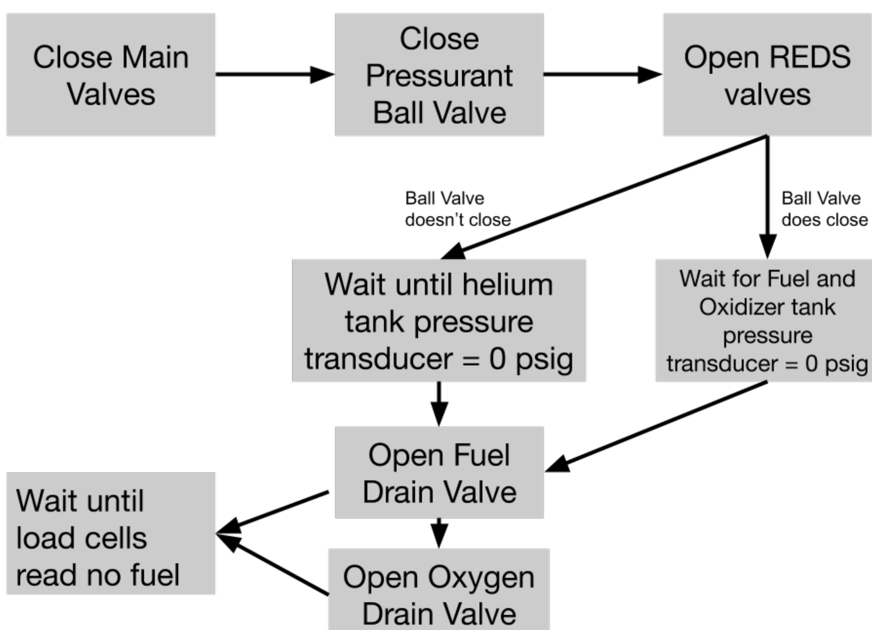


Figure 5: Block diagram detailing the block titled ”Abort” in Figure 4.

1.9 Budget and Bill of Materials

The Budget is in Appendix C, along with the Bill of Materials.

1.10 Schedule for completing fabrication and testing in spring quarter

WBS NUMBER	TASK TITLE	PLANNED START DATE 3/29/2020	PLANNED DUE DATE 6/12/2020
0	Propulsion	3/29/2020	6/12/2020
1	Main Deadlines	3/29/2020	6/12/2020
1.1	Test Deadlines	3/29/2020	6/12/2020
1.1.1	Ball Valve Functionality Tests	3/29/2020	4/5/2020
1.1.2	System Assembly	4/5/2020	4/13/2020
1.1.3	Subsystem Leak Test	4/13/2020	4/20/2020
1.1.4	Tanks Received+Full System Leak Test	4/20/2020	4/27/2020
1.1.5	Cold Flow Test	4/27/2020	5/11/2020
1.1.6	System Cleaning	5/11/2020	5/15/2020
1.1.7	Hot Fire	5/15/2020	5/21/2020
1.1.8	Data Postprocessing	5/21/2020	6/12/2020

WINTER QUARTER: WEEK 1, WEEK 2, WEEK 3, WEEK 4, WEEK 5, WEEK 6, WEEK 7, WEEK 8, WEEK 9, WEEK 10

2 Design and Analysis

2.1 Engine Design

2.1.1 Needs and Engineering Characteristics

A successful rocket engine will be low in mass and high in efficiency. The measure for the efficiency of an engine is ISP, the specific impulse measured in seconds, defined as follows.

$$ISP = \frac{F}{\dot{m}g} = \frac{v_e}{g} \tag{1}$$

Where F is the thrust of our rocket, $\dot{m}$ is the total mass flux of propellant, g is the acceleration due to gravity, and v_e is the velocity of our engine's exhaust gas. In order to maximise the efficiency of our engine, we will maximise the exhaust velocity to a reasonable degree, which involves the design of a converging-diverging sonic nozzle.
This sort of nozzle is well defined in literature. The section of minimum radius is known as the throat, and the right end is the exit of the nozzle. We know from [16][17] that the thrust of an engine can be defined by.

$$F = C_f A_t p_c \tag{2}$$

Where C_f, A_t, p_c are thrust coefficient, throat area, and chamber pressure. Assuming adiabatic and isentropic flow in the nozzle, we can write the thrust coefficient as.

$$C_f = \sqrt{\frac{2\gamma^2}{\gamma-1}\frac{2}{\gamma+1}^{\frac{\gamma+1}{\gamma-1}}\left[1-\frac{p_e}{p_c}^{\frac{\gamma-1}{\gamma}}\right]} + \epsilon\left[\frac{p_e-p_a}{p_c}\right] \tag{3}$$

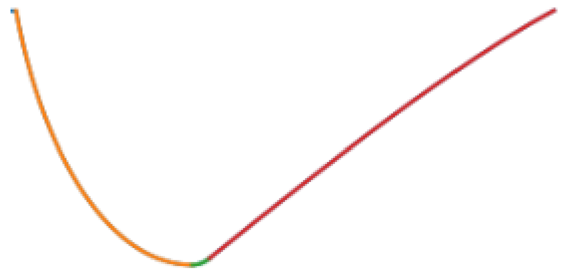


Figure 6: Breakdown of a bell nozzle

Where γ, p_e, p_a are the isentropic exponent, the exit pressure of our gas flow, and the pressure of the surrounding atmosphere. This gives us the throat area of our nozzle as per [16][17] . The same source provides a solution to the exit area A_e.

$$\frac{A_t}{A_e} = \frac{\gamma+1}{2}^{\frac{1}{\gamma-1}} \frac{p_e}{p_c}^{\frac{1}{\gamma}} \sqrt{\frac{\gamma+1}{\gamma-1}\left[1 - \frac{p_e}{p_c}^{\frac{\gamma-1}{\gamma}}\right]} \tag{4}$$

Having defined the important areas of consideration, we go on to define the full nozzle contour. It is defined by an 80 % bell nozzle, which is the industry standard for mass optimised performance. As per [18], it achieves 99% the efficiency of an optimal nozzle at 80% the length. We define the profile according to this bell nozzle, which is composed of an arc, another arc, followed by a bezier curve. [18]

Finally, we splice this nozzle onto a cylindrical combustion chamber of the same area as the exit area of the nozzle. The length of this chamber is defined by injector parameters.

Now that we have defined the ideal inner engine surface, we must begin to question whether this surface will be able to withstand the violent combustion that is occurring within the combustion chamber. The problem is split into two parts: thermally insulating the wall, and containing the pressure within the engine.

We have explored a wide design space of solutions to our thermal design requirements. The two main methods used in aerospace of solving the problem of thermal management are active cooling with channels in the walls through which the propellants flow, and the use of an ablative layer of material.

After extensive simulation, we decided that the cooling channel method is not feasible due to the difficulties of keeping cryogenic liquid from boiling in the cooling channels. The only way to address this problem would be to maintain the liquid methane at supercritical pressures, but this dramatically increases the weight of all aspects of our feed system. We have thus decided that the ablative cooling method is ideal for our purposes. This layer contains sacrificial material with a very low thermal conductivity which will undergo chemical reaction to remove heat from the walls. This chemical reaction causes the ablative material to become brittle at high temperatures and shear off, taking all of its absorbed heat with it as it exits the engine. We predict that this can keep our engine walls below 122 °F, well below the glass transition temperature of the resin used in our carbon overwrap.

As far as addressing the combustion pressure goes, the carbon overwrap can be easily designed to withstand the 350psi pressure within the engine. Carbon overwraps are notoriously effective at containing pressure and this case is no exception. We will be leaving the composite analysis to our manufacturer, CompositeX.

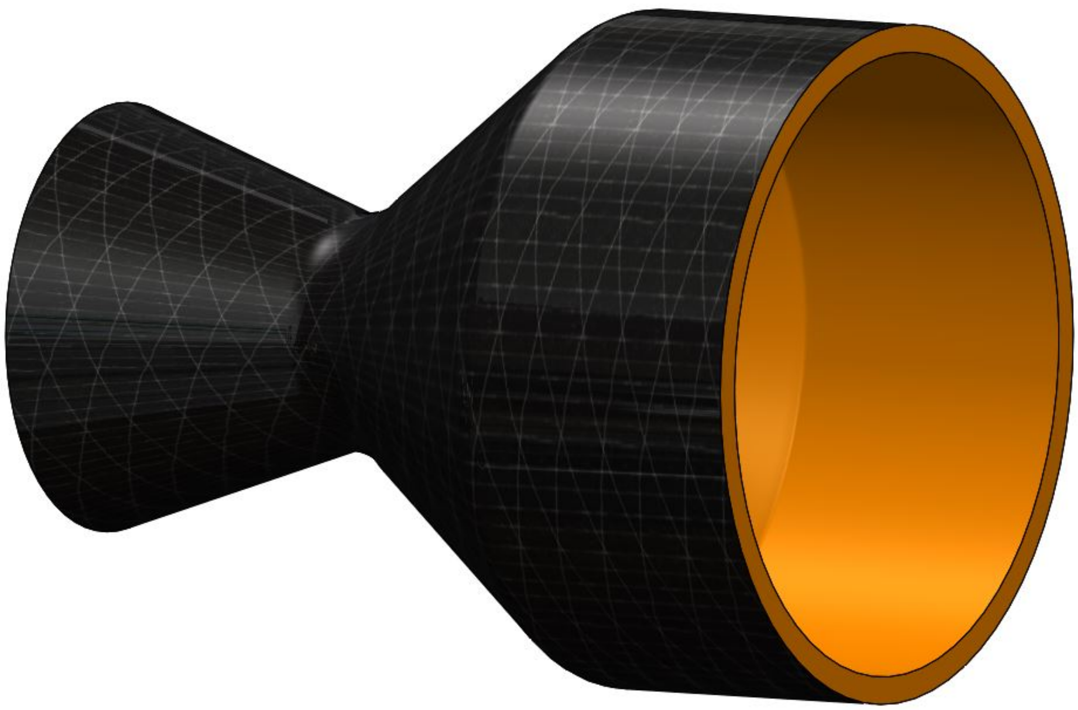


Figure 7: RPL-designed carbon-overwrap silica-phenolic ablative engine design

2.1.2 Concept

There are 3 concept engines that could theoretically satisfy all of these requirements. These engines are a regeneratively cooled inconel or steel engine, a carbon overwrap silica-phenolic ablative engine, or a thermally massive steel engine.

The regeneratively cooled engine transfers heat which entered the engine walls from combustion into the cryogenic liquid methane. It does this by running the liquid methane through the walls of the nozzle as the engine is firing. This increases the efficiency of your engine because, the hot methane entering the chamber will take less energy to combust. The downside of this engine is its complexity of design and weight.

The second method is light and cheap. This method of engine building produces a single-use ”throwaway” engine, but it is significantly lighter than its high-strength, high-thermal mass metal counterparts.

The last option omits the complexity of the regeneratively cooled engine design. The design process is also simpler because it requires no composites analysis.

2.1.3 Preliminary Design

The choice of a carbon-overwrapped ablative engine was easy. It is extremely low mass compared to other options such as an inconel engine, and is an industry standard for smaller engines.

Attempts were made at calculating the required ablative layer length. We were able to use empirically gathered data on the thermodynamic properties of Silica-Phenolic to predict temperature within the carbon overwrap. This produced an ablative layer thickness of 0.36 inches. However, after a discussion with CompositeX, an industrial manufacturer of similar engines, our layer thickness appears to be an underestimate in the throat region.

All of this lead us to our current design, shown in Figure 7.

Due to the discrepancies between this design and data from CompositeX, the final design has been outsourced. We have provided all the requirements based on calculations, but due to the difficulty and unpredictability of ablative layer degradation, they will have the final say. This opens up time to do more analysis on other parts of the system and thoroughly prepare for component testing.

2.2 Injector Design

The pressure drop across the injector should be 15%-20% of the chamber pressure (350 psi) to ensure combustion stability [1]. The pintle diameter is recommended to be between $\frac{1}{3}$ and $\frac{1}{5}$ the diameter of the chamber [2]. The ratio of skip distance to pintle diameter is recommended to be 1.0 [2]. The face plate must be wide enough to accommodate 1/4 NPT inlet threading.

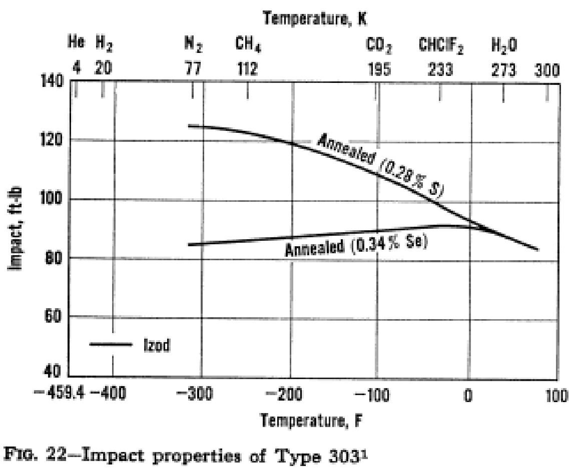
2.2.1 Material Selection

The injector material must be selected prior to creating any dimensions of the injector. Material selection is largely dependent on temperature. The average temperature of the injector is dependent on convection between the cryogenic liquids, the injector reservoir, and the hot combustion gasses. The convection coefficients for the fuel and the combustion chamber gasses are calculated using NIST data and Ted Bennet's "heatlib" code as shown in Equation (5).

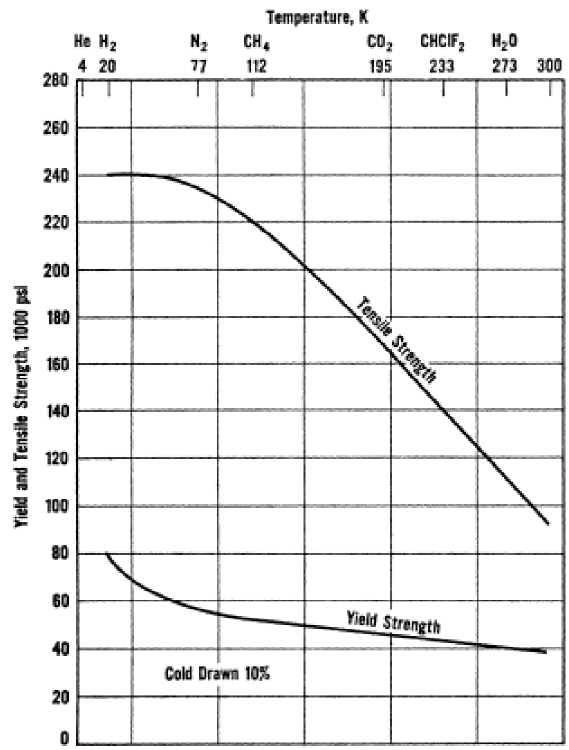
$$\frac{h_{\text{fuel}}}{h_{\text{chamber}}} \approx 100 \tag{5}$$

The liquid methane has a much higher density and flow rate than the hot combustion chamber gases, leading to massive differences in convection coefficients. The high ratio value causes the walls of the injector to be very heavily biased towards the temperature of the cryogenic fluid, so designs only need to account for those temperatures rather than temperature gradients. These thermal calculations were verified using a Solidworks thermal model. The model also determined that the heat flux across the final injector would be insufficient to boil the fuel.

With this in mind, Stainless steel 303 was chosen for its high yield strength and excellent impact durability at cryogenic temperatures. The property charts shown in Figure 8 show that its strength increases with falling temperatures, and that the material will not undergo a ductile to brittle transition during operation. It also has corrosive resistance with respect to the propellants that are being used. The strength used for the remainder of the analysis is 40 ksi which corresponds to its strength at room temperature. While the material has a higher strength at lower temperatures, the injector may be room temperature at the start of the fire, so it is necessary to calculate at the lowest strength.



(a) Impact properties



(b) Tensile properties

Figure 8: Stainless steel 303 properties

2.2.2 Flow Geometry

Now that the material is selected, the flow geometry can be defined. It should achieve the desired flow rate at the desired pressure drop. Pressure drop can be calculated for a certain orifice area and pressure across the orifice:

$$\dot{m} = C_{\text{d}} A \sqrt{2\rho \Delta P_{\text{inj}}} \tag{6}$$

where $\dot{m}$ is the mass flow rate of the fluid, C_{d} is the discharge coefficient, A is the total area of the injector orifices, ρ is the density of fluid, and ΔP_{inj} is the pressure drop across the injector. Using a pressure drop of 70 psi and a discharge coefficient (C_{d}) of 0.7 (determined from the water flow test) [6] the necessary orifice areas were calculated using Equation (6). To reach a momentum ratio of 1.0, which is recommended for maximum efficiency [3], the annular gap exit angle can be changed to solve the equation:

$$PR = 1.0 = \frac{p_{\text{lox}} * \cos(\theta)}{(p_{\text{meth}} + p_{\text{lox}} * \sin(\theta))} \tag{7}$$

where p_x is the momentum of each fluid.

This resulted in an oxygen gap of 0.021” and a methane gap of 0.024”.

2.2.3 Injector Part Design

To create these gaps while maintaining machinability, the injector was designed in four pieces: the thrust plate, the pintle body, the pintle tip, and the reservoir. The thrust plate takes the forces of the system and distributes them to the rest of the test rig. The pintle body and tip take in liquid oxygen through the thrust plate and eject it radially along the pintle tip. The reservoir takes in liquid methane through the thrust plate, distributes it around the reservoir, and ejects it axially along the pintle body. This allows the two fluids to impinge uniformly, then atomize into a combustible mist. The different regions are separated with the use of Teflon o-rings, and everything is held to the thrust plate using 4-40 screws.

Using the properties of stainless steel 303 at ambient temperatures, the minimum required wall thickness of a cylindrical body can be found using the pressure vessel equation:

$$t \geq \frac{\Delta P_{\text{inj}} D}{2 S_{\text{y,stainless}}} \tag{8}$$

where $S_{\text{y,stainless}}$ is the yield strength of stainless steel 303 at room temperature, D, is the diameter of the vessel body, and t is the desired thickness of the walls. The minimum thickness for a circular membrane under uniform load is given by Equation 9 which uses the same variables as before:

$$t \geq \frac{D}{4} \sqrt{\frac{3 \Delta P_{\text{inj}}}{S_{\text{y,stainless}}}} \tag{9}$$

Various parts of the pintle tip, face plate, and thrust plate were modeled as pressure vessels or circular membranes which informed their initial thickness. FEA was then done on the parts to verify parts strength, and increase it if necessary. The simulation inherently calculates the stress concentrations in the injector parts, which may not have been able to be calculated otherwise. Conditions were evaluated at the beginning of the rocket fire, where a 240 psi pressure drop exists across the injector and the stainless steel is at room temperature where it has the lowest tensile yield strength. Even with this worst case scenario, all components survive yield with a safety factor of 3.8.

All parts were modelled in Solidworks and then imported into COMSOL. They were subjected to 240 psi at room temperature. The models default to labelling stress in pascals, so the values were converted to ksi for all future analysis.

The thrust plate is machined from a 6 inch disc. This roughly matches the final diameter that it will have in the final rocket, and it is thick enough to easily withstand engine forces without deflection. Its main features are: inlet holes that the 1/4 NPT fittings screw into, rings of 4-40 through holes for mounting the pintle body and reservoir, and small steps for the reservoir and pintle tip to sit in - these guarantee concetricity of all parts. The plate has plenty of additive stress concentrations due to close holes, as well as due to the concentric steps. It was modelled in Figure 9a, resulting in a maximum stress of $\sigma = 7.0$ ksi corresponding to a safety factor of 5.8.

The pintle body has a few features: 8 4-40 tapped holes with sufficient depth to relieve screw thread stress concentrations and sufficient spacing to prevent deflection. O-ring grooves help seal the liquid oxygen channel. It has a diameter of 0.925" to match the $\frac{1}{3}$ to $\frac{1}{5}$ engine diameter specification on the injector. It sticks out of the reservoir by one of its diameter, conforming to design specifications. There is a central mounting point to attach the pintle tip. The pintle body is generally unstressed due to the high strength of pressure vessels. The one part that is stressed is the center cross where the tip is mounted. The tip exerts a lot of force, leading to stress in the threading and at corners. This center was modelled in Figure 9b, resulting in a maximum stress of $\sigma = 5.4$ ksi corresponding to a safety factor of 7.4.

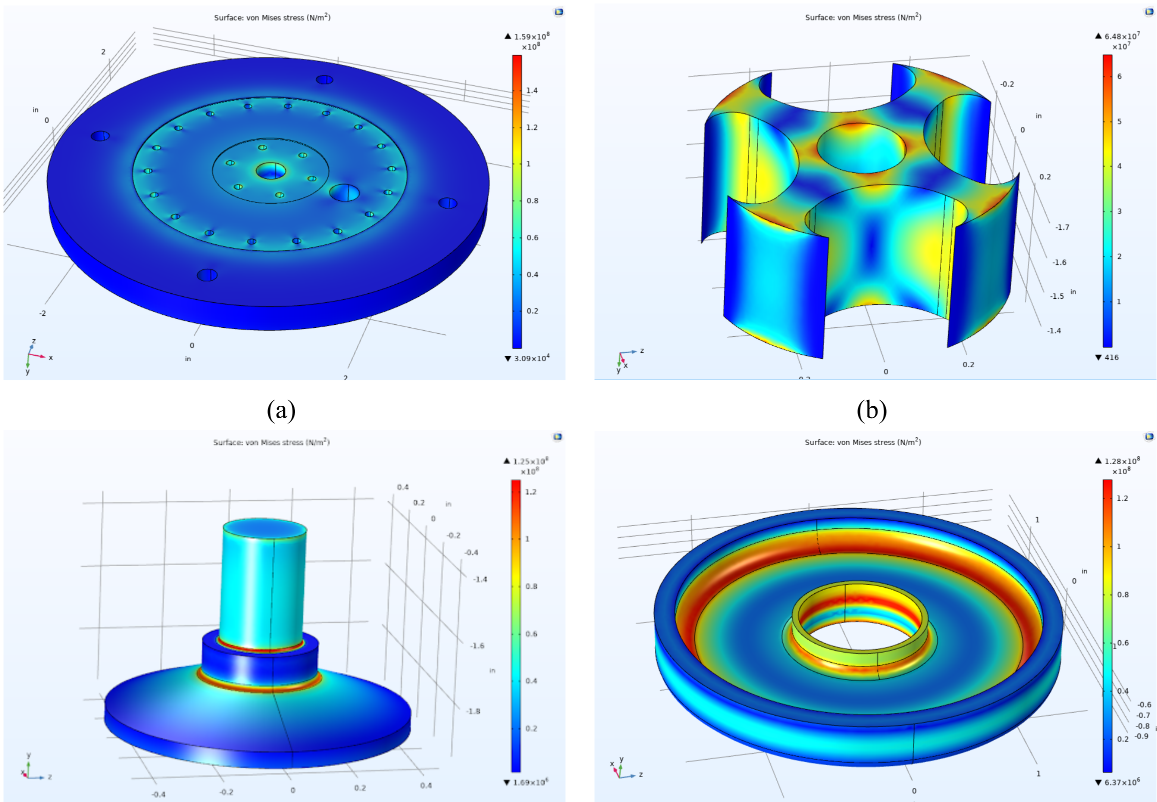
The pintle tip is mainly designed to match the dimensions of the pintle body while remaining rigid. It also forms the gap that oxygen flows through, which leads to extremely tight tolerances. To eject the oxygen at an angle, the bulk of the tip is sloped. It connects to the pintle body using 1/4-28 threading which also keeps it centered. Its strength is mostly an issue due to stress concentrations at corners and in the threading at its top. It was modelled in Figure 9c, resulting in a maximum stress of $\sigma = 10.3$ ksi corresponding to a safety factor of 3.9.

The reservoir's primary purpose is to create the gap for methane to flow through, so the tolerance on the inner ring is quite tight. However, it also needs to be wide enough to fit the 1/4 NPT fitting that the methane enters through. Therefore the reservoir ends up with an outer diameter of 3.740". Also within the reservoir are a ring of 18 4-40 tapped holes with similar specifications to the pintle body ones. A further similarity is the o-ring grooves that help seal the reservoir. The part is the most-stressed in the injector due to its large exposed surfaces. As such it is very thick, and has generous fillets to reduce stress concentrations. It was modelled in Figure 9d, resulting in a maximum stress of $\sigma = 10.6$ ksi corresponding to a safety factor of 3.8.

The bolts holding everything together need to resist the same pressure conditions as the other parts of the injector, but also need to prevent excessive deflection of the parts between the bolts. The equation for safety factor against yield is the following:

$$SF_{\text{yield}} = \frac{S_{\text{y,stainless}} N_{\text{bolts}} A_{\text{bolt}}}{\Delta P_{\text{inj}} A_{\text{inj}}} \tag{10}$$

where N_{bolts} is the number of bolts, A_{bolt} is the area within the minor diameter of the bolt, and A_{inj} is the flat area of the pressurized injector. A ring of 18 4-40 bolts made of 18-8 stainless steel was chosen due to the setup's high safety factor of 4.4 and the tight spacing preventing the the o-ring seal from breaking. This grade of stainless steel was chosen because it has a coefficient of thermal expansion very close to 303. These bolts are also readily available from McMaster-Carr.



(a) (b) (c) (d)

Figure 9: COMSOL analysis of injector parts

Teflon O-Rings were chosen as the sealing method for the injector as they are non brittle at cryogenic temperatures and are compatible with both oxygen and methane. The o-ring sizes were matched to the grooves. Sizing can be found in C.

2.3 Feed System Design

A pressure fed system that uses tank pressures to drive the fuel and oxidizer into the injector will be used rather than a pump fed system. This choice was made because a pressure fed system is ideal for a system that requires relatively low pressures and small quantities of propellants as our system does [8]. A pressure fed system is also simpler and cheaper than using a pump, since it eliminates all of the moving parts in a pump [8].

Helium will be used as the inert gas to pressurize the liquid methane/liquid oxygen feed system, rather than nitrogen, because nitrogen is miscible with liquid oxygen, while helium is not [9]. Nitrogen dissolving in the liquid oxygen would dilute the oxygen and reduce the engine performance [9]. Helium is non-combustible, non-flammable, and non-reactive at the temperatures and pressures in the feed system so it will not react with the cryogenic fuel and oxidizer. This Helium will run at 2200 psig in the upper section of the feed system before being down regulated to 540 psi and 460 psi by parallel pressure regulators PRREG-1 and PRREG-2 seen in Figure 11. These pressures are chosen to provide the correct flow rates and therefore mixture ratio necessary for optimal combustion, set out by the engine team.

Stainless Steel 316 will be the material used in the feed system and engine due to its proven strength in a low temperature, high vibration, and high pressure environment [10]. Stainless Steel 316 is preferable over Stainless Steel 304 since it provides higher corrosion resistance than Stainless Steel 304, while all of its other structural properties are the same [10]. Steel is also preferred over aluminum and titanium due to its much higher resistance to ignition in the presence of a vigorous oxidizer such as LOx [10].

2.3.1 Plumbing schematic

The static fire test rig consists almost entirely of valves, tanks, fittings, and sensors. Thus, all components of the propulsion system and its sensors are portrayed in the Piping and Instrumentation Diagram (P&ID) seen in Figure 11. When a component is referenced, for example a Pressure Regulator, it will have a Propellant, Function, and Numeric Designator, along with some valves having Valve Designators. When these components are referenced, they all reference Figure 11, unless otherwise specified.

2.3.2 Check Valves

Figure 10: Swagelok Stainless Steel Poppet 6000 psig Check Valve, SS-CHS8-1

The check valves allow flow to pass in one direction and automatically prevent backflow if fluid flow in the line reverses. The first check valves shall be placed upstream of the propellant and oxidizer tanks to prevent mixing from occurring in this region, see PRCK-1 & PRCK-2. The second set of valves will be placed downstream of each of the main valves to prevent potential combustion from flowing back into the tanks, OCK-1 & FCK-1.

Seen in Figure 10, the Swagelok Stainless Steel Poppet 6000 psig Check Valve will be used for the two upstream check valves PRCK-1 & PRCK-2. They are rated to 6000 psig, which has a safety factor of 10 on the pressure of 600 psig that the check valves are expected to experience. In the case of a Pressure Regulator Failure the safety factor on this check valve would be 2.7 on a max expected pressure of 2200 psig. It has a cracking pressure (the pressure at which the check valve opens in the forward direction) of 1 psig, which is well below the expected pressure of the fluid flowing in the forward direction. Finally, this valve is made

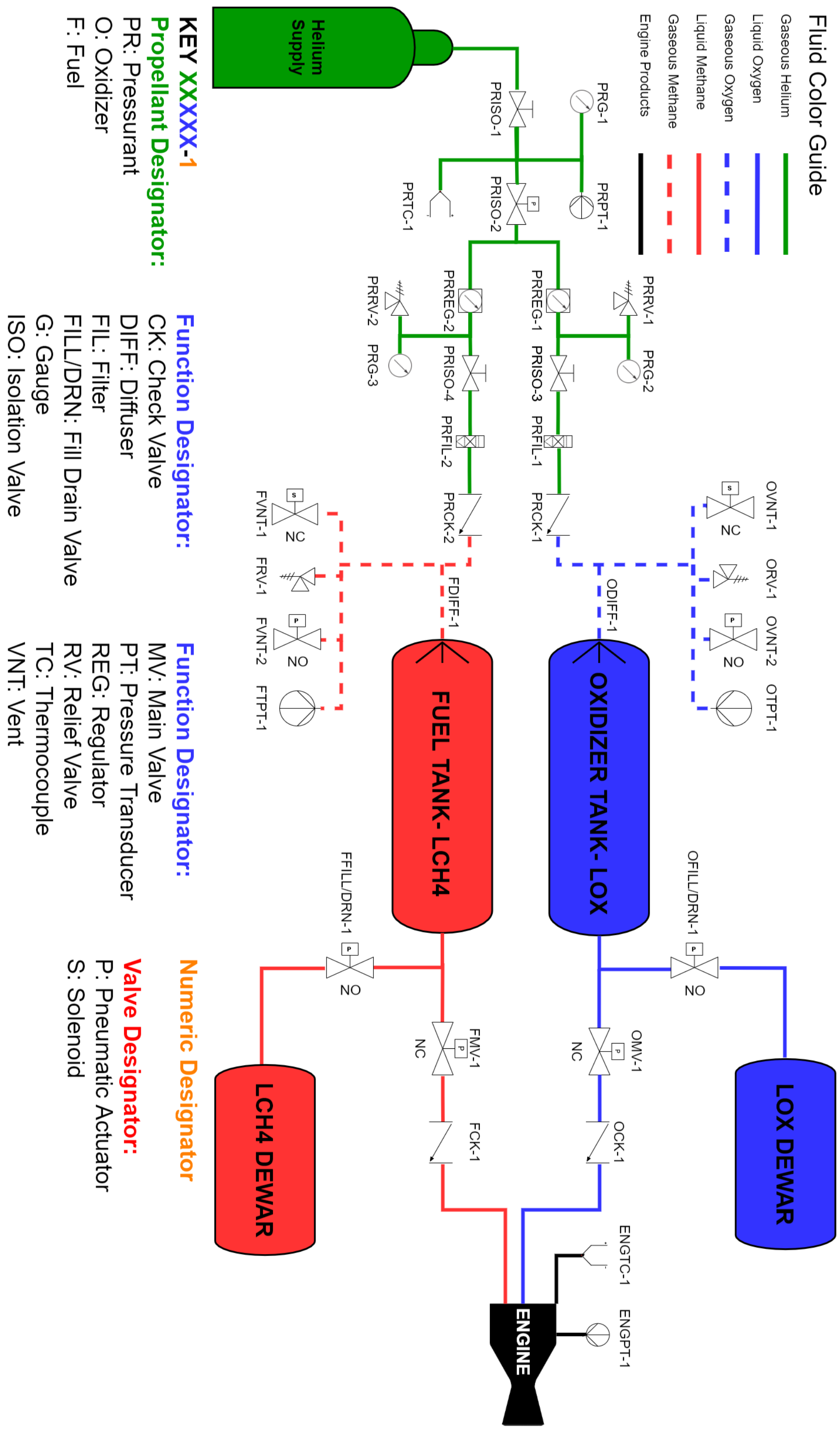


Figure 11: P&ID of the test rig during the static test fire, using liquid oxygen and liquid methane.

out of 316 stainless steel, Fluorocarbon FKM, and Polytetrafluoroethylene (PTFE).

Figure 12: Generant Cryogenic 4500 psig Check Valve, CV–500SS–T-3

Downstream of the Main Valves, Check Valves OCK-1 & FCK-1 will be Generant Cryogenic Check Valves. These check valves are designed for temperatures of down to -320 °F and a pressure of 4500 psig. This means it is well within operating temperatures and has a safety factor of nearly 10 on the methane line and a safety factor of over 8 on the oxygen line with respect to the expected pressure on each line.

2.3.3 Relief Valves

The relief valves will allow tank depressurization in the event of unwanted pressure build up. There are two relief valves on the pressurant line, PRRV-1 & PRRV-2, and two on the tanks, ORV-1 & FRV-2. The relief valves must have operating reliability to the pressure of the helium in case of a failure of the pressure regulator. The relief valves must be rated to low temperatures (-297 to -259 °F) on the tanks as well.

Figure 13: Swagelok Relief Valves with Cracking Pressure of 750 psig, SS-4R3A

PRRV-1 and PRRV-2 will be Swagelok Relief Valves and used when we calibrate the Pressure Regulators to their correct value. In the case of pressure build up, these relief valves will crack at 750 psi, which is 1.25

times the expected operating pressure in the line. These valves are also rated up to 6000 psig like PRCK-1 & PRCK-2.

Figure 14: Generant Relief Valves with Cracking Pressure of 750 psig, CRV-4-K-750

ORV-1 and FRV-2 will be Generant Cryogenic Relief Valves set to crack at the same 750 psig. The distinction between these and Swagelok is the fact boil off from the cryogenics in our tanks would flow through these relief valves so they must be rated to -320 °F. They work the same way as the Swagelok reliefs and act as an added safety measure over the vent valves.

2.3.4 Pressure Regulator

The pressure regulators, PRREG-1 & PRREG-2 will control the pressure downstream of the helium tank by reducing the pressure from 2200 psi to 540 psi for the LOx tank and 460 psi for the LCH4 tank. The risk of the PR failing drives the requirement of relief valves being capable of handling a purge of the helium system at its unregulated pressure.

Each pressure regulator is fed by an inlet pressure and reduced to a desired outlet pressure adjustable by a knob. However, for different flow rates, the outlet pressure could change significantly. Thus, a flow rate is maintained to ensure proper operating outlet pressures for all three valves. Temperature changes due to expansion of helium is negligible as calculated by modeling the regulators to be throttling valves under isenthalpic expansion. Below are the specification of the two regulators.

Propellant	Regulator Requirement	Cv	Part Number
Liquid Oxygen	2200 psi down to 540 psi	TBD	TBD
Liquid Methane	2200 psi down to 460 psi	TBD	TBD

2.3.5 Vent Valves

The vent valves on the propellant tanks will be Rocket Emergency Depressurization System (REDS) Valves, OVNT-1 & FVNT-1. These valves will be remotely activated in case of over pressurization while fueling the tanks. These valves remain normally closed and are powered by a solenoid. Since having a normally open vent is proper safety practice, we plan on using a ball valve with a normally open pneumatic actuator in case of a loss of power and pressure build up and would vent the flow outwards and in opposite directions.

2.3.6 Ball Valves

Figure 15: Sharpe C89 Cryogenic Ball Valves, 1/2” C89-6666-TTT-VB

The fill/drain valves will control the fueling procedures for all the tanks. This valve is pneumatically actuated and normally open in the case of power loss to allow draining of the liquids from the tanks into lines facing in opposite directions.

The main valve that controls the flow will be two normally closed ball valves. They shall allow flow into the injector when actuated. In the case of power loss the valves will close to force flow towards the fill/drain ports away from the combustion chamber. The current design uses Series C89 Cryogenic Ball Valves from Sharpe Valves.

In the case of ball valves in the upper plumbing, PRISO-1, -2, and -3, we plan on using swagelok ball valves. PRISO-2 will be the only pneumatically actuated, while 1 and 3 will be hand actuated.

2.3.7 Tubing & Fittings

Tubing was chosen over piping as the main path for flow. Tube systems have higher strength to weight ratio than pipes and have better flow characteristics due to their smooth inner surfaces which reduce fluid friction losses [11]. Tubing is cheaper than piping, easier to assemble and maintain, and performs better than piping in carrying fluids within a system. It can also be bent, further reducing head loss by allowing for smoother directional transitions. It reduces the risk of fire in cases where abrupt directional change causes large transfers of kinetic energy into heat.

Fittings provide location for quick disassembly, which is important in applications such as a test stand. Tube fittings are designed not to leak even in extreme conditions because they have mechanical metal to metal seals and minimize fluid entrance/exit head losses by having the same outer diameter as their tubing counterpart. Compression fittings are easy to assemble and disassemble and have incredible chemical/temperature flexibility. In areas where Swagelok tubing must interface with non-swagelok parts, we will use a Swagelok Compression-to-NPT fitting to connect our system together.

2.3.8 Pneumatic System

A pneumatic system will serve to control ball valves within the feed system and facilitate the timing of ball valve openings. As shown in Figure 16, the pneumatic system is comprised of five main components:

1. Air Compressor
2. Water Moisture Filter
3. Manifold
4. Solenoid Valves
5. Pneumatic Actuators

The air compressor will provide compressed air at 90 psi to the system. All air includes water, thus moisture is present in all compressed air systems. An air filter will be used to prevent any moisture from reaching the solenoid valves and potentially damaging them. The air will then flow from the air filter into the manifold, where it will be redirected into each of the five mounted solenoid valves. Solenoid valves, air will flow into the pneumatic actuators. By powering the solenoid valves on and off, the ball valves will then open and close.

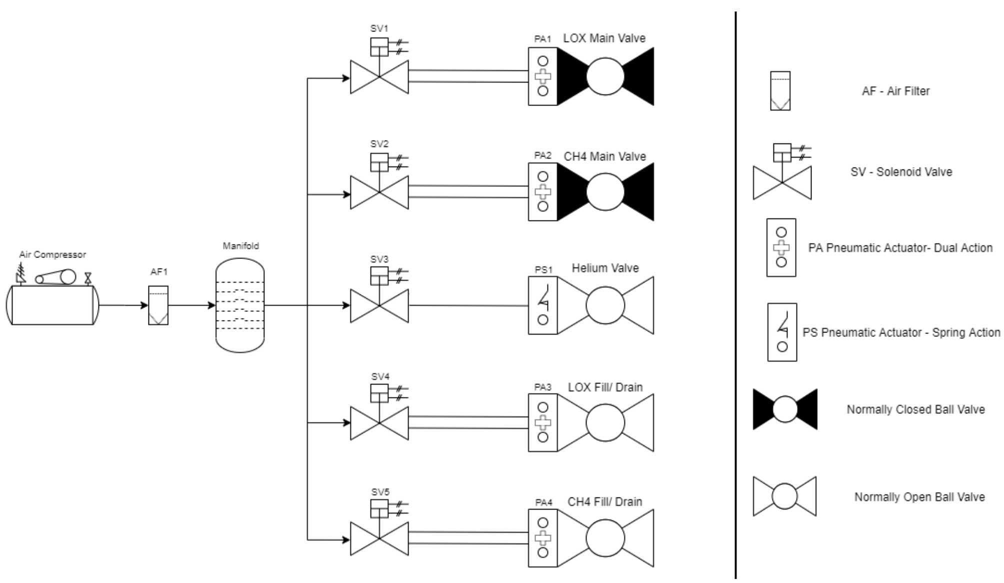


Figure 16: Diagram of the pneumatic system

The pneumatic system will incorporate a five way, two position solenoid valve, as depicted in Figure 17. This type of solenoid valve has one input port, which will take in compressed air from the air compressor in this system. There are two output valves that are directed to a dual acting pneumatic actuator. There are two exhaust valves as well. When the solenoid is not powered, compressed air will flow from the air compressor to the ”A” outlet port. ”B” will serve as an exhaust for air that is forced out of the chamber of the pneumatic system. When connected to a dual action pneumatic actuator, this will open a corresponding ball valve. When the solenoid is powered, compressed air will flow through the ”B” port and the ”A” port will act as an exhaust. This will cause the ball valve to close.

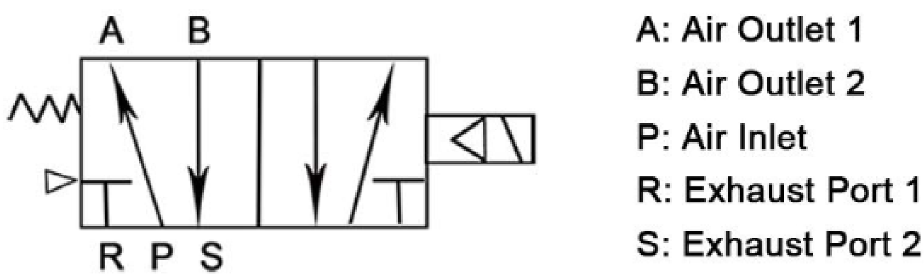


Figure 17: Solenoid valve flow diagram

The system will support one spring loaded pneumatic actuator as well. The solenoid connected to this actuator will only require one port of compressed air. Thus, this solenoid will have one of its output ports sealed.

The pneumatic system will enable the timely actuation of the following:

1. Liquid Oxygen and Methane Fill/ Drain Ball Valves
2. Liquid Oxygen and Methane Main Ball Valves
3. Liquid Oxygen and Methane Vent Valves
4. Helium Pressurization Ball Valve

2.3.9 Propellant Tanks

The propellant tanks are made of 4 components:

1. The cylindrical tank body
2. The 2:1 ellipsoidal endcaps
3. The Swagelok compression-weld fittings
4. The inlet diffuser

These parts all contribute to the overall integrity of the tank. The body holds the majority of the propellants, the end caps reduce stress concentrations by increasing curvature over a flat plate, the compression-weld fittings allow the tanks to interface with the feed system, and the diffuser prevents the helium pressurant from dissolving into the propellants during initial pressurization by spreading the pressurant jet into a fan shape.

