Spring 2023 Technical Report

Cornell Rocketry Team
Hybrid Test Stand
Propulsion
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SPACEPORT AMERICA® CUP

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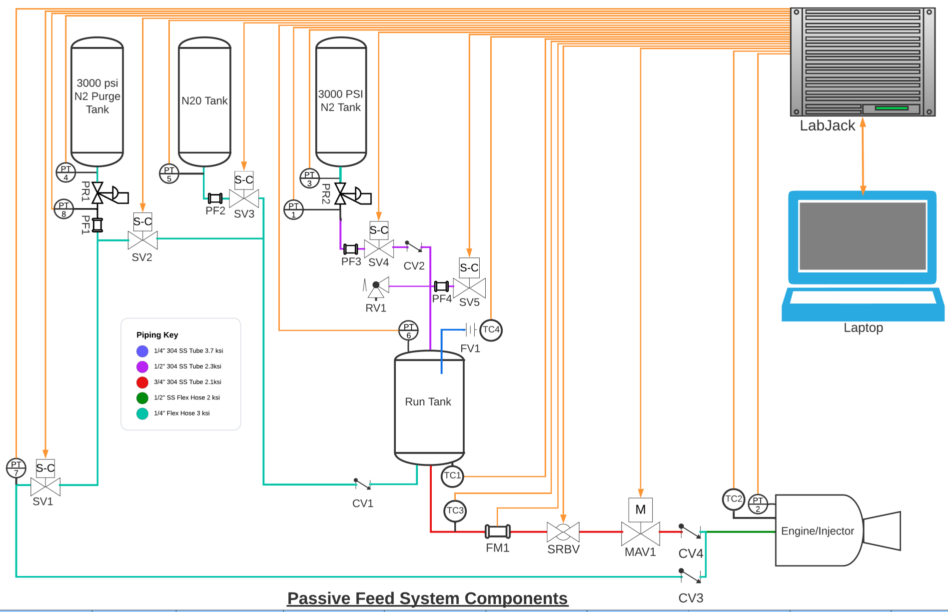
Nomenclature

ΔP	Pressure difference
C_v	Flow coefficient
Q	Flow rate
CV	Check Valve
LJ	LabJack
NVR	Non-Volatile Residue
P&ID	Piping and Instrumentation Diagram
PF	Particulate Filter
PT	Pressure Transducer
SG	Specific gravity
SV	Solenoid Valve
TC	Temperature Sensor
Ullage	Space left at the top of a tank when not completely filled with a liquid

1 System Overview



Passive Feed System Components

RV1	FV1	CV1	CV2	CV3	CV4	PR1	PR2	PF1	PF2	PF3	PF4
Pressure Relief Valve	Fill Indicator Vent	N2O Line Check Valve	N2 Supercharge Check Valve	N2 Engine Purge Check Valve	High Flow Feed Check Valve	N2 Purge Pressure Regulator	N2 Supercharge Pressure Regulator	Purge Particulate Filter	NItrous Purge Particulate Filter	Supercharge Particulate Filter	Tank Vent Particulate Filter

Electronic Valves

SV1	SV2	SV3	SV4	SV5	MAV1	SRBV
N2 Engine Purge Solenoid	N2 Tank/Line Purge Solenoid	N2O Fill Solenoid	N2 Supercharge Solenoid	Tank Vent Solenoid	High Flow Motor Actuated Ball Valve	Spring Return Ball Valve

Sensors

PT1	PT2	PT3	PT4	PT5	PT6	PT7	PT8	TC1	TC2	TC3	TC4	FM1
Supercharge Pressure Transducer	Injector Manifold Pressure Transducer	N2 Supercharge Tank Pressure Transducer	N2 Purge Tank Pressure Transducer	N2O Tank Pressure Transducer	Run Tank Pressure Transducer	Hot Side Purge Pressure Transducer	Purge Downstream Pressure Transducer	Run Tank Thermocouple	Injector Manifold Thermocouple	Feed Line Thermocouple	Fill Vent Thermocouple	Feed Flow Meter