To ensure high strength and fracture resistance at cryogenic temperatures, Type 304 stainless steel was chosen for the tank body and end caps. Type 304 stainless is also compatible with our propellants and the feed system, which is primarily composed of Type 316 stainless. Figure 18 shows the yield, tensile, and impact strengths of Type 304 over system operating temperatures. Both yield and tensile strengths increase as expected from room temperature to boiling point of oxygen (-297.3 °F). Additionally, the impact strengths are nearly equal at room and cryogenic temperatures due to the low ductile-to-brittle transition temperature of austenitic stainless steels (lower than -320 °F).

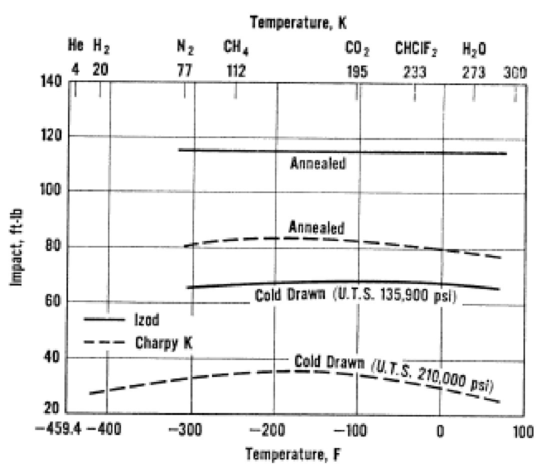
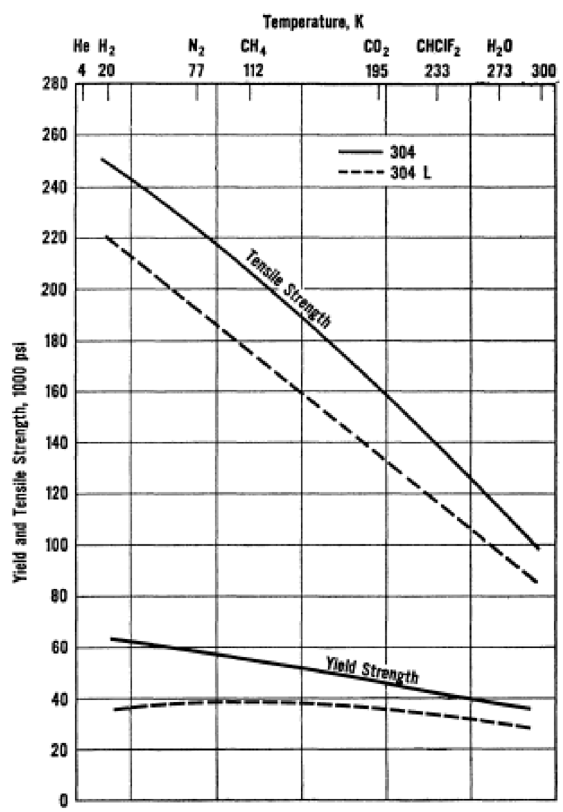


FIG. 23—Impact properties of Type 304[1, 8, 13, 18, 20, 25]

(a) Impact Strengths



(b) Tensile Strengths

Figure 18: Type 304 Stainless Steel Properties

The Swagelok fittings and diffuser will be made of Type 316 Stainless steel, which is similarly strong at cryogenic temperatures and compatible with the system. Both Type 304 and Type 316 are corrosion resistant to the propellants if cleaned to the proper standards before contact with either liquid oxygen or methane.

Another important consideration for tank manufacturing is the weld properties at joining sections. Austenitic stainless steels can become prone to stress corrosion cracking (SCC) without the correct weld metal. Selection of a filler metal with the proper amount of free ferrite will prevent SCC in the welded piece and improve the survivability of the tanks under pressure. There are three different welds in the tanks: Type 304 - Type 304 stainless at the tank body, Type 304 - Type 316 stainless at the fittings, and Type 316 - Type 316 stainless at the diffuser. These welds will require electrodes of Type 308, Type 309, and Type 316 stainless respectively to retain the correct amount of free ferrite.

The last property of welded austenitic stainless steels is intergranular carbide formation. Figure 19 shows the susceptibility to carbide formation of common austenitic stainless steels to Type 304. All tank materials and weld electrodes are equally or less susceptible than Type 304, which is commonly used in weldments due to its low carbon content of 0.08%.

Table 3
Relative Susceptibility of the Various Grades to Sensitization During Welding

	Grade	Commercial Analysis Range			Susceptibility to Intergranular Carbide Formation Compared To Type 304 (SEE NOTE 3)			Cause of Difference: Carbon Content Being		Cause of Difference: Ratio of Cr & Ni to C Being	
		% Chromium	% Nickel	% Carbon	Greater	Less	None	Higher	Lower	Higher	Lower
	304	18.0/20.0	8.0/10.5	0.08 max							
	302	17.0/19.0	8.0/10.0	0.15 max	X			X			X
	301	16.0/18.0	6.0/ 8.0	0.15 max	X			X			X
	305	17.0/19.0	10.5/13.0	0.12 max		Note 1			Usually X	X	
	308	19.0/21.0	10.0/12.0	0.08 max		X		Same		X	
Normal	316	16.0/18.0	10.0/14.0	0.08 max		Approximately the same as Type 304					
Compositions	317	18.0/20.0	11.0/15.0	0.08 max		Approximately the same as Type 304					
	309	22.0/24.0	12.0/15.0	0.20 max				X		Note 1	
	309S	22.0/24.0	12.0/15.0	0.08 max		X		Same		X	
	310	24.0/26.0	19.0/22.0	0.25 max	X			X		Note 1	
	314	23.0/26.0	19.0/22.0	0.25 max	X			X		Note 1	
Extra Low Carbon Compositions	304 L	18.0/20.0	8.0/12.0	0.03 max			Note 4		X	X	
	316 L	16.0/18.0	10.0/14.0	0.03 max			Note 4		X	X	
	347	17.0/19.0	9.0/13.0	0.08 max			Note 2				
Stabilized	321	17.0/19.0	9.0/12.0	0.08 max			Note 2				
Compositions	309 C	22.0/24.0	12.0/15.0	0.08 max			Note 2				
	318	17.0/19.0	13.0/15.0	0.08 max			Note 2				

Figure 19: Weld Properties of Austenitic Stainless Steels

The next design decision to be made for the tanks is shape, starting with endcaps. The three end cap designs considered were hemispherical, ellipsoidal, and flat, as seen in Figure 20 below:

Two hemispherical caps can be combined to make a spherical tank, which has the lowest mass for a given volume of fluid. However, a spherical tank will take up the most space on the test stand and is difficult to plumb given the curved surfaces. Spherical geometry is also difficult and expensive to manufacture, making it a less ideal solution.

Ellipsoidal end caps strike a balance between the manufacturing difficulty of spheres and added capacity over flat caps. They are still more expensive and complicated to manufacture than flat caps, and the added volume in the cap is equivalent to increasing the height of the center cylinder in a flat cap tank.

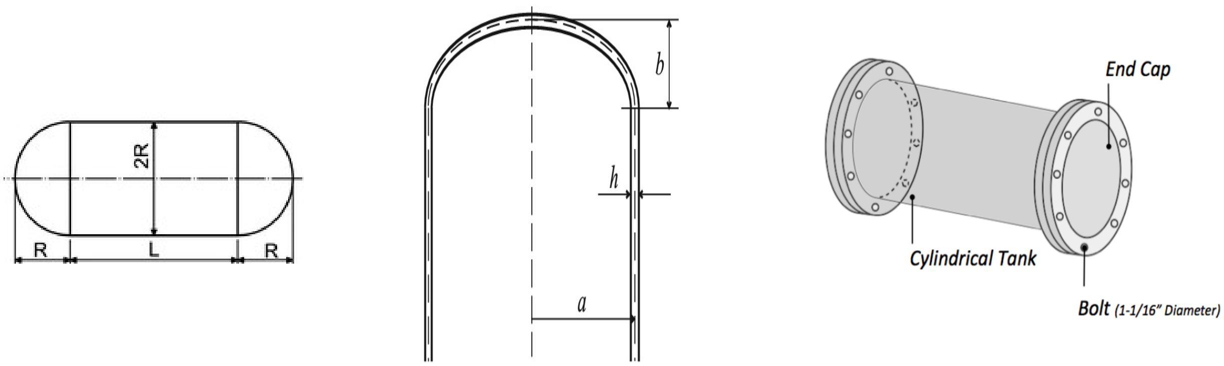


Figure 20: (Left to Right) Hemispherical end caps, ellipsoid end caps, and flat end caps

Flat end caps offer a few advantages: they are the cheapest design considered, simple to manufacture, and the lack of curvature allows for multiple ports for valves and plumbing. However, we found that the total weight of the tanks using flat endcaps was 380lbs. This is prohibitively heavy and simply adding branches to the main line attaching to the bulkhead of rounded tanks allows us to add incorporate several plumbing features to the endcaps. Ellipsoidal endcaps are thus the optimal choice for tank bulkheads in our system.

The next design decision to make in the development of our tanks is the thickness, radius and length of our tank body.

Equation 11, the expression for hoop stress in a thin-walled pressure vessel, was used to calculate internal stresses and safety factors in the propellant tanks.

$$\sigma_\theta = \frac{Pr}{t} \tag{11}$$

Additionally, the fracture toughness K_{Ic} at cryogenic temperatures was calculated using the Kussmaul-Roos equation (12) from yield strength and impact strength at the temperature of liquid oxygen. This equation takes in Charpy V-Notch impact CVN[J] and yield strength σ_y[MPa] and returns fracture toughness $K_{Ic}[\mathrm{MPa}\sqrt{\mathrm{m}}]$, which was then converted to $[\mathrm{ksi}\sqrt{\mathrm{in}}]$.

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 = 1.23\left(\frac{\mathrm{CVN}}{\sigma_y} - 0.0061\right) \tag{12}$$

These equations, along with the material properties of Type 304 and the tank dimensions, were used to calculate the safety factors against yield, ultimate tensile failure, and leak-before-break. To ensure operator safety and test success, these were set to a minimum of 4, 8, and 10 respectively. The calculated safety factors for each tank are presented in Table 1:
These are well in excess of ASME Boiler and Pressure Vessel Code Section VIII Division 1, which requires a safety factor of 1.5 against yield and 3.5 against tensile failure. With these high safety factors, the propellant tanks can be safely integrated into the static test-fire rig.

Failure Criterion	Liquid Oxygen 540 psi		Liquid Methane 460 psi	
	Room Temp	-297 °F	Room Temp	-258 °F
Yield	4.1	7.6	4.9	9.1
Tensile Failure	10.4	29.2	12.4	34.9
LBB	21.0	29.1	25.1	34.7

Table 1: Propellant Tank Safety Factors

2.4 Structure Design

The structure of the test rig must hold the feed system, tanks, injector and engine in place before, during, and after the static fire test. The structure consists of three main components:

1. The engine interface mounts the injector and engine to the welded thrust frame.
2. The steel welded thrust frame, or weldment, holds the engine and injector and attaches them to the I-beam at the test site.
3. The aluminum 8020 frame holds the feed system and attaches it to the I-beam.

The weldment and 8020 frame will be mounted on opposite sides of the I-beam. This allows both the feed system and engine to mount to I-beam and ensures that the feed system is as far from the engine as possible. To further protect the feed system, a 3 foot tall, 2 foot wide, 0.134 inch thick steel blast plate will be mounted between the weldment and I-beam.

2.4.1 Engine Interface

The engine interface consists of a thrust plate extension, hinge, and load cell, as shown in Figure 21. The thrust plate extension is a 12 inch tall, 8 inch wide, 1/2 inch thick steel plate, with a 4 inch hole in the center to which the thrust plate, that holds the injector and engine, mounts. The thrust plate extension is used, rather than simply extending the thrust plate, because the thrust plate has very tight tolerances for mounting the injector and engine and it is easier to machine those holes on a smaller circular plate than a large rectangular one. The thrust plate will be bolted to the thrust plate extension using four bolts evenly spaced around the central hole in the thrust plate extension. The exact placement and diameter of these four bolt holes is still to be determined since it depends on the specifications of the engine flange, which have not yet been determined by Compositex.

The bottom of the thrust plate extension is bolted to the hinge, which is attached to the weldment. The hinge is used to restrict the engine's motion to one degree of freedom so that the engine's thrust can be measured using a load cell. A 2 inch long, 1 inch diameter aluminum rod is bolted to the top of the thrust plate extension. This rod rests on the load cell, which is mounted at the top of the weldment. The hinge is mounted to the bottom of the weldment so that the engine can tilt downward during the chill down, which will limit the engine's exposure to cryogenic temperatures. The hinge is rated to 1,000 lbf, which results in a safety factor of 2.9, assuming that the hinge will support half of the engine's thrust, or 350 lbf. There are two holes at the top of the thrust plate extension which will be used to tie it to the weldment to prevent it from tilting before and after the fire.

2.4.2 Welded Thrust Frame

The welded thrust frame, shown in Figure 21, must be able to support the entirety of the engine's 1000 lbf maximum thrust. It is is 13.25 inches tall, 12 inches wide, and 7.5 inches deep. The weldment is built using 1.25 inch square low carbon steel tubes with 3/16 inch thick walls. The tubes are welded together so that the weldment will have higher strength to withstand the engine's vibrations during the static fire. The weldment is designed so that the engine's thrust will be divided equally between the horizontal tubes behind the load cell and the horizontal tubes behind the hinge.

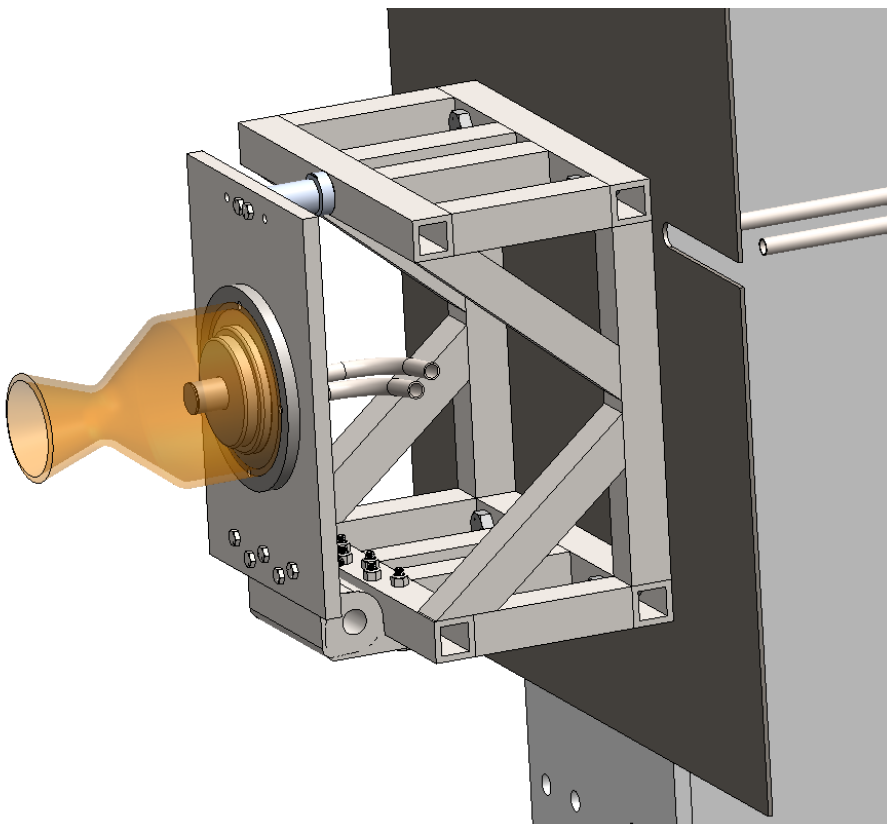


Figure 21: Model of engine interface and welded thrust frame

The top and bottom of the weldment each have four lateral members to support the compressive forces experienced when the engine fires. The center two members are immediately on either side of the load cell on the top of the weldment and directly behind the hinge mounting region on the bottom in order to minimize the bending moment created when the engine fires. There are two diagonal members on each side of the weldment to support any vertical and shear forces that the frame may experience. The hinge is bolted to the bottom front member and the load cell is mounted to the top front member of the weldment. The back top and bottom members will be bolted to the I-beam using two 9/16 inch bolts on each side. The bolts will be secured using locknuts to prevent the vibrations from the engine from loosening them.

The tensile yield strength of the steel tubes is 46 ksi. The greatest load that the weldment must support is the compressive force of the engine's thrust. This load is supported by the lateral members on the top and bottom of the weldment. Assuming that the maximum load of 1000 lbf is divided evenly between the 4 central members on the top and bottom of the weldment, the axial compressive stress in each member is 313.7 psi. This results in a safety factor of 147.

The longest compressively loaded members are the side diagonal members, which are 8 inches long. Assuming that one side of weldment tube (modeled as a rectangular bar with a 1.25 inch by 0.1875 inch cross section) is loaded with 250lb, the stress it experiences is 1066.7psi. The critical buckling load, calculated using the Johnson parabola, is 45.6 ksi. This results in a safety factor of 42.8. This calculation does not account for the other sides of the tube, which would help prevent buckling, so the safety factor is actually much higher. The safety factor for buckling of the 5 inch long lateral members is even higher since they are shorter. Thus, it can be concluded that the weldment will not fail in compression or buckling.

The weight of the engine, injector, and engine interface will be supported by the bottom diagonal members. This will create a shear stress and bending moment in these members. Assuming that the engine assembly weighs 40lb, the load is divided evenly between the top and bottom faces of each of the 2 tubes, and the side faces of the tubes are ignored, the bending moment in each member is 50 lbin. This creates a bending stress of 6826.7psi, which results in a safety factor of 6.7. This calculation also applies to the case of someone leaning on the top of the weldment with a force of 40lb. In reality, the sides faces of the weldment tubes support bending so the safety factor is much higher.

The 9/16 inch bolts that mount the weldment to the I-beam are 3 inches long, since they must go through the 1.25 inch thick weldment tube, the 0.134 inch thick blast plate, and 0.5 inch thick I-beam. This results in a 1.884 inch moment arm from the inner face of the bolt head to the nut. The bolts have a tensile yield strength of 120 ksi. If friction in the bolt is lost, the bolt shank will experience both shear and bending loads. Assuming that the weldment and engine assembly weighs 100 lb and an additional vertical force of 600 lb is applied is applied and that the load is divided evenly between the 4 bolts, each bolt experiences a shear stress of 396 psi and a bending stress of 18,869psi. This results in an equivalent stress of 18.9ksi using the maximum distortion energy theory, which results in a safety factor of 6.3. It is very unlikely that a 600lb load will be applied to the bolts, this would be like the engine firing nearly vertically, so this safety factor is very conservative. The worked out calculations for all of the previously discussed calculated values are shown in Appendix A.

To more fully analyze the stresses on the weldment, a finite element analysis of the top half of the weldment was performed, as shown in Figure 22. A load of 350 lbf, or half of the expected engine thrust, was applied to the load cell. Fixed boundary conditions were used at the interfaces of the weldment tubes, since it is assumed that the welded joints will be at least as strong as the parent material. Although the scale bar shows forces in metric, they were converted to imperial units for analysis. The maximum stress in the weldment occurs in the top horizontal tube behind the load cell at the interface with the central lateral tubes. This makes sense because this is the location of the maximum bending moment and a stress concentration at the 90 degree angle. The maximum stress was found to be around 2.6 ksi. Compared to the tube yield strength of 46 ksi, this produces a safety factor of 17.7. This high safety factor is preferred because it corresponds to a lower deflection during the test, leading to more stability and better data. The safety factor of the bottom horizontal tube behind the hinge will be even higher, since the load will be more distributed than at the load cell. Thus, it can be concluded that the weldment will be able to support the engine's thrust during the static fire.

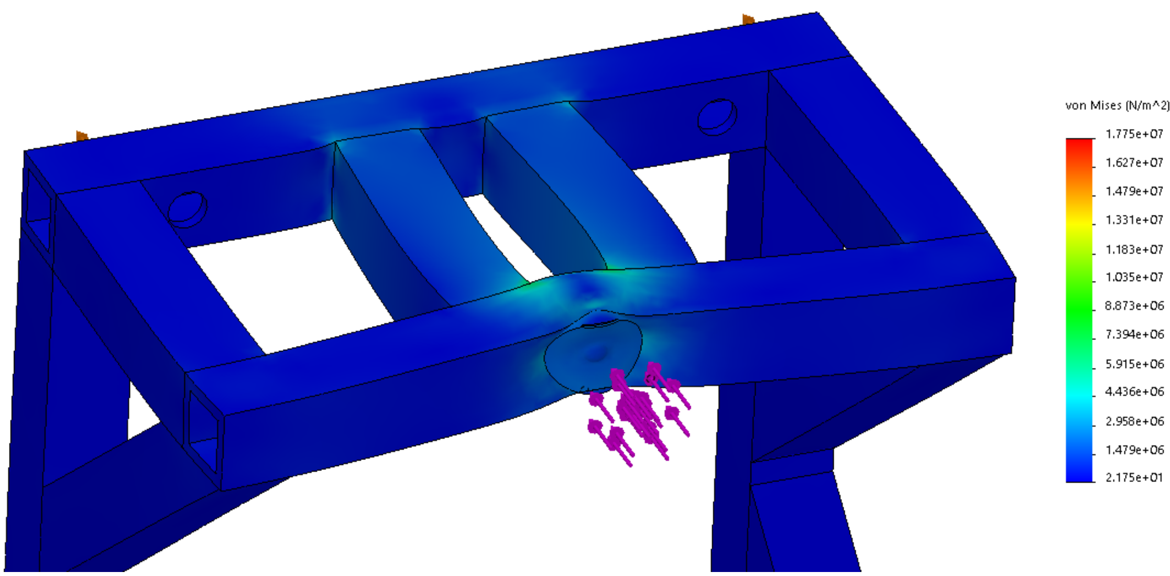


Figure 22: Solidworks FEA model of a the loaded weldment

2.4.3 Aluminum 80/20 Frame

The 80/20 frame, shown in Figure 23, is built out of 1.5 inch square cross section aluminum rails that are fastened together using 80/20 brackets and 5/16 in screws. The frame is 6 feet tall, 2 feet wide, and 2 feet deep in the bottom half and 9.5 feet deep in the top half. Aluminum is sufficiently strong for this frame because it will experience relatively small loads since it is isolated from the engine. 80/20 rails were chosen because they are standardized and easy to assemble and mount components to. All of the ninety degree angles between 80/20 rails are fastened using 80/20 corner brackets on all sides of the joint to support shear and bending loads, which will likely be experienced when the rig is transported. Shear and bending loads are further supported by 6 inch long diagonal corner braces along both axes at all corners that are not supported by a plate.

Locking castor wheels are bolted to the bottom of the frame to make it easy to transport and then lock in place at the test site. The frame will be attached to rungs on the I-beam using hose clamps. Double wide pieces of 80/20 are used to extend the frame towards the I-beam at the mounting points while maintaining sufficient clearance between the tanks and the I-beam. One of the double wide pieces is placed 9 inches from the top and the other is placed in the middle of the frame, about 2.5 feet from the ground. Two hose clamps

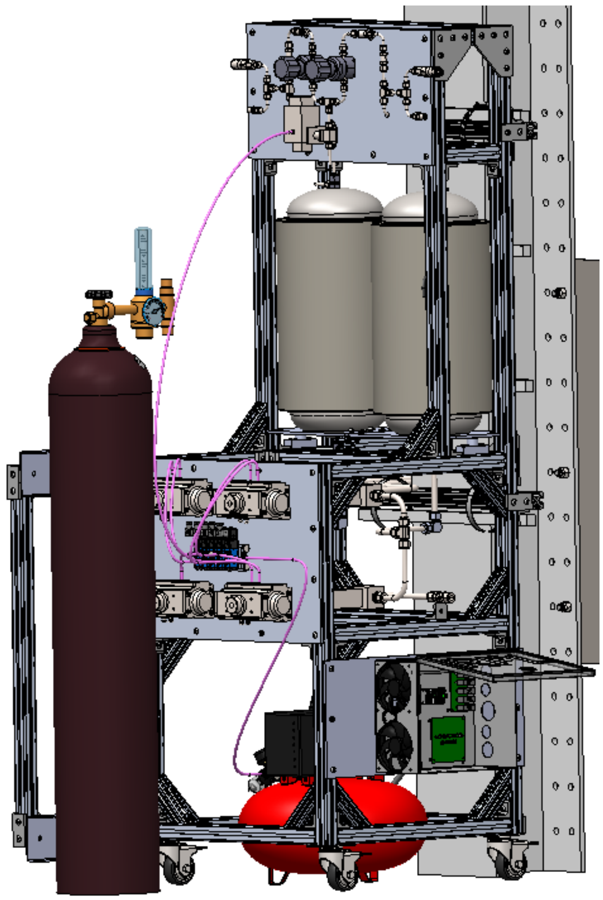


Figure 23: 80/20 frame and mounted feed system components

are attached to each of the double wide pieces, for a total of 4 attachment points.

The 80/20 frame creates separate regions to mount the plumbing components before and after the tanks. This is important because the conditions before and after the tanks are significantly different. The top plumbing before the tanks is at high pressure and ambient temperature, while the bottom plumbing after the tanks is at lower pressure and cryogenic temperature. The separate mounting regions eliminate the need for the top plumbing parts to be rated to cryogenic temperatures and the bottom plumbing to be rated to as high a pressure.

The top plumbing is mounted to a 2 foot wide, 1 foot tall, and 1/4 inch thick aluminum plate at the top of the 80/20 structure. The plate is mounted to the 80/20 rails using 5/16 in bolts and 80/20 nuts. The pressure control valve and any other heavy components will be bolted to the plate. The tubing will be mounted to the plate using P-clamps at several locations. The plate also has two holes for the tubing to route to each of the tanks.

If friction in the bolts is lost, the weight of the plate and top plumbing will create a bending moment in the plate with a stress concentration at the bolt holes. The aluminum plate has a tensile yield strength of 66 ksi. Assuming that the plate and top plumbing weigh 25lb, the plate can be treated like a beam supported by a pin on each side and the support from the 2 center bolts is neglected, and the weight of the plate and plumbing can be treated as a concentrated load at the center of the plate, the maximum bending stress at the bolt holes is 2.3 ksi. This results in a safety factor of 28.9. In reality, the bolts support bending moments so the plate is more like a double cantilevered beam and there are 2 central bolts supporting loads, so this is a conservative estimate. Furthermore, it is very unlikely that the bolts will lose friction under such a small load.

Each tank is mounted to a 11.75 inch wide, 9.5 inch deep, and 1/4 inch thick aluminum plate. Each plate is loosely bolted to a lateral 80/20 rail on the inside and rests on a load cell on the outside. The load cells are used to measure the level of fluid in the tanks as they are being filled. Each plate has a 6.5 inch diameter hole in the center for the tanks to rest in because the tanks have spherical end caps so they cannot lay on a flat surface. The plates also have filleted cuts at each outer corner in order to fit around the vertical 80/20 rails.

Each tank will weigh 80 lb when it is filled. This will create a bending moment in the plates that hold the tanks, with a stress concentration on the central hole. The tensile yield strength of the aluminum plates is 66ksi. Assuming that the tank and plate weigh 81lb, the plate can be treated like a beam supported by a pin on each side, and the weight of the tank can be treated as a concentrated load at the center of the hole which is in the center of the plate, the maximum bending stress at each hole is 9.1 ksi. This results in a safety factor of 7.2. The loosely bolted joints will support some moment, so this is likely a conservative estimate.

The bottom plumbing is located in the central part of the 80/20 frame, just below the tanks. A corner bracket is mounted to each of the lateral rails that are 2 feet from the bottom of the structure, to provide a support and attachment point for the fill/drain bulkheads. The pneumatic actuators are bolted to a 2 foot wide, 16 inch tall, and 1/4 inch thick aluminum plate at the front of the 80/20 structure. The plate is bolted to the 80/20 rails using 5/16 in screws and has a 2 inch square cut at its top left corner to fit around the lateral 80/20 rail. The pneumatic actuators have about the same weight as the top plumbing and this plate is taller than the top plumbing plate, so the safety factor for bending stress will be even greater than that of the top plumbing plate.

The 80/20 frame extends 15.5 inches on the front left side to provide an attachment point for the helium tank. The tank is strapped to the frame using two cylinder racks, one at the bottom and one near the top of the tank. The avionics box is mounted to a 2 foot wide, 11 inch tall, and 1/4 inch thick aluminum plate on the right side of the frame. The box has fans on one side and ventilation holes on the other to ensure that the electronics remain cool, and a front lid that opens to provide easy access to the components.

2.5 Thermal Analysis

Thermal analysis of our system is worth serious consideration due to the possible consequences of unaccounted thermal effects. Of these effects, boil off and freezing of our cryogenic propellants are being analyzed. Boil off within the feed system and propellant tanks is present throughout the entirety of the static fire test due to the inherent temperature differences when dealing with cryogenic liquids. Boil off can happen during the chill and fill procedures, which results in accumulating back pressure that may slow down fill time. Boil off may also occur throughout the feed system's plumbing during the static fire test, resulting in catastrophic mixture ratios. Additionally, the team faces the risk of freezing the propellants from prematurely filling post chill down, as a consequence from liquid nitrogen chilling the system lower than both propellants' freezing points. To take preventative measures we analyze the thermal properties of the liquids and compute thermal resistance networks to predict all thermal effects.

2.5.1 Insulation Design

The tank and feed system must insulate cryogenic liquids from heat transfer throughout the entirety of the static fire test. The tanks are wrapped in a 1 inch layer of insulation and a reflective mylar film, as shown in the Figure 25 below.

Figure 24: Tank and insulation

The feed system is wrapped in 1 inch styrofoam in the same manner and wrapped in a reflective mylar film.

2.5.2 Boil Off Analysis

The heat transfer rate can be approximated by calculating the tanks and feed systems total resistance to heat transfer due to radiation, conduction, and convection. The heat transfer rate for conduction, radiation, and convection can be calculated using Equations (10-12)

$$Q_{cond} = \frac{T_1 - T_2}{R_{cond}} \tag{13}$$

$$Q_{rad} = \frac{T_s - T_\infty}{R_{rad}} \tag{14}$$

$$Q_{conv} = \frac{T_s - T_\infty}{R_{conv}} \tag{15}$$

where $Q_{cond}, Q_{rad},$ and Q_{conv} are rates of heat transfer in J/s due to their respective modes, and $T_1 - T_2$ expresses the temperature difference and the are the temperatures at the surface and infinity are T_s, T_∞, respectively . The resistances due to conduction, radiation, and convection are $R_{cond}, R_{rad}, R_{conv}$, respectively. Because we are using mylar as a reflector with an albedo of 92% -97% around the tanks, we assume negligible heat transfer due to radiation. A secondary assumption is that the tank's thin wall has negligible resistance compared to the styrofoam insulation. Due to similarity, the total heat transfer rate can be expressed as the following:

$$Q_{total} = \frac{\Delta T}{R_{tot}} \tag{16}$$

where ΔT, and R_{eq} are the temperature difference and equivalent thermal resistance respectively.

For the tanks, the total thermal resistance to conduction is calculated by considering the thermal end caps and cylindrical body in parallel. The thermal resistance of an end cap is given by:

$$R_{ec} = \frac{\frac{1}{r_1} - \frac{1}{r_2}}{4\pi k} \tag{17}$$

where r_1 and r_2 are the inner and outer radius of the insulation, and k is the thermal conductivity of the styrofoam. For the main portion of the cylinder, the thermal resistance is given by:

$$R_{cyl} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi L k} \tag{18}$$

The tank's total resistance to conduction is extracted by solving the following equation for $R_{con,tot}$:

$$\frac{1}{R_{cond,tot}} = \frac{1}{R_{ec}} + \frac{1}{R_{cyl}} \tag{19}$$

The thermal resistance to convection is calculated by the following equation:

$$R_{conv} = \frac{1}{Ah} \tag{20}$$

where A is the surface area of the tank, and h is the convection coefficient due to a $2m/s$ crosswind. It was calculated by Ted Bennet's "heatlib" code. The total resistance R_{tot} of the tank to conduction and convection can now be calculated by:

$$R_{tot} = R_{conv} + R_{cond,tot} \tag{21}$$

Using Equation 17 within the constraints of our system, the total heat transfer rate across the tank is 160 ± 10 watts. The equations can also be applied to the pipes in the system. The pipes don't have endcaps, so their thermal resistance is neglected. Applying the equation again, the heat transfer rate across the pipe system is 26 ± 5 watts.

The heat into the system can be combined with thermal properties of whatever liquid is in the system. At atmospheric temperature with the tanks open and venting, liquid nitrogen evaporates at a rate of 7.5 lbm/h, liquid oxygen evaporates at a rate of 6.4 lbm/h, and liquid methane evaporates at a rate of 2.6 lbm/h. All these values have error bars of $\pm 10\%$. These values inform how much extra fuel we should put in to account for delay between filling and firing. The value of liquid nitrogen evaporation can also be verified during the boil-off test.

2.6 Ground Systems Design

The ground systems division will integrate all the electrical subsystems to provide a comprehensive control and testing system. Electronics and control systems are crucial for safely controlling the engine during testing and collecting data from the fire. Additionally, the data collected is crucial for receiving FAR approval to enter the rocket into the FAR Mars competition. Ground systems will also be responsible for designing an instrument enclosure for the on-board systems to regulate temperature and protect sensitive electronics from electromagnetic or other types of interference.

2.6.1 Controls Overview

The controls division main purpose is to provide electrical ignition during static fire, and control valve actuation for the rocket engine to adapt propellant and pressurant flow during different procedures. Additionally, controls is responsible for building and testing the Rocket Emergency Depressurization System (REDS), which is required by FAR as a safety standard that allows the propellant tanks to be vented in the case of over-pressurization and an aborted launch.

This physical command and control system consists of two parts: electronics in the on-board housing, including the microcontroller (STM32H7), relay array (Panasonic SSR) and power converters, as well as the control box manned by an operator in the bunker a safe distance from the test site. Details on the interconnections and communication protocol between these two systems will be discussed in Section 2.6.8: data transmission and processing. Additionally, controls is responsible for programming the various engine (valves) control sequences, and ensuring redundancies on all vital systems.

2.6.2 Valve Controls

The on-board microcontroller will be programmed with control sequences for timed actuation of internal solenoids for fueling, ignition, abort, and checkout sequences. These are the required available states of operation during the test, and with very fine margins of error for flow control, these sequences must be preprogrammed. This will help reduce the chance of error due to propellant buildup, or feedback through the plumbing system during static fire.

Based on our engines requirements, we will be actuating 6 valves, requiring 6 channels on the relay array. Due to the high power requirement (24 V, 1 A) of our load, the solenoid valves, we chose a high power solid state relay array for our system. To allow for independent actuation of the valves, each array is controlled by a separate GPIO (General Purpose Input/Output) pin on the microcontroller. By supplying 3.3 V from the microcontroller to the control pin of the relay arrays in a timed sequence, we can control 24 V across the output to actuate the valves accordingly. The activation of the control sequences will be triggered via a switch on the physical control box housed in the bunker with the operator, who will also have control of the remote ignition circuit and the REDS. When triggered, the on-board ignition circuit will supply a given voltage to trigger a solid model rocket, oriented such that it will ignite the propellant spray from the injector.

To ensure system functionality during operation, we are implementing a feedback system that will verify the state each valve is in (open/closed) and relay this information to the operator. Because the valves are controlled by two different elements, the electrically-actuated solenoid that controls the mechanical pneumatic actuator, two separate systems must be implemented to verify electrical and mechanical functionality. Limit switches mounted on the exterior of the pneumatic actuators will be triggered when the valves change state, sending a signal that will trigger the corresponding LED on the bunker control box. This will not only verify proper fluid flow for the operator during each sequence, but in case of a problem, can be compared with electrical feedback data on the solenoids to confirm whether its an electrical or mechanical problem.

2.6.3 REDS: Rocket Emergency Depressurization System

The Rocket Emergency Depressurization System (REDS) is an integral requirement of FAR for their rocketry competition, but also an essential safety feature for any rocket propulsion system. The system allows pressurized fuel and oxidizer tanks to be vented in the case of an aborted launch. Without a system to remotely vent these tanks, the rocket is unsafe to approach after static fire and could potentially explode due to pressure build-up. All of the REDS valves are rated to work at 24V, 1A, and will be hardwired separate from the rest of the valve control system [19].

1. Vent Valves
   - On pressurant and oxidizer tanks
2. REDS Plug
   - Connects the vent valves to the REDS Pigtail
   - Friction fit type plug
3. REDS Pigtail
   - Lower end will connect to the REDS Junction Box
   - Upper end will connect with the REDS Plug
   - Upper end will disconnect from REDS Plug during launch to sever the connection with the junction box to prevent an airborne hazard
4. REDS Junction Box
   - Signal relay from REDS Control Box
   - Holds down REDS Pigtail (connected via threaded clamshell or cannon-plug type connector)

5. REDS Control Box
   - The REDS Control Box allows the REDS Operator to arm, check and activate REDS as required. The REDS Control Box cannot close the vent valve.
6. REDS Power Supply
   - Must accommodate the voltage drop from the REDS Control Box to the REDS Junction Box.

The REDS requirements come directly from FAR, providing us with a baseline to design the hardlined system, and a list of required parts to use. The REDS Control Box (Figure 25) will be integrated with the ground systems control box so that all the operators controls are centralized.

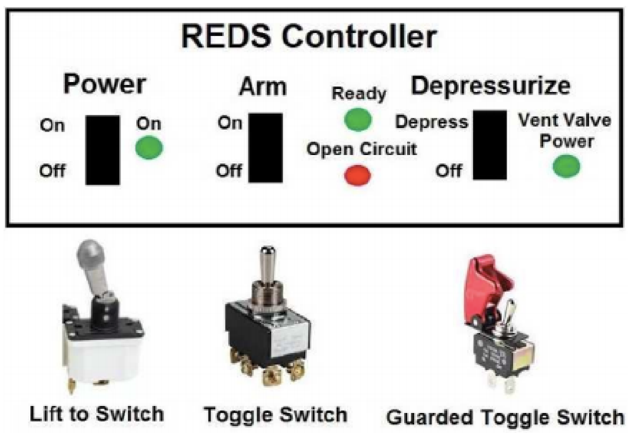


Figure 25: REDS Control Box

2.6.4 Control Box

The ground systems bunker control box will house the manual controls for the operator to manage valve control, ignition, REDS, and see status feedback on the feed system. The control box will consist of an interface of 11 switches for each sequence, valve control, and the ignition power, as well as the REDS control box system, LED indicators, and possibly a display for the error feedback system. It will house an independent system to relay the signals from the physical switch controls to the engine, as well as LED circuits to indicate each valves current state (open/close) and a circuit to control the error display screen.

The system will require another microcontroller that will relay the toggle switch signals and illuminate the feedback LEDs. While it may take more time to integrate a second microcontroller, our system would be far more capable, and reusable for the actual launch. The control box will be connected to the on-board systems via ethernet, due to its reliability over distance. As a stretch goal, we plan to integrate the sensor data and processing with the control box to create a feedback system capable of providing real-time error reporting allowing the operator to abort or adjust the launch. This could prevent damage to the engine due to an error during static fire, and would provide relevant data to the operator to monitor operation during static fire.

2.6.5 Sensors

The objective of the sensor array is to collect pressure, force, and temperature data on different points on the static fire rig throughout the different operation sequences. This is both to ensure that we don't see any irregular data values during the firing sequence, and to collect this data to present to FAR so that our rocket may qualify for the contest. Our sensor array will consist of eight analog sensors on our tanks and engine.

Our oxidizer and fuel tanks will each have one pressure transducer and one load cell. The pressure transducers will have a range of 0 to 1000 psig and will measure tank pressure via an oil standoff tube to ensure that we are at our target pressures for each tank. Our load cells will be below each tank, and they will weigh the tanks to measure the fuel level. These load cells have a range of 0 to 100 lbf, and they should be measuring between 40 and 50 lbf. This is due to the fact that each tank weighs 80 lbs and the propellants weigh 20 lbs per tank, but our fuel tanks will be partially suspended by a hinge that will absorb approximately half of the load.

Our pressurant tank will have one pressure transducer and the line going out from it will have one thermocouple. The pressure transducer will ensure that our helium pressure does not exceed the expected limit and it will monitor the rate at which the pressure decreases as the tanks empty. This pressure transducer will have a range of 0 to 2500 psig, which is ideal for monitoring the decrease in pressure. The thermocouple on the helium line will measure the rate at which the temperature of the helium decreases throughout the test fire. This helps us improve our design after the test fire, as a higher initial helium pressure will yield a larger change in temperature.

The engine will contain one load cell to gather thrust measurements and one pressure transducer to monitor the frequencies at which the chamber pressure oscillates. The load cell will use a hinge system, so it is expected to absorb half of the load due to the thrust of the engine. This load cell has a range from 0 to 500 lbf, and it is expected to take about 375 lbf during the fire. The pressure transducer in the engine will have a range of 0 to 500 psig, and it will operate at a faster sampling rate so we can analyze the frequencies at which the pressure oscillates in the combustion chamber.

2.6.6 Analog-to-Digital Converter

The ADC on the STM32H743ZI was selected to collect the pressure, temperature, and force data, because it has 20 channels per ADC, a CPU with 480 MHz, and adjustable resolution. Twenty channels is more than enough to collect data for all of our sensors, and a CPU with 480 MHz is well above our 10 kHz sampling frequency. The adjustable resolution also allows us to meet the 1 lbf, 1 degree Fahrenheit, and 5 psi requirements.