Figure 1: Hybrid Test Stand P&ID

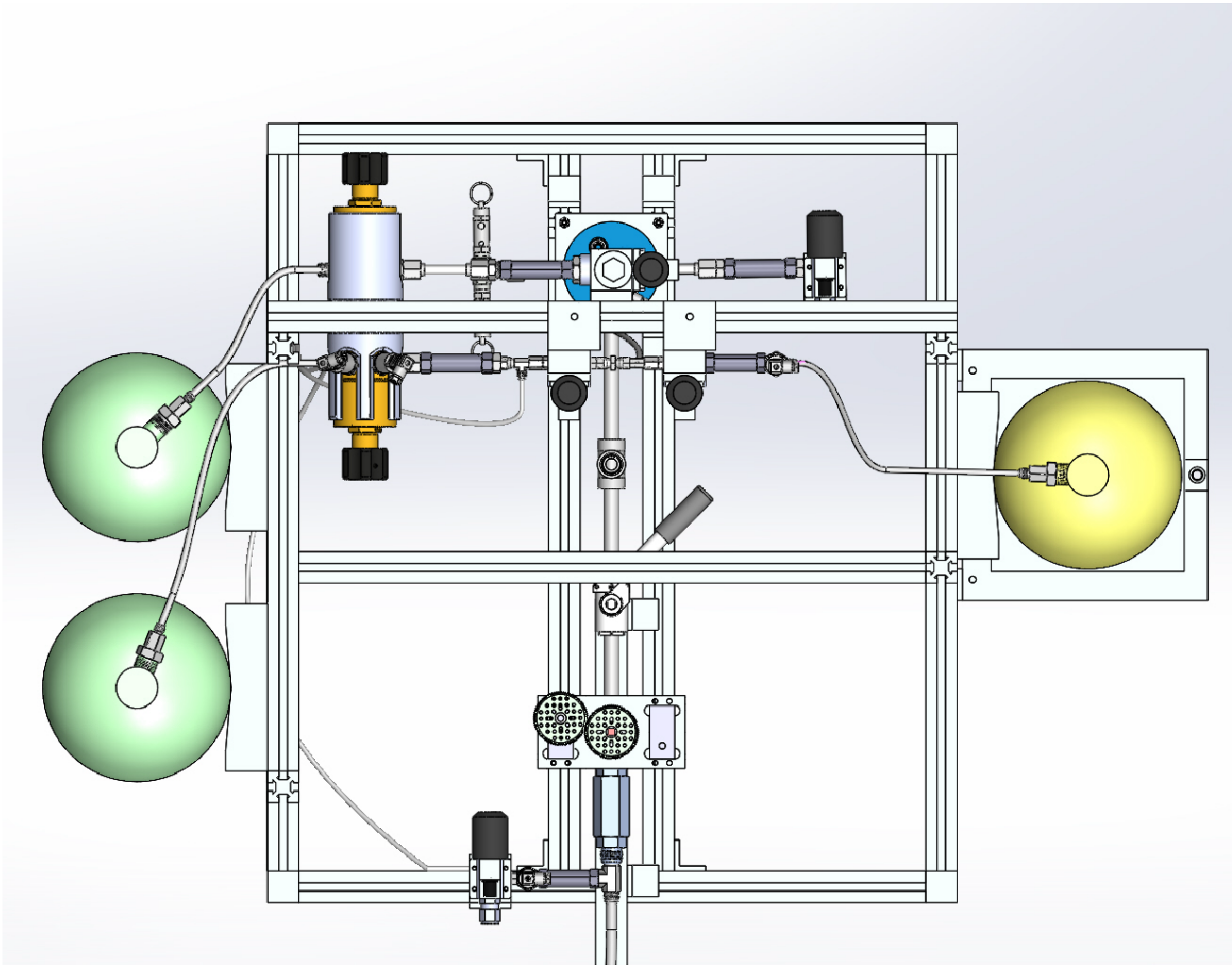


Figure 2: Test Stand CAD Top View

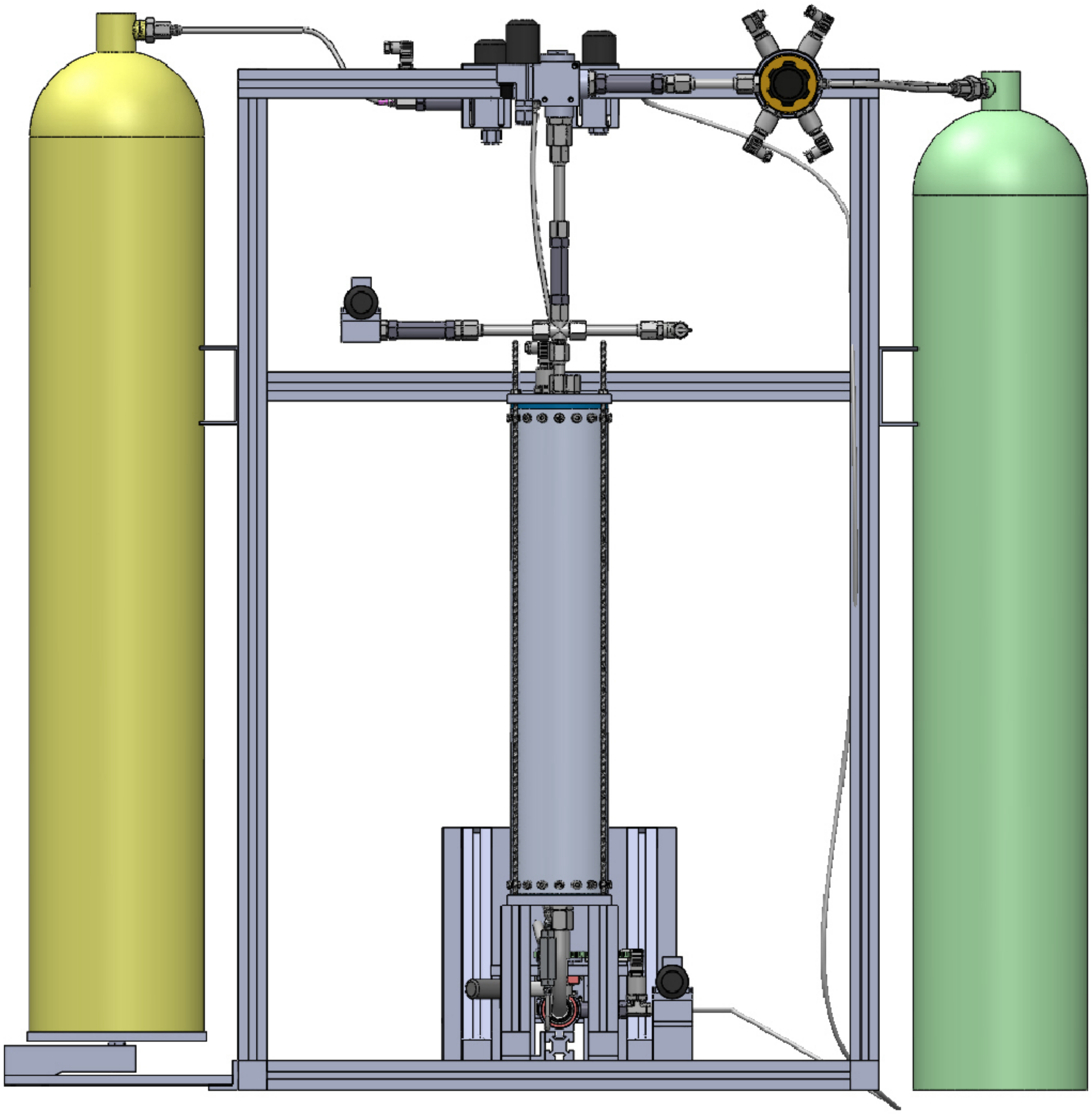


Figure 3: Test Stand CAD Back View

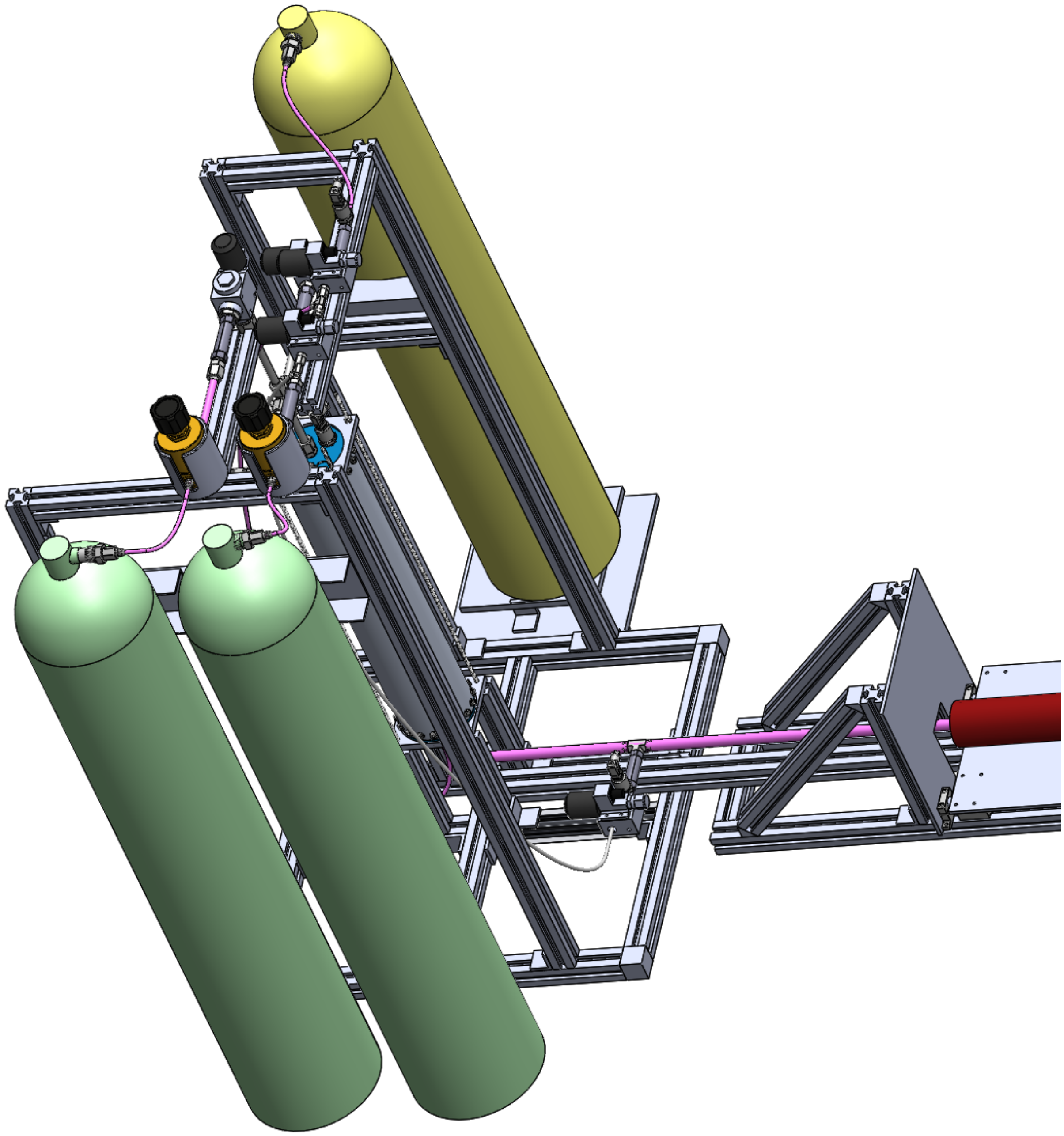


Figure 4: Test Stand CAD Side View

1.1 System Purpose

- The purpose of this test stand is to allow the propulsion team to test all aspects of hybrid engine design under a controlled environment while collecting data on key variables

  These variables include:

  - Thrust

- Run tank Pressure
- Run tank Temperature
- Oxidizer Flow rate
- Oxidizer fill level
- Combustion chamber pressure
- Igniter Continuity

These aspects include:

- Fuel grain geometry
- Injector design
- Nozzle design
- Combustion chamber design
- Igniter Design
- Fluid system Design

2 Overview of key Concepts

These key concepts drive the

- Cleanliness

  Particulate matter and non volatile residue (NVR) within the fluid system poses a component and system level danger. Particulate matter can cause wear on moving parts and cause leaks. NVR contamination can react with N20 and cause a decomposition event. Therefore, all wetted components must be sufficiently cleaned prior to assembly. Wetted components must be purchased already precision cleaned, or precision cleaned in house.

- Thermodynamics

  Temperatures and pressures in the fluid system are driven by phase changes of N2O, and by the release of high pressure N2 gas. When N2O changes from a liquid to a gas, a large amount of energy is absorbed, causing cooling to temperatures as low as -77°C.

- Nitrous Oxide Properties

  Nitrous oxide, in gaseous form, given sufficient activation energy, may decompose exothermically, causing a rapid increase in temperature and pressure. When this occurs in any part of the feed system, the resulting pressure will exceed any reasonable factor of safety, and cause a rupture of the pipe or pressure vessel. The decomposition of Nitrous Oxide is highly dependent on physical conditions: Presence of a hydrocarbon, presence of a catalyst, pressure, cross sectional area of container, temperature, and whether the N2O is in gaseous form. There is not a risk of decomposition of pure liquid Nitrous Oxide: "it was not possible to ignite N2O in the liquid phase even with the use of blasting caps." [10] Hydrocarbon contamination lowers the activation energy required for N2O decomposition. Nitrous oxide is a good solvent of hydrocarbons, so any grease, oil, or certain polymers may be dissolved by N2O. Catalysts also lower the activation energy of N2O. These catalysts include iron oxide, copper oxides, zinc oxides.[11] With regards to temperature and pressure, N2O begins to decompose at a measurable rate at 850K and the rate of decomposition increases with temperature. This is a risk where local temperatures reach high levels, such as due to adiabatic compression. This mechanism for decomposition is not seen as the primary risk. The primary risk is due to local thermal ignition, such as if hot gases from the combustion chamber traveled backwards and entered the feed system, and encountered gaseous N2O. This could begin a decomposition reaction which could propagate through the pipes of the feed system, and reach the run tank, which would cause a large explosion, if it is full of N2O vapor. This propagation of the flame front through the pipe, is highly dependent on pipe diameter. Smaller diameter pipes inhibit the propagation of the decomposition reaction. In 1/2" diameter pipe, G. W. Rhodes, at the USAF weapons laboratory, said "It was very difficult to ignite the N2O in the 1/2" diameter pipe, and no ignitions were obtained at ambient temperature, up to 1000 psi." Reactions were only observed when the pipe and N2O were preheated to 400 degrees Fahrenheit, at 800 and 1000 psi. These ignitions were initiated through a high energy electric arc, or an electricity triggered explosion by passing a high current through a coil of wire.[9]