Based on the ADC input requirements signal amplification is required for all sensors. All the sensors being implemented consist of max outputs in mV, which is much less than the ADC's required input range of $0 \leq V_{in} \leq V_{ref}^{+}$ where V_{ref}^{+} must be greater than the negative supply of the ADC, but no bigger than the positive supply V_{DDA}. Now for simplicity purposes V_{ref}^{+} has been set equal to V_{DDA}, which is equal to 3.3 volts. In selecting this V_{ref}^{+} we allow for a maximum detectable voltage of $\frac{V_{ref}}{2^n}$=3.2 mV/bit, when the resolution n is 10 bits. These input requirements were much greater than our sensor outputs and step sizes as seen in Figure 26.

Sensor	Max output Voltage	Max sensor value	Step Value
FC23 Compression Load Cell	0.1 V	500 lbf	0.1 mV/lbf
FC22 Compression Load Cell	0.15 V	100 lbf	1.5 mV/lbf
M3021 Pressure Transducer	0.1 V	500 PSI	0.1 mV/lbf
M3021 Pressure Transducer	0.1 V	1000 PSI	0.1 mV/lbf
M3021 Pressure Transducer	0.1 V	3000 PSI	0.1 mV/lbf
Conax K-Type Thermocouple	3.474 mV	85 degrees Celsius	0.0409 mV/C

Figure 26: Output Voltage Step of each Sensor

We then selected the instrumentation amplifier shown in Figure 27 for it's high CMRR and adaptable transfer function. The derived transfer function for our the amplifier is $V_{out,amp}$ = (V_1 - V_2)(1 + $\frac{10kOhm}{R_g}$); where (V_1 - V_2) is the differential input cominig from the sensors, 10 kOhms is the sum of the 5 kOhm resistors seen in Figure 27, R_g is an external resistor used to set the gain, and $V_{out,amp}$ is the amplified output.

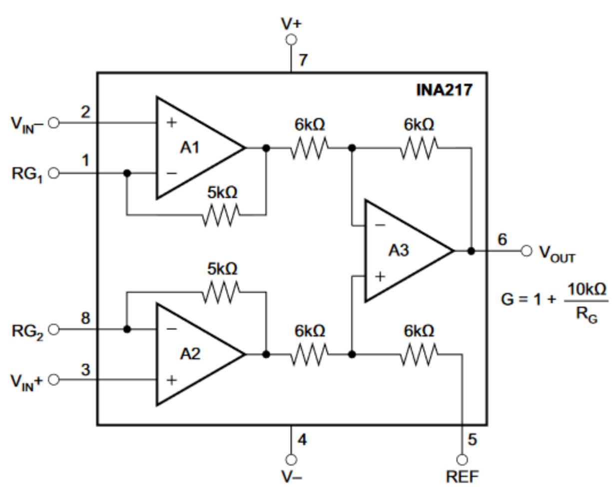


Figure 27: Instrumentation Amplifier Circuit Diagram

In order to calculate R_g, we need to have a known output and input, which we chose to be $V_{out,amp}$=V^+_{ref} and (V_1 - V_2) = Max sensor output voltage for each sensor. This works because V^+_{ref} is the max voltage that our ADC can take as an input, and we want this to correspond to the upper limit of the range we want to measure. We used this information for each sensor to calculate the gain and value of R_g for each amplifier. The corresponding values for gain, R_g, and the amplified voltage step are detailed in Figure 28.

Sensor	$(V_1 - V_2)$	R_g Max	G_{min} (V/V)	Amplified Step
FC23 Load Cell	0.1 V	312.5 Ohms	33	3.3 mv/lbf
FC22 Load Cell	0.15 V	476.2 Ohms	22	33 mv/lbf
M3021 Pressure Transducer	0.1 V	312.5 Ohms	33	3.3 mv/psi
M3021 Pressure Transducer	0.1 V	312.5 Ohms	33	3.3 mv/psi
M3021 Pressure Transducer	0.1 V	312.5 Ohms	33	3.3 mv/psi
Conax K-Type Thermocouple	3.474	10.54 Ohms	949.91	38.82 mv/psi

Figure 28: Gain, R_g, and Amplified Voltage Step of each Sensor

2.6.7 Sensor Implementation

The circuit diagrams are given in Figure 29. These were made based off of and analysis that was done assuming ideal components, so the prototype will be used to calibrate our sensors and see if any changes need to be made to these circuits. In order to perform the calibration we will first run the ideal version of the circuits, and measure some known quantity than compare it to the quantity outputted by our amplifier. Through the comparison and examination of the actual versus expected output, we will look at either compensating for the variation through the STM or changing of our design depending on the issue. Once properly calibrated we will begin to look at environmental effects like the length of the wire needed to reach the sensors to the STM, and surrounding temperature.

2.6.8 Data Transmission

The test rig is located about 100 feet away from the bunker. To acquire data from such distance, we decided to use an Ethernet cable and transmit data through TCP/IP Protocol. The data transmission flow is simple. First, ADCs on micro controller will scan through the bus and convert the analog input of the sensor to digital data and store the data on the memory. The bunker computer periodically sends TCP requests to the micro controller and acquires data in the memory. Once the data is sent, the micro controller will automatically clear its memory and store new data. All data sent by the micro controller will be stored in the bunker computer. Due to the large amount of the raw data that will be collected, it needs processing before it can be displayed on the graphical user interface. We only need to know the value of the reading for most of our sensors except for the pressure transducer. For those only requires value, readings will be displayed in the average of all the data collected in the previous packet. The pressure transducer on the combustion chamber, however, needs special data processing to get the pressure oscillation frequencies inside the chamber. Fast Fourier Transform will be applied to the data and only the three most significant frequencies will be shown.

2.6.9 Graphical User Interface

In order to monitor the status of the rocket, we need a user interface to display all the sensor data we collected. To better show different sensor values and status, we developed a 3 area chart system, which includes one bar diagram, one line chart, and one P&ID diagram to show different information.

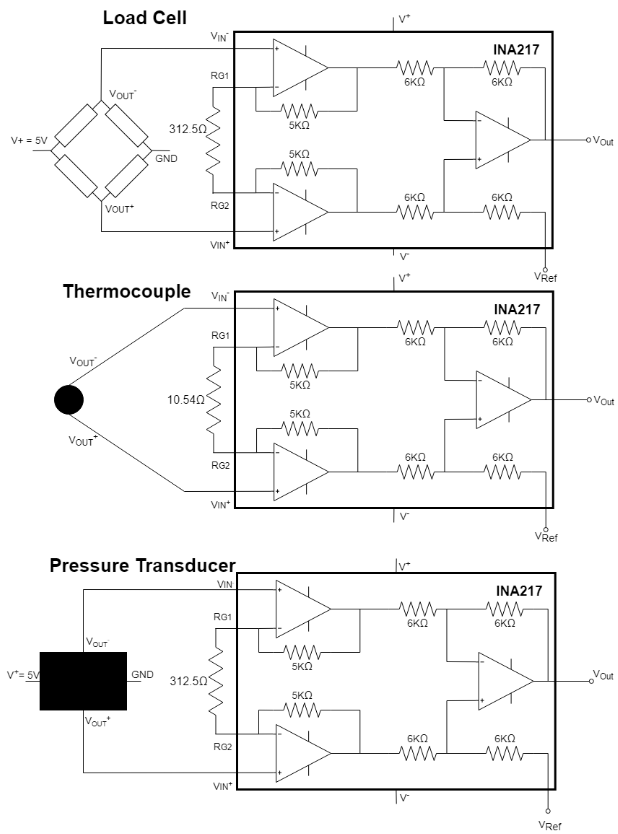


Figure 29: Circuit Schematic of each Type of Sensor and their Instrumentation Amplifiers

The bar diagram indicates the level of each sensor respect to the normal range of operation. The data displayed in the bar diagram is normalized and color coded so that if any sensor shows abnormal reading, it can be tell directly from the bar diagram. The line chart will show the data for each sensor in the last 1 minutes. This will allows team members in the bunker monitor the fill level in the filling process. The P&ID diagram shows the location of the sensor in the system as well as their status. With the P&ID diagram, it will be easier for the team to analyze the potential error in our system.

3 Prototypes and Testing

The very premise of this project is to validate the performance of our propulsion system by prototyping the components and testing the sequences used to operate the completed propulsion system. While some of these tests and prototypes have been completed already, many are to be completed in the Spring of 2020 and onward. Below is a brief description of each test conducted, and an accompanying Safe Operating Procedure (SOP) is included in Appendix B.

3.1 Injector Water Test

One of the defining characteristics of the injector is its discharge coefficient, which is a geometric property that indirectly determines the flow rate through each channel, thus determining the mixture ratio. It is of critical importance to obtain accurate discharge coefficients for each of the oxygen and methane channels, so multiple low-pressure water flow tests have been conducted to validate the dimensions of the injector. Additionally, the water flow tests can be used to validate the ideal spray angle from the injector.

The discharge coefficient can be calculated from the experimentally determined pressure drop across the injector and mass flow rate through each channel. This calculation can be done using Equation (22):

$$C_d = \frac{\dot{m}}{A\sqrt{2\rho\Delta P}} \tag{22}$$

where C_d is the discharge coefficient, $\dot{m}$ is the mass flow rate of the water, A is the total area of the injector orifices, ρ is the density of water, and ΔP is the pressure drop across the injector. Since the discharge coefficient depends only on the geometry of the injector, the experimentally determined value can then be used to calculate the mass flow rate of fuel and oxidizer through the injector. This is important to confirm that the injector will supply the correct flow rates to the combustion chamber during the static fire.

An aluminum prototype of the injector was created in order to conduct the water flow test. Aluminum was used for the prototype because it is much easier and cheaper to machine than stainless steel and the injector has many parts with very tight tolerances. The injector will be manufactured completely in house, so the aluminum prototype also served to prove that the tight tolerances can be achieved in the UCSB machine shop.

The flow test consists of three main parts: a test of the flow through the fuel side of the injector, a test of the flow through the oxidizer side of the injector, and a test of the flow through both sides of the injector simultaneously. A pressurized water source is connected to each inlet of the injector. A pressure transducer is integrated into the injector inlet to obtain the pressure drop through the injector to the atmosphere. The mass flow rate of the water is measured for each of the steps by weighing the water output by the injector over a measured amount of time. This is a simple yet accurate method of measuring mass flow rate. Multiple trials were conducted and the pressure and flow rate results were used to obtain the discharge coefficient for each fluid channel. In the last part of the test, the flow from the fuel and oxidizer outlets was visually inspected to confirm that the correct impingement pattern was achieved. A hydraulic diagram of the test set up is shown in Figure 30. An SOP for the flow test is shown in Appendix B.

The average mass flow rate through the fuel side of the injector was 0.848 lbm/s with an average pressure drop of 11.27 psi. This resulted in a discharge coefficient of 0.69 for the fuel channel. The average mass flow rate through the oxidizer side of the injector was 0.882 lbm/s with an average pressure drop of 11.72 psi. This resulted in a discharge coefficient of 0.70 for the oxidizer channel. The optimal discharge coefficient is 0.7 for both channels, so these test results confirm that the injector design is correct. Now that the discharge coefficient has been determined, the final stainless steel injector will be machined in the Spring of 2020. A final flow test will be conducted on the this injector, to confirm that the discharge coefficients are correct.

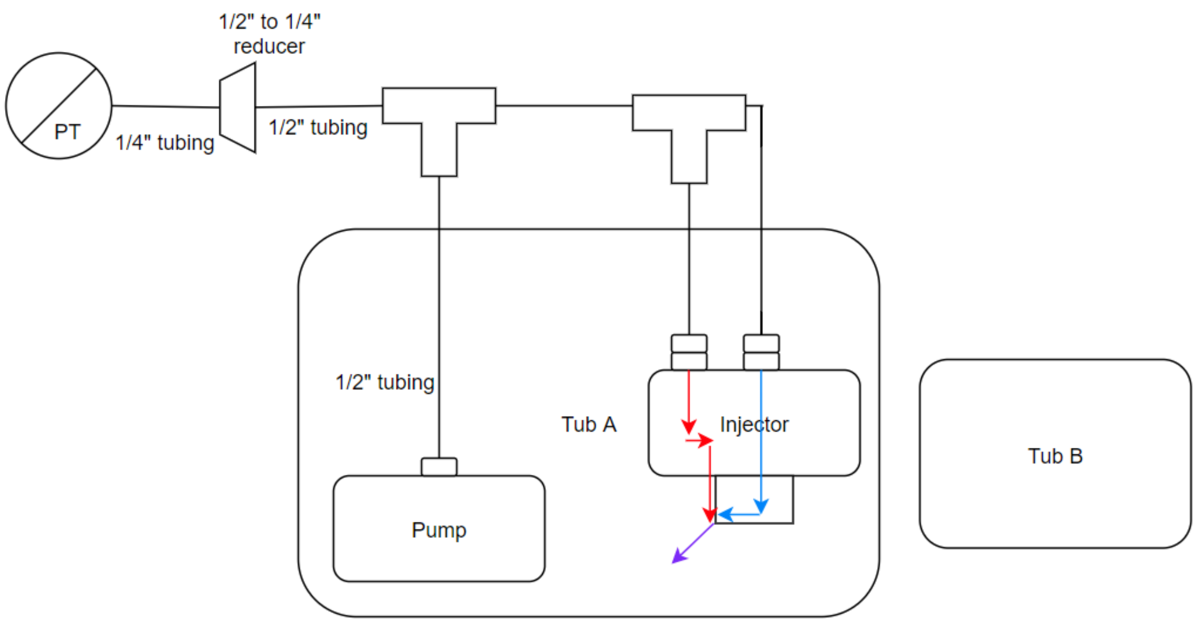


Figure 30: Flow Test Hydraulic Diagram

3.2 Pneumatic System Test

To ensure our pneumatic system can interface with the rest of the ground systems, a pneumatic functionality test will incorporate the air compressor, solenoid valves, and pneumatic actuators, as well as the GUI and the avionics control box.

The air compressor will be connected to the manifold, which interfaces with the solenoid valves that control the pneumatic actuators which actually turn the valves. The solenoid valves will be connected to the avionics system to electrically actuate the solenoids. Additionally, limit switches attached to the actuators will serve to provide confirmation that the actuators have opened or closed, and will give valuable actuation time data.

3.3 Valve Functionality Test

To add onto the pneumatic functionality test, the fluid control valves will be incorporated to the pneumatic system and the ground system to verify valve actuation capabilities at room temperature. Cold actuation tests will be conducted as part of the tank boil-off test.

3.4 Feed System Leak Tests

Before the feed system is completely assembled and tested with liquid nitrogen, various subsections will be filled with water and pressurized to examine any leaks between fittings or valves. If no leaks are found immediately, a subsequent leak test with pressurized helium will be conducted, and the helium pressure will be monitored for any slower leaks.

To better identify leaks in fittings and valves, the feed system will be leak tested separately in four different modules. Each module will have open ends plugged, with the exception of the port used to fill the module with water and pressurize. When the module has been filled, it will be pressurized with a pump up to 100 psi, and the fittings will be monitored for water leaking to the outside of the feed system. If no water leaks, then the module will be drained, dried, and filled with helium pressurized to 100 psi. A transducer will monitor the pressure inside the module, and if it drops by more than 1 psi in 5 minutes, the fittings will be examined for gas leaks using a soap-water leak detection solution. If components continue to leak despite reattachment and repair, they will be replaced with spare components and the test will be repeated.

3.5 Propellant Tank Proof Test

Before the tanks may be incorporated into the test rig, they must be proof tested past their expected operating pressures to ensure safe operation during subsequent tests. The tanks will be filled with water and pressurized at a third party facility in accordance with ASME Boiler and Pressure Vessel Code.

3.6 Level Sensing Calibration Test

Once proof tested, the tanks can be incorporated into the test rig, along with the feed system and the level sensing load cells. The level sensing configuration will be tested and calibrated by gradually filling the tanks with water and monitoring the load cell response for various known quantities of water. Multiple trials will be conducted to establish reliable operating ranges.

3.7 Liquid Nitrogen Tank Boil-off Test

Once all components have been tested as laid out above, a tank and downstream plumbing boil-off test must be completed. This test will use Liquid Nitrogen to fill our tanks through our downstream plumbing. Once the tanks are filled, we will time how long it takes for the Nitrogen to either boil off completely or after 3 hours measure the mass of the fluid left. This test will help characterize the boil-off rate of fluid in our system and confirm our components' compatibility with cryogenics. This test occurs with no active pressurization and also would be our first handling of cryogenics in a test setting, increasing our experience with these temperatures prior to a cold or hot flow.

3.8 Liquid Nitrogen Cold Flow System Test

A crucial test prior to the static fire is a cold flow of the entire system with pressurization using liquid nitrogen. This test is nearly identical to what we would expect in a static fire, except without the propellants or an ignition source. This test will characterize the flow parameters in our feed system and confirm we are achieving the correct mixture ratio for the injector. This test includes a chill-down of our system, filling of our tanks with liquid nitrogen, pressurization of the tanks with gaseous Helium, and opening of our main valves representing ”firing” of our propellants.

3.9 Ground Systems Testing

All ground system products will be used in the individual test components. Their continued use will work to reveal any bugs in the system. Ground systems will initially be responsible for calibrating sensors and testing the data transmission method. Furthermore, an initial prototype of the relay array circuit for valve actuation will be necessary before integration with the mechanical system for testing. Early testing during the leak tests will focus on the ability to open and close valves from the user interface and report sensor measurements. Later testing in the cold flow test will ensure the functionality of auto-shutoff conditions and the automation of fire sequences.

Additionally, the REDS system must be tested before integration with the propellant tanks. A circuit for testing of the vent valves (Figure 27) is outlined by FAR and must be constructed and used by teams competing in the competition [19]. While the regular REDS valves can only be opened, the test set allows repeated opening and closing of the valves to ensure reliability.

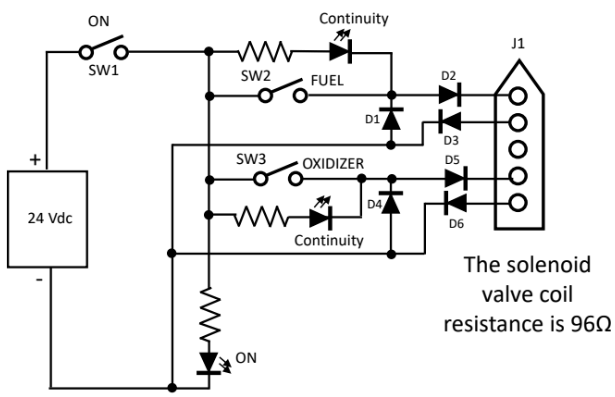


Figure 31: Circuit diagram for REDS Test Set

3.10 Static Fire Test

The goal of this capstone project is to perform a hot static fire of our engine with both propellants, liquid oxygen, and achieve combustion of these propellants in the engine chamber. This procedure is laid out in Figure 4 and Section 1.8. The main goal of the static fire is to safely assemble our rig, chill down our system, fill our propellants, and pressurize the tanks. Then we will proceed into the ignition sequence. Once the fire is complete we depressurize the system and drain remaining fluids in order to disassemble and clean the launch pad. This entire procedure (besides assembly) is done at the FAR site in the Mojave Desert.

The important data we will collect and analyze are engine thrust, pressure and temperature readings. The tank and injector inlet pressure over time data will be analyzed and compared to the expected flow rates. The pressurant line will also have a pressure and temperature reading which will be used to determine if there is a substantial pressure drop from the helium supply and to characterize the temperature profile of the helium as it pressurizes and does work on the propellants.

A Calculations

A.1 Welded Thrust Frame

A.1.1 Compression of Horizontal Members

Assumptions: The maximum load of 1,000 lbf is divided evenly between the 4 central tubes on the top and bottom of the weldment

Known values: A=0.7969 in^2 $F = 1000$ lbs, $S_y = 46$ ksi

$$P = \frac{F}{4} = \frac{1000 \text{ lbs}}{4} = 250 \text{ lbs} \tag{23}$$

$$\sigma = \frac{P}{A} = \frac{250 \text{ lbs}}{0.7969 \text{ in}^2} = 313.7 \text{ psi} \tag{24}$$

$$SF = \frac{S_y}{\sigma} = \frac{46,000 \text{ psi}}{313.7 \text{ psi}} = 147 \tag{25}$$

A.1.2 Buckling of Central Diagonal Members

Assumptions: One side of weldment tube is loaded with 250lb

Known values: $h = 1.25$ in, $b = 0.1875$ in, $L = 8.07$ in $F = 700$ lb, $E = 30 \times 10^6$ psi $S_y = 46$ ksi
For a rectangular cross section, ρ=0.289h=0.289(1.25in)=0.361in

$$Le = 0.65L = 0.65(8.07 \text{ in}) = 5.25 \text{ in} \tag{26}$$

$$\frac{Le}{\rho} = \frac{5.25 \text{ in}}{0.361\text{in}} = 14.52 \tag{27}$$

Check tangency point:

$$\frac{Le}{\rho} = \sqrt{\frac{2\pi^2 E}{S_y}} = 113.5 \tag{28}$$

$\frac{Le}{\rho} < tangency\ point$ so use Johnson Parabola

$$S_{cr} = S_y - \frac{S_y^2}{4\pi^2 E}(\frac{Le}{\rho})^2 = 46,000 \text{ psi} - \frac{(46,000 \text{ psi})^2}{4\pi^2(30 \times 10^6 \text{ psi})}(14.52)^2 = 45.623 \text{ ksi} \tag{29}$$

$$\sigma = \frac{P}{bh} = \frac{250\text{lb}}{(1.25\text{in})(0.1857 \text{ in})} = 1066.67 \text{ psi} \tag{30}$$

$$SF = \frac{S_{cr}}{\sigma} = \frac{45.6 \text{ ksi}}{1.067 \text{ ksi}} = 42.8 \tag{31}$$

A.1.3 Bending of Bottom Diagonal Members due to Weight of Engine/Injector Assembly

Assumptions: The thrust plate extension, hinge, injector and engine weigh 40lb
The load is divided evenly between the top and bottom faces of the 2 tubes
The side faces of the tubes are ignored

Known values: $h = 1.25$ in, $b = 0.1875$ in, $F = 40$ lb, $L = 5$ in, $S_y = 46$ ksi

$$P = \frac{F}{4} = \frac{40 \text{ lb}}{4} = 10 \text{ lb} \tag{32}$$

$$M = PL = 10 \text{ lb} \times 5 \text{ in} = 50 \text{ lb} \cdot \text{in} \tag{33}$$

$$\sigma_b = \frac{6M}{bh^2} = \frac{6(50 \text{ lb} \cdot \text{in})}{(1.25 \text{ in})(0.1875 \text{ in})^2} = 6826.67 \text{ psi} \tag{34}$$

$$SF = \frac{S_y}{\sigma_b} = \frac{46 \text{ ksi}}{6.827 \text{ ksi}} = 6.7 \tag{35}$$

A.1.4 Bending and Shear of Bolts to I-beam if Friction is Lost

Assumptions: Vertical load of 700lb
Load is divided evenly between the 4 bolts

Known values: $d = 0.5625$ in, $L = 1.884$ in, $F = 700$ lb, $S_y = 120$ ksi

$$A = \pi\frac{d^2}{4} = \pi\frac{(0.5625 \text{ in})^2}{4} = 0.442 \text{ in}^2 \tag{36}$$

$$P = \frac{F}{4} = \frac{700\text{lb}}{4} = 175 \text{ lb} \tag{37}$$

$$\tau = \frac{P}{A} = \frac{175 \text{ lb}}{0.442 \text{ in}^2} = 396 \text{ psi} \tag{38}$$

$$M = PL = 175 \text{ lb} \times 1.884 \text{ in} = 329.7 \text{ lb} \cdot \text{in} \tag{39}$$

$$\sigma_b = \frac{My}{\frac{\pi}{64}d^4} = \frac{(329.7 \text{ lb} \cdot \text{in})(\frac{0.5625 \text{ in}}{2})}{\frac{\pi}{64}(0.5625 \text{ in})^4} = 18,869 \text{ psi} \tag{40}$$

$$\sigma_e = \sqrt{\sigma^2 + 3\tau^2} = \sqrt{(18,869 \text{ psi})^2 + 3(396 \text{ psi})^2} = 18.9 \text{ ksi} \tag{41}$$

$$SF = \frac{S_y}{\sigma_e} = \frac{120 \text{ ksi}}{18.9 \text{ ksi}} = 6.3 \tag{42}$$

A.2 Tank Mounting Plates: Stress Concentration at Hole due to Bending Stress

Assumptions: The tank and plate weigh 81lb
The plate can be treated like a beam supported by a pin on each side
The weight of the tank can be treated as a concentrated load at the center of the hole which is in the center of the plate

Known values: $h = 0.25$ in, $b = 9.5$ in, $F = 81$ lb, $L = 11.75$ in, $d = 6.5$ in, $S_y = 66$ ksi

$$M_{max} = (\frac{F}{2})(\frac{L}{2}) = (\frac{81 \text{ lb}}{2})(\frac{11.75 \text{ in}}{2}) = 237.94 \text{ lb} \cdot \text{in} \tag{43}$$

$$\sigma_{nom} = \frac{6M}{(b-d)h^2} = \frac{6(237.94 \text{ lb} \cdot \text{in})}{(9.5 \text{ in} - 6.5 \text{ in})(0.25 \text{ in})^2} = 7,614 \text{ psi} \tag{44}$$

$$\frac{d}{b} = \frac{6.5 \text{ in}}{9.5 \text{ in}} = 0.68 \tag{45}$$

$$\frac{d}{h} = \frac{6.5 \text{ in}}{0.25 \text{ in}} = 26 \tag{46}$$

$k_t = 1.2$ from Figure 4.40a in the Machine Design textbook

$$\sigma_{max} = k_t \sigma_{nom} = 1.2(7,614 \text{ psi}) = 9,137 \text{ psi} \tag{47}$$

$$SF = \frac{S_y}{\sigma_{max}} = \frac{66 \text{ ksi}}{9.1 \text{ ksi}} = 7.2 \tag{48}$$

A.3 Top Plumbing Plate: Stress Concentration at Bolt Holes due to Bending Stress

Assumptions: The plate and top plumbing weigh 25lb
The plate can be treated like a beam supported by a pin on each side and the support from the 2 center bolts is neglected
The weight of the plate and plumbing can be treated as a concentrated load at the center of the plate

Known values: $h = 0.25$ in, $b = 12$ in, $F = 25$ lb, $L = 24$ in, $d = 0.3175$ in, $S_y = 66$ ksi

$$M_{max} = (\frac{F}{2})(\frac{L}{2}) = (\frac{25 \text{ lb}}{2})(\frac{24 \text{ in}}{2}) = 150 \text{ lb} \cdot \text{in} \tag{49}$$

$$\sigma_{nom} = \frac{6M}{(b-d)h^2} = \frac{6(150 \text{ lb} \cdot \text{in})}{(12 \text{ in} - 0.635 \text{ in})(0.25 \text{ in})^2} = 1267 \text{ psi} \tag{50}$$

$$\frac{d}{b} = \frac{0.375 \text{ in}}{12 \text{ in}} = 0.0.03125 \tag{51}$$

$$\frac{d}{h} = \frac{0.375 \text{ in}}{0.25 \text{ in}} = 1.5 \tag{52}$$

$k_t = 1.8$ from Figure 4.40a in the Machine Design textbook

$$\sigma_{max} = k_t\sigma_{nom} = 1.8(1267 \text{ psi}) = 2281 \text{ psi} \tag{53}$$

$$SF = \frac{S_y}{\sigma_{max}} = \frac{66 \text{ ksi}}{2.3 \text{ ksi}} = 28.9 \tag{54}$$

A.4 Choked Flow Calculations

Choked flow occurs when the speed of a gas or fluid reaches the speed of sound in the medium. Since flow speed is fastest at the most narrow orifices, these locations tend to be in valves where flow is restricted. The choked flow rate of the pressure regulator can be characterized using the equation and values below, but the values can be updated to check for choked flow in the relief valves as well:

$$Q = 0.471 N_2 C_v P_1 \sqrt{\frac{1}{G_g T_1}} \tag{55}$$

Where

Symbol	Parameter	Value	Units
Q	Orifice Choked Flow	TBD	SCFM
N_2	conversion constant	22.67	SCFM
C_v	Flow Coefficient	TBD	-
P_1	Inlet Pressure of Orifice	2200	psia
G_g	Specific Gravity of Helium	0.138	-
T_1	Temperature of inlet Helium	540	Rankine

B Detailed SOPs

Note: Unless approved, these SOPs are not complete and are subject to revision. Red text is currently unconfirmed or subject to change in the future.

B.1 Injector Water Test

Safe Operating Procedure:
RPL Injector Water Flow Test

Author:	RPL Capstone Team
Department:	Mechanical Engineering
Building/Room:	503/2226
Date Approved:	1/23/2020
Approved by: Trevor Marks	Signature:

1. Description

This SOP describes a test to determine the discharge coefficient of the injector that will be used in the RPL capstone team's static test rig. The discharge coefficient will be calculated from the mass flow rate of water through the injector. The mass flow rate will be measured by weighing the water output by the injector over a measured amount of time. The pressure drop across the injector will be measured using a pressure transducer. The voltage from the pressure transducer will be measured using a voltmeter and recorded by hand.

2. Hazards Overview

- Water flowing at pressure has the potential of getting into people's eyes.
    - Wear safety glasses.
- Electrical hazard.
    - Keep water away from all electronics and electrical cords.
    - Ensure all wires and electrical cords are in good working order.
    - Only plug electronics into GFCI outlets.
- Slip hazard.
    - Clean up spills.

3. Required Personal Protective Equipment (PPE)

- Safety glasses
- Proper lab attire

4. Waste Disposal

- Water can be disposed of in the sink since it is non-hazardous.
- Pieces of tubing and any other waste can be disposed of in a standard trash can since it is non-hazardous.

5. Accident and Spill Procedure

- Spilled water can be dried using paper towels, and/or mopped.
- Seek medical help in the event of significant falls/injury: Call 911.

The lab manager must be notified in the event of any significant injury. A significant injury is any injury that cannot be addressed by the contents of the room's Band-Aid station.

The lab manager must be notified in the event of a large spill, i.e., greater than 5 gallons, or a spill of any hazardous waste.

6. Equipment

- Water and large tub
- Water pump
- Pressure transducer
- Plastic tubing and fittings as per plumbing schematic
- Two buckets; one must hold 5+ gallons (for sump pump) and the other 2+ gal for water collection.
- Timer
- Scale

7. Approvals Required

Initial test monitored by lab manager.

Approver's initials: JM

8. Procedure

1. Setup/Start/Pre-run
    A. Build system as outlined in the plumbing diagram shown in Figure 1 below.
    B. Calibrate the pressure transducer as per *SOP – Pressure Transducer Calibration.*
    C. Fill a tub A (larger tub) with water and submerge the pump in it.
    D. Note: the pump turns on as soon as it is plugged in so double check that all tubing is connected and directed towards the tub or bucket before plugging it in. **Plug in the pump, turning it on.**
    E. Apply back pressure to tubing and bleed the transducer.
    F. Unplug the pump.
    G. Place the injector in the tub A and connect pipe network.
    H. Attach the injector.
    I. Zero the transducer output. Record weight of tub B.
2. Process/Run
    A. Note: the pump turns on as soon as it is plugged in so double check that all tubing is connected and directed towards the tub or bucket before plugging it in. **Plug in the pump, turning it on.**
    B. Record pressure reading from transducer readout.
    C. Transfer the injector to tub B and start timer.
    D. Collect water for some time.
    E. Return the injector to the tub A, record time and weight of water.
    F. Dump water from tub B into tub A.
    G. Repeat as the above steps for additional runs.
    H. Unplug the pump, turning it off.
3. Post-Run/Shut-down/Clean-up
    A. Double check that the pump is unplugged and disconnect all of the tubing.
    B. Dry the injector.
    C. Dry any water that may have spilled.
    D. Dump water in sink.
    E. Return all components to their proper place.

Approver's initials:

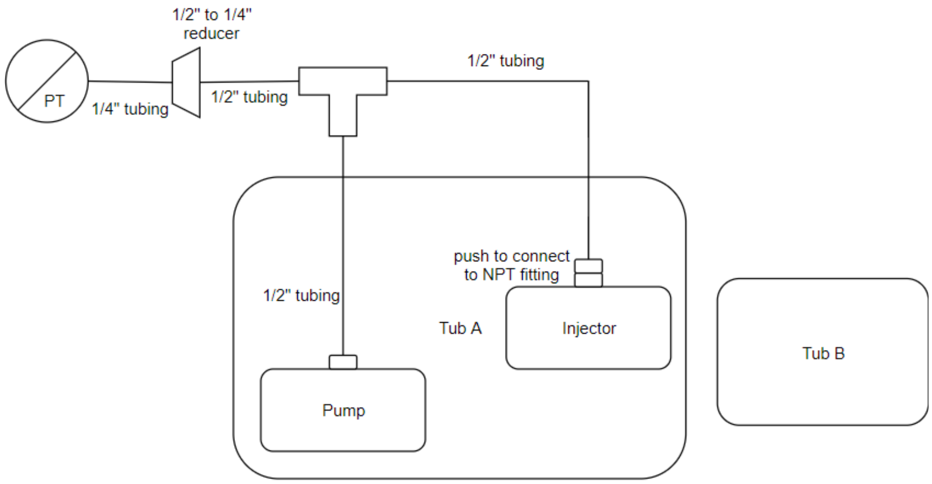


Figure 1. Plumbing diagram

<u>BOM</u>

- Large tub – over 5gal
- Small tub – 2gal
- Pump
- Tee – ½" OD compression fitting
- Reducer – ½" OD to ¼" OD compression fittings
- ½" OD push-to-connect to ¼" NPT fitting
- ½" OD firm plastic tubing – 6'
- ¼" OD firm plastic tubing – 1'
- Pressure transducer
- Injector

Approver's initials: TM

B.2 Pneumatic system test

This SOP is in progress.

B.3 Valve functionality test

This SOP is in progress.

B.4 Feed system leak tests

Leak Test Safety Operating Procedure

Author:	Katherine La	
Department:	Mechanical Engineering	
Building/Room:	Make sure to fill this out when you land on a testing location	
Date Approved:		
Approved by:	Signature:	

1. Description

This document outlines the procedures for performing a leak test of the top and bottom plumbing for the feed system. This test will check the entire system for leaks by pressurizing each section, one at a time. These sections are: the top plumbing system leading to the liquid oxygen tank, the top plumbing system leading to the liquid methane tank, the bottom plumbing system leading to the liquid oxygen tank, and the bottom plumbing system leading to the liquid methane tank.

During each of these tests, leaks will be detected with a three-step method. The first step involves flushing through the individual sections with water. The second step involves overseeing any pressure changes after a section has been sealed off. If no leaks are detected in the first two steps, the procedure is complete. If leaks are detected, a third step involving a detergent-based solution will be needed for the failed section in order to locate the faulty part.

2. Hazards Overview

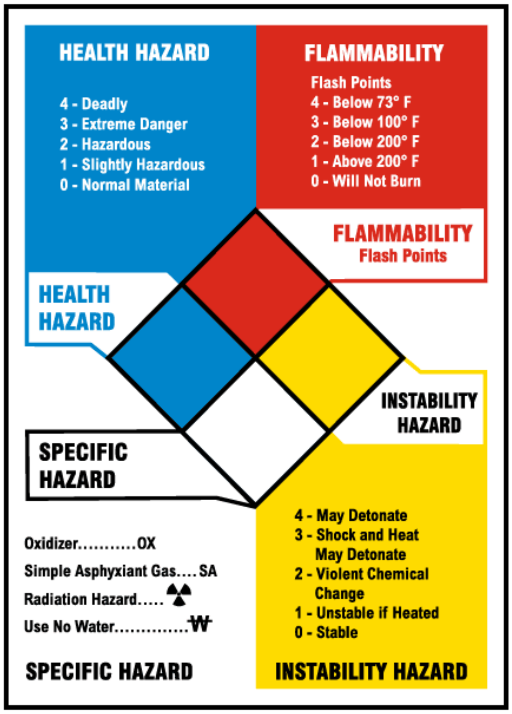


Figure 1: *Helium is a colorless and odorless gas. It is stored as a compressed gas and is chemically inert.*

Safety Precautions

- ***Helium can cause potential asphyxiation due to oxygen displacement.***
  - *Work in a well-ventilated area, preferably outdoors.*
  - *Store containers, when not in use or connected to a closed system, in a well ventilated storage area.*
- ***Helium tanks must be handled with caution****, as they are kept at a high pressure.*
  - *When transporting, keep helium tanks upright at all times. Helium tanks must be strapped down during transport. Wear covered shoes.*
- ***Fire hazard:*** *Helium is non-combustible. However, tank exposure to heat or fire can lead to increase in pressure which will cause it to rupture.*
  - *Ensure helium tanks are placed in a well-ventilated area, away from direct sources of heat.*
- ***Pressurized vessel hazard:*** *Pressurized vessels may rupture unexpectedly, generating dangerous shrapnel and discharging high amounts of gas.*
  - *Never approach an untested pressurized vessel or pressurized components. Depressurize all components before approaching and after utilizing.*
  - *In the event that a vessel has ruptured, immediately relocate personnel to a well-ventilated area.*
- ***Eye irritant hazard:*** *Extended eye exposure to helium can lead to discomfort.*
  - *Adverse effects are not expected. In case of discomfort, rinse eyes immediately with water or the appropriate solution. If irritation worsens, contact an ophthalmologist.*

Approver's initials:

____

3. Required Personal Protective Equipment

- Safety goggles
- Long sleeved shirt or laboratory coat, full length pants
- Closed-toe shoes
- Hearing protection

4. Waste Disposal

None of the materials used are hazardous to the environment.

- Water should be discarded at any drain.
- Used helium will dissipate with no further action needed. **This must be done in a well-ventilated environment.**
  - Excess helium should be kept in the tank and returned to proper storage.
  - If tank is empty:
    - Open valve completely to release any residual pressure in tank.
    - Unscrew and remove nozzle by hand or with a wrench.
    - Write "EMPTY" on the tank in permanent marker.
    - Transport tank to a steel recycling center or place with curbside recycling pickup. If necessary, dispose with trash.
- Detergent solution should be removed from plumbing system and discarded in trash bin.

5. Accident and Spill Procedure

- ***In case of prolonged helium respiration:*** *Inhalation of helium can cause dizziness, lethargy, headaches and may displace oxygen leading to suffocation.*
  - *Immediately relocate to fresh air. Give artificial respiration if not breathing. If breathing is difficult, call 911. Qualified personnel may give oxygen. Notify supervisor.*
- ***In case of prolonged eye exposure:*** *Prolonged eye exposure can cause irritation or frostbite.*
  - *Flush affected eyes with water or appropriate solution for at least 30 seconds. If irritation continues or worsens, immediately call 911.*
- ***In case of helium tank or vessel rupture:*** *Both the helium tank and the vessel to be pressurized have a risk of rupturing.*
  - *Immediately relocate to a well-ventilated area. Note any shrapnel injuries and resolve as needed.*
- ***In case of fitting detachment:*** *Loose fittings have a risk of detachment during helium test.*
  - *Stop helium source. note any shrapnel injuries and resolve as needed.*
- ***In case of detergent solution spill:*** *The solution is non-toxic and safe for skin contact.*
  - *Clean and dry contaminated areas with paper towels.*
- *Minor injuries can be resolved using the first-aid kit supplied at testing site.*
- *For significant injuries, call 911 and notify supervisor.*

The appointed supervisor must be notified in the event of any significant injury. A significant injury is any injury that cannot be resolved by the first-aid kit.

Approver's initials:

____

6. Equipment

- *Screwdrivers and wrenches*
- *Pressure gauge*
- *Ball valve*
- *T-fittings*
- *Stoppers*
- *Water source*
- *Helium tank and regulator*
- *Detergent solution*

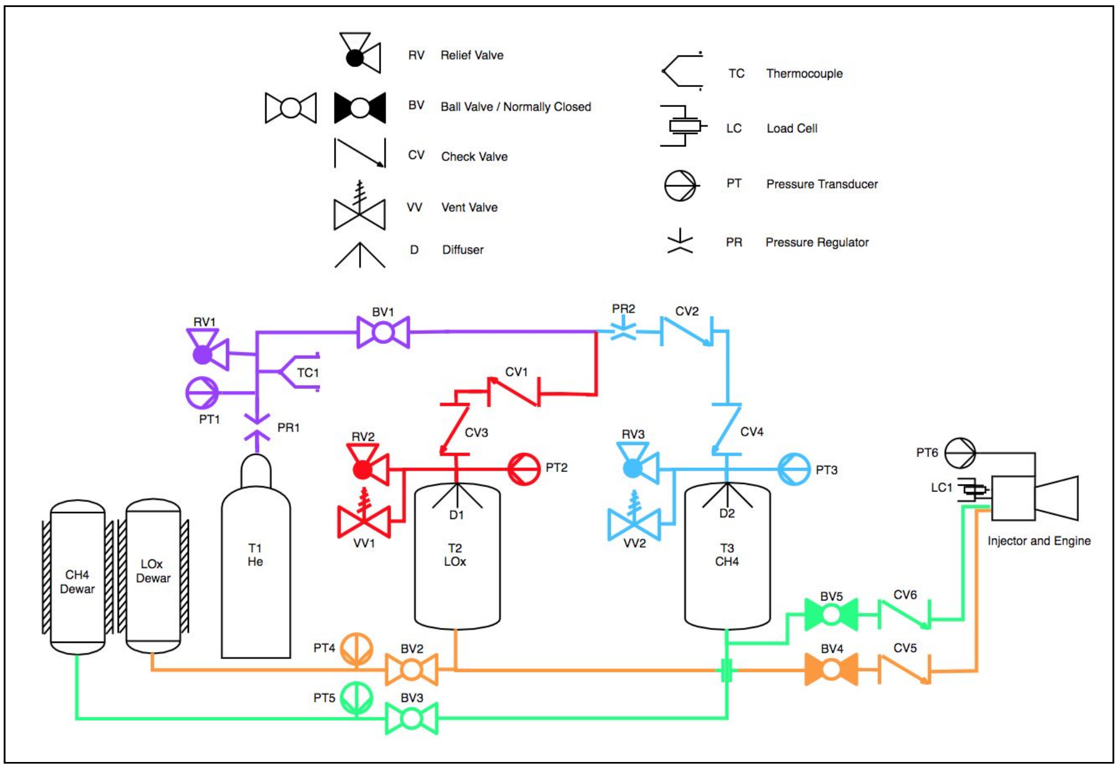


Figure 2: *Complete feed system including helium tank, liquid oxygen tank, liquid methane tank, dewars, injector, and engine.* ***During this test, the tanks, dewars, injector, and engine will not be connected.***

Notes: *The section highlighted in purple and red is the liquid oxygen component of the top plumbing system. It will be referenced as* ***section A.***

The section highlighted in purple and blue is the liquid methane component of the top plumbing system. It will be referenced as ***section B.***

The section highlighted in orange is the liquid methane component of the top plumbing system. It will be referenced as ***section C.***

The section highlighted in green is the liquid methane component of the bottom plumbing system. It will be referenced as ***section D.***

Approver's initials: ____________

7. Approvals Required

List circumstances under which the procedure will require prior approval from the lab manager, PI, or other supervisor.