  - Material Compatibility All wetted materials must be compatible with nitrous oxide. O-rings and other polymeric fluid system components must be evaluated for compatibility. Many polymers will absorb N2O and swell, to different degrees depending on the polymer. This swelling can cause moving components, such as check valves or solenoid valves to malfunction. Polymers that are saturated with N2O are more prone to combustion. Certain polymers are more easily ignited than others. For example, fluoropolymers such as Viton, are resistant to ignition as compared to non fluoropolymers such as Buna-N.

2.1 System Function

- Safely Fire hybrid rocket motor
- Control Run tank pressure
- Control Oxidizer flow to injector
- Purge Engine
- Collect data

3 Test Stand Key Requirements

1. System shall be capable of remote operation
2. Pressurized system shall not require personnel intervention in event of failure
3. System shall be capable of delivering 0.5 kg/s N2O to injector
4. Fluid system shall be easily scaled to deliver 1.0 kg/s N2O
5. System must be capable of both blow-down and externally pressurized operation

4 Subsystems

The test stand is composed of five subsystems:

- Fill/vent system
  - Fills run tank with N2O
  - Indicates when run tank is full
  - Constantly vents run tank
- Purge system
  - Purge run tank with N2
  - Purge lines with N2
  - Purge hot side with N2
- Supercharge system
  - Controls the pressure in the run tank
  - Relieves pressure in case of run tank over-pressure
  - Allows for solenoid valve controlled release of run tank pressure
- Hot Side
  - Controls the flow of pressurized liquid N2O from the run tank to the injector
- Run Tank
  - Contain pressurized N2O
- Electrical system
  - Controls the operation of the test stand
  - Receives data from the pressure, temperature, and load sensors
  - Sends actuation signals to electronically controlled valves

4.1 Hot Side

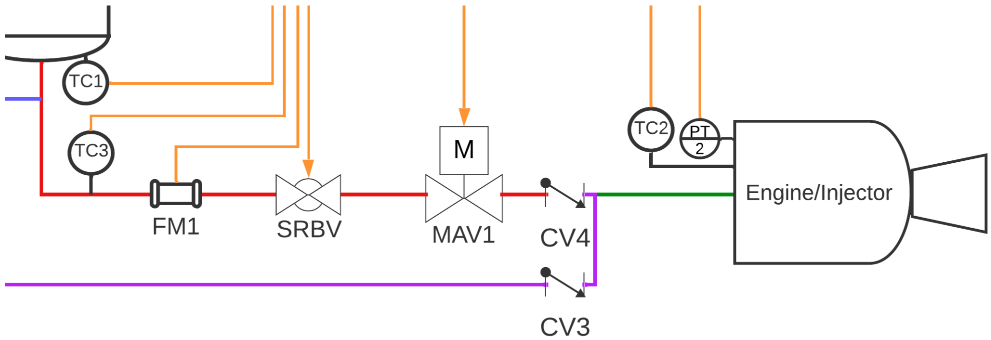


Figure 5: **Hot side P&ID diagram**

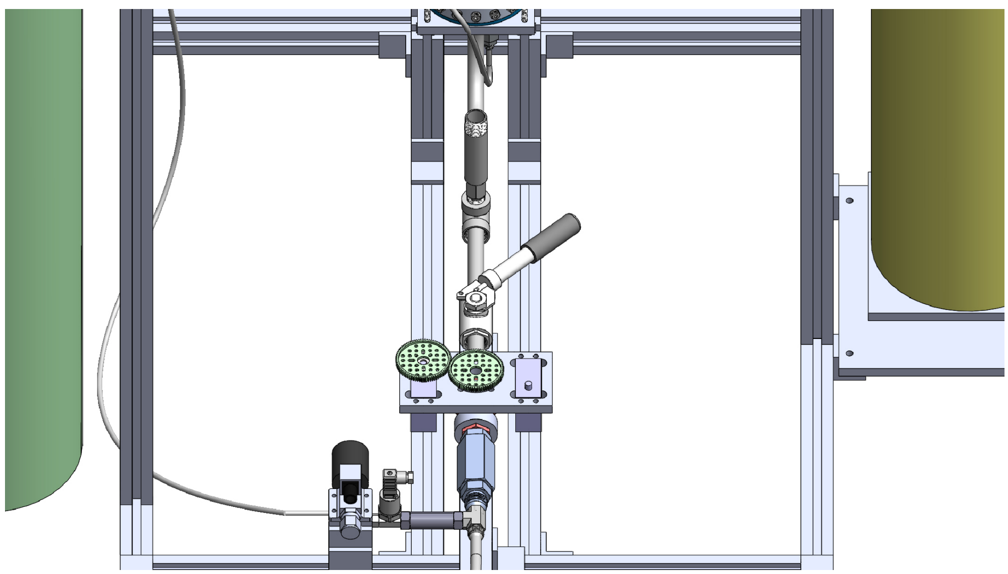


Figure 6: **Hot side CAD**

4.1.1 System Function

1. Control flow of liquid N2O from run tank to injector
2. Prevent flashback into run tank
3. Measure N2O flow rate

4.1.2 Requirements

1. Wetted surfaces must be compatible with N2O
2. Yield pressure must be > 1.5 MEOP
3. Must maintain pressure throughout flow path

4.1.3 Design Choice Justification

Turbine Flow Meter: This was implemented to measure flow of liquid N2O to injector during firing. Other flow meters such as Venturi, or Coriolis meters are not appropriate for this application due to cost.

Spring Return Ball Valve: Stop oxidizer flow in event of electrical failure. This also prevents the run tank from running dry, which would greatly increase the risk of catastrophic flashback.

Mechanically Actuated Ball Valve: Start or stop N2O flow in a more gradual manner than a solenoid valve. This prevents a water hammer effect which can cause adiabatic compression of N2O, and consequently a decomposition event.

Check Valve: Prevent hot combustion chamber gasses from traveling up the feed line.

Flexible steel tubing: Allow for repositioning of motor away from fluid system. This also reduces strain on the tubing connections.

3/4" OD Stainless Steel Tubing This was chosen to accommodate the 3/4" flow meter connections. This large size also reduces flow resistance. Stainless Steel is compatible with N2O.

4.1.4 Testing

With the dip tube in high position, liquid flow was observed for 8 seconds. This was estimated based on video footage showing a large quantity of white mist flowing from the injector. Because the dip tube was in the high position, the run can be assumed to have been filled to 80% capacity with CO2 when the MAV was actuated. There is also CO2 in the hot side line leading up to the MAV, but this is negligible for this rough estimation. At 80% capacity the run tank (9L max capacity) is holding approximately 7.2L of CO2. To find the volumetric flow rate, divide the volume by the time elapsed: 7.2/8 which is around .9 L/s. The density of CO2 is 0.8kg/L, so therefore the mass flow rate is 0.7 kg/s.

The flow rate through the injector was previously calculated to be around 0.4 kg/s CO2, based on the injector characteristics and data from Benjamin Waxman in "Mass Flow Rate and Isolation Characteristics of Injectors for Use with Self-Pressurizing Oxidizers in Hybrid Rockets" [12]

Conclusions: This mass flow rate is higher than expected as estimated in previous research, however it is within reasonable bounds. There is a high uncertainty in the pressure of the run tank due to the lack of calibrated pressure transducer data. The run tank pressure affects upstream pressure, which affects mass flow rate. It is likely that the pressure in the run tank is less than the saturation pressure of 800 psi at room temperature due to the chilling effect of the liquid CO2 boiling off from the dip tube venting. Therefore, it would be expected that the mass flow rate is lower than calculated, but this was not the case.

However, fine tuning of the injector flow rate is not the focus of this report. The data shows that the test stand is functioning as expected, and supplying CO2 to the injector without major pressure drops. Therefore, this system is validated, and can be used for further tests without improvement.

4.2 Run Tank

4.2.1 System Overview

The run tank is a pressure vessel that contains the nitrous oxide and interfaces with the supercharge, fill, hot side, and vent system. This run tank is based off of the solid motor casing and bulkheads. The length of the casing was modified to accommodate the correct volume of N2O, and the bulkheads were modified to include ports for the fluid system attachments. The SRAD run tank was developed because the commercial options were highly costly $3000, and had a lead time of 6+ weeks. CRT has previously manufactured pressure vessels that have been tested to 1500 psi, and also that fit the relevant form factor, and could be done for a much lower cost. Developing the SRAD run tank also brings CRT closer to a flight ready hybrid propulsion system, as the current run tank design can be easily optimized for flight.

4.2.2 Requirements

The requirements of this pressure vessel consist of internal requirements, and also hybrid propulsion specific requirements

Table 1: Pressure Vessel Requirements

Requirement	Notes
PROP 9	SRAD and modified COTS pressure vessels shall be proof pressure tested successfully (without significant anomalies) tested to 1.5 times the maximum expected operating pressure for no less than twice the maximum expected system working time, using the intended flight article(s) (e.g., the pressure vessel(s) used in proof testing must be the same one(s) flown at the IREC). The maximum system working time is defined as the maximum uninterrupted time duration the vessel will remain pressurized during pre-launch, flight, and recovery operations.
PROP 8	SRAD and modified COTS pressure vessels constructed entirely from isotropic materials (e.g., metals) shall be designed to a burst pressure no less than 2 times the maximum expected operating pressure, where the maximum operating pressure is the maximum pressure expected during pre-launch, flight, and recovery operations.
PROP 5	All pressure-containing hardware interfaces should be verified with FEA.

4.2.3 Design Choice Justification

Bulkhead design: Top bulkhead: The top bulkhead has three O-Boss ports. It accommodates a pressure transducer (-04), the dip tube passthrough fitting (-06), and the supercharge outlet (-08). Bottom Bulkhead: The bottom bulkhead has two O-Boss ports. It accommodates the hot side inlet (-12) and fill outlet (-04).

Ports were placed in a way which maximized clearance between adjacent ports, while also maintaining appropriate clearance from shoulder screw holes. During machining, the ports must be accurately placed relative to bolt holes, because there is more clearance between two adjacent bolt holes. The bulkhead was also thickened so that the wide portions of the ports were above the bolt holes which allowed the ports to be spaced further apart.

Temperature sensors were not installed yet during cold flow so temperature readings were not recorded, however due to the presence of ice crystals on the run tank, it can be assumed that temperatures dropped below 0°C. Temperatures were most likely much lower than 0°C during the venting of the tank. This temperature drop is caused by the N2O evaporating when pressures in the run tank are below the vapor pressure of N2O.

Therefore, Fluorosilicone O rings were selected rather than Viton O Rings, because they are still flexible at temperatures of -74°C vs Viton which is only rated for -26°C.

O-Boss ports were used instead of NPT ports because they can be removed and reinserted many more times. NPT ports are much easier to machine because they simply use a tapered tap, but because they seal on the threads, they cause much more wear when they are inserted. The O-Boss ports were designed in accordance to SAE-J1926 specifications. They require more complex geometry, such as a spotface, a 12 or 15° chamfer, a 45° chamfer, and rounded edges. This is because these seal with an o ring which is compressed against the chamfers when the fitting is tightened. Torque specs are less important when installing these fittings, however take care to not over-torque. These can be installed by turning the fitting a certain angle after reaching finger tight, rather than using a torque wrench. The torque is only required so that the fitting does not inadvertently loosen.