Example I:

Permission of the lab manager is required before each run of the procedure.

Example II:

Permission of the lab manager is required only before the initial run of the procedure.

Enter N/A if there are no circumstances.

8. Procedure

General Preliminary Process

I. Ensure all personal protective equipment is in working condition.
II. Ensure all equipment is available.
III. Locate nearest first-aid supply kit and confirm supply kit is stocked.
IV. Ensure safety procedure is being performed in a well-ventilated area.
V. Secure helium tank on level surface.

Approver's initials:

____

Section A: Water Test Procedure [Step 1]

Water Test Setup

I. Isolate liquid oxygen component of top plumbing system to prepare for water test, as shown in Figure 3.
   A. Replace T-fitting connecting *purple*, *red*, and *blue* tubes (as shown in Figure 2) with T-fitting with a stopper connecting *purple and red* tubes (shown *pink* in Figure 3).
   B. Change helium tank [T1] to water source.
   C. Leave opening [WO1] unsealed.

Water Test Process

I. Verify that [BV1] is open; verify that [RV1], [RV2], and [VV1] are closed.
II. Initiate water flow starting from [T1] and exiting through [WO1]. Allow water to run freely through system for 1 minute.
III. Terminate water source [T1]. Observe all fittings and valves.
IV. If there is no trace of water:
   A. Discard water from system.
   B. *Proceed to **helium test procedure**.*
V. If there is water leakage:
   A. Use tools to secure all leaking connections.
   B. *Repeat **water test process**.*

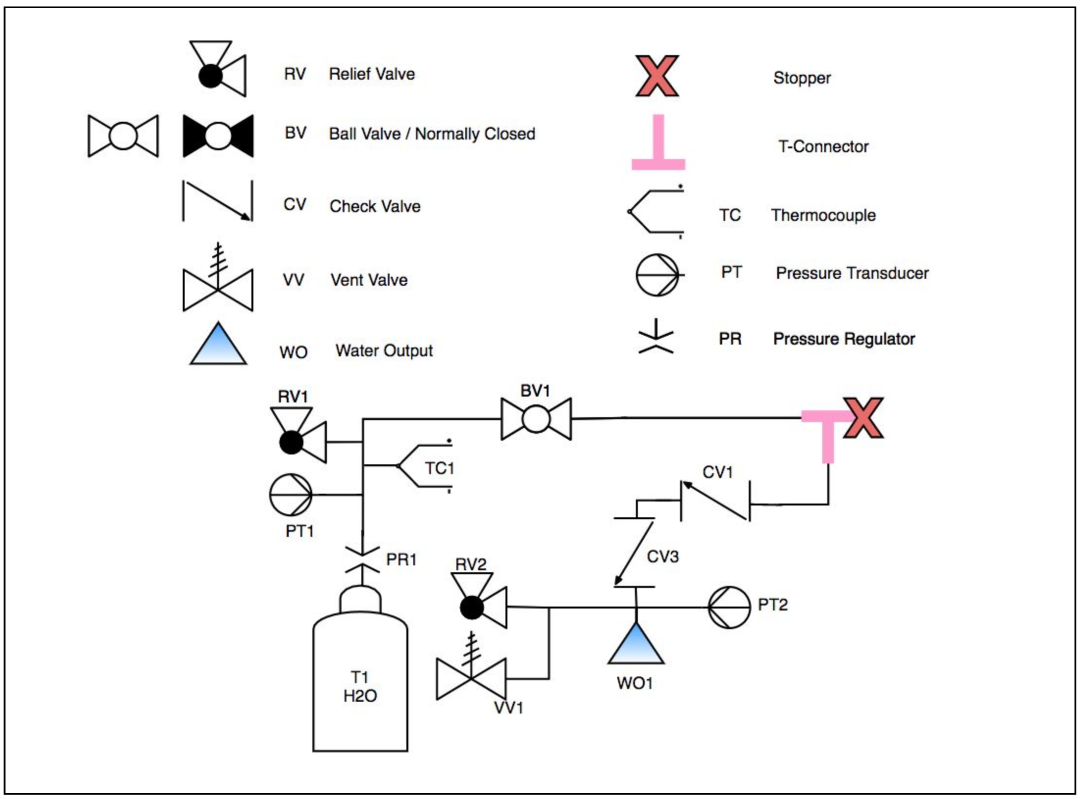


Figure 3: *Top plumbing section leading to liquid oxygen tank for water test procedure, step 1.*

Approver's initials:

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Section A: Helium Test Procedure [Step 2]

Helium Test Setup

I. Isolate liquid oxygen component of top plumbing system to prepare for helium test, as shown in Figure 4.
   A. Change water source [T1] to helium tank with regulator.
   B. Replace [WO1] from Figure 5 with T-fitting, shown in *pink* in Figure 6.
      1. On right end of T-fitting, install closed ball valve [BV6].
      2. On left end of T-fitting, install pressure gauge [PG1].

Helium Test Process

I. Verify that [BV1] is open; verify that [RV1], [RV2], and [VV1] are closed.
II. Slowly initiate helium release from [T1] at 100 psi.
III. Continue helium flow from [T1] until [PG1] reads 100 psi.
IV. Terminate helium source when [PG1] reads 100 psi.
V. Monitor [PG1] for a duration of 5 minutes.
VI. If [PG1] does not decrease:
   A. Vent feed system by slowly opening [BV6] to release helium.
   B. *Proceed to **post test procedure,** page 15.*
VII. If [PG1] decreases by 1 psi or more within the 5 minute duration:
   *A. Proceed to **detergent test procedure**, page 14.*

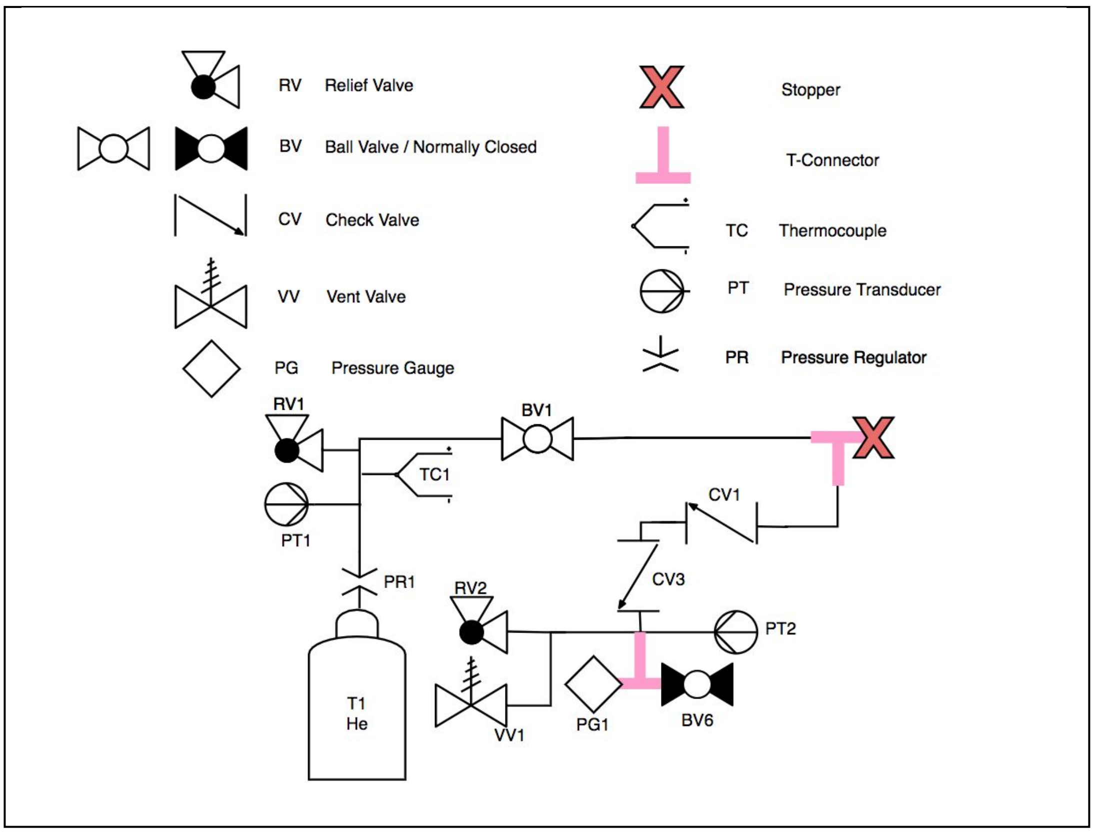

***Figure 4**: Top plumbing section leading to liquid oxygen tank for helium test procedure, step 2.*

Section B: Water Test Procedure [Step 1]

Water Test Setup

I. Isolate liquid methane component of top plumbing system to prepare for water test, as shown in Figure 5.
   A. Link *purple* and *blue* tubes (as shown in Figure 2) using a T-fitting and stopper (shown *pink* in Figure 5).
   B. Change helium tank [T1] to water source.
   C. Leave opening [WO1] unsealed.

Water Test Process

I. Verify that [BV1] is open; verify that [RV1], [RV3], and [VV2] are closed.
II. Initiate water flow starting from [T1] and exiting through [WO1]. Allow water to run freely through system for 1 minute.
III. Terminate water source [T1]. Observe all fittings and valves.
IV. If there is no trace of water:
   A. Discard water from system.
   B. *Proceed to **helium test procedure**.*
V. If there is water leakage:
   A. Use tools to secure all leaking connections.
   B. *Repeat **water test process**.*

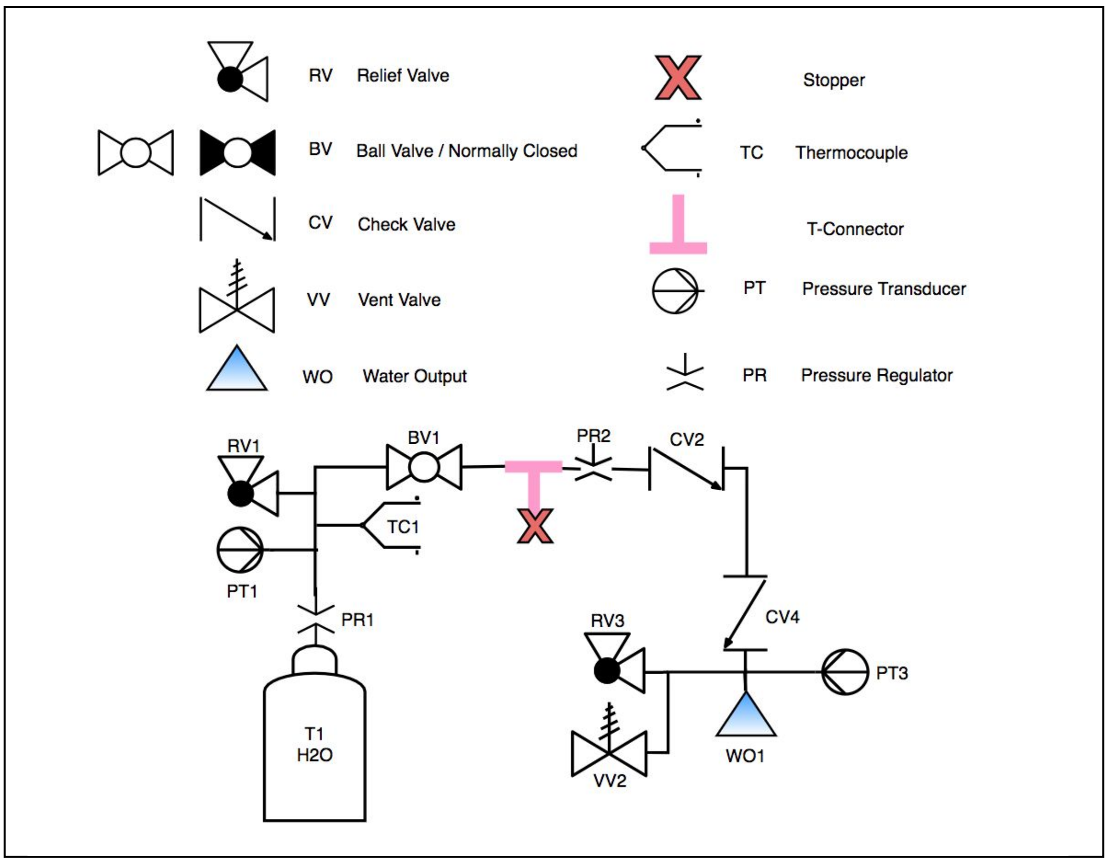

Figure 5: *Top plumbing section leading to liquid methane tank for water test procedure, step 1.*

Approver's initials:

Section B: Helium Test Procedure [Step 2]

Helium Test Setup

I. Isolate liquid oxygen component of top plumbing system to prepare for helium test, as shown in Figure 6.
   A. Change water source [T1] to helium tank with regulator.
   B. Replace [WO1] from Figure 5 with T-fitting, shown in *pink* in Figure 6.
      1. On right end of T-fitting, install closed ball valve [BV6].
      2. On left end of T-fitting, install pressure gauge [PG1].

Helium Test Process

I. Verify that [BV1] is open; verify that [RV1], [RV3], and [VV2] are closed.
II. Slowly initiate helium release from [T1] at 100 psi.
III. Continue helium flow from [T1] until [PG1] reads 100 psi.
IV. Terminate helium source when [PG1] reads 100 psi.
V. Monitor [PG1] for a duration of 5 minutes.
VI. If [PG1] does not decrease:
   A. Vent feed system by slowly opening [BV6] to release helium.
   B. *Proceed to **post test procedure,** page 15.*
VII. If [PG1] decreases by 1 psi or more within the 5 minute duration:
   A. *Proceed to **detergent test procedure,** page 14.*

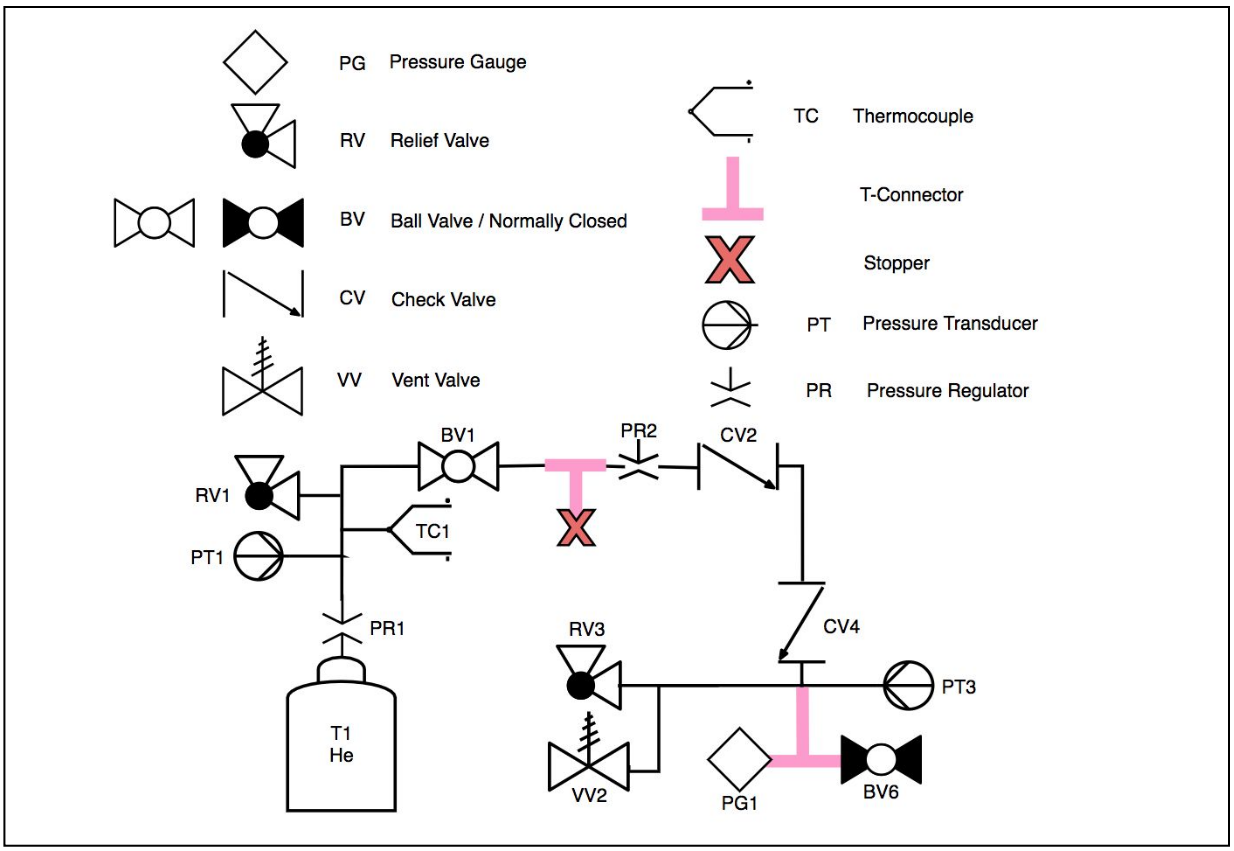

Figure 6: *Top plumbing section leading to liquid methane tank for helium test procedure, step 2.*

Approver's initials:

Section C: Water Test Procedure [Step 1]

Water Test Setup

I. Isolate liquid oxygen component of bottom plumbing system to prepare for water test, as shown in the two examples in Figure 7.
   A. Disconnect Dewar and replace with water source.
   B. Disconnect liquid oxygen tank and injector.
      1. Place stopper over tube opening for either liquid oxygen tank or injector, leaving the other opening unsealed.

Water Test Process

I. Verify that [BV2] and [BV4] are open.
II. Initiate water flow starting from [T1] and exiting through [WO1]. Allow water to run freely through system for 1 minute.
III. Terminate water source [T1]. Observe all fittings and valves.
IV. If there is no trace of water:
   A. Discard water from system.
   B. *Proceed to **helium test procedure**.*
V. If there is water leakage:
   A. Use tools to secure all leaking connections.
   B. *Repeat **water test process**.*

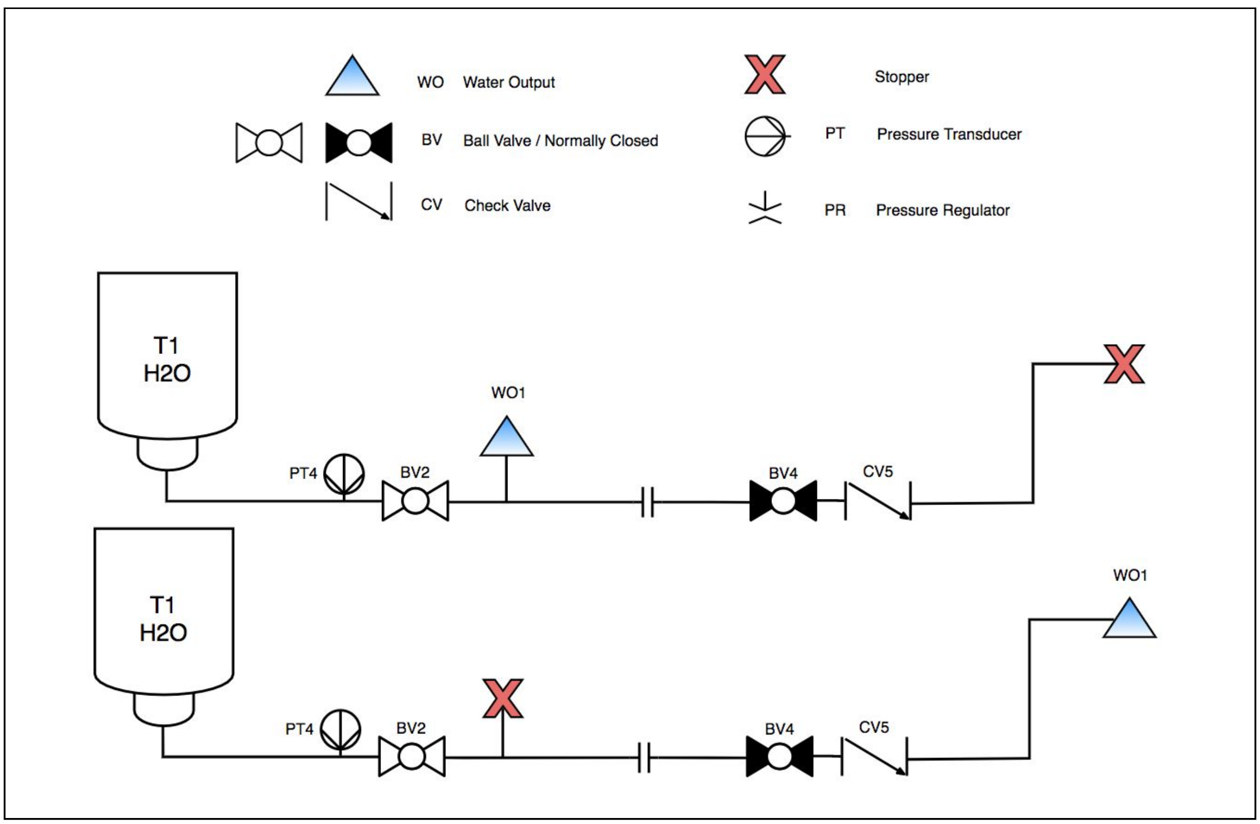

Figure 7: *Bottom plumbing section leading to liquid oxygen tank for water test procedure, step 1. Two valid testing configurations are pictured.*

Approver's initials:

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Section C: Helium Test Procedure [Step 2]

Helium Test Setup

I. Isolate liquid oxygen component of bottom plumbing system to prepare for helium test, as shown in Figure 8.
   A. Change water source [T1] to helium tank with regulator.
   B. Place [PG1] in one tube opening and [BV6] in the other.

Helium Test Process

I. Verify that [BV2] and [BV4] are open.
II. Slowly initiate helium release from [T1] at 100 psi.
III. Continue helium flow from [T1] until [PG1] reads 100 psi.
IV. Terminate helium source when [PG1] reads 100 psi.
V. Monitor [PG1] for a duration of 5 minutes.
VI. If [PG1] does not decrease:
   A. Vent feed system by slowly opening [BV6] to release helium.
   B. *Proceed to **post test procedure,** page 15.*
VII. If [PG1] decreases by 1 psi or more within the 5 minute duration:
   A. *Proceed to **detergent test procedure,** page 14.*

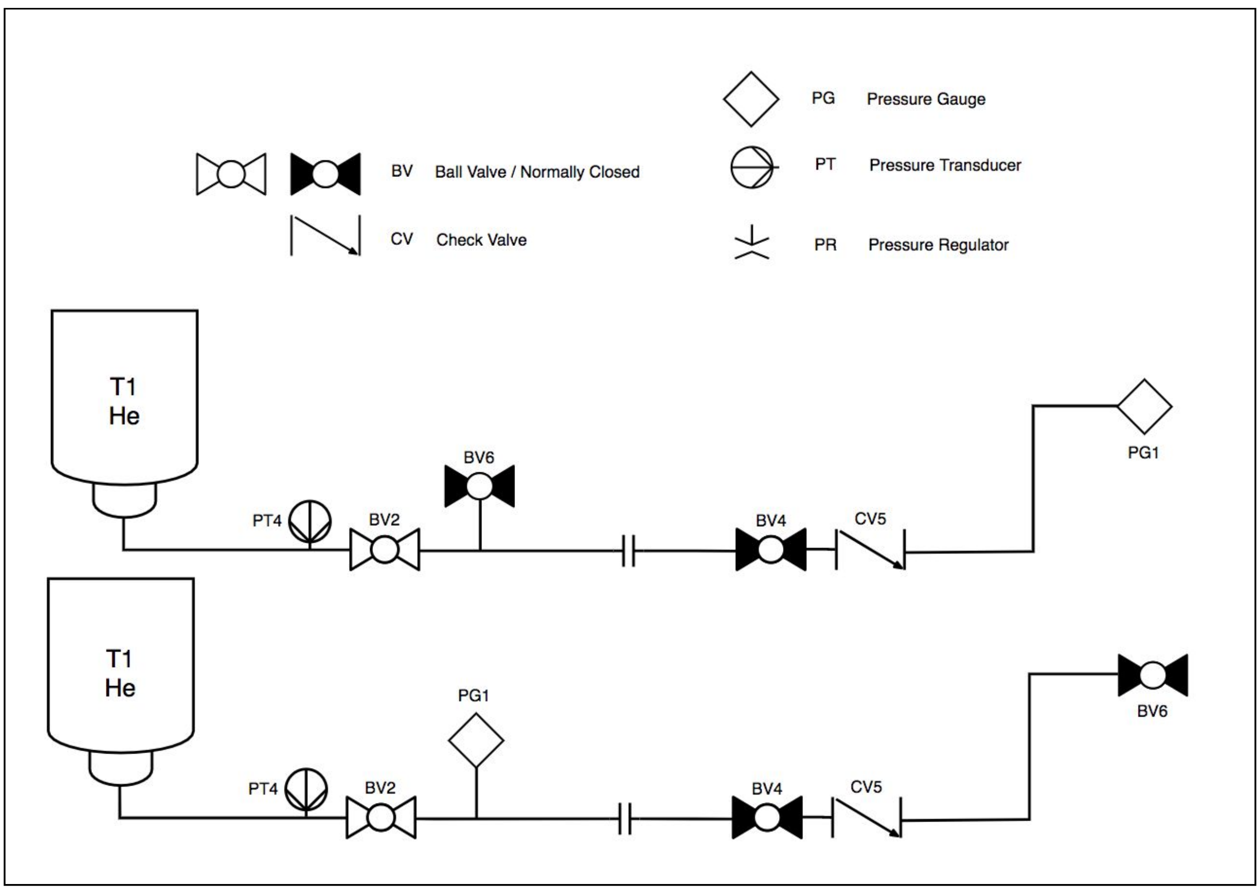

Figure 8: *Bottom plumbing section leading to liquid oxygen tank for helium test procedure, step 2. Two valid testing configurations are pictured.*

Approver's initials: ____________

Section D: Water Test Procedure [Step 1]

Water Test Setup

I. Isolate liquid methane component of bottom plumbing system to prepare for water test, as shown in the two examples in Figure 9.
   A. Disconnect Dewar and replace with water source.
   B. Disconnect liquid methane tank and injector.
      1. Place stopper over tube opening for either liquid methane tank or injector, leaving the other opening unsealed.

Water Test Process

I. Verify that [BV3] and [BV5] are open.
II. Initiate water flow starting from [T1] and exiting through [WO1]. Allow water to run freely through system for 1 minute.
III. Terminate water source [T1]. Observe all fittings and valves.
IV. If there is no trace of water:
   A. Discard water from system.
   B. *Proceed to **helium test procedure**.*If there is water leakage:
V. If there is water leakage:
   A. Use tools to secure all leaking connections.
   B. *Repeat **water test process**.*

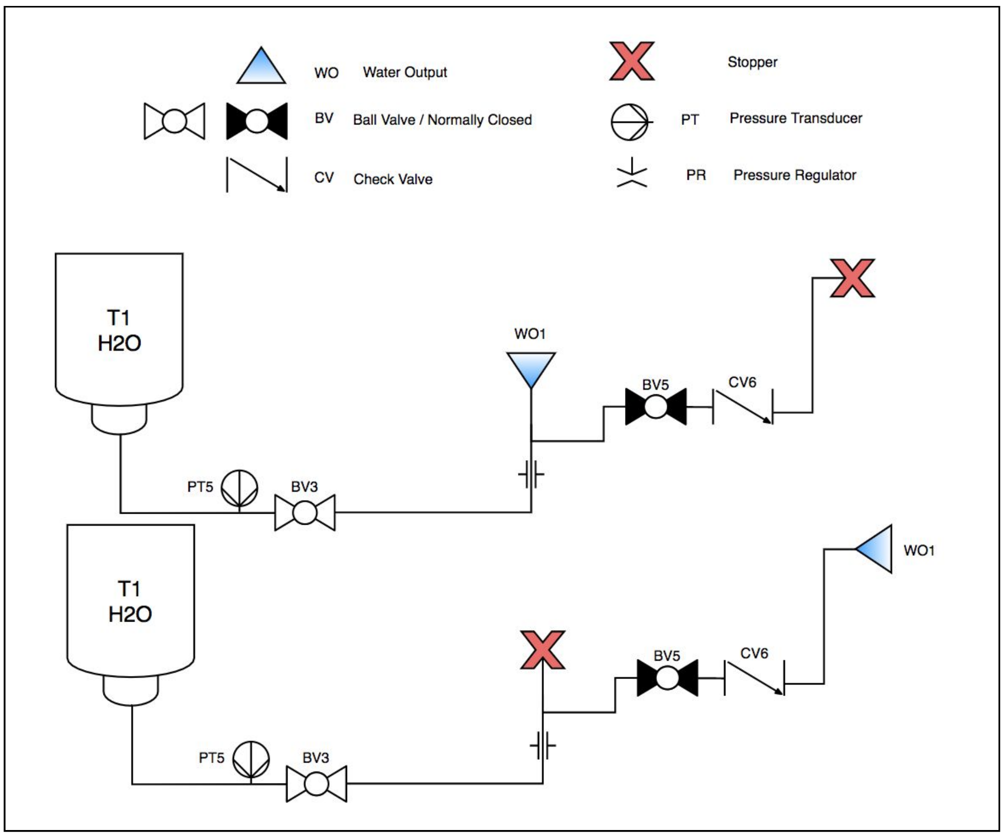

Figure 9: *Bottom plumbing section leading to liquid methane tank for water test procedure, step 1. Two valid testing configurations are pictured.*

Approver's initials:

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Section D: Helium Test Procedure [Step 2]

Helium Test Setup

I. Isolate liquid methane component of bottom plumbing system to prepare for helium test, as shown in Figure 10.
   A. Change water source [T1] to helium tank with regulator.
   B. Place [PG1] in one tube opening and [BV6] in the other.

Helium Test Process

I. Verify that [BV3] and [BV5] are open.
II. Slowly initiate helium release from [T1] at 100 psi.
III. Continue helium flow from [T1] until [PG1] reads 100 psi.
IV. Terminate helium source when [PG1] reads 100 psi.
V. Monitor [PG1] for a duration of 5 minutes.
VI. If [PG1] does not decrease:
   A. Vent feed system by slowly opening [BV6] to release helium.
   B. *Proceed to **post test procedure,** page 15.*
VII. If [PG1] decreases by 1 psi or more within the 5 minute duration:
   A. *Proceed to **detergent test procedure,** page 14.*

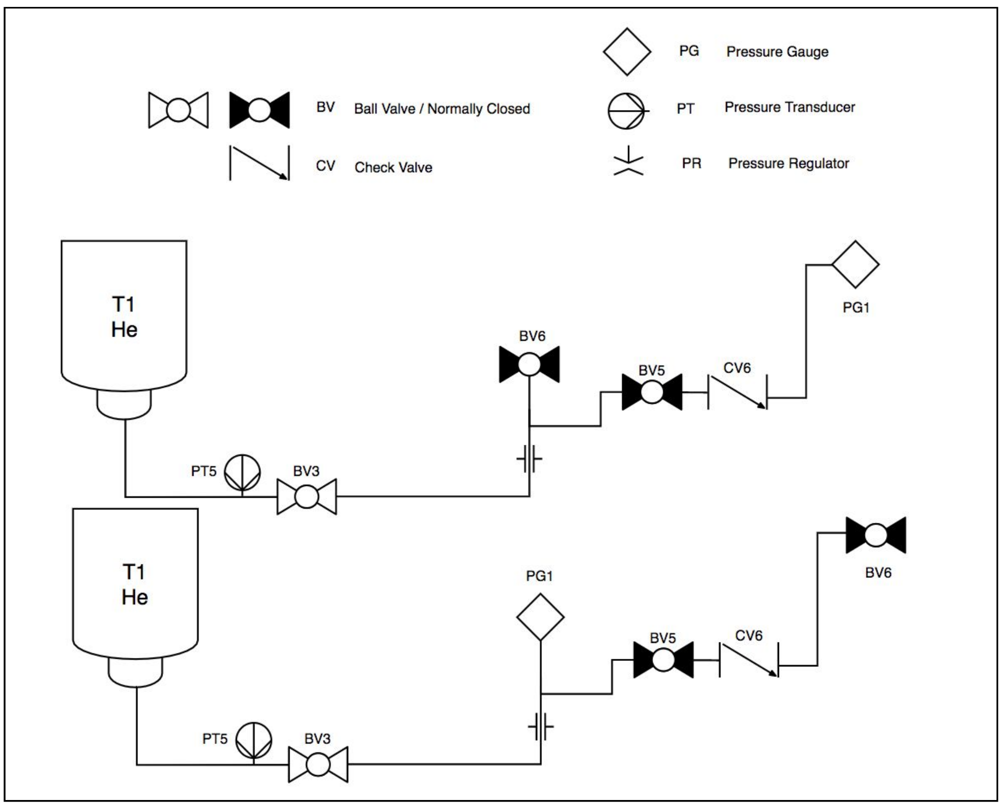

Figure 10: *Bottom plumbing section leading to liquid methane tank for helium test procedure, step 2. Two valid testing configurations are pictured.*

Approver's initials:

____

General Detergent Test Procedure [Step 3]

Note: *The general detergent test is only to be done if the section has failed the helium test.*

Detergent Test Setup

I. Keep [BV6] closed to maintain system pressurization.
II. Prepare detergent solution in spray bottle.

Detergent Test Process

I. Spray detergent solution on the outside surface of all connective joints.
II. Observe all joints for bubble formation.
III. If bubble formation is observed:
   - A. Depressurize system by slowly opening [BV6].
   - B. Secure connective joint(s).
   - C. Close [BV6].
   - D. Repressurize system by initiating helium release from [T1].
   - E. Terminate helium source when [PG1] reads 100 psi.
   - F. *Repeat **detergent test process**.*
   - G. If bubble formation is still observed after repressurization, replace faulty part(s).

IV. After completion of joint testing, repressurize system.
V. Spray detergent solution on all input and output valves.
VI. Observe all input and output valves for bubble formation.
VII. If bubble formation is observed:
   - A. Depressurize system by slowly opening [BV6].
   - B. Replace faulty valve(s).

VIII. After successful leak diagnosis and repair, *proceed to* ***post test procedure***, page 15.

Approver's initials:

____

Section A: Post Test Procedure

I. Confirm all vessels are depressurized.
II. Remove T-fittings and stopper shown in *pink* in Figure 4.
III. Remove [PG1] and [BV6] for later use.
IV. If detergent test was used, sanitize and dry all surfaces.

Section B: Post Test Procedure

I. Confirm all vessels are depressurized.
II. Remove T-fittings and stopper shown in *pink* in Figure 6.
III. Remove [PG1] and [BV6] for later use.
IV. If detergent test was used, sanitize and dry all surfaces.

Section C: Post Test Procedure

I. Confirm all vessels are depressurized.
II. Remove [PG1], [BV6], and stopper for later use.
III. If detergent test was used, sanitize and dry all surfaces.

Section D: Post Test Procedure

I. Confirm all vessels are depressurized.
II. Remove [PG1], [BV6], and stopper.
III. If detergent test was used, sanitize and dry all surfaces.

Approver's initials:

____

B.5 Propellant tank proof test

Provided by FAR as a stand-in until a full SOP can be written:

Figure 4:

Tank Hydrostatic Test Procedure[11]	
1.	Check the tank for dents and damage. If the tank is dented or damaged, do not do this test.
2.	WARNING: HIGH-PRESSURE OPERATIONS. Wear safety glasses. Limit people handling and standing near the tank when pressurized.
3.	Completely fill tank with water. WARNING: Do not leave any air pockets in the tank. Fill from the bottom of the tank and vent the air from the top.
4.	Check and tighten all fittings to make sure they are not leaking.
5.	Using a water hand pump, pump the tank pressure up to 150% of the operating pressure. WARNING: If the tank pressure is not rising while pumping, the tank is expanding and may rupture. STOP PUMPING.
6.	Hold the pressure for 3-minutes.
7.	Relieve the pressure.
8.	Pressurize and relieve the tank two additional times using steps 4 through 6.
9.	If the tank bursts, springs a leak, or deforms: the tank is unusable.
10.	Drain the tank of water.
11.	Rinse the tank with isopropyl alcohol.
12.	Force air through the tank to dry out.
13.	When you can do longer smell alcohol in the tank, it is dry.

[11] From FAR-0004 Design and Test page 10.

B.6 Level sensing calibration test

This SOP is in progress.

B.7 Liquid nitrogen tank boil-off test

Safe Operating Procedure:
Boil-Off Test

Red text is currently unconfirmed or subject to change in the future.

Author:	Sebastian Vargas, Delvin Huang
Department:	Mechanical Engineering
Building/Room:	Machine Shop, Arts Building 534, Room 0249
Date Approved:	Click or tap to enter a date.
Approved by: [Approver's name. Should be the person in charge of the space you will be performing the procedure in.]	Signature:

1. Description

This SOP describes a test to characterize boil off rates for our propellants, liquid oxygen and liquid methane, under atmospheric conditions. Due to its nonreactive properties compared to the propellants, liquid nitrogen will be used to conduct the test. The boil off rates and thermal properties of our system are characterized by measuring the change in weight of liquid nitrogen and tank temperature over 3 hours. Prior to the test, the load cells used will need to be calibrated using water. The tanks are set up on a assembled static test fire rig without the pressurant plumbing or engine to conduct this experiment. Tank temperature and tank weight are acquired through thermocouples and load cells, respectively. Flow rates during load cell calibration will be acquired through flowmeters. Expected boil off rates of liquid oxygen and methane can be determined based on the data obtained for liquid nitrogen in this test.

2. Hazards Overview

- Pressure buildup and explosions from boiled off liquid nitrogen poses a threat of rupturing, flying debris and possible chemical splashes. Preventative measures:
    - o *Vent valve at the top of each tank to evacuate any gases from boil off*
    - o *Storing of liquid nitrogen in containers with a venting point and/or loose fitting lids*
    - o *Maintaining a safe distance of at least 10 feet away during boil off test*

- Extreme cold from the vapor from liquid nitrogen can rapidly freeze skin tissue and eye fluid, resulting in cold burns, frostbite, and permanent eye damage even with only brief exposure. Direct skin contact to cold surfaces may cause flesh to rapidly stick and tear. Preventative measures:
    - o *Wearing of all PPE as described below to minimize risk of exposure*
    - o *Handling the liquid slowly to minimize boiling and splashing*
    - o *Avoiding of direct contact with cold surfaces*

- Asphyxiation from reduction of environmental oxygen percentage due to boil off may cause unconsciousness. Inhalation of high partial pressures of nitrogen may result in nitrogen narcosis. Preventative measures:
    - o *Performing the test and any handling of liquid nitrogen in a well ventilated area and ensuring all boiled off liquid nitrogen is safely directed away from people*
    - o *Minimizing time spent handling or in the proximity of containers containing liquid nitrogen*

- Oxygen in the air surrounding any cryogen can dissolve and increase oxygen levels, increasing the flammability of materials. Preventative measures:
    - o *Equipment containing cryogenic fluids must be kept well clear of combustible materials*
    - o *All personnel are prohibited of wearing highly flammable material*
        - ▪ *Highly flammable materials include: Nylon, Spandex, Polyester, Acetate, etc.*

A hazard assessment can be performed to help identify risks. This form is available upon request or at the “ME Labs” GauchoSpace page.

3. Required Personal Protective Equipment (PPE)

- Splash-proof safety goggles
- Full face shield
    - o Goes over goggles when transferring cryogenic liquids
- Cryogenically rated, loose-fitting gloves
    - o Loose-fitting gloves can be quickly removed.
    - o **Cryogenically rated gloves are not rated for immersion in or prolonged handling of cryogenic materials.**
- Cryogenically rated lab coat or apron
- Long-sleeve shirt
- Full length cuffless pants that extend past neck of footwear

Approver’s initials:

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    - Clothing must be made from a non-flammable material.
    - Highly flammable materials such as Nylon, Spandex, Polyester, Acetate, etc. are prohibited.
- Close-toed shoes

4. Waste Disposal

Waste water can be disposed of in a sink, down a drain, or, ideally, outside on a lawn.

There is typically little to no waste generation in the use of liquid nitrogen. If needed, small amounts of waste liquid nitrogen can be disposed of by pouring onto bare earth or gravel where it can safely evaporate.

- Do not pour onto pavement or grass.
- Do not dispose of in an unventilated area or a closed container.

5. Accident and Spill Procedure

In the event of an emergency, remain calm at all times. Evaluate the status of the accident scene:

A. Tank rupture or explosion due to pressure buildup:

- *Evacuate the area away from any debris and ensure proper ventilation.*
- *In the event of an accident involving personnel, see "6. First Aid and Medical Emergency Procedure".*
- *In the event of a spillage or leak, see below.*

B. Liquid nitrogen spillage or leak (not on personnel):

- *Do not approach without proper PPE equipped.*
- *Evacuate the area and ensure proper ventilation.*
    - *If safe, shut off liquid nitrogen source.*
- *Liquid nitrogen evaporates into gaseous nitrogen and disperses into the atmosphere given proper ventilation. No special cleanup procedures are necessary.*

C. Gaseous nitrogen spillage or leak

- *Evacuate the area and ensure proper ventilation.*
    - *Gaseous nitrogen is typically harmless but may be pressurized or cold due to liquid nitrogen.*
    - *Inhalation of high partial pressures of nitrogen may cause nitrogen narcosis, a temporary state of mental impairment. Victims should be relocated to a well-ventilated area to ensure safety and recovery and minimize collateral damage. (See "6. First Aid and Medical Emergency Procedure")*

Approver's initials:

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<u>The lab manager must be notified</u> in the event of a large spill, i.e., greater than 5 gallons, or a spill of any hazardous waste.

6. First Aid and Medical Emergency Procedure

In the event of an emergency, remain calm at all times. Evaluate the status of the accident scene:

A. Liquid nitrogen spillage onto personnel:

- Immediately call 911 (or 9-911 from a campus phone) to contact emergency services, then notify UCSB Environmental Health and Safety at 805-893-3194.
    - Your location is: [Enter room/building], UC Santa Barbara, Santa Barbara, CA 93106
    - The closest hospital is: Goleta Valley Cottage Hospital, 351 S Patterson Ave, Goleta, CA 93111
    - Carefully and accurately explain accident and any injuries to dispatcher. Be prepared to answer:
        - What is the problem or incident?
        - What is the victim's age?
        - Is the victim conscious?
        - Is the victim breathing?
        - What is your location?
- If safe, remove the victim away from any source of liquid nitrogen into a well-ventilated area.
- Remove contaminated garments and footwear.
    - Clean garments and footwear thoroughly before reuse.
- **In case of direct skin exposure:**
    - Warm affect area with lukewarm water not exceeding 105 °F, body heat, or warm air.
    - Maintain skin warming for at least 15 minutes or until normal coloring and sensation has returned.
    - In the event of massive exposure, warm victim using emergency shower (if possible, warm). All clothing must be removed prior to using shower. Seek medical evaluation and treatment as soon as possible. Maintain affected areas at normal body temperature until emergency services arrive.
    - Keep victim calm and avoid aggravating injury. Do NOT rub or massage affected areas. Frostbitten feet should not be used to walk.
- **In case of eye exposure:**
    - Rinse eyes thoroughly with warm water for at least 15 minutes. Hold eyelids open and away from the eyeballs.
    - Check for and remove any contact lenses.
    - Seek immediate medical attention and contact an ophthalmologist immediately.
- Provide necessary information, including Safety Data Sheets to emergency responders.

Approver's initials:

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B. Other serious or life-threatening injuries

- *Includes: uncontrolled bleeding, deep cuts, severe burns or heatstroke, badly broken bones, head/spine injuries, sudden unconsciousness, etc.*
- *Immediately call 911 (or 9-911 from a campus phone) to contact emergency services, then notify UCSB Environmental Health and Safety at 805-893-3194.*
    - *Your location is: [Confirm room/building], UC Santa Barbara, Santa Barbara, CA 93106*
    - *The closest hospital is: Goleta Valley Cottage Hospital, 351 S Patterson Ave, Goleta, CA 93111*
    - *Carefully and accurately explain accident and any injuries to dispatcher. Be prepared to answer:*
        - *What is the problem or incident?*
        - *What is the victim's age?*
        - *Is the victim conscious?*
        - *Is the victim breathing?*
        - *What is your location?*
- *Administer first aid as required or instructed.*
- *Provide necessary information, including Safety Data Sheets to emergency responders.*

C. Moderate or minor injuries:

- *Includes: minor cuts and scrapes, sprains, dislocations, mild suspected bone breaks (no bleeding or cold sensation), mild heat-related illness, small or localized burns, etc.*
- *If safe, move victim to a safe and well-ventilated location.*
- *Ensure the victim is in a stable condition.*
    - *If not, refer to "Other serious or life-threatening injuries" above.*
- *Administer first aid as required or instructed.*
- *Have the personnel stop all testing activities and rest.*
- *If necessary, transport victim to nearby hospital or UCSB Student Health Services.*
- *The closest hospital is: Goleta Valley Cottage Hospital, 351 S Patterson Ave, Goleta, CA 93111*

<u>The lab manager must be notified</u> in the event of any significant injury. A significant injury is any injury that cannot be addressed by the contents of the room's Band-Aid station.

7. Equipment

- 304 Stainless Steel ASME Code Pressure Vessel (15Liters) - 2 count
- Load Cell: TE Connectivity FC2211 100lb capacity
- Thermocouple:
- Flowmeter:
- Hose
- Multimeters (4)
- Containers (non-sealed) to hold excess liquid nitrogen

- Liquid nitrogen dewar
- Microcontroller
- Any wiring to interface sensors
- Camera(s)

8. Approvals Required

Approval pending confirmation of testing location.

9. Procedure

Before any filling of any liquid, double-check that all connections and fittings are correctly and properly secured to prevent spillage.

NEVER handle or approach liquid nitrogen without all proper PPE equipped (See "3. Required Personal Protective Equipment")

NEVER store liquid nitrogen in any sealed container at any point before, during, or after the test.

ALWAYS ensure that the work area is well-ventilated for the entire duration of the test.

ALWAYS properly dispose of liquid nitrogen (See "4. Waste Disposal")

A.1 Setup/Insulation

1. Assemble the test rig. The upper plumbing (pressurant plumbing and pressurant tank) and engine do not have to be assembled.
    a. See Rig Assembly SOP
2. Connect both load cells and both thermocouples measuring the tanks to (...). Connect a flowmeter to the fill line of each tank and to (...). Ensure all sensors are functioning properly and ready to measure data.
3. Wrap one tank with one inch of Styrofoam insulation. Leave the other one without insulation.
    a. Wrap the insulation over the thermocouple and feed the wire through a hole in the insulation.

A.2 Load Cell Calibration with Water

1. Close Ball Valves 4 and 5 located after the propellant tanks.
    a. BV 4 and 5 are left closed for the remainder of the entire boil-off test.

Approver's initials:

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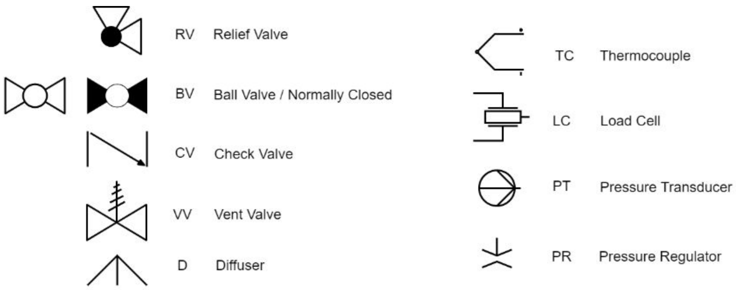

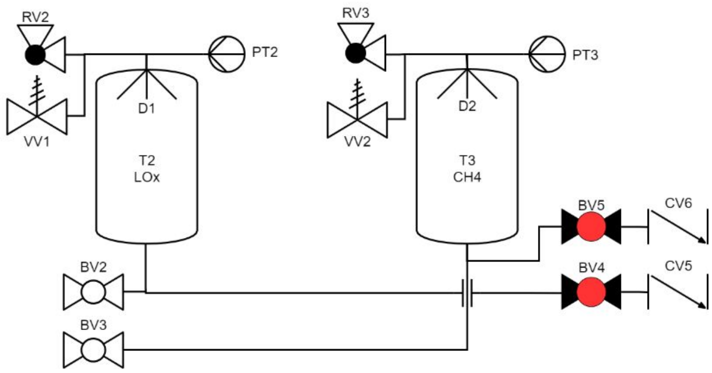

2. Connect a hose to one of the fill lines.
    a. Record the diameter of the hose.
3. Connect the load cell and flowmeter on the fill line to a multimeter each. Set up a camera to videotape the reading of each multimeter. (Alternatively, some other way to continuously monitor data, through avionics, etc.)
4. Turn on the hose to fill the tank with water while recording data through both the flowmeter and the load cell to obtain a weight/volume curve that will be used to calibrate the load cell.
5. Turn off the hose when the tank is filled with approximately 15 L of water.
6. Stop data collection, disconnect the hose, drain the water, and dispose of the water in a safe manner (See "4. Waste Disposal").
7. Repeat steps 3-6 for the same tank several times.
8. Repeat steps 2-7 for the other tank.
9. Drain both tanks and dispose of the water in a safe manner (See "4. Waste Disposal").
10. Allow sufficient time for any leftover water to evaporate

B. Tank Filling and Data Collection

1. **All personnel must equip all required PPE (see "3. Required Personal Protective Equipment") before handling or approaching any cryogenics.**
2. See Fill SOP to continue with filling of the liquid nitrogen.
3. Connect the load cell and thermocouple on each fill line to a multimeter each. Set up a camera to videotape the reading of each multimeter. (Alternatively, some other way to continuously monitor data, through avionics, etc.)
4. Begin recording weight and temperature data for both tanks.
5. Fill one tank up to [known amount] using the calibrated load cell reading as a reference.

Approver's initials:

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6. Fill other tank up to [known amount] using the calibrated load cell reading as a reference.
7. Observe change in weight over time in both tanks using load cell readings for a maximum of 3 hours or until all of the liquid nitrogen boils off.
8. Observe temperature readings in each tank using thermocouple readings over the course of the test.
9. Should any spillage of nitrogen occur, refer to "5. Accident and Spill Procedure".
10. Should any injuries to personnel be sustained, refer to "6. First Aid and Medical Emergency Procedure".

C. Post Boiloff Test / Cleanup

1. Stop and save all data collection.
2. **Assembly may still be extremely cold. Do not handle or touch any part of assembly without equipping all proper PPE (see "3. Required Personal Protective Equipment") or until the assembly is at a safe temperature.**
3. Drain excess liquid nitrogen into a designated container and safely dispose. See "4. Waste Disposal."
4. Wait at least 10 minutes for remaining liquid nitrogen in the system to completely boil off.
    a. Continue ensuring proper ventilation during this step
5. Wait at least 20 minutes until the assembly has reached ambient temperatures before handling.
6. If different rig or insulation configurations need to be tested or an error occurred during the test, repeat the test as necessary.
7. Disassemble assembly.

Approver's initials:

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B.8 Liquid nitrogen cold flow system test

Only the fill of the system is written. There will be other SOPs for other parts of the test.

Safe Operating Procedure: Fill

Author:	Alan Thomas, Vicente Lopez
Department:	Mechanical Engineering
Building/Room:	Enter the location where the work will be performed. For the Design Lab enter “503/2226. For the *Advanced Instructional Lab*, enter “503/2133”.
Date Approved:	Click or tap to enter a date.
Approved by: [Approver’s name. Should be the person in charge of the space you will be performing the procedure in.]	Signature:

1. Description

This SOP describes the filling procedure that needs to be followed in order to prepare for the hot fire. Preceded by the pre-chilling of the lines and tanks, the fill is carried out while the system is still cool in order to reduce the amount of propellant boil-off. First, the LOx-containing dewar is attached to the feed system with a cryogenic hose. The dewar’s liquid-use valve is opened manually and the feed system’s fill/drain valves are opened by the pneumatic actuators. The dewar pressure of roughly 22 psi drives the flow of the LOx propellant from the dewar to its respective tank. When the tank is filled to its desired value, the fill/drain is closed, the dewar’s liquid-use valve is closed, and the cryogenic hose is disconnected. This process is then repeated identically for LCH4.

After the fill is complete, proceed to the pressurization stage.

2. Hazards Overview

- Propellant phase change from liquid to gas may occur due to excessive exposure to heat or other factors. In the event of a relief valve failure, this can cause pressure buildup within pressurized vessels, which includes dewars and tanks, as well as the consequent violent rupturing of the vessel.
    - Ensure that anyone going near the vessels is wearing the proper PPE.
    - Make sure that vent valves on dewars and tanks are properly functioning.
    - Make best effort to store dewars at appropriate temperatures and not leave them sitting out in the sun.
    - If a dangerous pressure buildup is detected, evacuate the immediate vicinity and take cover behind any available barriers.

- Vented or leaked methane gas, which is colorless and odorless, can accumulate in hazardous amounts, especially in low-lying areas that are not well-ventilated. This poses an asphyxiation risk for anyone in the vicinity.
    - Ensure the environment is well ventilated. It is preferable to perform the fill outdoors.
    - Minimize the duration that personnel are in the direct vicinity of the rig during fill.
    - When leaking liquid methane after disconnecting cryogenic hose, take care to point hose away from all personnel to prevent any evaporated methane gas from being directed towards them.

- Excessive vented or leaked oxygen gas can lead to hyperoxia in nearby personnel
    - Ensure the environment is well ventilated. It is preferable to perform the fill outdoors.
    - Minimize the duration that personnel are in the direct vicinity of the rig during fill.

- Venting or leakage of propellants, especially oxygen, poses a potential combustion and fire risk.
    - Ensure no combustible materials are present in the area, especially when the oxygen tank is being filled.
    - Make sure that the oxygen and methane dewars are always kept at a safe distance from each other to prevent mixture of gases of an oxidizer and fuel

Approver's initials:

____

- Proper PPE must be worn by all personnel performing the fill to minimize the risk of burn injuries in the case of a fire.
    - During the actual filling, make sure to move a certain distance away from the oxygen fill location when filling methane to prevent mixture of any lingering liquid on the ground or vapor in the air.

- Cryogenic propellants can cause major damage if they come into direct contact with skin or eyes.
    - The use of cryogenically rated PPE is essential on all personnel performing the fill.
    - Handle equipment with caution and move slowly to avoid splashing liquid or producing excess boiled-off vapor

- Electronics on the rig are a potential shock hazard
    - All personnel near the rig must wear appropriate PPE to minimize electric shock risk
    - Avoid accidentally touching electrical components that are not necessary to the procedure

These are mostly preventative measures. See “Accident and Spill Procedure” for more detailed instructions on what to do in case of accident or emergency.

3. Required Personal Protective Equipment (PPE)

- Splash-proof safety goggles
- Full face shield
    - Goes over goggles when transferring cryogenic liquids
- Cryogenically rated, loose-fitting gloves
    - Loose-fitting gloves can be quickly removed
    - Cryogenically rated gloves are NOT rated for immersion in or prolonged handling of cryogenic materials
- Cryogenically rated lab coat or apron
- Long-sleeve shirt
- Full length pants, no cuffs, that extend over top of footwear
    - Clothing must be made from a non-flammable material
    - Highly flammable materials such as: Nylon, Spandex, Polyester, Acetate, Under-Armour, etc. are prohibited
- Close-toed shoes
- Possible gas mask/respirator

4. Waste Disposal

Under normal circumstances, the waste from the fill procedure would be the amount of propellants present in the lines between the fill/drain valve and the dewar interface after the dewar is depressurized to funnel the majority of stuck propellant back into the dewar and the propellant dewars are detached.

Possibility: drain liquid in tubes through purge valve into bucket with hot gravel to quickly vaporize it

Once the dewar is detached,

Product removed from the cylinder must be disposed of in accordance with appropriate Federal, State, and local regulations.

5. Accident and Spill Procedure

In case of skin contact:

- *Immediately flush the area with large quantities of warm (not hot) water*
- *If the skin is blistered or the eyes have been exposed, obtain medical attention immediately*

In case of clothing contact:

- *If clothing is frozen to skin, thaw before removing*
- *Remove and isolate contaminated clothing and shoes*

SPILL PROCEDURE:

Note: Spilling of propellants results in a quick evaporation. If possible, spill into a gravel bucket.

- ELIMINATE all ignition sources
- All equipment used must be grounded
- Do not touch / walk through spilled material
- Stop leak if it is possible without risk
- If possible, turn leaking containers so that gas escapes rather than liquid
- Do not direct water at spill or source of leak
- Isolate area until gas has dispersed

6. Equipment

- *Liquid Oxygen (LOx) dewar*
- *Liquid Methane (LCH4) dewar*
- *Two 6 foot cryogenic hoses*
- *Screwdrivers and wrenches to attach dewar and hoses (specify which ones later)*

Manufactured equipment

- Test rig

7. Approvals Required

Click to enter text.

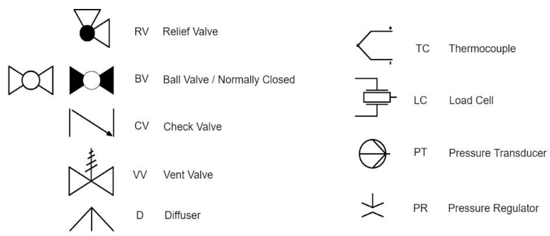
List circumstances under which the procedure will require prior approval from the lab manager, PI, or other supervisor.

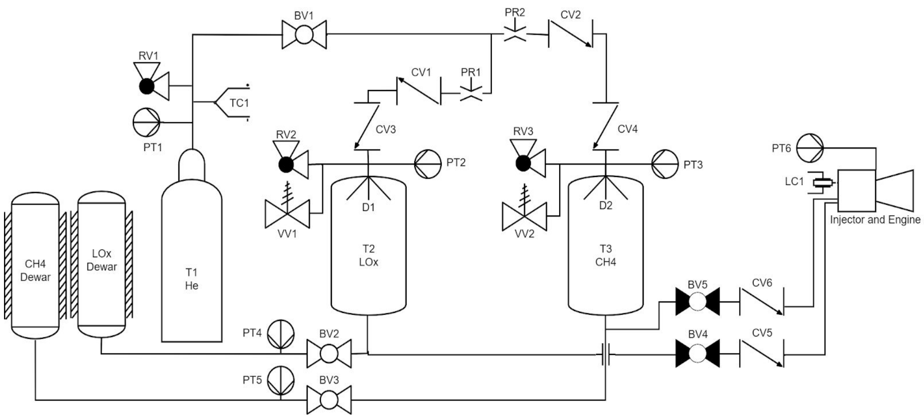
Need to figure out where cold flow test will be taking place

8. Procedure

General Safety:

- Ensure that all people going near the testing are wearing proper PPE
- Work in an open or well ventilated area to reduce the risk of vapors





1. Setup:
    a. Provide any special start-up instructions. Such as, what the appropriate time allowances is a heating unit to reach the normal operating parameters.
        i. Before beginning the fill, reference the chilldown procedure
        ii. Monitor temperature in tank until it reaches certain value
        iii. Ensure control valves are controlled by electronics
        iv. Ensure valves are ready for procedure:
            1. Vent valves, VV1 and VV2, are open
            2. Pressure valve, BV1, is closed
            3. Fill / drain valves, BV2 and BV3, are closed
            4. Main valves, BV4 and BV5, are closed
2. Process/Run
    a. Provide step-by-step instructions for the process.
        i. Attach one end of cryogenic hose to fill/drain valve BV2 for LOx tank T2 and ensure tight fit
        ii. Attach other end of cryogenic hose to LOx dewar and ensure tight fit

iii. Open the liquid use valve on the LOx dewar (need to include how much to turn based on proper flow rate) and ensure proper flow rate based on data
iv. Open BV2 to fill up T2 with LOx from dewar
v. VV1 is left open so that excess vapor can drain
vi. Fill T2 to desired level (not sure what this is, do we want a certain volume, weight, or pressure?), then close BV2
vii. Close liquid use valve on LOx dewar
viii. Detach LOx dewar
ix. Attach one end of cryogenic hose to fill/drain valve BV3 for LOx tank T3 and ensure tight fit
x. Attach other end of cryogenic hose to LCH4 dewar and ensure tight fit
xi. Open the liquid use valve on the LCH4 dewar (need to include how much to turn based on proper flow rate) and ensure proper flow rate based on data
xii. Open BV2 to fill up T3 with LCH4 from dewar
xiii. VV1 is left open so that excess vapor can drain
xiv. Fill T3 to desired level (not sure what this is, do we want a certain volume, weight, or pressure?), then close BV3
xv. Close liquid use valve on LCH4 dewar
xvi. Detach LCH4 dewar

b. Detail what data is to be collected and how it is acquired.

c. Include the applicable safety precautions and operating conditions to be maintained. That is, include instructions about pressure limits, temperature ranges, flow rates, etc. You should as also include instructions for what to do when an upset condition occurs, what alarms and instruments are pertinent if an upset condition occurs, and what steps to be taken should an out-of-normal condition occur.

3. Post-Fill

a. Begin preparations for pressurization stage

i. Remove personnel from area

B.9 Static fire test

This SOP is in progress.

C Bill of Materials and Budget

Part #	Part Name (Hyperlink to design documentatio	Supplier	Supplier Part #	Cost (individual)	Quantity	Total Cost
100-000	Engine					$5,000
100-001	[Engine Assembly]()	CompositeX	N/A	$2,500	2	$5,000
200-000	Injector					182.94
210-000	Custom Parts					137.38
210-001	Thrust Plate	McMaster	9198k17-9198K1	54.88	1	54.88
210-002	Pintle Body	McMaster	8984k43	31.86	1	31.86
210-003	Pintle Tip	McMaster	8984k18	16.02	1	16.02
210-004	Reservoir	McMaster	9198k15-9198K6	34.62	1	34.62
220-000	Ordered Parts					45.56
220-001	Teflon O-ring 019	McMaster	9559K114	12.89	1	12.89
220-002	Teflon O-ring 027	McMaster	9559K122	12.01	1	12.01
220-003	Teflon O-ring 041	McMaster	9559k337	3.16	1	3.16
220-004	Teflon O-ring 043	McMaster	9559k139	13.03	1	13.03
220-005	4-40 x 9/16"	McMaster	92196a111	4.47	1	4.47
300-000	Feed System					$ 10,548.33
310-000	Valves					$ 5,666.03
311-000	Top Assembly					$ 2,410.55
311-001	Helium Pressurization Control Valve	Swagelok	SS-43GS4-31C	420.01	1	$ 420.01
311-002	Helium Check Valves	Swagelok	SS-CHS8-1	110.19	4	$ 440.76
311-003	Helium Relief Valve	Swagelok	SS-4R3A	174.89	2	$ 349.78
311-004	LOx Relief Valve	Generant	CRV-4-K-750		1	$ -
311-005	LCH4 Relief Valve	Generant	CRV-4-K-751		1	$ -
311-006	Pressure Regulator	Swagelok	KPP1LWH422P2	600.00	2	$ 1,200.00
311-007	LOx REDS Vent Valve					$ -
311-008	LCH4 REDS Vent Valve					$ -
311-009	Upper Feed System Inline Filter				1	$ -
312-000	Bottom Assembly					$ 3,255.48
312-001	LOx Check Valve	Generant	KCV-500B-X		1	$ -
312-002	LCH4 Check Valve	Generant	KCV-500B		1	$ -
312-003	LOx Main Ball Valve Normally Closed	Sharpe	1/2" C89-6666KI	813.87	1	$ 813.87
312-004	LCH4 Main Ball Valve Normally Closed	Sharpe	1/2" C89-6666KI	813.87	1	$ 813.87
312-005	LOx Fill/Drain Ball Valve	Sharpe	1/2" C89-6666KI	813.87	1	$ 813.87
312-006	LCH4 Fill/Drain Ball Valve	Sharpe	1/2" C89-6666KI	813.87	1	$ 813.87
320-000	Plumbing					$ 1,975.56
321-000	Tubing					$ 981.16
321-001	1/4" Stainless Steel Tubing	Swagelok	SS-T4-S-049-20			$ -
321-002	1/2" Stainless Steel Tubing	Swagelok	SS-T8-S-049-20	20.00	15	$ 300.00
321-003	1/4 " P-Clamp (pack of 25)	McMaster-Carr	8863T25	6.47	2	$ 12.94
321-004	1/2 " P-Clamp (pack of 25)	McMaster-Carr	8863T27	9.21	2	$ 18.42
321-005	1/4" Tube Benders	Swagelok	MS-HTB-4T	210.68	1	$ 210.68
321-006	1/2" Tube Benders	Swagelok	MS-HTB-8	439.12	1	$ 439.12
321-007	Cryo Hoses	CryoFab			1	$ -
322-000	Fittings					$ 994.40
322-001	1/4" Compression to 1/4" Male NPT Fittings	Swagelok	SS-400-1-4	8.40	6	$ 50.40
322-002	1/2" Compression to 1/2" Male NPT Fittings	Swagelok vs Ger	SS-810-1-8	19.24	10	$ 192.40
322-003	1/4" Compression to 1/4" Female NPT Fitting	Swagelok	SS-400-7-4	13.71	2	$ 27.42
322-004	1/2" Compression to 1/4" NPT Fittings	Swagelok vs Ger	SS-810-1-4	16.69	2	$ 33.38
322-005	1/4" Compression Tee Fittings	Swagelok	SS-400-3	26.46	5	$ 132.30
322-006	1/2" Compression Tee Fittings	Swagelok vs Ger	SS-810-3	52.60	4	$ 210.40
322-007	1/2" Compression Elbow Fittings	Swagelok	SS-810-9	37.94	2	$ 75.88
322-008	1/2" Compression to 1/2" Male NPT Elbow Fit	Swagelok	SS-810-2-8	35.17	2	$ 70.34
322-009	1/2" Compression to 1/2" Compression Bulkh	Swagelok	SS-810-61	40.80	4	$ 163.20

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100-000	Engine					$5,000
100-001	[Engine Assembly]()	CompositeX	N/A	$2,500	2	$5,000
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311-009	Upper Feed System Inline Filter				1	$ -
312-000	Bottom Assembly					$ 3,255.48
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321-000	Tubing					$ 981.16
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321-007	Cryo Hoses	CryoFab			1	$ -
322-000	Fittings					$ 994.40
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322-009	1/2" Compression to 1/2" Compression Bulkh	Swagelok	SS-810-61	40.80	4	$ 163.20

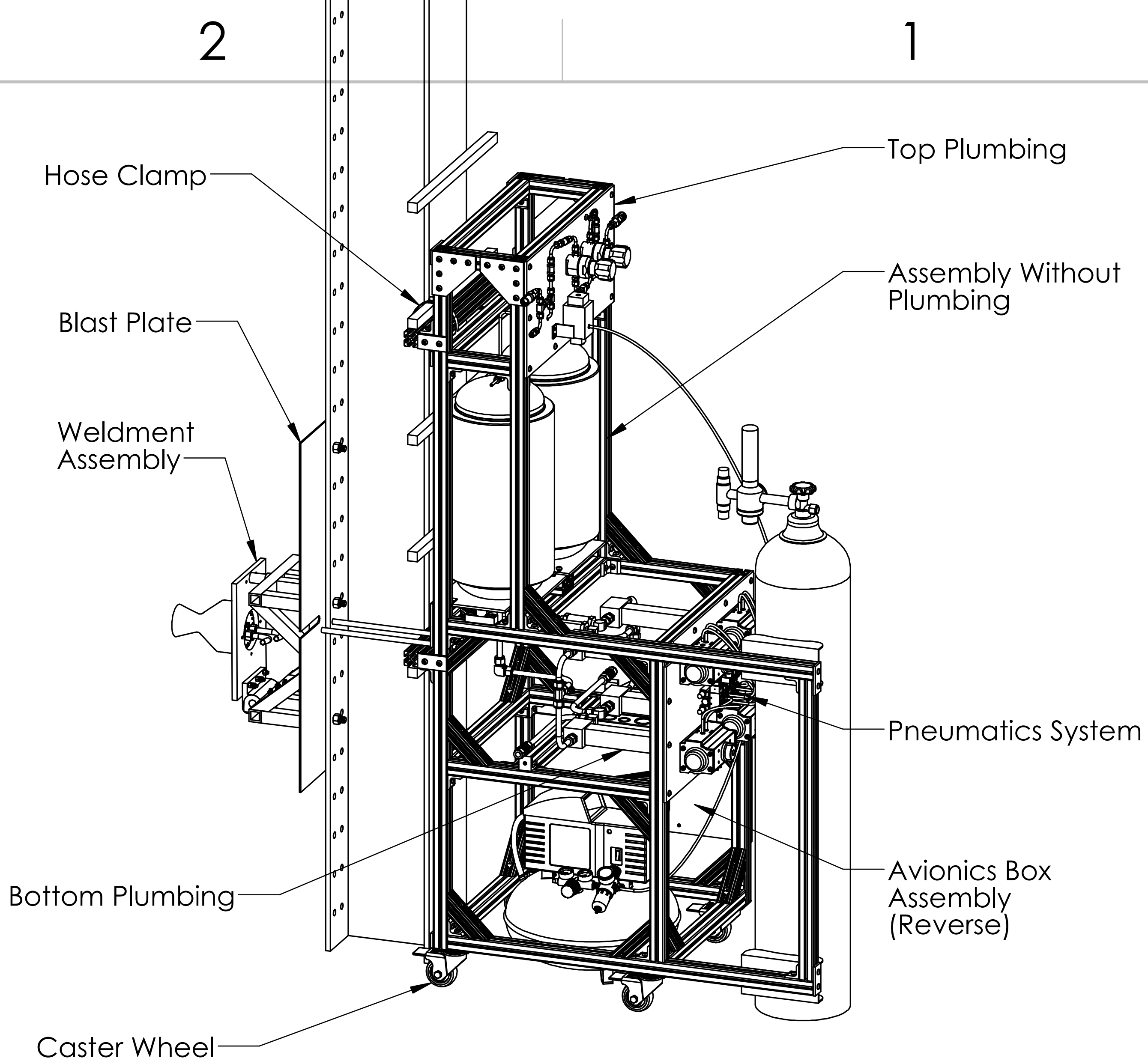
421-001	**Weldment Tube**	McMaster	6527K48	71	3	213
421-002	**Heavy Duty Hinge**	McMaster	1805A15	192.2	1	192.2
421-003	**I-beam Mounting Screws**	McMaster	91247A409	7.66	1	7.66
421-004	**I-beam Mounting Nut**	McMaster	95615A240	11.66	1	11.66
421-005	Hinge Mounting Screw	McMaster	91247A551	8.63	1	8.63
421-006	Hinge Mounting Nut	McMaster	95615A120	4.39	1	4.39
421-007	Load Cell Mounting Screw	McMaster	91290A111	8.71	1	8.71
421-008	Blast Plate	McMaster	6544K74	92.72	1	92.72
421-009	Blast Plate Mounting Screw	McMaster	92865A404	8.93	1	8.93
422-000	Engine Interface					82.46
422-001	**Thrust Plate Extension**	McMaster	9143K729	63.3	1	63.3
422-002	Extension Extender	UCSB Machine S	x	3	1	3
422-003	Screws Hinge-TPE	McMaster	92865A546	6.75	1	6.75
422-004	Screws to TPE-Extension Extender	McMaster	92865A542	9.41	1	9.41
423-000	Sensor and Valve Interface					$1,881.96
500-000	Ground Systems					$1,225.58
510-000	Ground Computer (Controls)					$560.63
511-000	Control Circuit					$95.75
511-001	STM32H7 Nucleo Board	Mouser	511-NUCLEO-H7	$27.00	2	$54.00
511-002	24 V Power supply	Amazon		$8.99	1	$8.99
511-003	USB-USB Cable (Power STM)	Amazon		$7.12	1	$7.12
511-004	Ignition Circuit Materials					
511-005	IRFZ44NPBF - Power MOSFET	Digikey		1.13	8	$9.04
511-006	2N3904BU - BJT	Digikey		0.2	8	$1.60
511-007	DC DC converter			15	1	$15.00
511-008	Relay Array	Mouser		$11.50	8	$92.00
512-000	REDS					$360.63
512-001	Push in Power Connector	McMaster	69295K97		2	$3.50
512-002	250V Gauge Wires	McMaster	69295K112	10.76	1	$10.76
512-003	Solenoid Valve, Normally Closed, Orifice 1/32”, MOPD: 1000-psi, 24-Vdc, 1/8”-FNPT, Plunger & O-Ring Seals PTFE	Gems	A2211-T-T0_C20	$66.00	4(5min to order(	$330
512-004	Push-In Power Connector	McMaster	69295K5	$3.50	1	$3.50
512-005	Sleeves, Gauge Wire	McMaster	69295K115	$11.72	1	$11.72
	Toggle Switch (need to spec)					
513-002	Diodes 1kV	Digikey	1N4007-TPMSCT	$0.12	10	$1.15
513-000	Control Box					$104
513-001	Housing			$50	1	$50
	Plate for Avionics Box	McMaster	89015K28	$47		$47
411-008	**8020 screw and nut set**	McMaster	47065T215	2.38	3	7.14
513-002	Toggle Switch (need to spec)				8	
513-003	LEDs				8	
520-000	Sensors Array					$540.97
521-000	Filter Circuits					77.19
521-001	Instrumention Amplifier	Digikey	AD8429ARZ	8.54	10	77.19
522-000	Sensors					$463.78
522-001-001	FC23 Compression Load Cell	Mouser	824-FC23-1-100	$134.79	1	$132.16
522-001-002	FC22 Compression Load Cell	Mouser	824-FC2211-000	$57.42	2	$114.84
522-002-001	M3021 Pressure Transducer (1k)	Digikey	MSP3102P1-ND	$56.58	2	$113.16
522-002-002	M3021 Pressure Transducer (2.5k)	Digikey	223-1874-ND	$53.66	1	$53.66
522-002-003	M3021 Pressure Transducer (500)	Digikey	MSP3501P1-ND	$56.58		
522-003-001	Conax K-Type Thermocouple	Conax	Contact Andrea S	$115-$150	1	$49.96

530-000	Data Transmission and Processing					0
530-001	Ethernet Cable					0
540-000	Test Sequencing and Operations					$123.98
540-001	Digital T-Type Thermometer	MMI	DM6803	$64.99	1	$64.99
540-002	Infrared Digital Pyrometer	HOLDPEAK	HP-2732	$58.99	1	$58.99

Team	**Projected Cost**
Feed System	
Injector	
Engine	
Ground Systems	
Structure	
B_O_M Total	$0.00
Allowance for Sa	$0.00
Safety Net	$7,500.00
Generous Minin	**$7,500.00**

D Assembly Drawings

1. Assembly Without Plumbing
2. 8020 Frame
3. Tank Assembly
4. Weldment Assembly
5. Injector
6. Bottom Plumbing
7. Upper Plumbing



ITEM NO.	PART NUMBER	QTY.
1	Assembly Without Plumbing*	1
2	Weldment Assembly*	1
3	Blast Plate*	1
4	Bottom Plumbing*	1
5	Top Plumbing*	1
6	Caster Wheels	4
7	Flexible Tubing to Injector (not imaged)	2
8	Hose Clamp	4
9	Avionics Box Assembly	1
10	Pneumatics System	1

NEXT ASSY | USED ON

APPLICATION

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

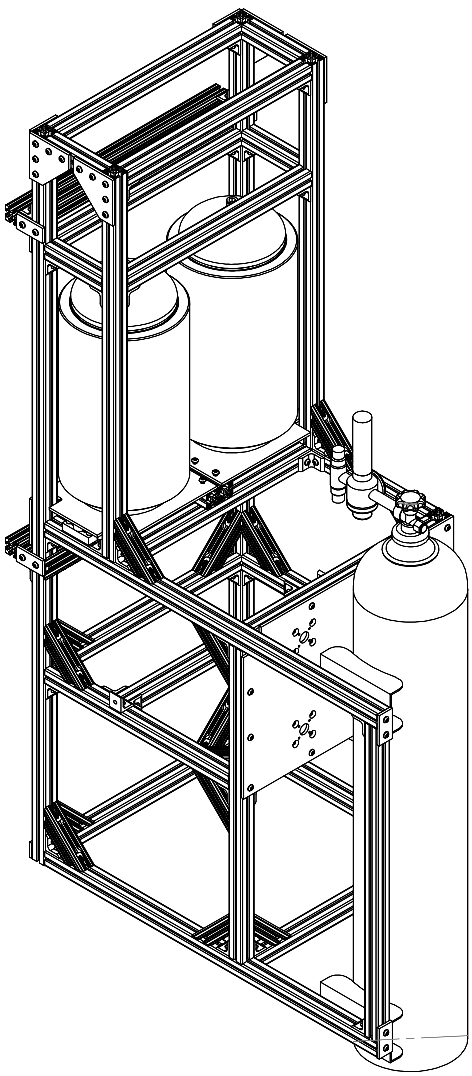
COMMENTS:

SIZE A | DWG. NO. Full Assembly Drawing | REV.