4.2.4 Manufacturing

The run tank bulkheads took much longer to manufacture than initially planned. The run tank required both HAAS work and Green lathe work during the weeks where the shop was at peak demand. The casing was out of round and was measured incorrectly which meant that one bulkhead did not fit, and the bulkhead had to be re-manufactured. Both ends of the casing had to be bored extensively so that it was round. Correctly threading the bulkhead is difficult and time consuming, so a jig was made to clamp the bulkhead vertically. In the future, these threads should be made on the HAAS. The O ring grooves on the bulkheads were post processed with very fine grit sandpaper to remove the sharp edges. On the bulkheads, ports were created by machining the features using the HAAS, and then manually threading the ports. For the PLV-34 manifolds, the ports were created using a porting tool which cuts all of the desired geometry, except for threads which are done manually, in one operation.

4.2.5 Calculations

The run tank is an aluminum 6061 pressure vessel with an outside diameter of 5 inches and a minimum wall thickness of 0.2 inches. To calculate the burst pressure, the thin walled cylindrical vessel approximation can be used. The maximum stress will be the hoop stress (σ_h).

According to the thin-walled pressure vessel theory, the hoop stress (σ_h) for a cylindrical vessel can be calculated as follows:

$$\sigma_h = \frac{PD}{2t}$$

where P is the internal pressure, D is the outside diameter, and t is the wall thickness.

$$\begin{aligned}\sigma_h &= \frac{(2000 \text{ psi}) \times (5 \text{ in})}{2 \times 0.2 \text{ in}} \\ &= 25000 \text{ psi}\end{aligned}$$

The minimum burst pressure (P_b) is determined by the yield strength (σ_y) of the material. For aluminum 6061, the yield strength is approximately 40 ksi.

To calculate the burst pressure, rearrange the equation for pressure as follows:

$$P_b = \frac{2t\sigma_h}{D}$$

Substituting the values:

$$P_b = \frac{2 \times 0.2 \text{ in} \times 40000 \text{ psi}}{5 \text{ in}}$$
$$= 3200 \text{ psi}$$

Therefore, the minimum burst pressure of the aluminum 6061 pressure vessel is 3200 psi.

Since the internal pressure of 2000 psi is less than the minimum burst pressure, the vessel will not burst under this pressure, and the PROP 8 requirement is met.

$$SF = \frac{\text{Burst Pressure}}{\text{Maximum Expected Operating Pressure}}$$

With a minimum burst pressure of 3200 psi and a Maximum Expected Operating Pressure (MEOP) of 1000 psi, we can substitute these values into the equation to calculate the safety factor:

$$SF = \frac{3200 \text{ psi}}{1000 \text{ psi}} = 3.2$$

Therefore, the safety factor in burst is 3.2.

Volume requirements can be calculated as follows:
Given a flow rate of 0.5 kg/s for 5 seconds, the total mass of N_2O required is:

$$\text{Mass} = 0.5\,\text{kg/s} \times 5\,\text{s} = 2.5\,\text{kg}$$

To account for the next test requiring approximately twice the mass, the new calculation becomes:

$$\text{Mass} = 1\,\text{kg/s} \times 5\,\text{s} = 5\,\text{kg}$$

Adding approximately 20% for ullage space (upper limit), the total mass becomes:

$$\text{Mass} = 5\,\text{kg} + (5\,\text{kg} \times 0.2) = 6\,\text{kg}$$

To prevent flashback, an additional 20% of the mass is needed so that there is liquid N_2O remaining at the bottom of the tank at the end of the test, resulting in a total mass of:

$$\text{Mass} = 6\,\text{kg} + (6\,\text{kg} \times 0.2) = 7.2\,\text{kg}$$

Since the density of N_2O is approximately 0.8 kg/L, the required capacity of the tank can be calculated as:

$$\text{Capacity} = \frac{\text{Mass}}{\text{Density}} = \frac{7.2\,\text{kg}}{0.8\,\text{kg/L}} = 9\,\text{L}$$

Solve for the dimensions of the tank:
The area of the tank can be calculated using the inner diameter (ID) as:

$$\text{Area} = \pi \left(\frac{\text{ID}}{2}\right)^2$$

Given an inner diameter of 11.43 cm (4.5 in)

$$\text{Area} = \pi \left(\frac{11.43\,\text{cm}}{2}\right)^2 = 102.61\,\text{cm}^2$$

To solve for the length of the tank:

$$\frac{\text{Volume}}{\text{Area}} = \text{Length} \tag{1}$$

$$\text{Volume} = 9000\,\text{cm}^3 \tag{2}$$

$$\frac{9000\,\text{cm}^3}{102.61\,\text{cm}^2} = 87.71\,\text{cm} \tag{3}$$

To compensate for the bulkheads intruding into the tank by 3.5 centimeters each, add 7 cm to the length (L) of the tank. The equation becomes:

$$87.71\,\text{cm} + 7\,\text{cm} = 94.71\,\text{cm}$$

The final length can then be rounded to 95 centimeters

Assembly Procedure:

1. Ensure that all tank components have been oxidizer cleaned prior to assembly.
2. Assemble the components in a clean environment.
3. Wear gloves and apply oxidizer safe PTFE lubricant to grease the O-rings and O-ring grooves.
4. Carefully place the O-rings into their respective grooves, taking care not to stretch them excessively.
5. Align the bulkhead screw holes with the casing holes and gently press the bulkhead until it is fully inserted. Avoid pinching or tearing the O-rings during this step.
6. Insert all shoulder screws and tighten them securely.
7. Cover all open port holes with clean plugs and set them aside.