SCALE:1:64 | WEIGHT: | SHEET 1 OF 1

2 1

B



ITEM NO.	PART NUMBER	QTY.
1	8020_frame	1
2	Tank_Assembly	2
3	Pneumatic Mounting Plate	1
4	Corner Bracket	2
5	80/20 Screw with Insert	19
6	Tank Mounting Plate	2
7	Long 80/20 Screw with Insert	8
8	FC22 Compression Load Cell	2
9	Level Sensor Mount	2
10	Sensor Mount Screw 4-40x0.25"	4
11	Offset Mount Screw 5/16x1"	4
12	Helium Mounting Bracket	2
13	Gas Bottle	1
14	Avionics Mounting Plate*	1

B

A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ALL ± 0.1	DRAWN	Brandon	2/26/20
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL N/A	COMMENTS: * part has associated drawing		
FINISH N/A			
DO NOT SCALE DRAWING			

TITLE:

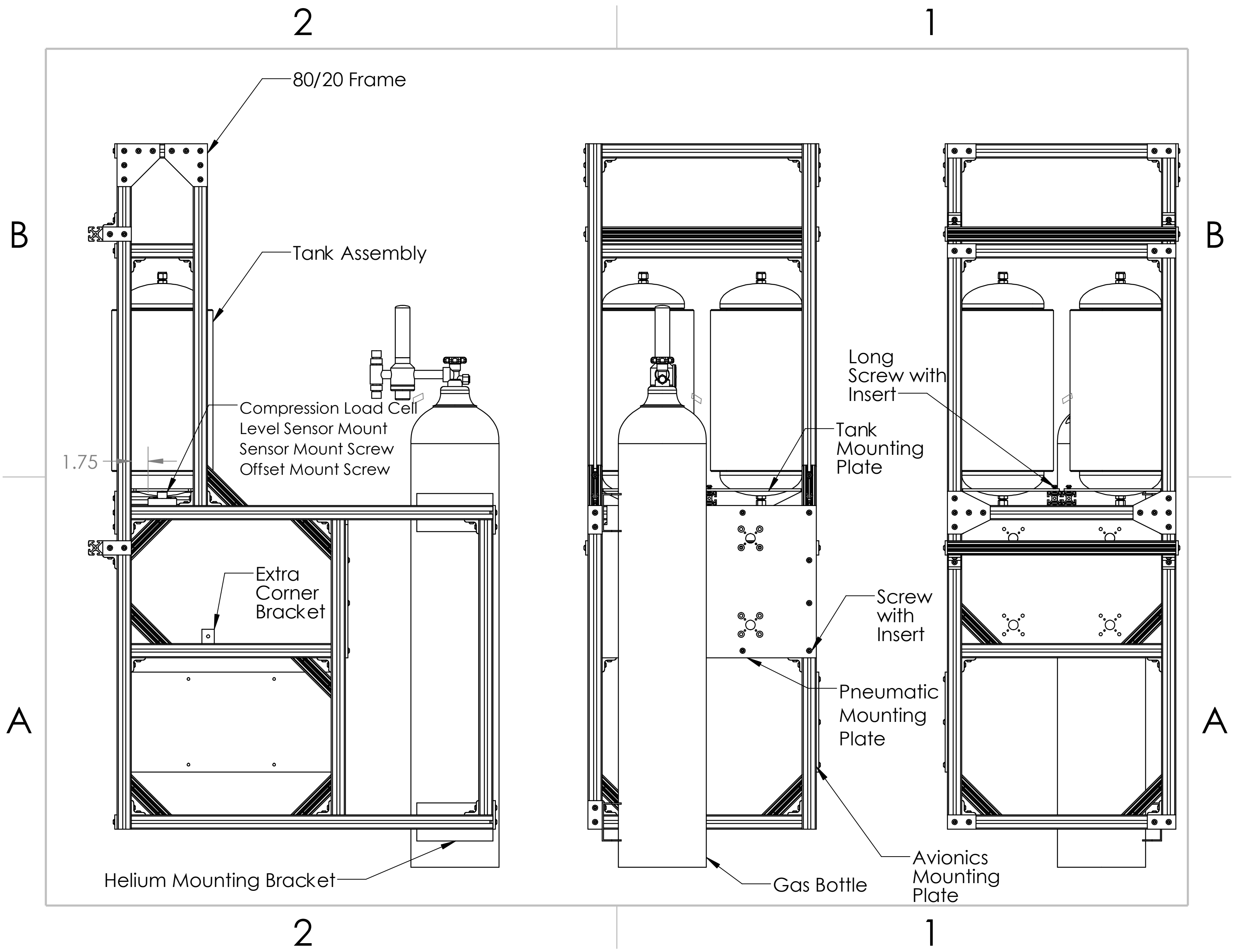
Assembly Without Plumbing

SIZE	DWG. NO.	REV
A	Assembly Without Plumbing	1

SCALE: 1:12 WEIGHT: SHEET 2 OF 2

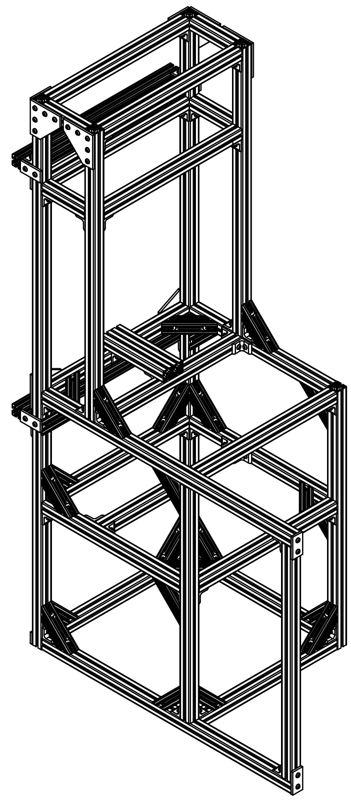
A

2 1



2
1
B
A
80/20 Frame
Tank Assembly
Compression Load Cell
Level Sensor Mount
Sensor Mount Screw
Offset Mount Screw
1.75
Extra Corner Bracket
Helium Mounting Bracket
Long Screw with Insert
Tank Mounting Plate
Screw with Insert
Pneumatic Mounting Plate
Avionics Mounting Plate
Gas Bottle

ITEM NO.	PART NUMBER	QTY.
1	72in	2
2	38in	4
3	21in	16
4	34 in	1
5	31 in	2
6	9.5 in	2
7	6.5 in	4
8	Double Wide 80/20	2
9	Corner Bracket	54
10	Straight Bracket	12
11	L Bracket	4
12	T Bracket	2
13	Corner Brace	24
14	Screw with Insert	210



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
All ± 0.1

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: Mostly Aluminum

FINISH: As assembled

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Brandon	2/26/20
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

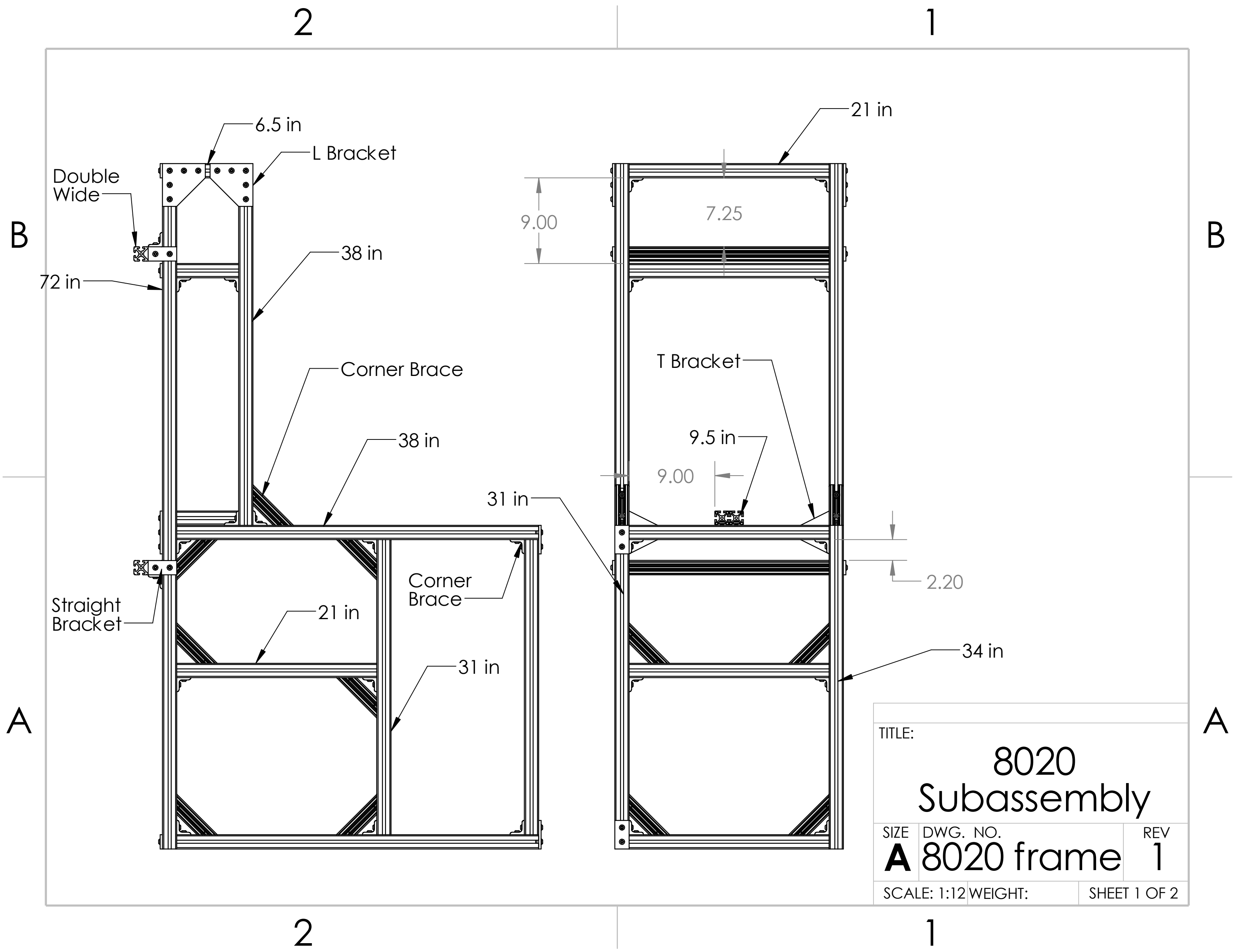
COMMENTS:

TITLE:

8020 Subassembly

SIZE: **A** DWG. NO. 8020 frame REV

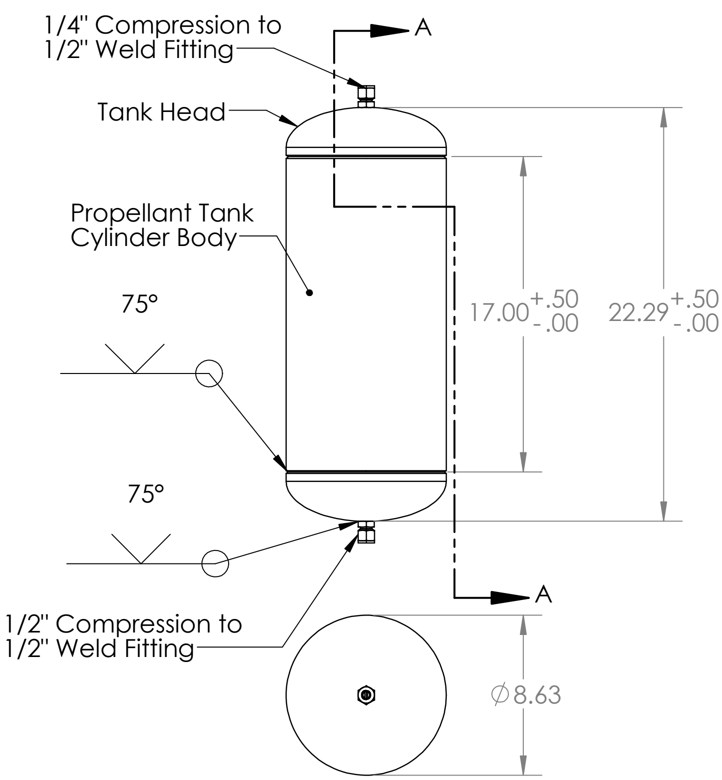
SCALE: 1:24 WEIGHT: SHEET 2 OF 2

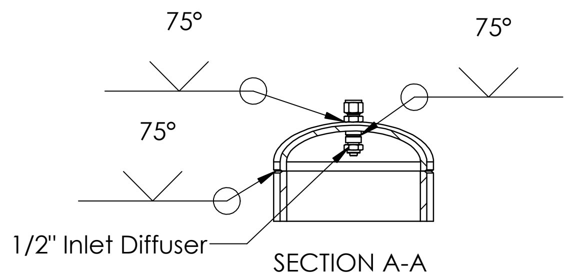


TITLE:

8020 Subassembly

SIZE	DWG. NO.	REV
A	8020 frame	1
SCALE: 1:12	WEIGHT:	SHEET 1 OF 2





SECTION A-A

ITEM NO.	PART NUMBER	QTY.
1	Propellant Tank Cylinder Body*	1
2	Tank_Head*	2
3	1/4" Compression to 1/2" Weld Fitting	1
4	1/2" Compression to 1/2" Weld Fitting	2
5	1/2" Inlet Diffuser	1

Tank Head to Cylinder Body welds are 304-304 stainless.
Tank Head to Fitting welds are 304-316 stainless.
Fitting to Diffuser weld is 316-316 stainless.

UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	
INTERPRET GEOMETRIC TOLERANCING PER: ANSI	
MATERIAL	Stainless Steel 304 & 316
FINISH	Machined/Welded
NEXT ASSY	USED ON
APPLICATION	DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Jacob	2/29/20
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
*part has associated drawing

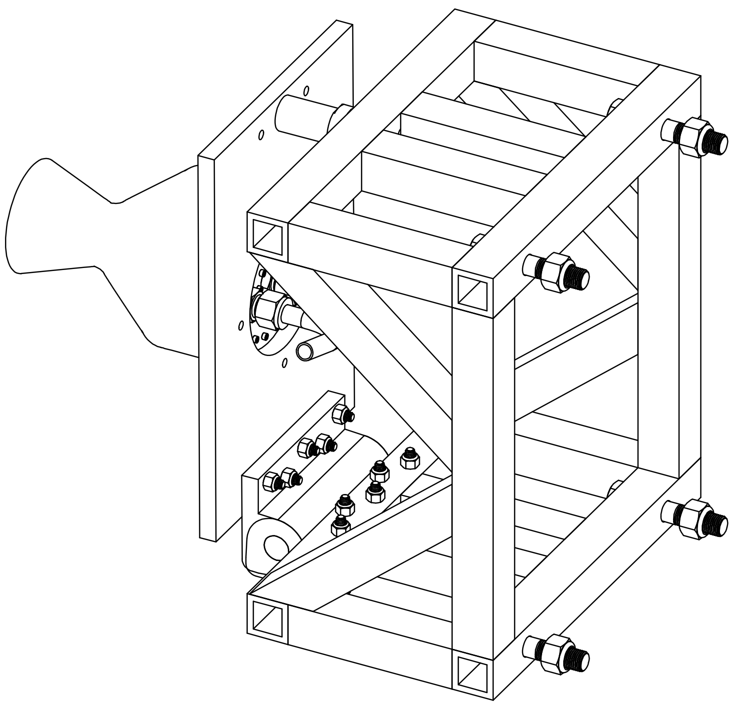
TITLE:
Propellant Tank Assembly

SIZE	DWG. NO.	REV
A	N/A	1

SCALE: 1:8 WEIGHT: SHEET 1 OF 1

2 | 1

B

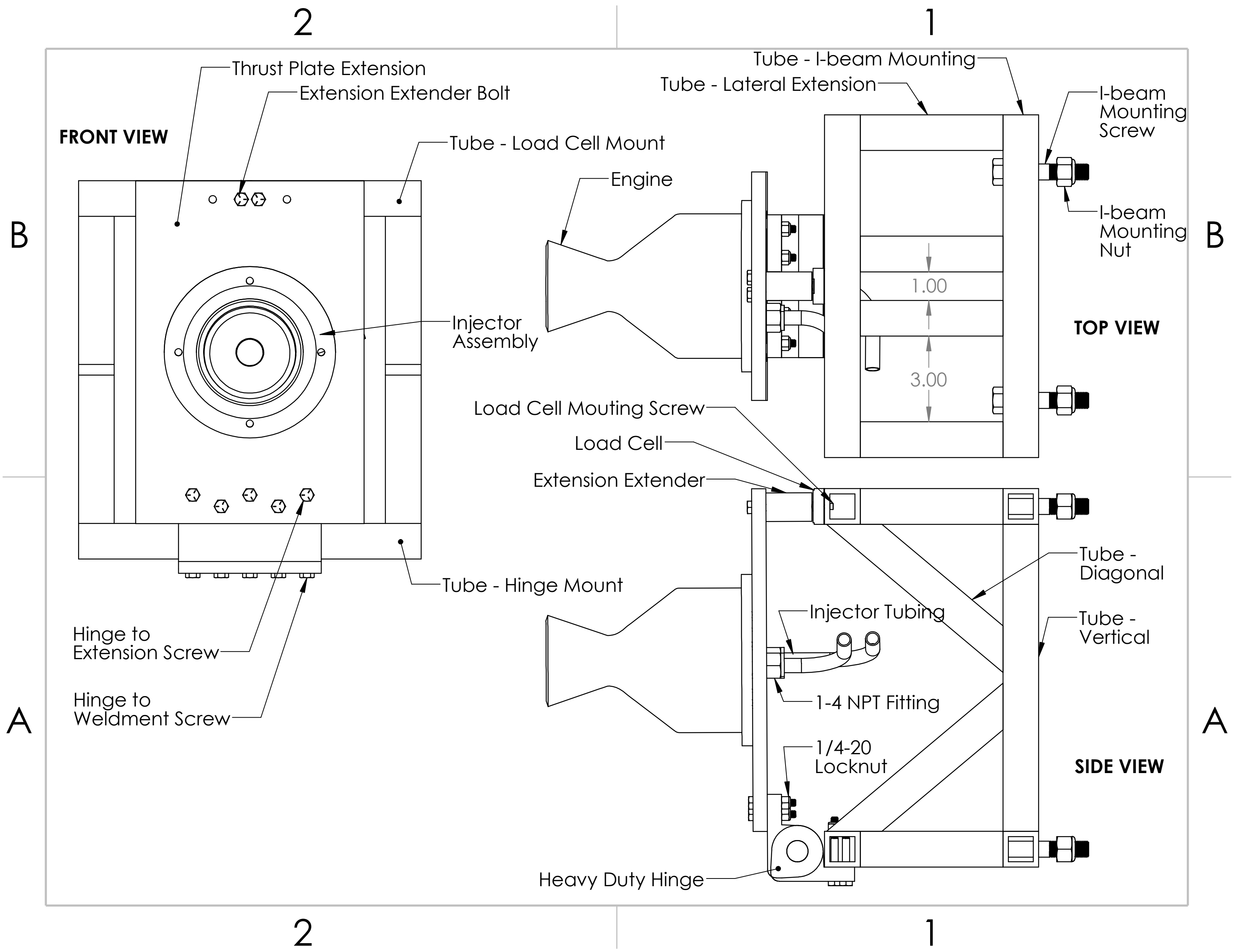


ITEM NO.	PART NUMBER	QTY.
1	Tube - I-beam Mounting*	2
2	Tube - Vertical*	2
3	Tube - Lateral Extension*	8
4	Tube - Load Cell Mount*	1
5	Tube - Hinge Mount*	1
6	Tube - Diagonal*	4
8	I-beam Mounting Screw 9/16-18x3"	4
9	I-beam Mounting Nut	6
10	Heavy Duty Hinge*	1
11	Hinge to Weldment Screw 1/4-20x2.25"	5
12	1/4-20 Locknut	10
13	Thrust Plate Extension*	1
14	Hinge To Extension Screw 1/4-20x1.5"	5
15	Extension Extender*	1
16	Extension Extender Bolt 1/4-20x1"	2
17	Load Cell	1
20	Load Cell Mounting Screw	2
21	Injector Assembly*	1
22	1-4 NPT to 1-2 OD Fitting	2
23	Injector Tubing Short*	1
24	Injector Tubing Long*	1
25	Engine	1

A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: ALL ± 0.1	DRAWN	Brandon	2/27/20	TITLE:
	CHECKED			**Weldment Assembly**
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL Mostly Steel	COMMENTS: * This part has anassociated drawing Tube-Tube connections done with TIG welding h > 3/16			SIZE A · DWG. NO. WeldmentAssm · REV 1
FINISH Deburr Sharps				
NEXT ASSY · USED ON				
APPLICATION · DO NOT SCALE DRAWING				SCALE: 1:4 · WEIGHT: · SHEET 2 OF 2

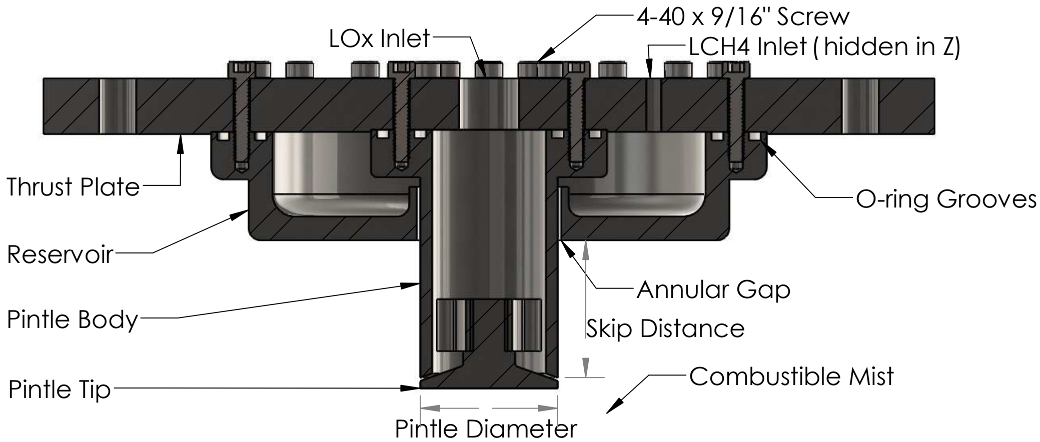
2 | 1



2
1
B
A
FRONT VIEW
Thrust Plate Extension
Extension Extender Bolt
Tube - Load Cell Mount
Injector Assembly
Tube - Hinge Mount
Hinge to Extension Screw
Hinge to Weldment Screw
Tube - I-beam Mounting
Tube - Lateral Extension
I-beam Mounting Screw
I-beam Mounting Nut
Engine
1.00
3.00
TOP VIEW
Load Cell Mouting Screw
Load Cell
Extension Extender
Tube - Diagonal
Tube - Vertical
Injector Tubing
1-4 NPT Fitting
1/4-20 Locknut
SIDE VIEW
Heavy Duty Hinge

2 1

B B



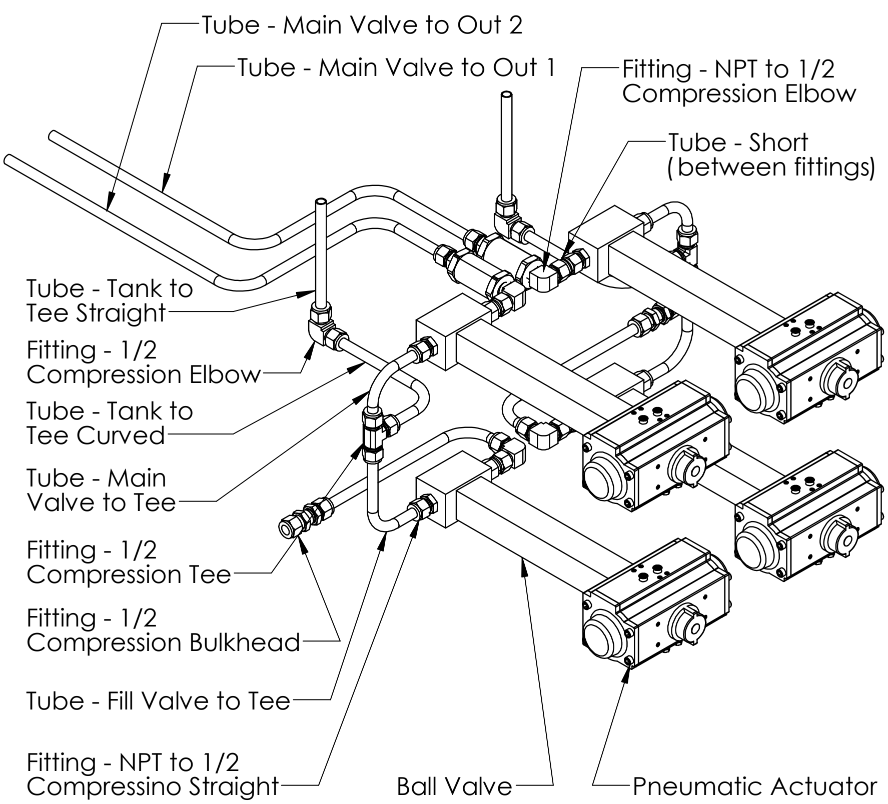
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Thrust Plate*		1
2	Reservoir*		1
3	Pintle Body*		1
4	Pintle Tip*		1
5	4-40 x 9/16" Screw		26
6	O-Ring	4 different sizes in BOM	4

A A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Brandon	2/26/20		
	CHECKED			TITLE:	Injector
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.				
MATERIAL Stainless Steel	COMMENTS: *part has an associated drawing			SIZE A	DWG. NO. Injector Full — REV 1
FINISH As Machined					
DO NOT SCALE DRAWING				SCALE: 1:4	WEIGHT: — SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

2 1



ITEM NO.	PART	QTY.
1	Ball Valve	4
2	Pneumatic Actuator	4
3	Check Valve	2
4	Fitting - 1/2 Compression Elbow	4
5	Fitting - 1/2 Compression Tee	2
6	Fitting - NPT to 1/2 Compression Straight	10
7	Fitting - NPT to 1/2 Compression Elbow	2
8	Fitting - 1/2 Compression Bulkhead	2
9	Pipe - Short	4
10	Tube - Main Valve to Out 1*	1
11	Tube - Main Valve to Out 2*	1
12	Tube - Main Valve to Tee*	2
13	Tube - Tank to Tee Curved*	2
14	Tube - Tank to Tee Straight*	2
15	Tube - Fill/Drain Valve to Tee*	2
16	Tube - Fill/Drain Valve to Out*	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ANGULAR ERROR ± 2
INTERPRET GEOMETRIC TOLERANCING PER: ANSI
MATERIAL
Stainless Steel 316
FINISH
N/A
DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

	NAME	DATE
DRAWN	Brandon	2/29/20
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

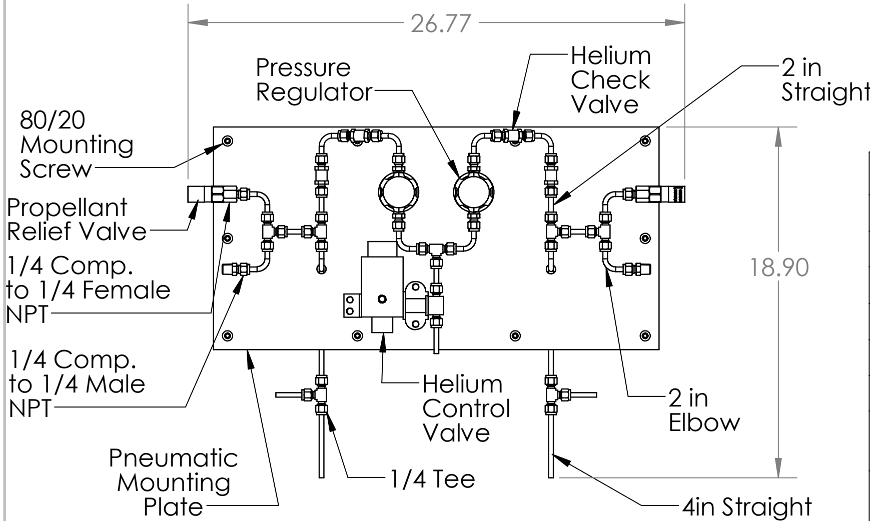
COMMENTS:
All pipe segments are orthogonal
Assemble from mounted Pneumatic Actuator going backwards

TITLE:
Bottom Plumbing Subassembly

SIZE A | DWG. NO. Bottom Plumbing | REV 1
SCALE: 1:7 | WEIGHT: | SHEET 1 OF 1

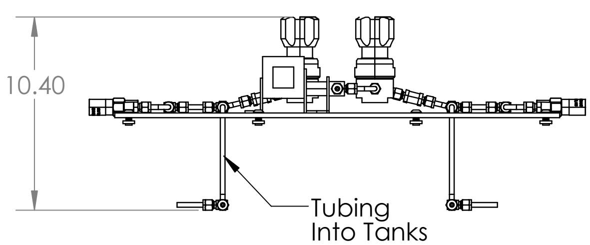
2 1

B



ITEM NO.	PART NUMBER	QTY.
1	2 in Straight*	8
2	2 in Elbow*	10
3	4 in Straight*	2
4	Tubing into Tank*	2
5	Pressure Regulator	2
6	1/4 Tee	7
7	1/4 Compression to 1/4 Male NPT	6
8	1/4 Compression to 1/4 Female NPT	2
9	Helium Check Valve	4
10	Propellant Relief Valve	2
11	Helium Control Valve	1
12	Aluminum Sheet*	1
13	80/20 Mounting Screw	10

B



A

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.05
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL Al / SS 316

FINISH N/A

DO NOT SCALE DRAWING

NEXT ASSY | USED ON

APPLICATION

	NAME	DATE
DRAWN	Brandon	2/22/20
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

Upper Plumbing

SIZE A | DWG. NO. Upper Plumbing | REV 1

SCALE: 1:8 | WEIGHT: | SHEET 1 OF 1

A

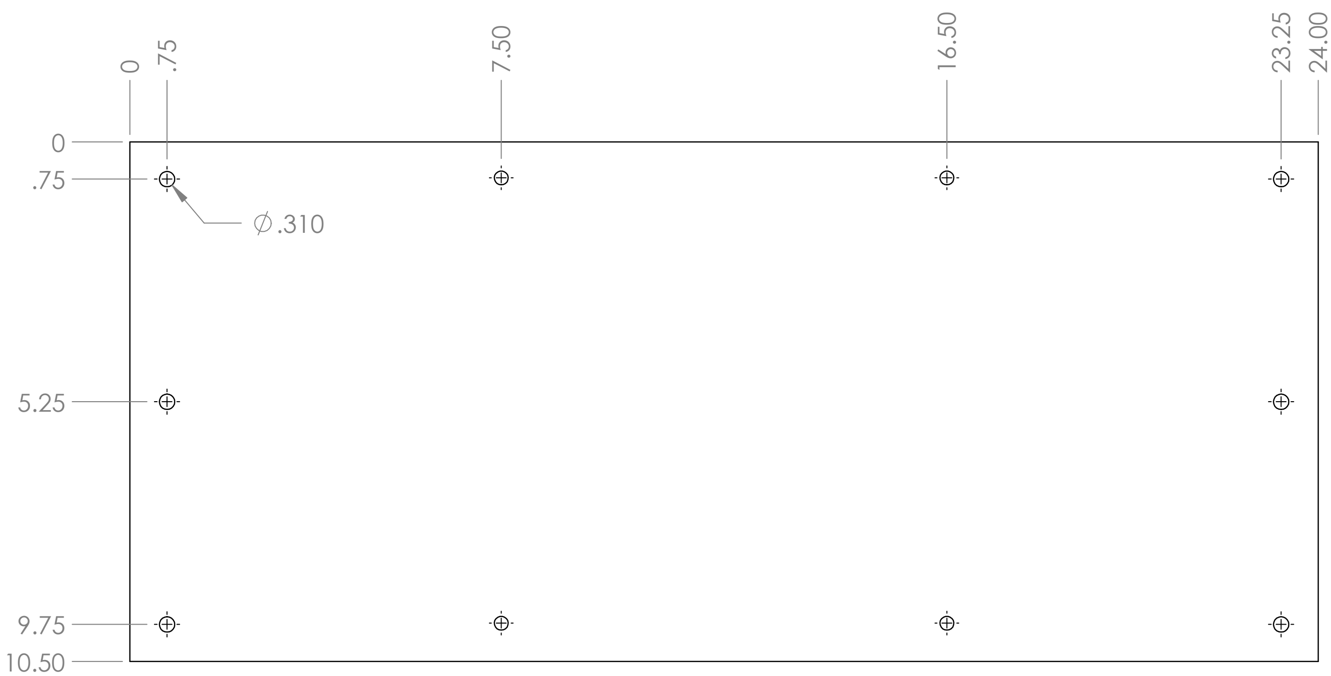
2 1

E Part Drawings

1. Assembly Without Plumbing Parts
   - Avionics Mounting Plate
   - Pneumatic Mounting Plate
   - Tank Mounting Plate
   - Level Sensor Mount
2. 8020 Frame Parts
   - Extrusion Framing
3. Tank Assembly Parts
   - Propellant Tank Cylinder Body
   - Tank Head
   - Foam Insulation
4. Weldment Assembly Parts
   - Weldment Tube (6)
   - Hinge Half
   - Thrust Plate Extension
   - Extension Extender
   - Tubing Solid Injector (2)
5. Injector Parts
   - Thrust Plate
   - Pintle Body
   - Pintle Tip
   - Reservoir
6. Bottom Plumbing Parts
   - Tube - Fill Valve to Out
   - Tube - Fill Valve to Tee
   - Tube - Main Valve to Out
   - Tube - Main Valve to Tee
   - Tube - Short
   - Tube - Tank to Tee Curved
   - Tube - Tank to Tee Straight

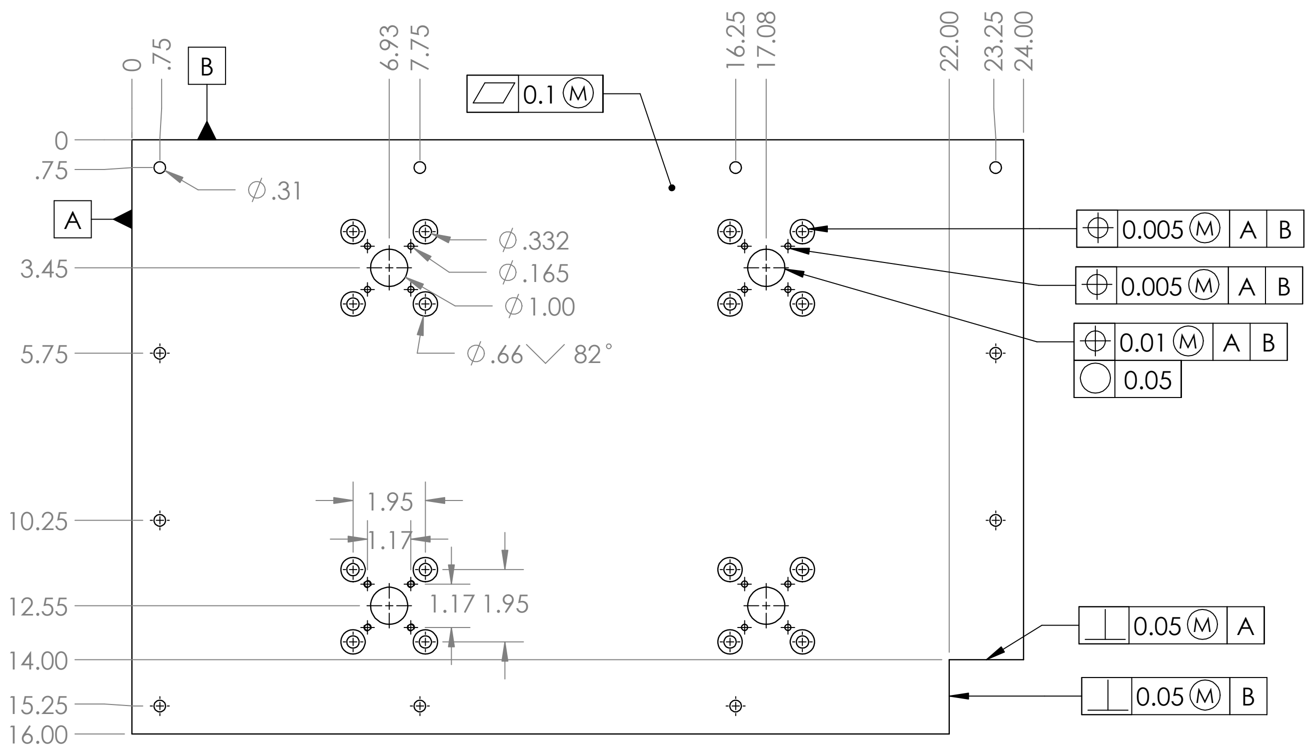
7. Upper Plumbing Parts

    - Top Mounting Sheet
    - 2 in Elbow
    - 2 in Straight
    - 4 in Straight
    - Tubing Into Tank



Sheet Depth: 0.25

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Brandon	2/28/20	
			CHECKED			TITLE: Avionics Mounting Plate
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Aluminum	COMMENTS:			SIZE A / DWG. NO. Avionics Mounting Plate / REV 1
NEXT ASSY	USED ON	FINISH Deburr				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:3 / WEIGHT: / SHEET 1 OF 1



Notes: sheet is 0.25 in thick
Hole spacing should line up with 8020
All holes through all

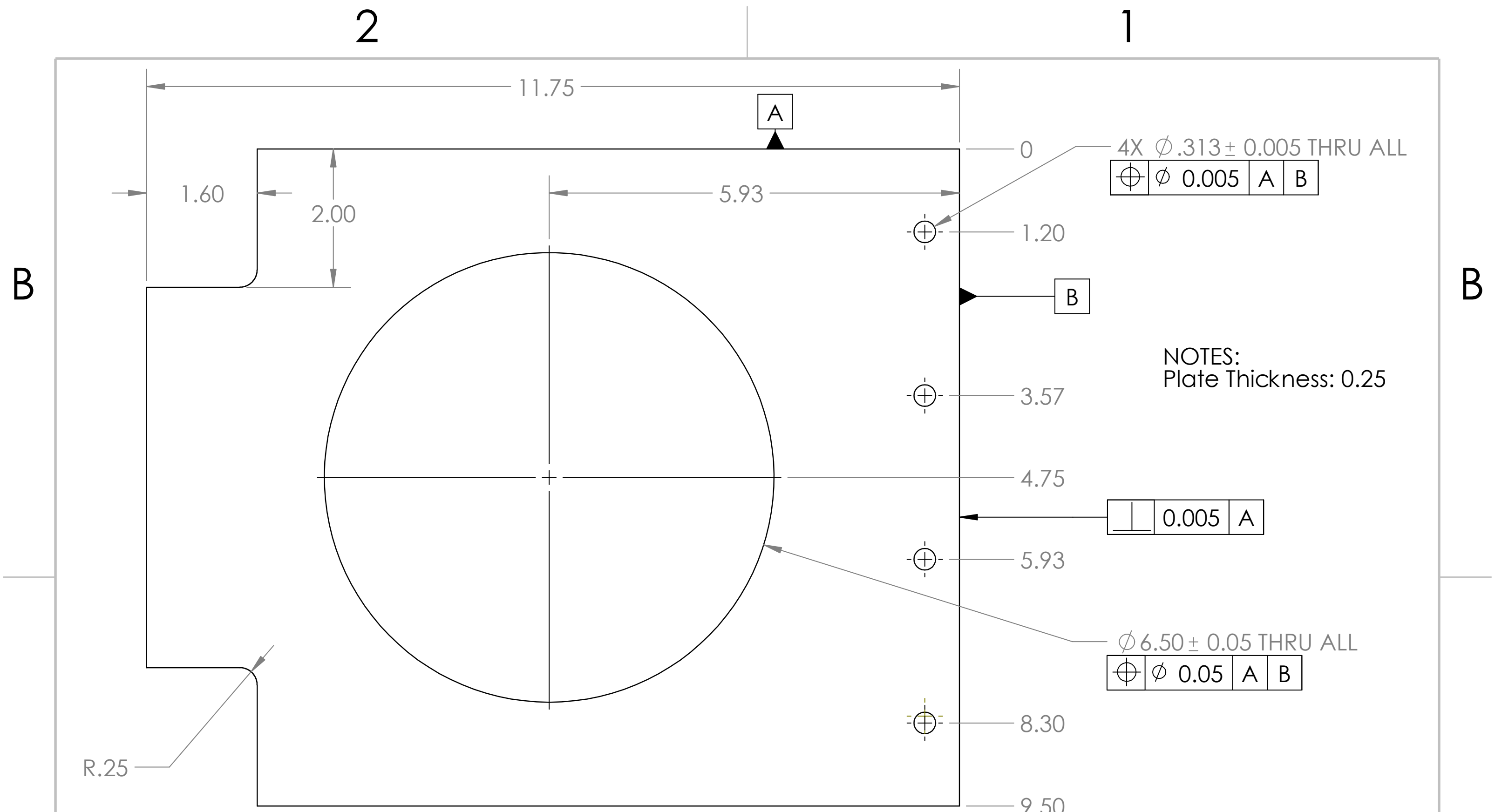
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005	DRAWN	Jack Dibachi	3/1/2020
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL Aluminum	COMMENTS:		
FINISH As machined			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

TITLE:

SIZE **A** DWG. NO. Pneumatic Mounting Plate REV

SCALE: 1:4 WEIGHT: SHEET 1 OF 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Mitchell	3/5/2020
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.		
		MATERIAL Aluminum	COMMENTS:		
NEXT ASSY	USED ON	FINISH As Machined			
APPLICATION		DO NOT SCALE DRAWING			

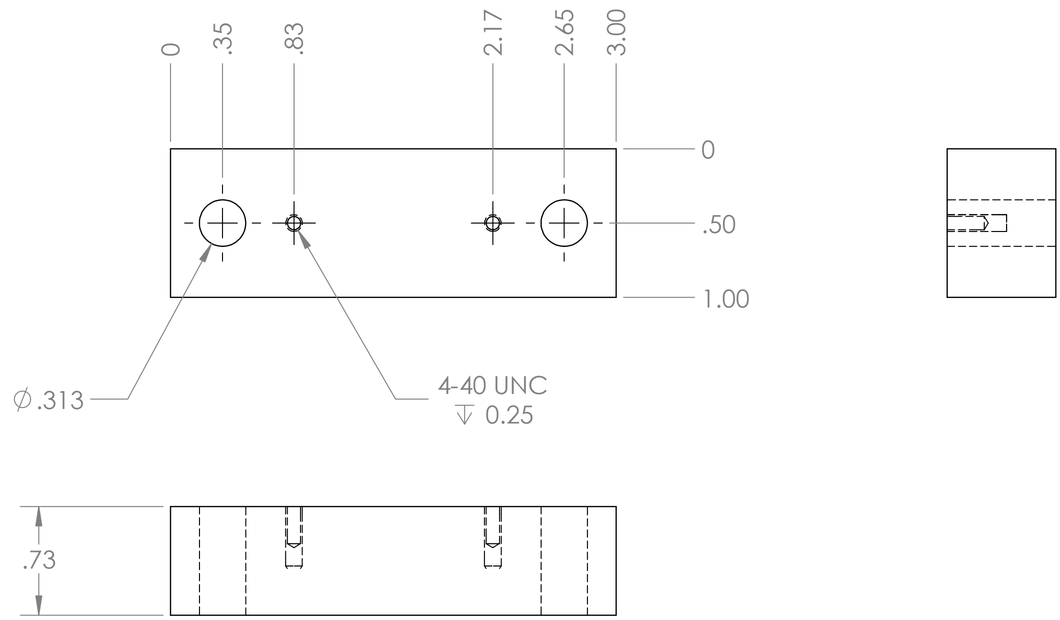
TITLE:

Tank Mounting Plate

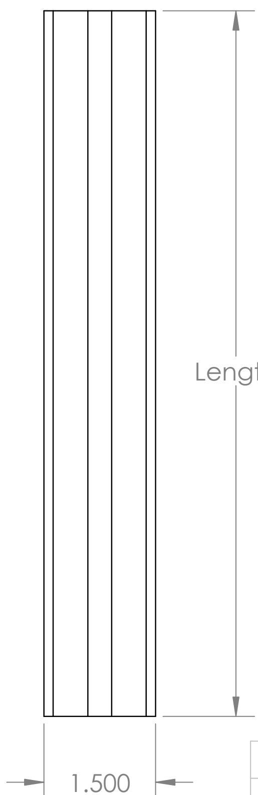
SIZE	DWG. NO.	REV
A	Tank Mouting Plate	02

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Brandon	2/22/20	
			CHECKED			TITLE: Level Sensor Mount
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.			
		MATERIAL Aluminum	COMMENTS:			SIZE A · DWG. NO. Level Sensor Mount · REV 1
NEXT ASSY	USED ON	FINISH As Machined				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 · WEIGHT: · SHEET 1 OF 1



ITEM NO.	LENGTH	DESCRIPTION	QTY
1	72	Long back pieces	2
2	38	Upper front pieces	4
3	34	Long lower front pieces	1
4	31	Short lower front pieces	2
5	21	All cross-braces	16
6	9.5	Tank support	2
7	6.5	Top connecting pieces	4

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
Length ± 0.05
Width as purchased