4.3 Fill/Vent

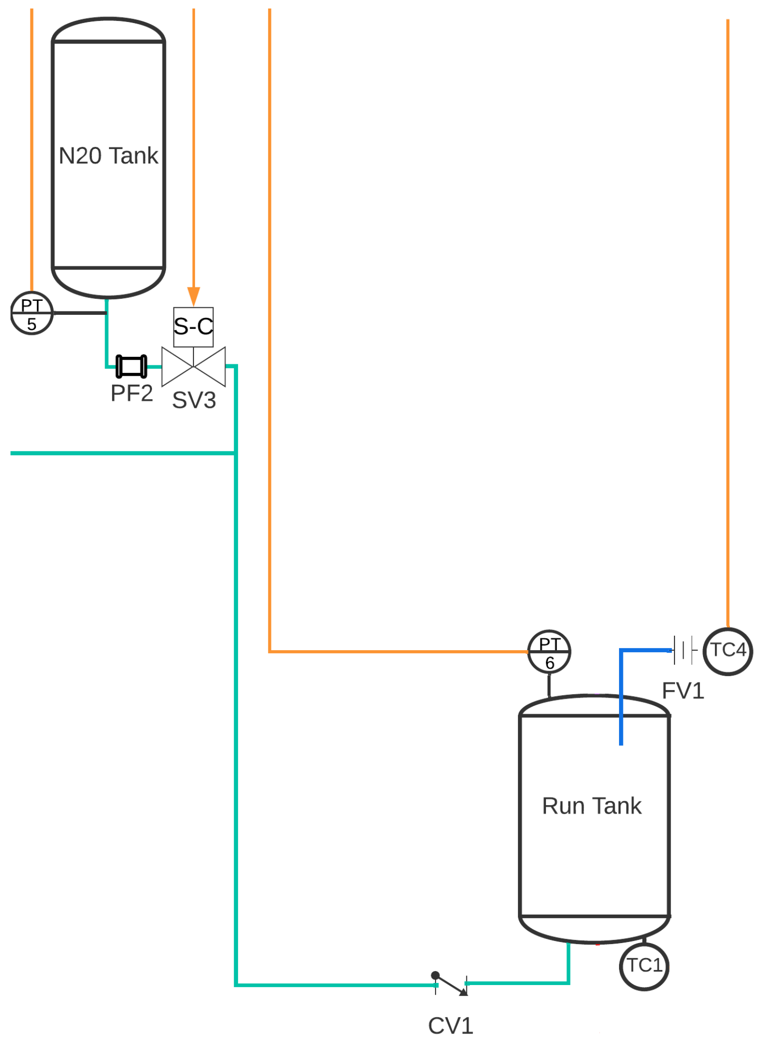


Figure 7: **Fill/Vent P&ID diagram**

Figure 8: **Fill outlet during operation**

Figure 9: **Ice accumulation on dip tube outlet**

Figure 10: **Full tank indicated by liquid venting from dip tube orifice**

4.3.1 System Function

1. Fill run tank with liquid N2O
2. Constantly and slowly vent run tank
3. Monitor N20 supply tank pressure
4. Indicate run tank fill status

4.3.2 Overview

The fill vent system fills the run tank with N2O (or CO2 for cold flow).

- Fill system details:
  - Attaches to the supply cylinder using a CGA 320 (CO2) or CGA 660 (N2O) fitting.
  - Monitors the supply tank pressure using the PT5 pressure transducer.
    - The PT5 pressure transducer measures the vapor pressure of the supply tank, but does not measure the fill level of the supply tank.
    - Fill level of the supply tank is measured using the tank load cell reading.
- Flow path:
  1. The liquid N2O passes from the supply cylinder through the CGA fitting.

2. Flows through a -04 stainless steel hose to PF2, which filters particulates
3. Flows through the SV3 solenoid valve, which controls the filling process.
4. Further flows through another -04 stainless steel hose to a check valve (CV1) leading to the run tank. See Figure 8
5. Once the liquid N2O level reaches the bottom of the dip tube, the liquid N2O sprays out of the orifice (FV1) as seen in Figure 10

- **N2O Supply cylinder:**
  - UN 50PPM SULFUR DIOXIDE BALANCE NITROUS OXIDE
  - SIZE 200 UNANALYZED STANDARD CGA 660 SYPHON TUBE
  - 64 LB 2265 PSI CYLINDER
  - Airgas code: (X02NS99U200C384)
  - Price: $286.24
- **CO2 Supply cylinder:**
  - CARBON DIOXIDE 50LBS SIPHON CGA 320
  - Airgas code: (CD 50S)
  - Price: $15.83

4.3.3 Requirements

1. Wetted surfaces must be compatible with N2O
2. Yield pressure must be > 1.5 MEOP
3. Fill tank within 5 minutes

4.3.4 Design Choice Justification

(PF2) 50 Micron Particulate Filter This in line particulate filter is used to protect the downstream solenoid valve from potential particulate contaminants.

(SV3) Solenoid Valve A direct acting solenoid valve was chosen to control the flow of the N2O into the tank at any positive pressure differential.

The Marotta PLV-34 Solenoid valve was used in an assembly with the manifold designed by Murphy Klein.

Specifications:

- CV= 0.06
- Min temp: -54°C

(CV1) Check valve The check valve prevents back-flow from the run tank into the N2O tank. This is an added safety feature in the event that SV3 fails.

The check valve selected is a Check-All TFBSSTF.500SS. This is a 1/4" TF style check valve in 316 Stainless with a PTFE seat and a 1/2- PSI spring cracking pressure. The spring material will be made of 316 SS.

PTFE was selected as the seat material because it is rated to -320F, which is the lowest available.[6] It also is compatible with N2O. Using PTFE seats decreases the sealing capabilities of the check valve, and a leak rate of 180cc/min per inch diameter of line can be expected at 80 psi. However, this leak rate may be higher or lower at the operating pressure.

This check valve was factory oxygen cleaned.

(FV1) Fill Vent This fill vent dip tube assembly indicates the fill level of the Run Tank by venting liquid N2O, which is then detected by the TC4 temperature sensor. This design was chosen because it is much simpler than a direct electronic measurement method, such as an ultrasonic sensor.

The Fill Vent also constantly vents the run tank at a low rate, so that in the event of a complete electronic failure, the run tank will eventually return to a safe pressure without intervention.

During operation ice may accumulate on the external surfaces of the dip tube and vent due to the low temperatures. See: Figure 9

The the dip tube height can be adjusted to change the fill level of the run tank.

-04 Braided Stainless Steel PTFE lined hose Compatible with N2O, low flow rates so large diameter tubing is not necessary.