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Aluminum 6061

FINISH
As purchased

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

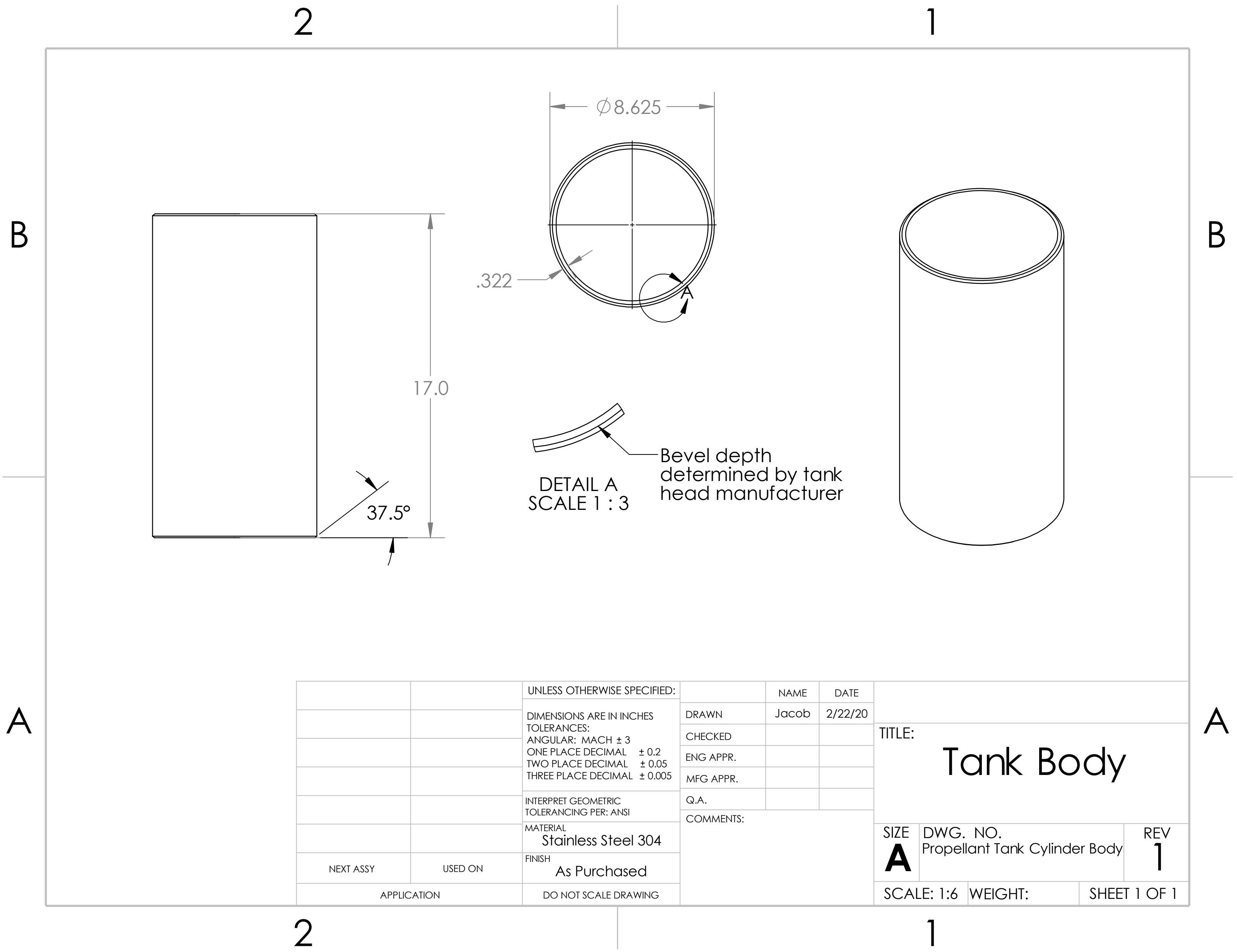
	NAME	DATE
DRAWN	Brandon	2/22/20
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
80/20 Series 15 Aluminum Extrusions
Cut to length on metal chop saw

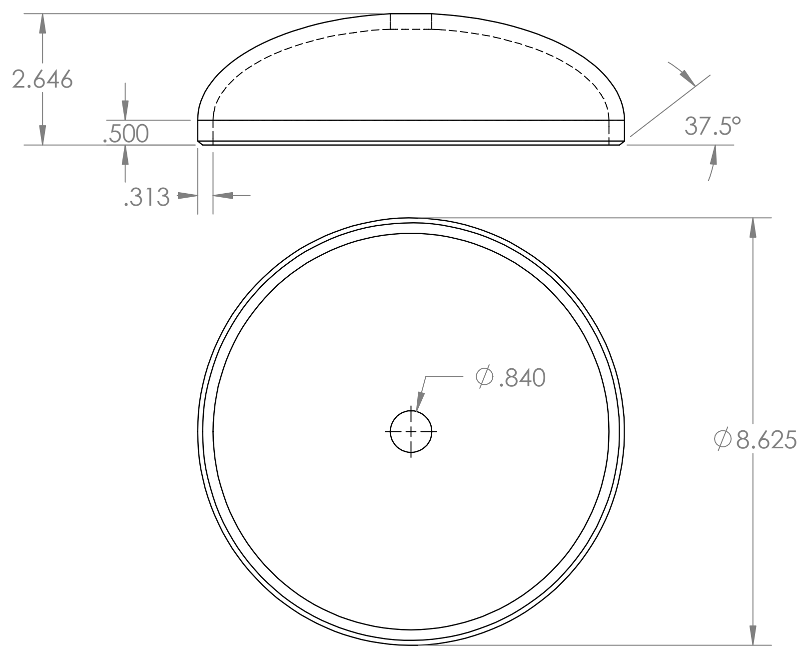
TITLE:
8020 Framing Extrusion

SIZE A | DWG. NO. Framing | REV 1

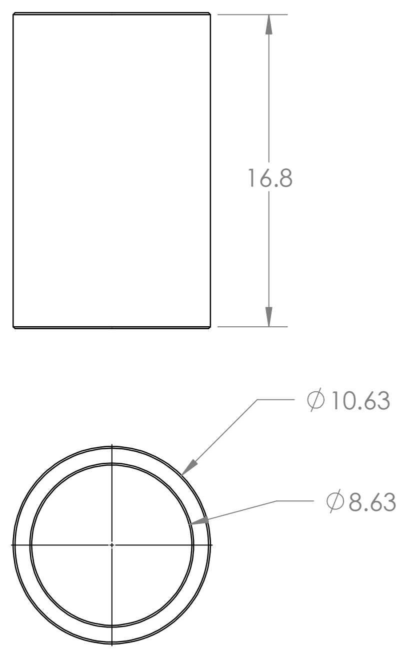
SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1



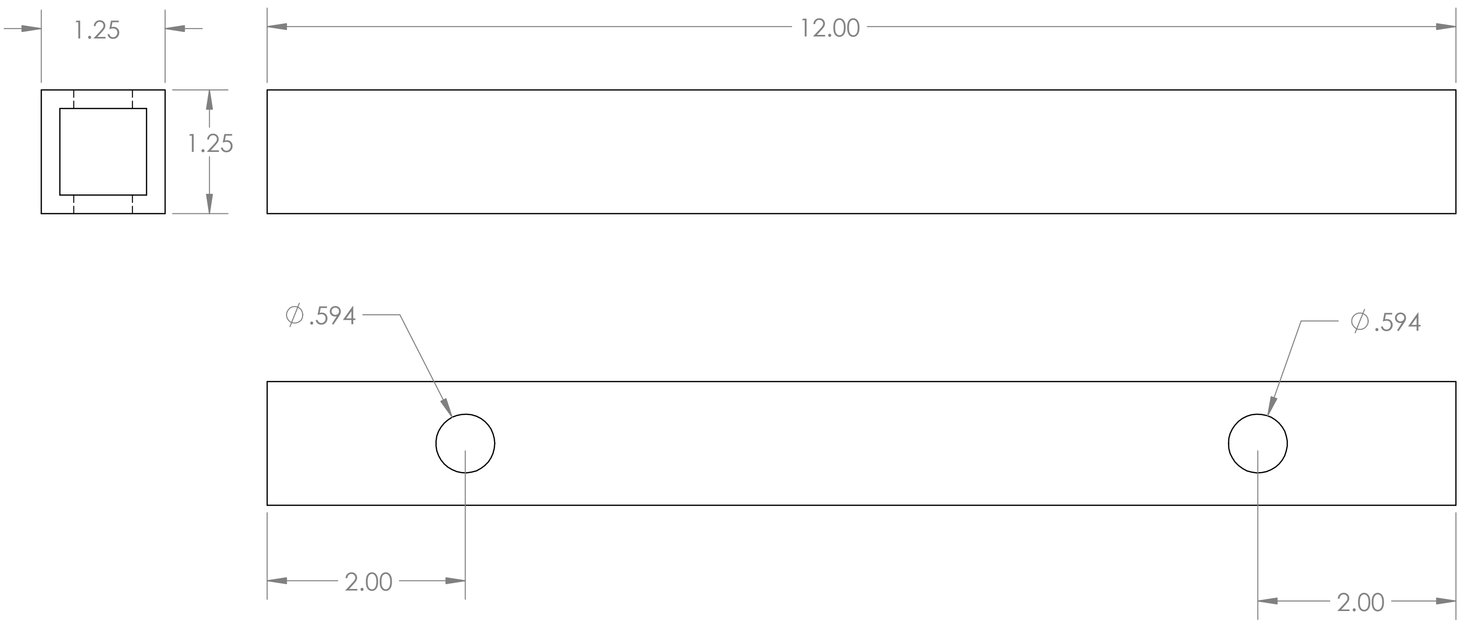
UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: MACH ± 3 ONE PLACE DECIMAL ± 0.2 TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Jacob	2/22/20	TITLE:	Tank Body
	CHECKED				
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.				
MATERIAL: Stainless Steel 304	COMMENTS:			SIZE A	DWG. NO. Propellant Tank Cylinder Body — REV 1
FINISH: As Purchased					
NEXT ASSY / USED ON / APPLICATION					
DO NOT SCALE DRAWING				SCALE: 1:6	WEIGHT: — SHEET 1 OF 1



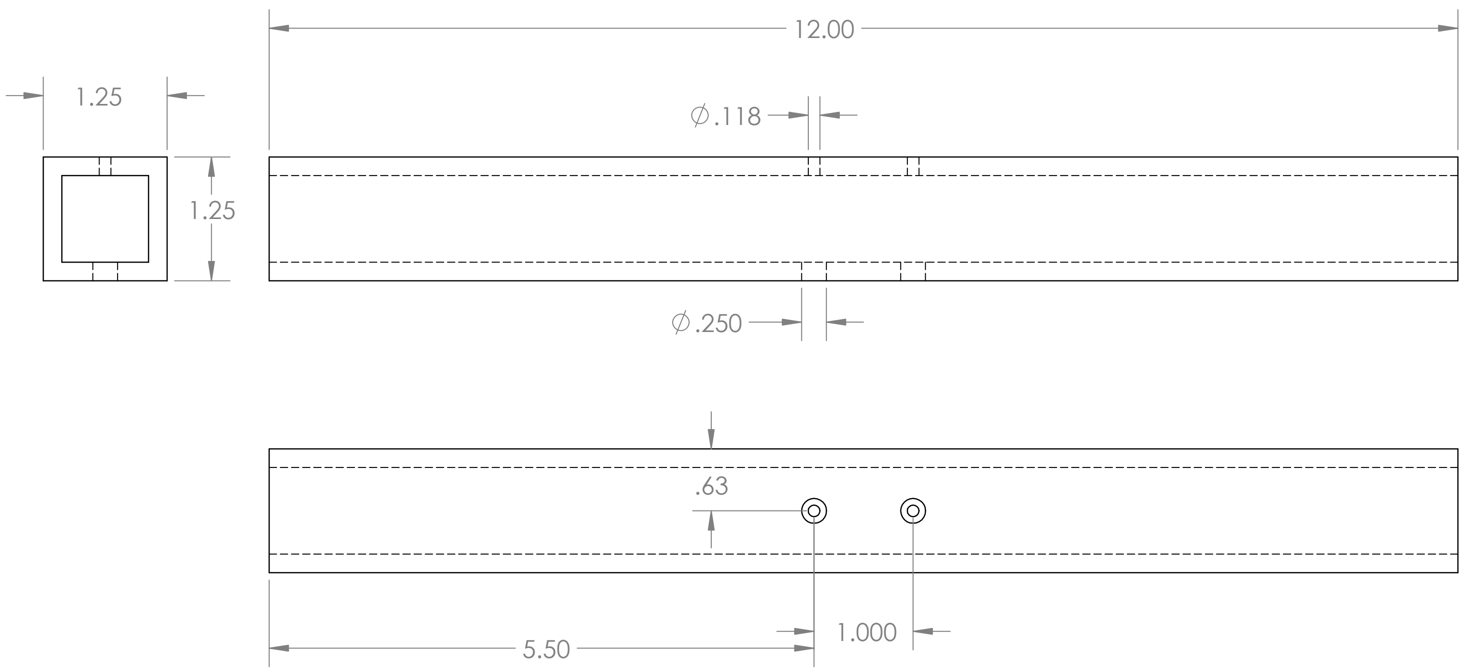
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: MACH ± 4 TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Jacob	2/22/20	
			CHECKED			TITLE: Tank Heads
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.			
		MATERIAL Stainless Steel 304	COMMENTS:			SIZE A · DWG. NO. Tank_Head · REV 1
NEXT ASSY	USED ON	FINISH As Purchased				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:3 · WEIGHT: · SHEET 1 OF 1



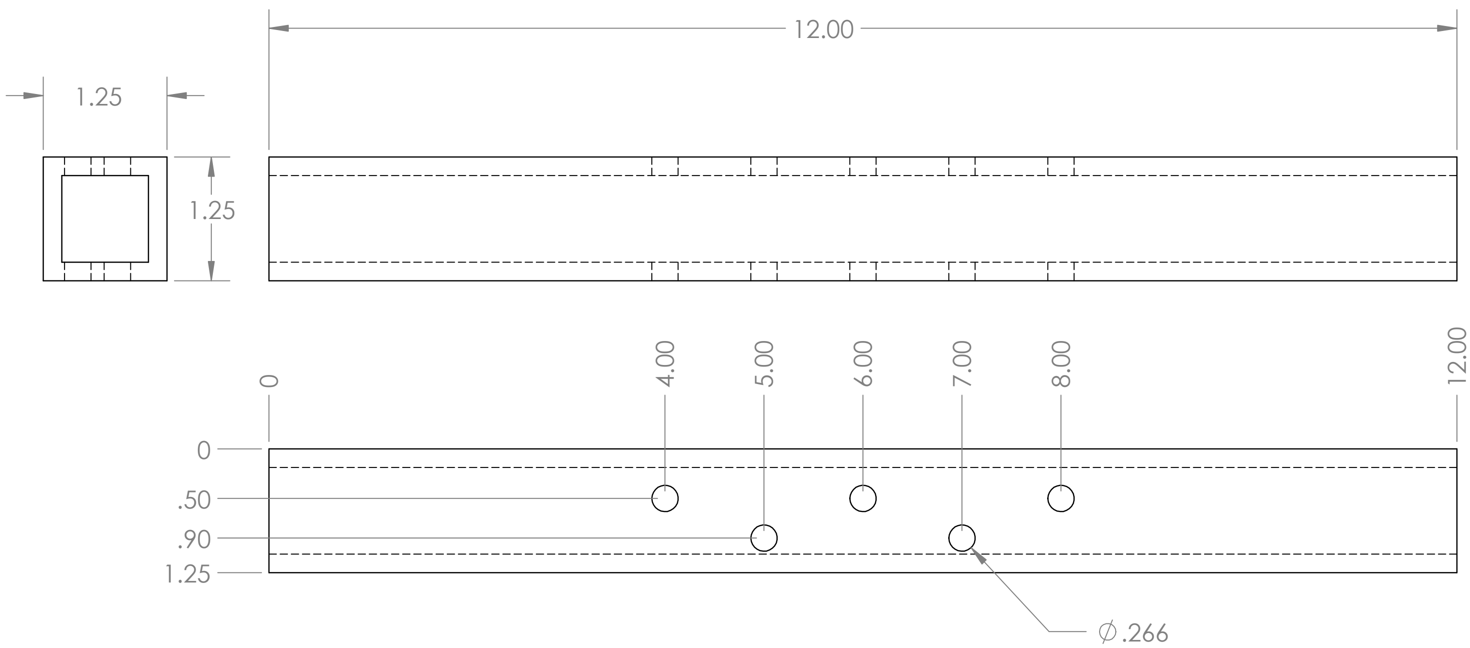
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05	DRAWN	Brandon	2/22/20	TITLE: Tank Insulation
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.			
		MATERIAL Styrofoam	COMMENTS:			SIZE A DWG. NO. Foam_Insulation REV 1
NEXT ASSY	USED ON	FINISH As Machined				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:8 WEIGHT: SHEET 1 OF 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.1 THREE PLACE DECIMAL ± 0.05	DRAWN	Brandon	2/27/20	
			CHECKED			TITLE: Tube - I-Beam Mounting
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Low Carbon Steel Tube	COMMENTS: May be able to use metal chop saw			SIZE A · DWG. NO. Weldment Tube · REV 1
NEXT ASSY	USED ON	FINISH Deburr. Prepare for Weld				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1.5 · WEIGHT: · SHEET 1 OF 6



UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.1 THREE PLACE DECIMAL ± 0.010	DRAWN	Brandon	2/27/20	TITLE:	
	CHECKED			Tube - Load Cell Mounting	
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL Low Carbon Steel Tube	COMMENTS: May be able to use metal chop saw			SIZE A	DWG. NO. Weldment Tube · REV 1
NEXT ASSY · USED ON · FINISH Deburr. Prepare for Weld					
APPLICATION · DO NOT SCALE DRAWING				SCALE: 1:1.5 · WEIGHT:	SHEET 2 OF 6



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.1
THREE PLACE DECIMAL ± 0.010
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Low Carbon Steel Tube
FINISH
Deburr. Prepare for Weld
DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

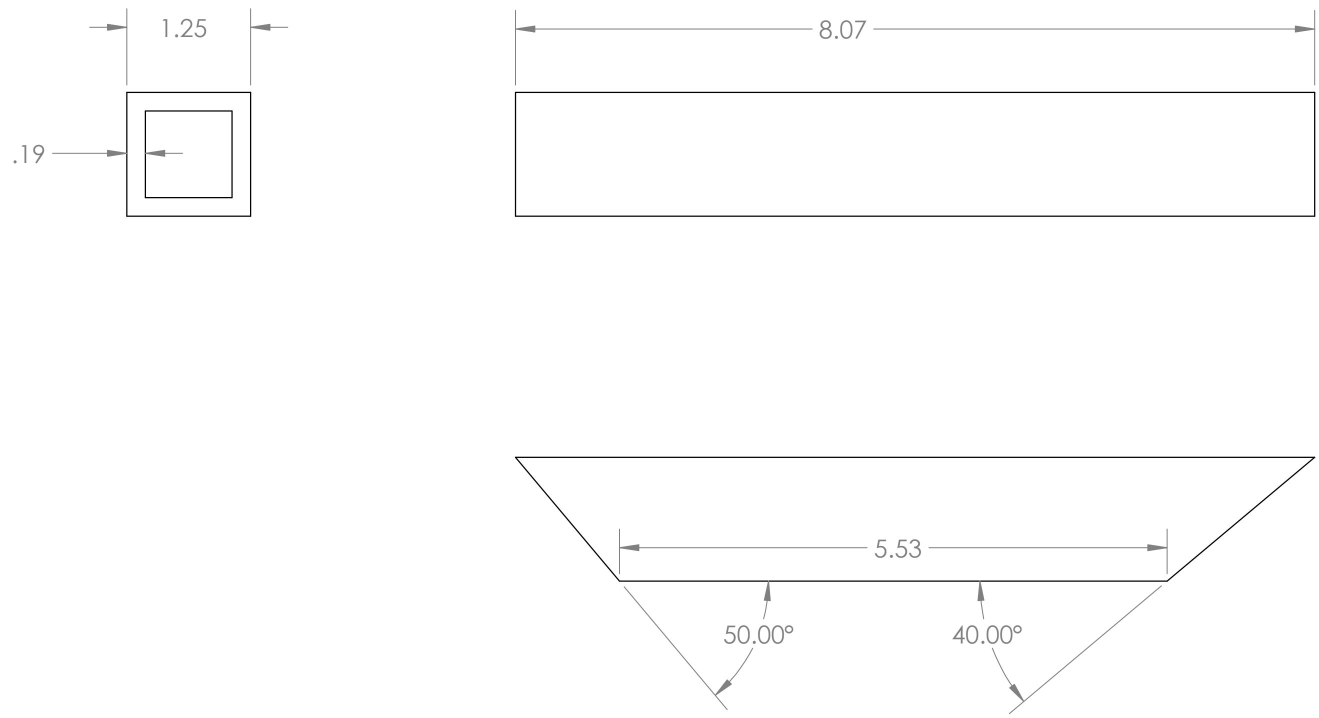
	NAME	DATE
DRAWN	Brandon	2/27/20
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
May be able to use metal chop saw

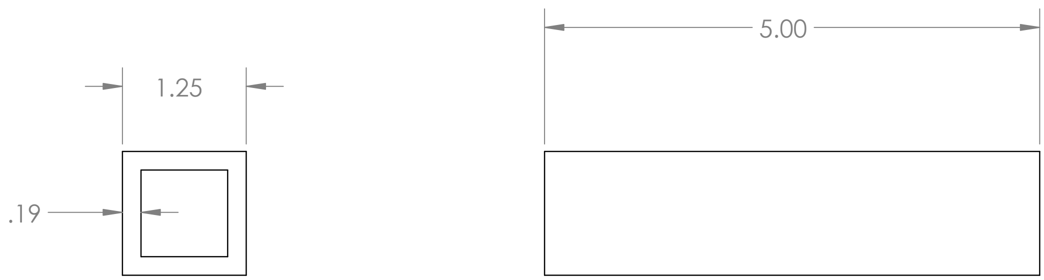
TITLE:
Tube - Hinge Mounting

SIZE A | DWG. NO. Weldment Tube | REV 1

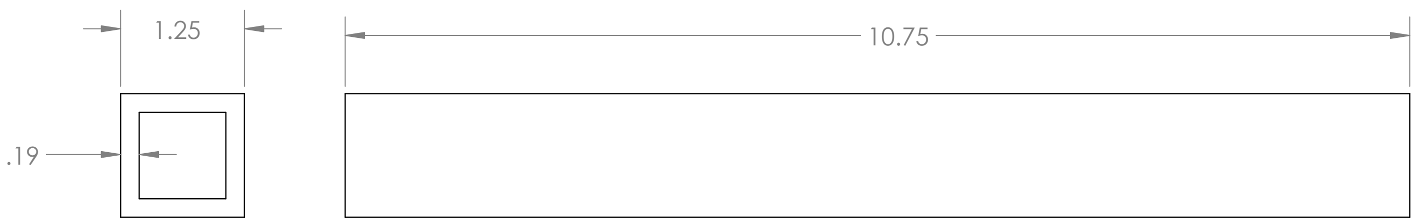
SCALE: 1:1.5 WEIGHT: SHEET 3 OF 6



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: MACH ± 3 TWO PLACE DECIMAL ± 0.1	DRAWN	Brandon	2/27/20	
			CHECKED			TITLE: Tube - Diagonal
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Low Carbon Steel Tube	COMMENTS: May be able to use metal chop saw			SIZE A · DWG. NO. Weldment Tube · REV 1
NEXT ASSY	USED ON	FINISH Deburr. Prepare for Weld				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1.5 · WEIGHT: · SHEET 4 OF 6



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR ± 3 TWO PLACE DECIMAL ± 0.1	DRAWN	Brandon	2/27/20	
			CHECKED			TITLE: Tube - Lateral Extension
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Low carbon steel tube	COMMENTS: May be able to use a metal chop saw			SIZE A · DWG. NO. Weldment Tube · REV 1
NEXT ASSY	USED ON	FINISH Deburr. Prepare for weld				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1.5 · WEIGHT: · SHEET 5 OF 6



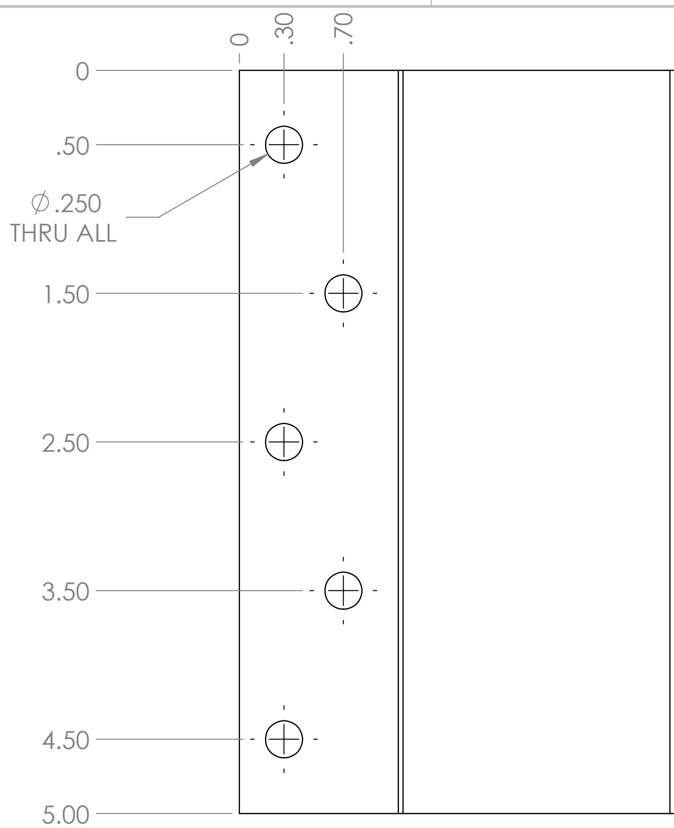
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR ± 3 TWO PLACE DECIMAL ± 0.1	DRAWN	Brandon	2/27/20
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Low carbon steel tube	COMMENTS: May be able to use a metal chop saw		
NEXT ASSY	USED ON	FINISH Deburr. Prepare for weld			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Tube - Vertical

SIZE	DWG. NO.	REV
A	Weldment Tube	1

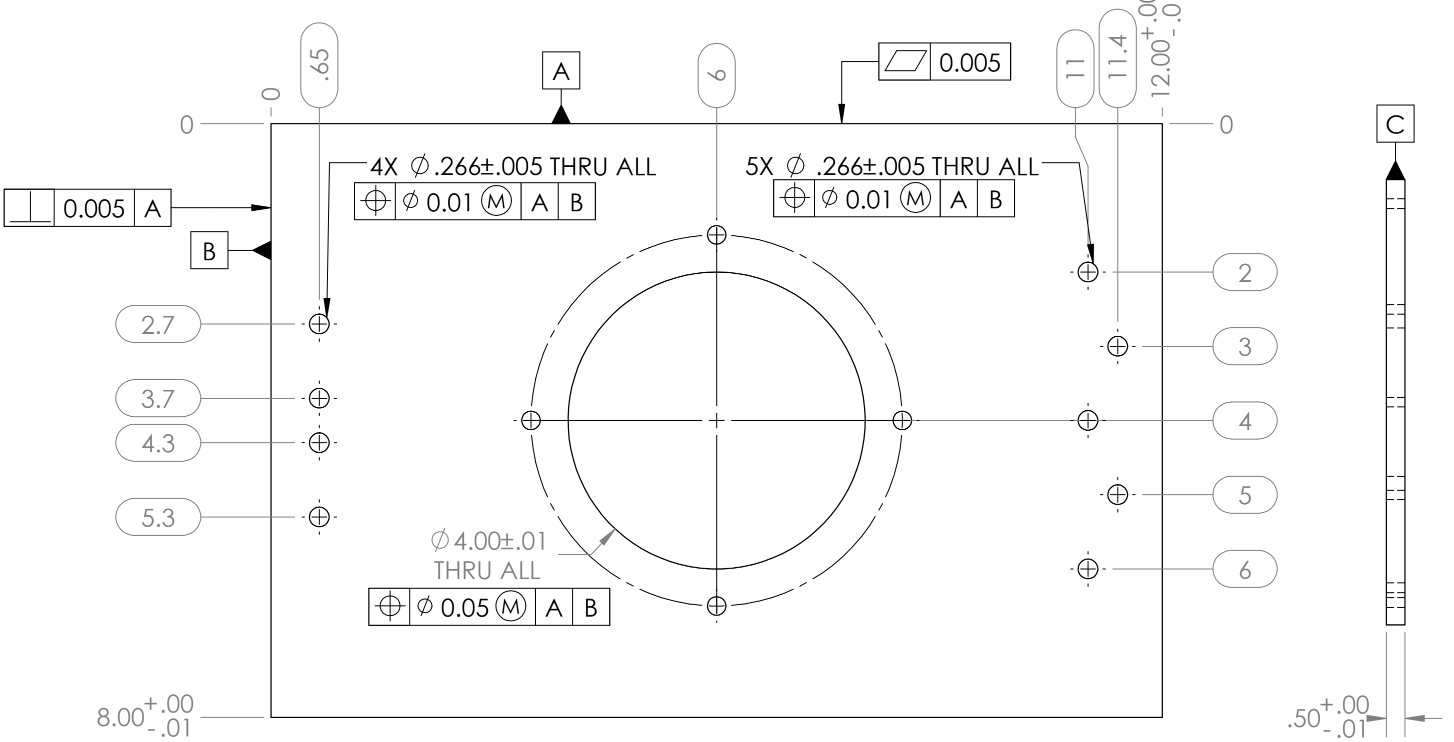
SCALE: 1:1.5 WEIGHT: SHEET 6 OF 6



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005	DRAWN	Brandon	2/27/20	
			CHECKED			TITLE: Hinge Half
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Heavy duty hinge	COMMENTS: Hinge halves cannot be disconnected Only clamp one at a time			SIZE A DWG. NO. Hinge half REV 1
NEXT ASSY	USED ON	FINISH Deburr				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 1 OF 1

2 1

B B



A A

Begin with 12"x8"x0.5" steel plate		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
Use water jet cutter to make 4" diameter central hole		DIMENSIONS ARE IN INCHES TOLERANCES UNLESS SPECIFIED: ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Meital	3/4/20
Use mill to drill all of the 0.266" diameter holes (use drill size H)			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Low Carbon Steel	COMMENTS: Central small holes are left undimensioned TBD		
NEXT ASSY	USED ON	FINISH Deburr sharps			
APPLICATION		DO NOT SCALE DRAWING			

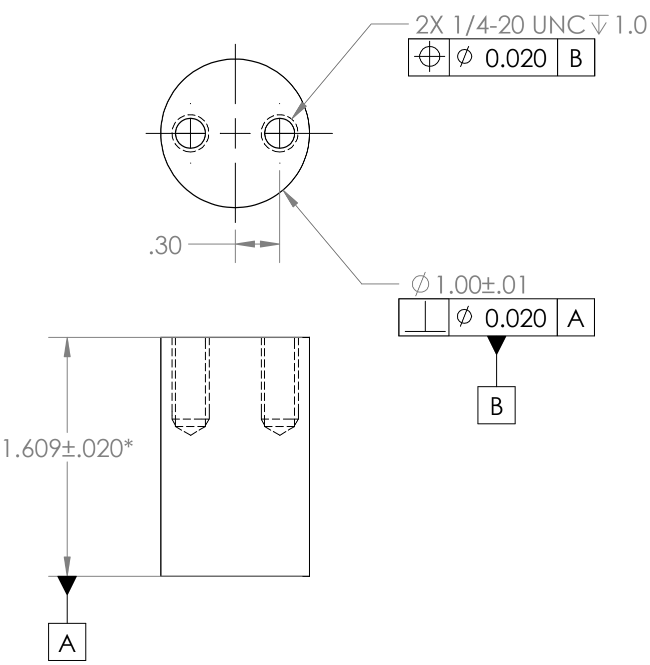
TITLE:

Thrust Plate Extension

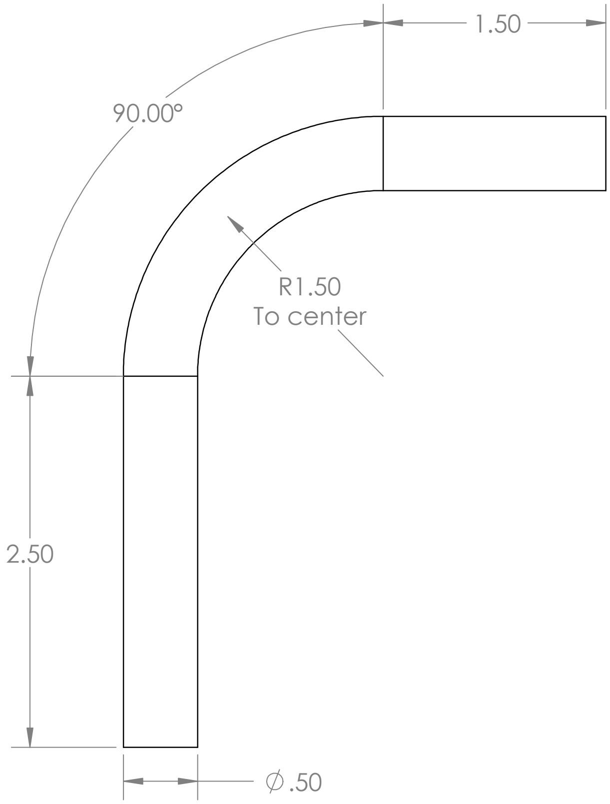
SIZE	DWG. NO.	REV
A	Thrust Plate Extension	1

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005	DRAWN	Jack B.	3/5/20	
			CHECKED			TITLE: Extension Extender
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Aluminum Stock	COMMENTS:			SIZE A · DWG. NO. Extension Extender · REV 1
NEXT ASSY	USED ON	FINISH Deburr sharps				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 · WEIGHT: · SHEET 1 OF 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 5 TWO PLACE DECIMAL ± 0.1	DRAWN	Brandon	2/27/20
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Stainless Steel 316 Tubing	COMMENTS:		
NEXT ASSY	USED ON	FINISH Deburr. Prepare for mating			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

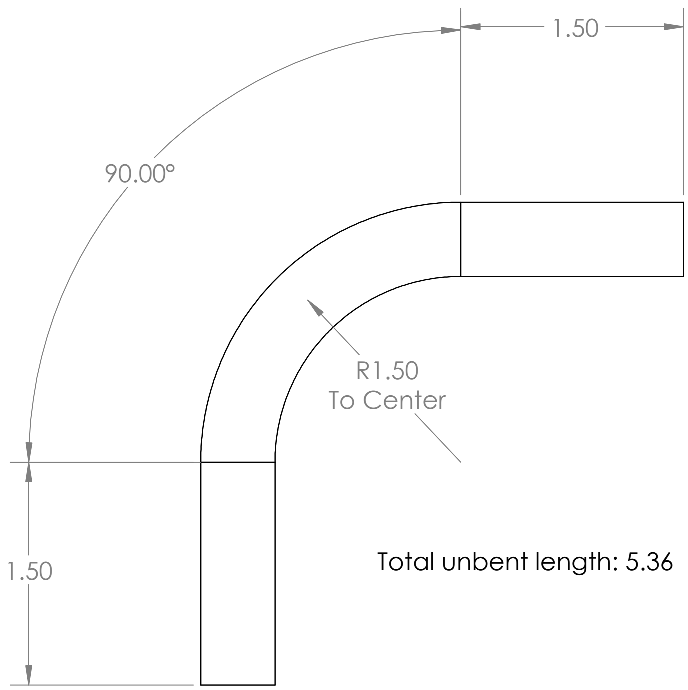
Injector Tubing Long

SIZE A | DWG. NO. Tubing Solid Injector | REV 1

SCALE: 1:1 | WEIGHT: | SHEET 1 OF 2

2 1

B B



Total unbent length: 5.36

A A

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 5 TWO PLACE DECIMAL ± 0.1	DRAWN	Brandon	2/27/20
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Stainless Steel 316 Tubing	COMMENTS:		
NEXT ASSY	USED ON	FINISH Deburr. Prepare for mating			
APPLICATION		DO NOT SCALE DRAWING			

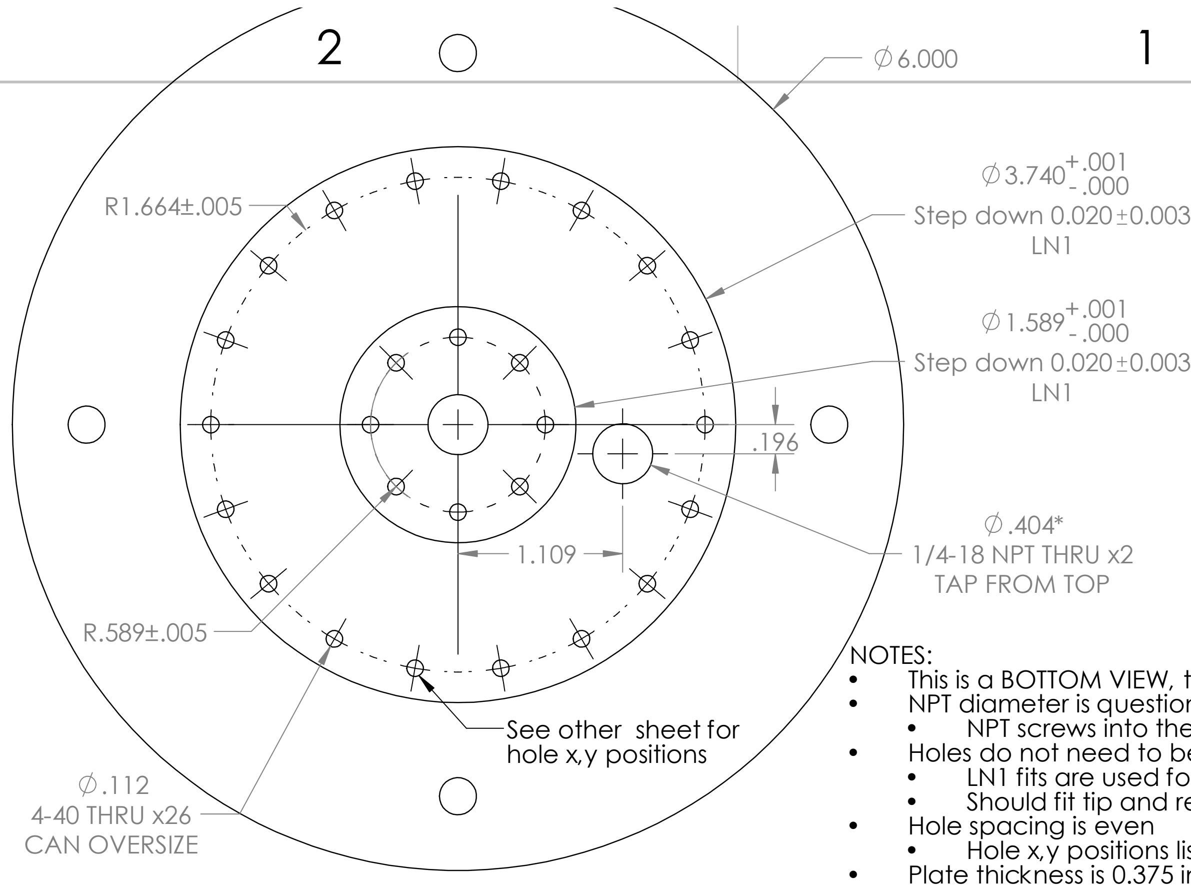
TITLE:

Injector Tubing Short

SIZE **A** DWG. NO. Tubing Solid Injector REV 1

SCALE: 1:1 WEIGHT: SHEET 2 OF 2

2 1



NOTES:
- This is a BOTTOM VIEW, top does not have steps
- NPT diameter is questionable
  - NPT screws into the TOP of the plate
- Holes do not need to be absolutely perfect
  - LN1 fits are used for seating
  - Should fit tip and reservoir while machining
- Hole spacing is even
  - Hole x,y positions listed
- Plate thickness is 0.375 in. at the edge

A | | | | A

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Brandon	2/22/20
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.		
		MATERIAL Stainless Steel 303	COMMENTS:		
NEXT ASSY	USED ON	FINISH Machined			
APPLICATION		DO NOT SCALE DRAWING			

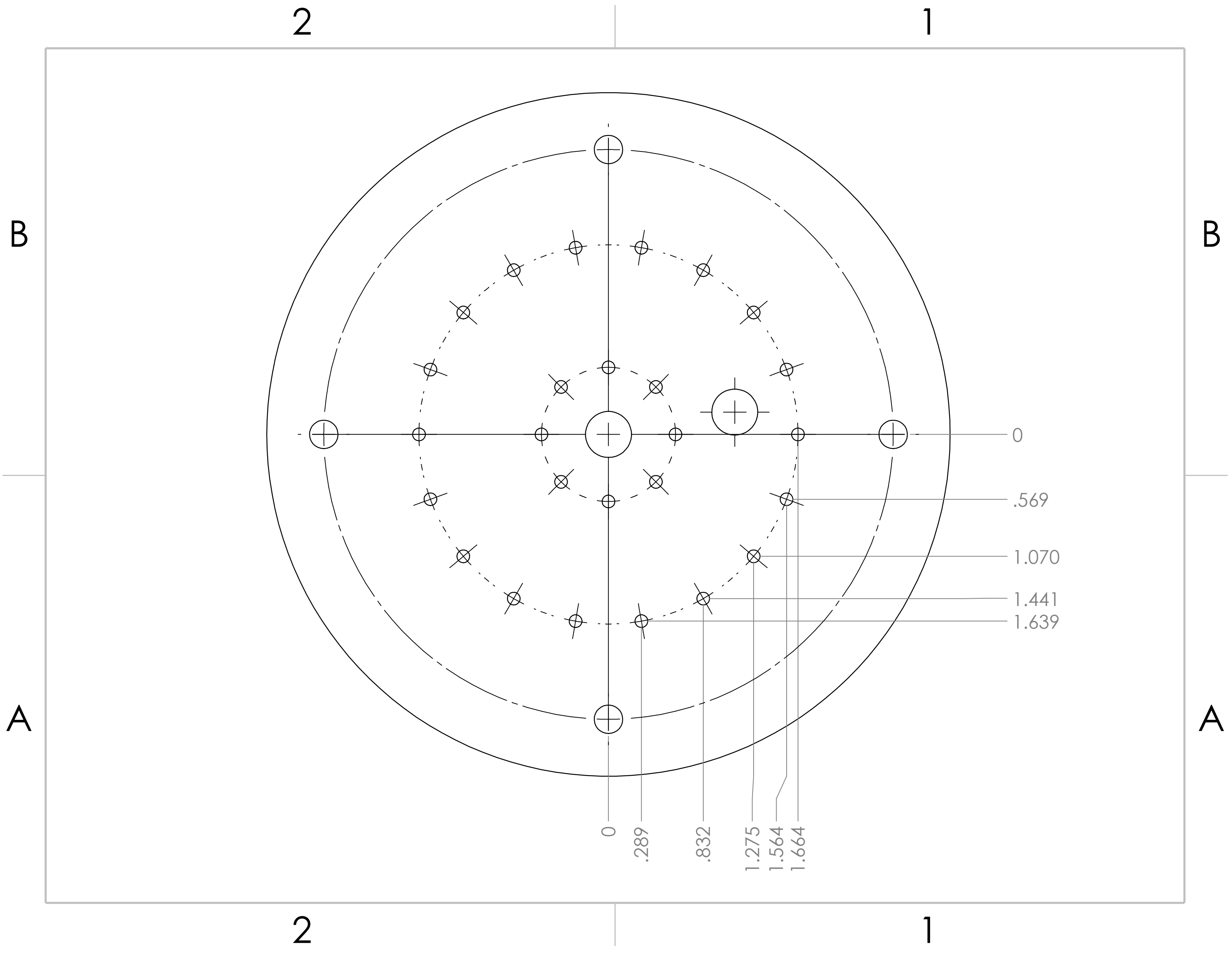
TITLE:

Thrust Plate

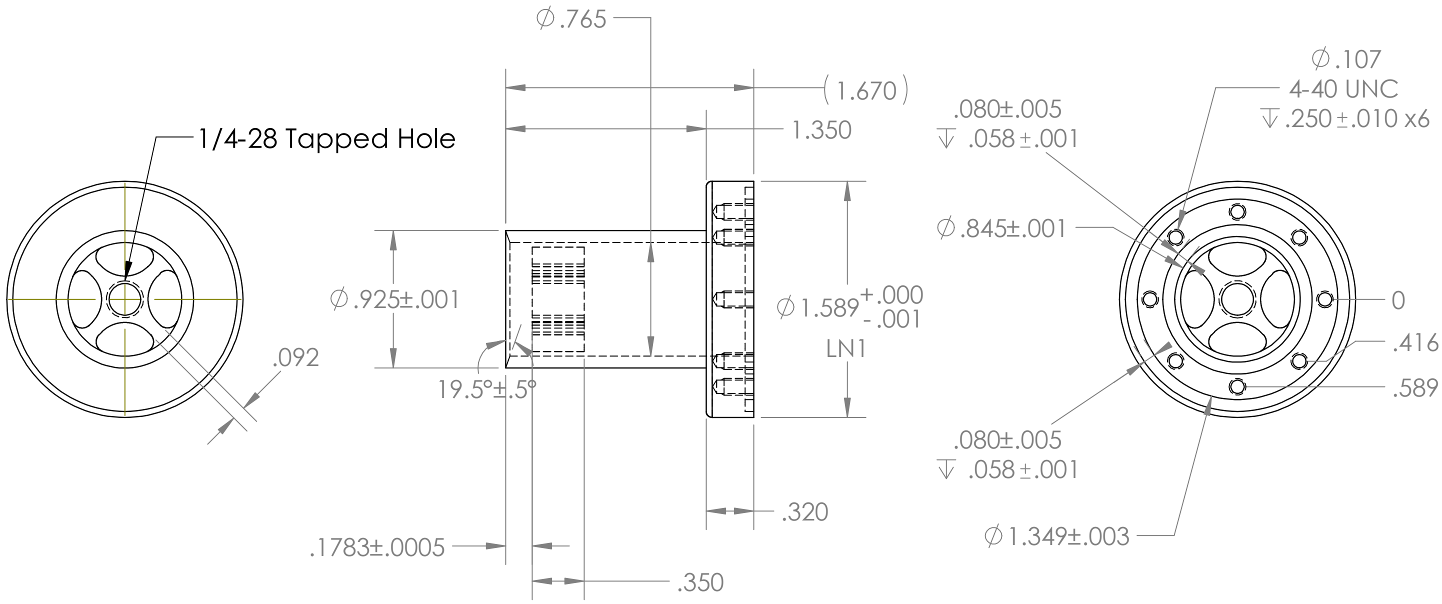
SIZE	DWG. NO.	REV
A	Thrust Plate	1

SCALE: 1:1 WEIGHT: SHEET 1 OF 2

2 1



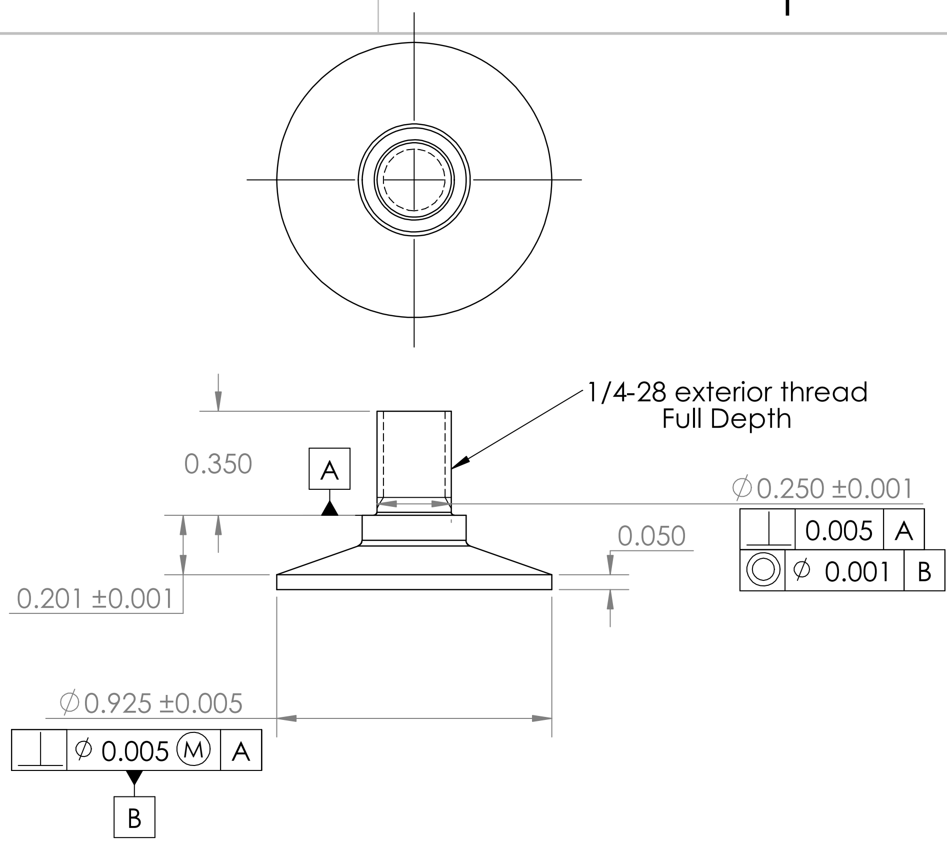
2
1
B
B
A
A
2
1
0
.569
1.070
1.441
1.639
0
.289
.832
1.275
1.564
1.664



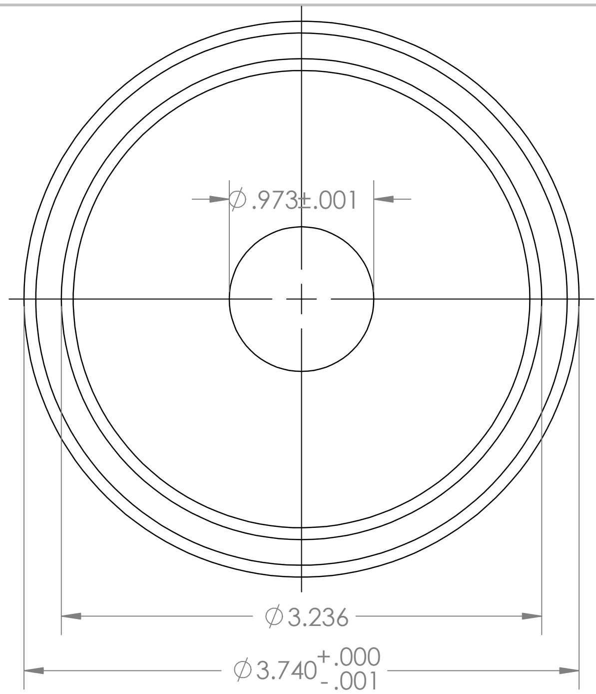
NOTES:

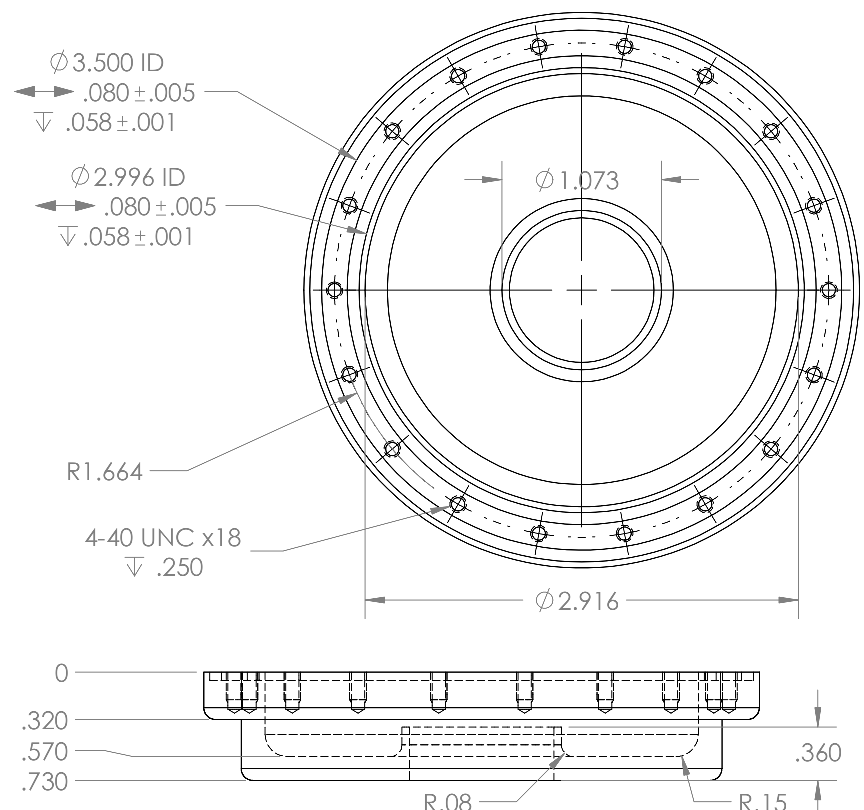
- It is very important that the two outer diameters be almost perfectly concentric for alignment
- Relative rotation of feature groups is unimportant
- Odd cross features: minimum R=0.07in
- Holes in cross do not have to intersect with wall

				NAME	DATE	
		UNLESS OTHERWISE SPECIFIED:				
		DIMENSIONS ARE IN INCHES TOLERANCES: THREE PLACE DECIMAL ± 0.005	DRAWN	Brandon	2/22/20	TITLE: Pintle Body
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.			
		MATERIAL Stainless Steel 303	COMMENTS:			SIZE A	DWG. NO. Pintle_Body	REV 1
NEXT ASSY	USED ON	FINISH Machined				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1	WEIGHT:	SHEET 1 OF 1



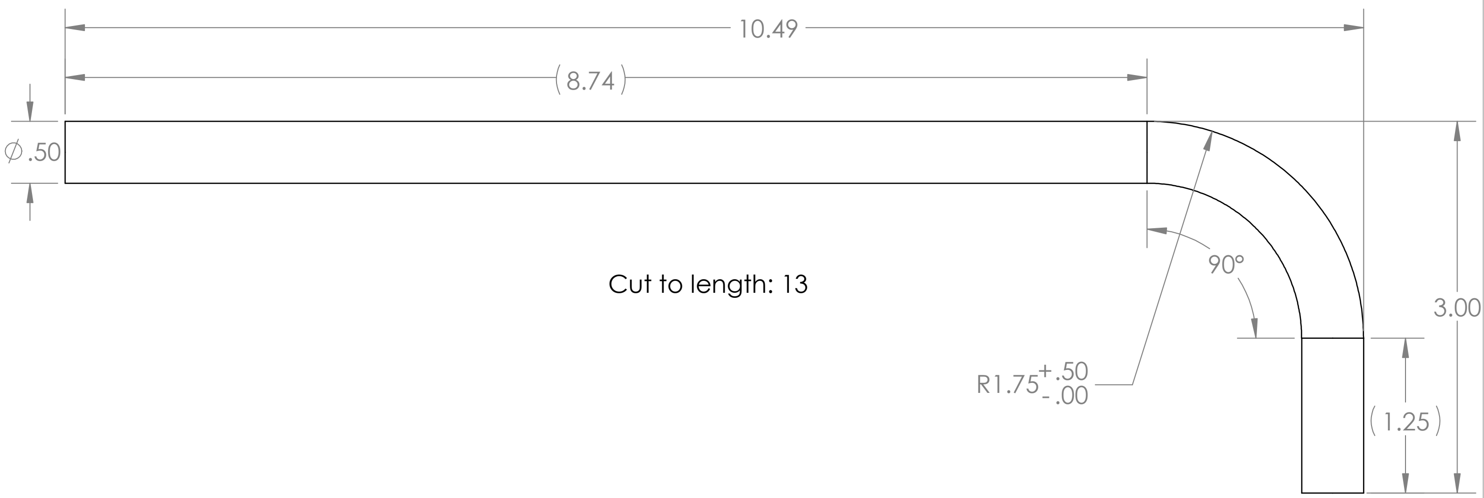
				NAME	DATE	
		UNLESS OTHERWISE SPECIFIED:	DRAWN	Brandon	2/22/20	
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	CHECKED			TITLE: Pintle Tip
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.			
		MATERIAL Stainless Steel 303	COMMENTS:			SIZE A / DWG. NO. Pintle_Tip / REV 1
NEXT ASSY	USED ON	FINISH As Machined				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 2:1 / WEIGHT: / SHEET 1 OF 1





NOTES:
Inside and outside circles concentric
See thrust plate for hole x,y positions
Outside fillets are subjective

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Brandon	2/22/20	TITLE:
			CHECKED			Pintle Reservoir
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.			
		MATERIAL Stainless Steel	COMMENTS:			SIZE A	DWG. NO. Reservoir	REV 1
NEXT ASSY	USED ON	FINISH Machined				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT: SHEET 1 OF 1



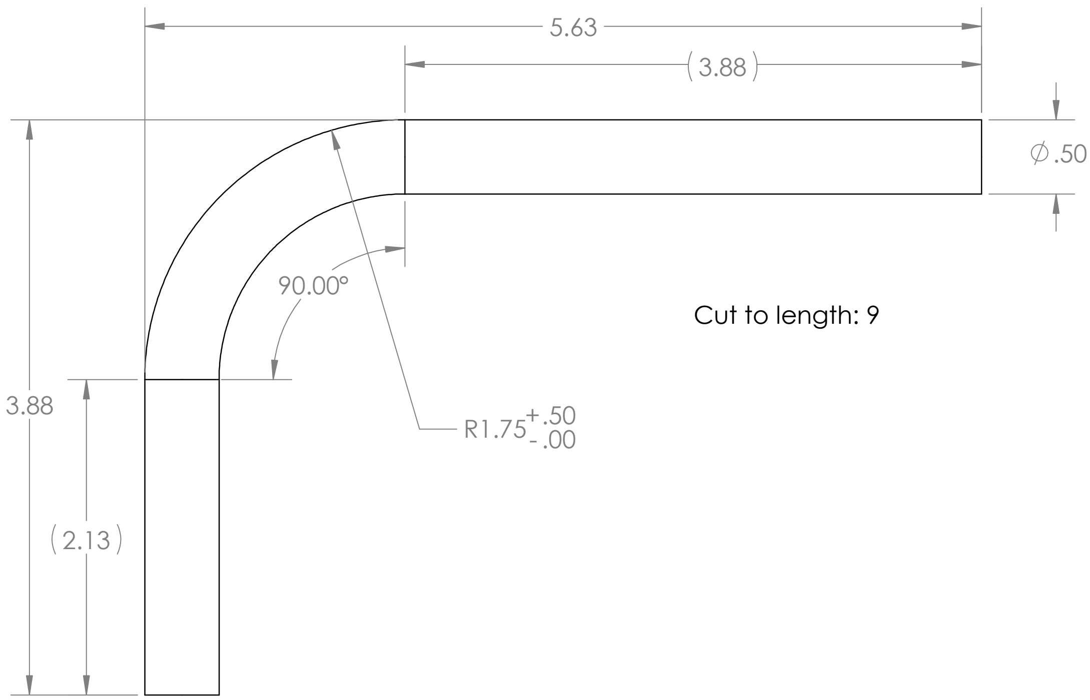
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 2 ONE PLACE DECIMAL ± 0.2 TWO PLACE DECIMAL ± 0.05	DRAWN	Brandon	3/3/30
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL SS-316 1/2" Tubing	COMMENTS:		
NEXT ASSY	USED ON	FINISH Deburr. Prepare for mate			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Tube - Fill Valve to Out

SIZE	DWG. NO.	REV
A	Tube - Fill Valve to Out	1

SCALE: 1:1.2 WEIGHT: SHEET 1 OF 1



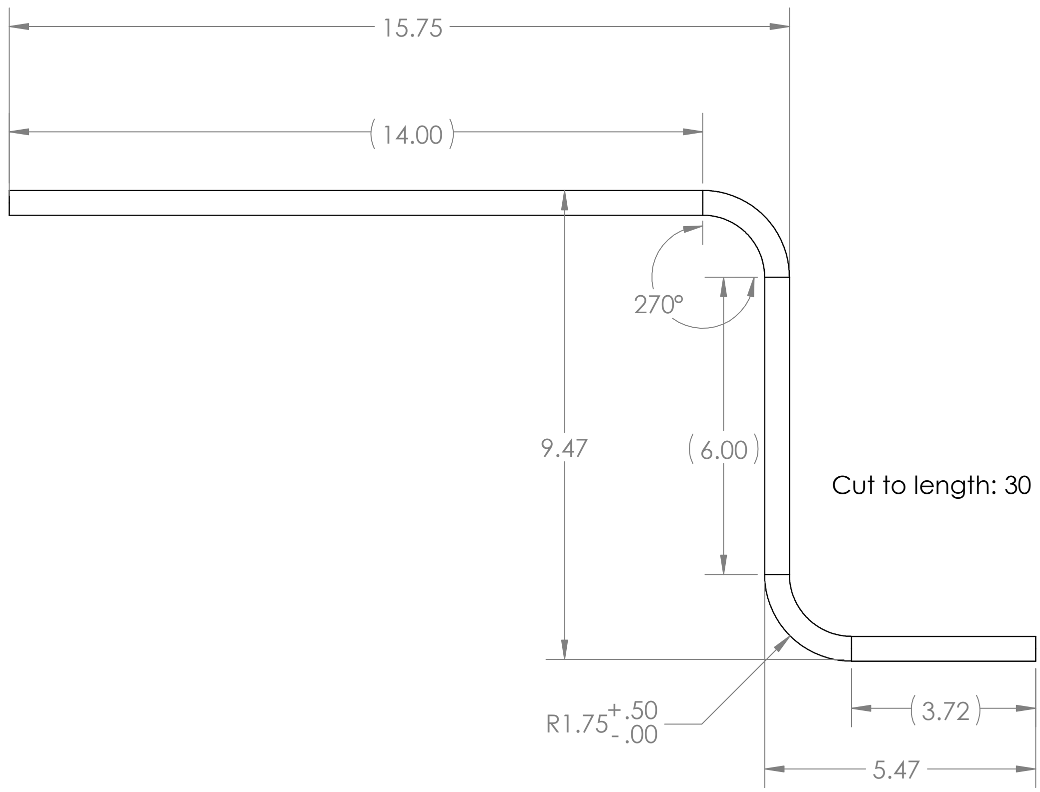
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 2 ONE PLACE DECIMAL ± 0.2 TWO PLACE DECIMAL ± 0.05	DRAWN	Brandon	3/3/30
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL SS-316 1/2" Tubing	COMMENTS:		
NEXT ASSY	USED ON	FINISH Deburr. Prepare for mate			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Tube - Fill Valve to Tee

SIZE	DWG. NO.	REV
A	Tube - Fill Valve to Tee	1

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



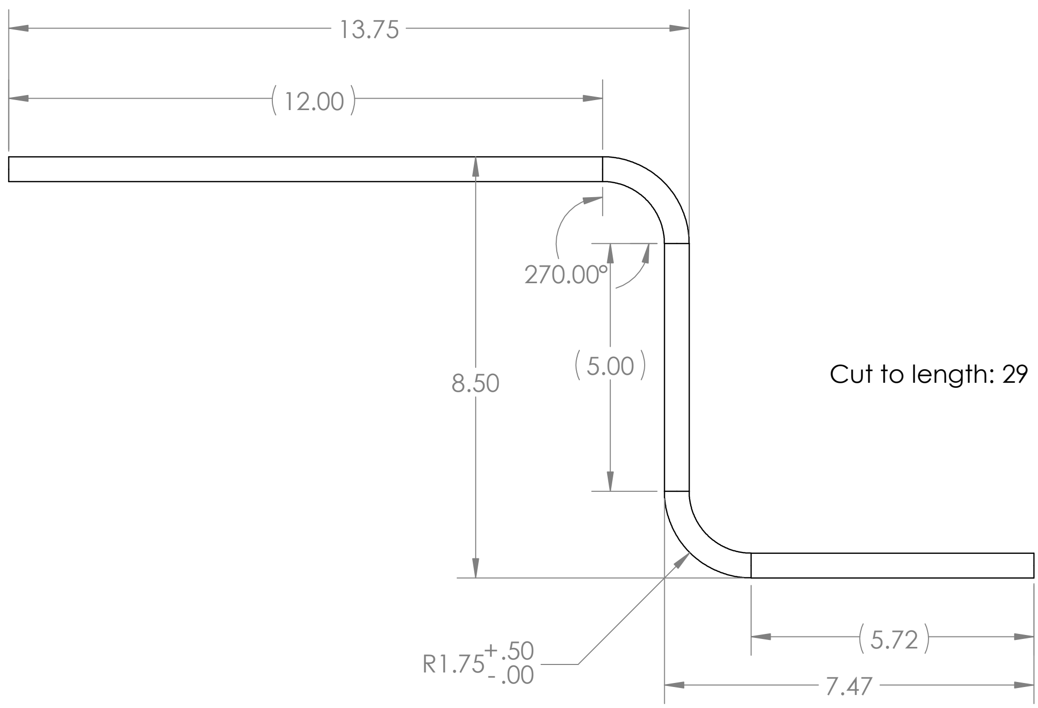
Cut to length: 30

				NAME	DATE
		UNLESS OTHERWISE SPECIFIED:	DRAWN	Brandon	2/29/20
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 5 TWO PLACE DECIMAL ± 0.2	CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL SS-316 1/2" Tubing	COMMENTS:		
NEXT ASSY	USED ON	FINISH Deburr. Ready to mate			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

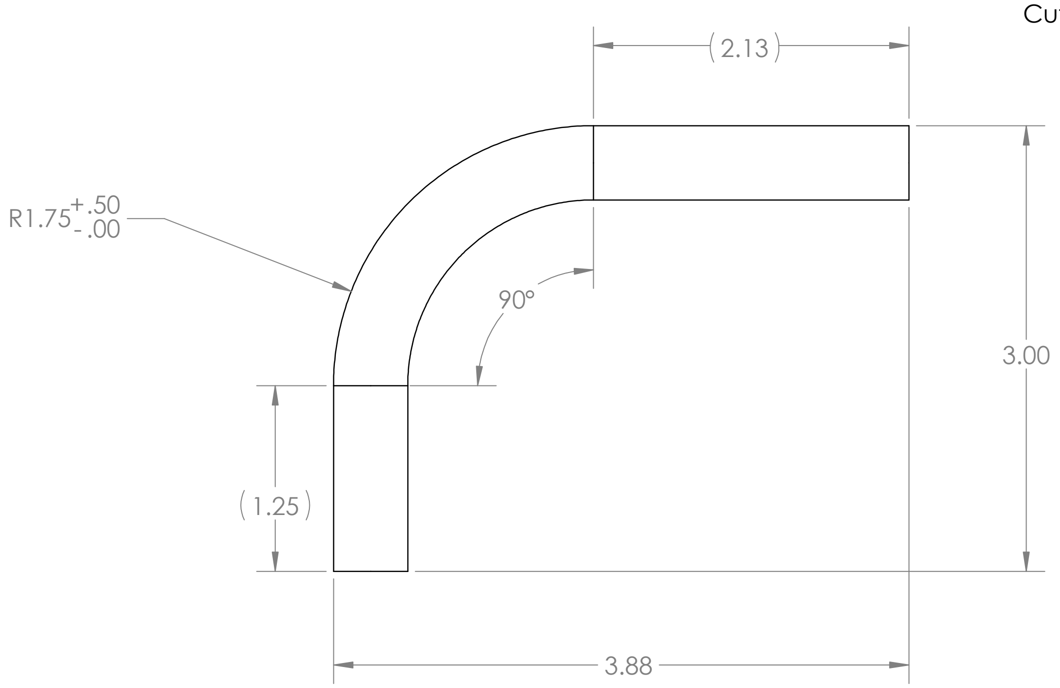
Tube - Main Valve to Out 2

SIZE	DWG. NO.	REV
A	Tube - Main Valve to Out	1
SCALE: 1:3	WEIGHT:	SHEET 1 OF 2

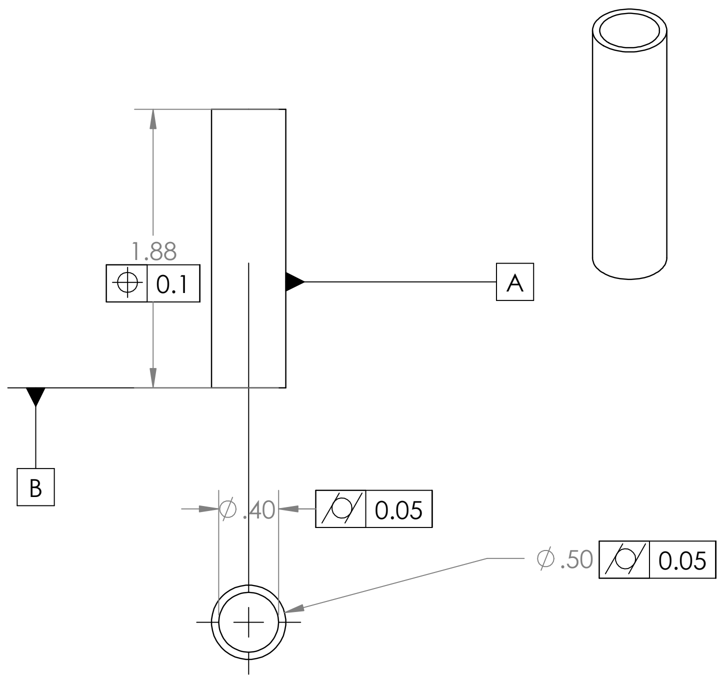


	UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
	DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 5 TWO PLACE DECIMAL ± 0.2	DRAWN	Brandon	2/29/20	TITLE:
		CHECKED			Tube - Main Valve to Out 1
		ENG APPR.			
		MFG APPR.			
	INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
	MATERIAL SS-316 1/2" Tubing	COMMENTS:			SIZE A | DWG. NO. Tube - Main Valve to Out | REV 1
NEXT ASSY | USED ON	FINISH Deburr. Ready to mate				
APPLICATION	DO NOT SCALE DRAWING				SCALE: 1:3 | WEIGHT: | SHEET 2 OF 2

Cut to length: 7



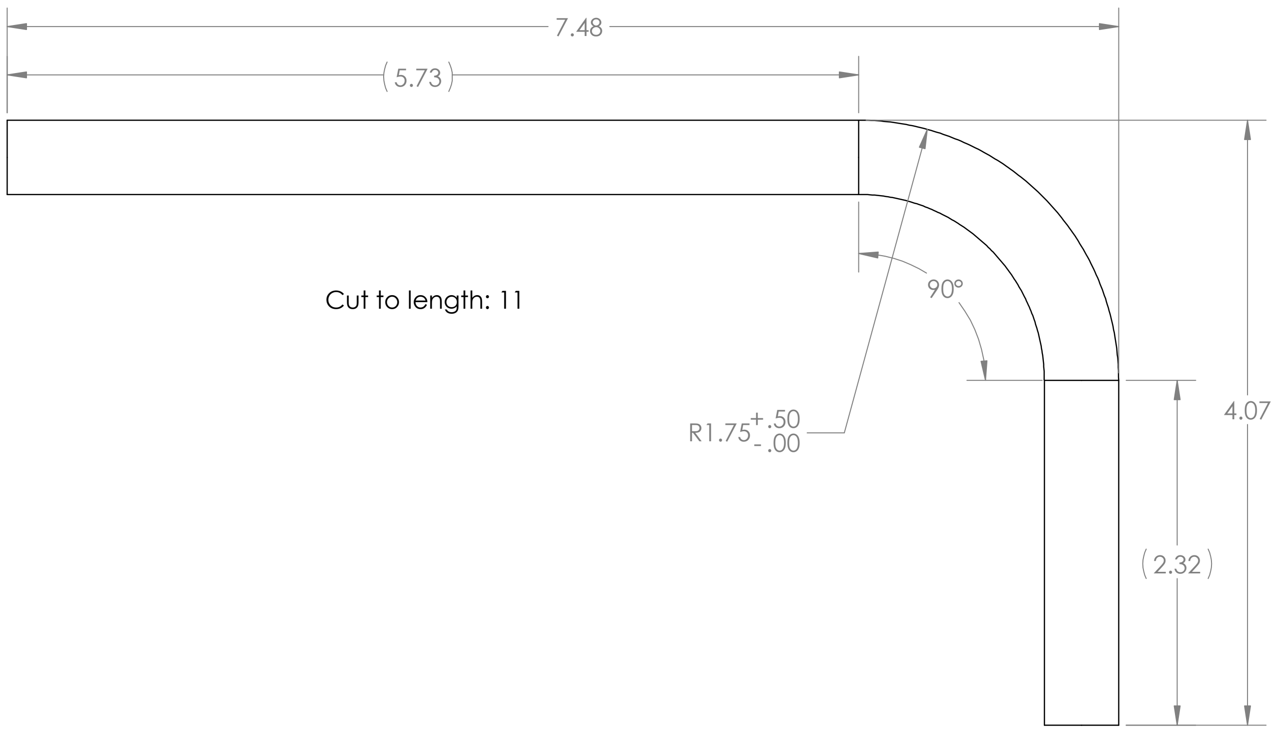
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 2 ONE PLACE DECIMAL ± 0.2 TWO PLACE DECIMAL ± 0.05	DRAWN	Brandon	2/29/20	TITLE: Tube - Main Valve to Tee
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL SS-316 1/2" Tubing	COMMENTS:			SIZE A	DWG. NO. Tube - Main Valve to Tee	REV 1
NEXT ASSY	USED ON	FINISH Deburr. Prepare for mate				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1	WEIGHT:	SHEET 1 OF 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Nolan	3/4/20	
			CHECKED			TITLE: Tube - Short
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL 1/2in SS316 Tube	COMMENTS:			SIZE A	DWG. NO. Tube - Short -GDT	REV 1
NEXT ASSY	USED ON	FINISH Deburred				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

2 1

B B



Cut to length: 11

A A

		UNLESS OTHERWISE SPECIFIED:
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 2 ONE PLACE DECIMAL ± 0.2 TWO PLACE DECIMAL ± 0.05
		INTERPRET GEOMETRIC TOLERANCING PER:
		MATERIAL SS-316 1/2" Tubing
NEXT ASSY	USED ON	FINISH Deburr. Prepare for mate
APPLICATION		DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Brandon	2/29/20
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

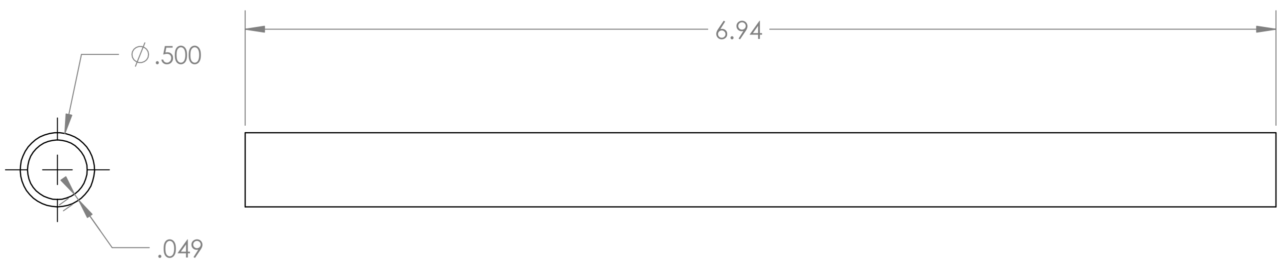
TITLE:

Tube - Main Valve to Tee

SIZE	DWG. NO.	REV
A	Tube - Tank to Tee Curved	1

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

2 1



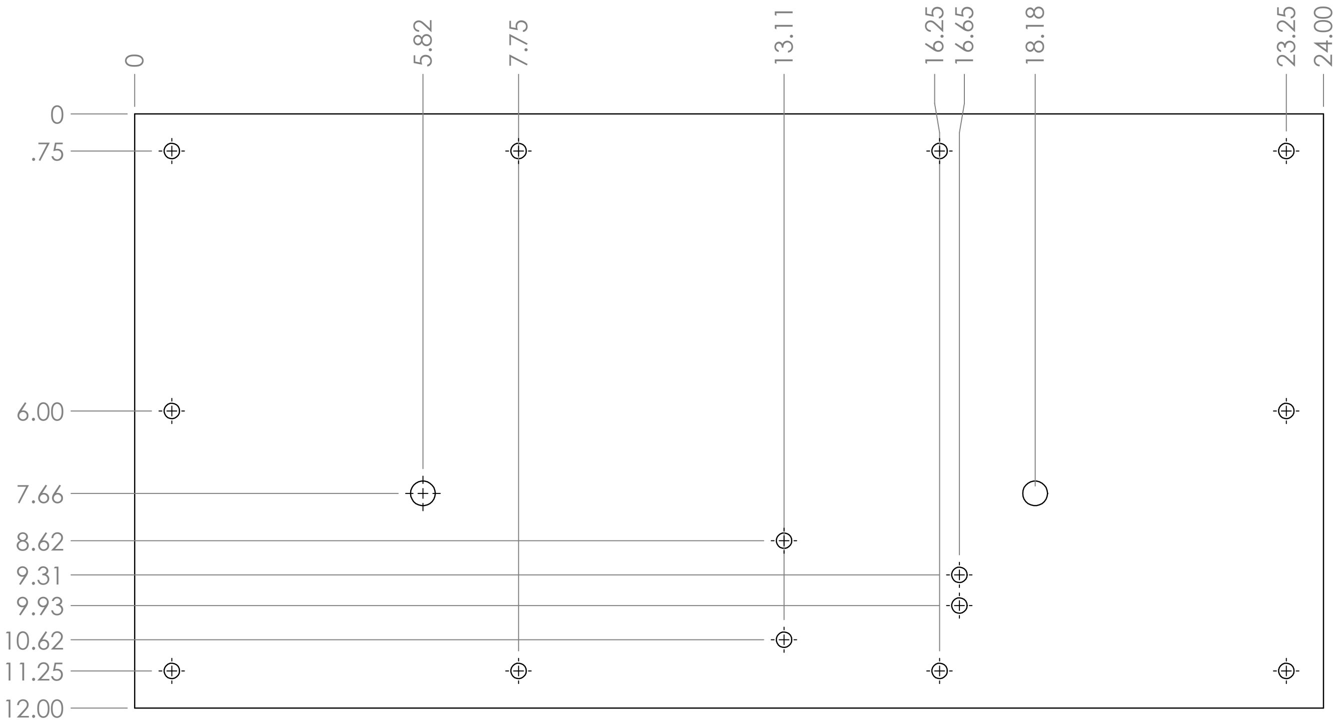
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Brandon	3/3/20
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL SS-316 1/2" Tubing	COMMENTS:		
NEXT ASSY	USED ON	FINISH Deburr. Prepare for mate			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Tube - Tank to Tee Straight

SIZE	DWG. NO.	REV
A	Tube - Tank to Tee Straight	1

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



NOTES:
Plate depth: 0.25

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.005	DRAWN	Brandon	2/22/20
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.		
		MATERIAL Aluminum	COMMENTS:		
NEXT ASSY	USED ON	FINISH As Machined			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:
Pneumatic Mounting Plate

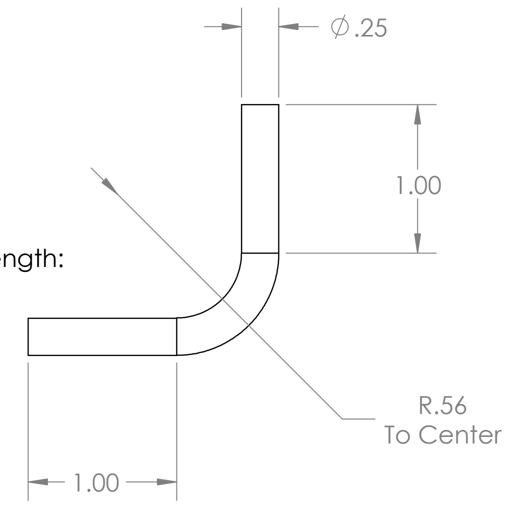
SIZE	DWG. NO.	REV
A	Top Mounting Sheet	1

SCALE: 1:3 | WEIGHT: | SHEET 1 OF 1

2 1

B B

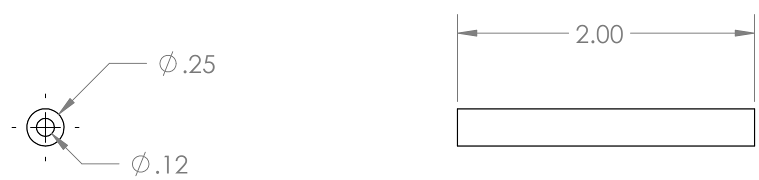
Total Unbent Length:
2.88



A A

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 2 TWO PLACE DECIMAL ± 0.05	DRAWN	Brandon	2/27/20	TITLE: 2in Elbow
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Stainless Steel 316 Tubing	COMMENTS:			SIZE A — DWG. NO. 2in Elbow — REV 1
NEXT ASSY	USED ON	FINISH Deburr. Prepare for mate				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 — WEIGHT: — SHEET 1 OF 1

2 1



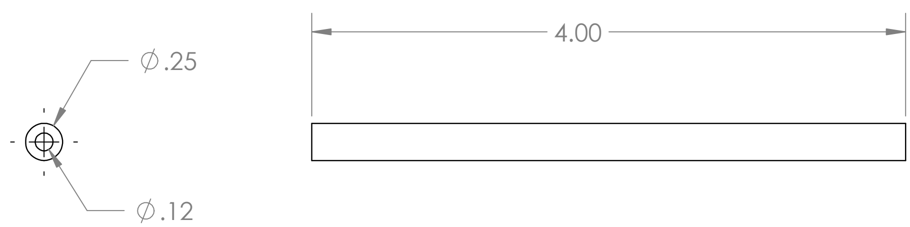
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 2 TWO PLACE DECIMAL ± 0.05	DRAWN	Brandon	2/27/20
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Stainless Steel 316 Tubing	COMMENTS:		
NEXT ASSY	USED ON	FINISH Deburr. Prepare for mate			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

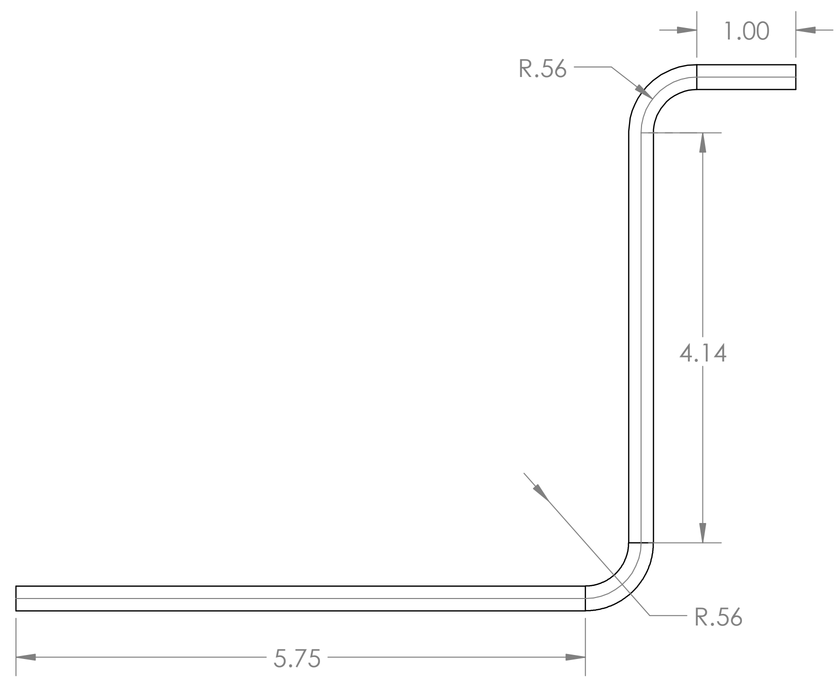
2in Straight

SIZE A DWG. NO. 2in Straight REV 1

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 2 TWO PLACE DECIMAL ± 0.05	DRAWN	Brandon	2/27/20	
			CHECKED			TITLE: 2in Straight
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Stainless Steel 316 Tubing	COMMENTS:			SIZE A · DWG. NO. 4in Straight · REV 1
NEXT ASSY	USED ON	FINISH Deburr. Prepare for mate				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 · WEIGHT: · SHEET 1 OF 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: BEND ± 2 TWO PLACE DECIMAL ± 0.05	DRAWN	Brandon	2/27/20	TITLE: Tubing Into Tank
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Stainless Steel 316 Tubing	COMMENTS:			SIZE A · DWG. NO. Tubing Into Tank · REV 1
NEXT ASSY	USED ON	FINISH Deburr. Ready for mate				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1.5 · WEIGHT: · SHEET 1 OF 1

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