4.3.5 Calculations

This simple matlab function is used to roughly estimate the fill rate using this liquid flow rate equation:

$$Q = C_v \sqrt{\Delta P / SG}$$

```
function flowRate_LPM = calculateFlowRate(CV, upstreamPressure,
↪  downstreamPressure, specificGravity)
    % Calculate the pressure difference in psi
    pressureDifference = (upstreamPressure - downstreamPressure);

    % Calculate the flow rate in gpm
    flowRate = CV * (sqrt(pressureDifference)/sqrt(specificGravity));

    % Convert flow rate from gpm to liters per minute (LPM)
    flowRate_LPM = flowRate*3.78541;
end
```

Because the downstream pressure is currently unknown, a range of values is provided:

Given an upstream pressure of 750 psi and a downstream pressure of 50 psi the flow rate could be 7 LPM.

Given a downstream pressure of 500 psi, the flow rate would be 4 LPM.

These values are underestimates because the viscosity of liquid nitrous oxide is much lower than the viscosity of water. [7], [8]

4.3.6 Testing

System was tested during cold flow

Results:

- The Run tank fills faster than expected. The run tank was filled with liquid CO2 in approximately 45-60 seconds, which is much less than the requirement of 20 minutes.
- This is closer to the high range of the estimated fill rate.
- The volume of the tank with the dip tube in the higher position was approximately 7 L. Therefore the fill rate is 7 LPM.
- This was estimated based on the time elapsed between beginning fill procedure and observation of white spray from the dip tube orifice as seen in Figure 10
- The dip tube also vents at a higher rate than expected.

4.4 Supercharge

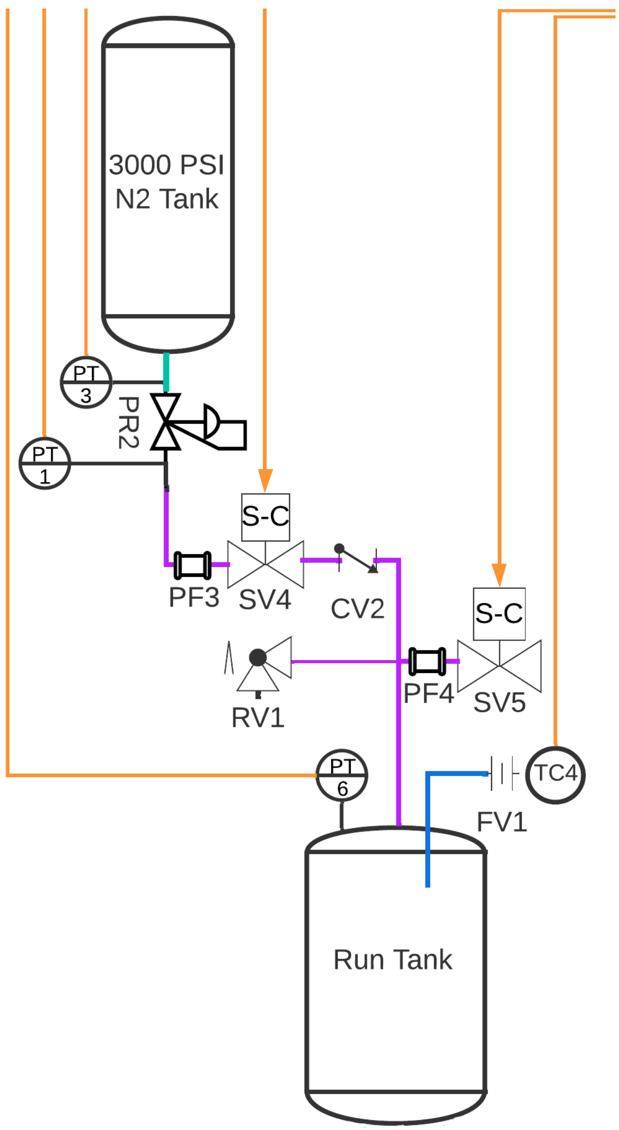


Figure 11: **Supercharge P&ID diagram**

4.4.1 System Function

1. Control pressure of Run Tank
   (a) Monitor run tank pressure
   (b) Flow N2 into run tank
2. Prevent decomposition of N2O in run tank

4.4.2 Theory of Operation

Flashback Protection When the supercharge system is used, the ullage of the run tank will be filled with gaseous nitrogen, which will lower the likely hood that the gaseous N2O will decompose. [10] This is another safety feature

Run tank pressurization

4.4.3 Requirements

1. Wetted surfaces must be compatible with N2O
2. Yield pressure must be > 1.5 MEOP
3. Must maintain run tank at +- 100psi set pressure

4.4.4 Design Choice Justification

(PR2) High Flow Regulator The regulator controls the supercharge pressure. This method of pressurization was selected because it is passive, and less complicated than a bang-bang system. The regulator that was selected is the 873-5000 High Flow Reducing regulator from Aqua Environment. It was selected based on its high CV (0.8), low price, and ability to house an upstream and downstream pressure transducer.

(PF3, PF4) 50 Micron Particulate Filter This in line particulate filter is used to protect the downstream solenoid valve from potential particulate contaminants.

(SV4) Solenoid Valve A high CV pilot operated solenoid valve (MV524) is used to control flow of N2 into the run tank. This valve was selected because it was high CV and sponsored by Marotta. High CV is required because the N2 must be flowed into the run tank at a high rate to maintain the run tank pressure. A direct acting solenoid valve would be preferred, but the pilot actuated solenoid valve allows for much higher flow in a more compact package.

(CV2) Check valve The check valve prevents back-flow from the run tank into the Supercharge system. Upstream of the check valve, there are components that are not compatible with N2O.

(RV1) Fill Vent A relief valve was selected to vent excess pressure, to protect the run tank in the event of over-pressure from the supercharge system.

1/2" Stainless Steel tubing Larger diameter is required to maintain high N2 flow rates.

4.4.5 Analysis

A matlab script was developed to determine the appropriate regulator CV. This script will be improved to accurately take into account the Joule-Thompson effect, so that the temperature and pressure of N2 reaching the run tank can be estimated. Each flow component is modeled as an adiabatic throttling valve, so that enthalpy is conserved across the valve.

```
function [p2,error,scfm] = flowcalc(p1,gpm1,t1,CV)
    error=0;
    G=.967; %specific gravity
    t1=t1+460;

    Q=(gpm1/7.48052)*60*(t1/(460+70))*((14.7+1000)/14.7);% flow rate in scfh
    scfm=Q/60;
    u=(G*t1*((Q/(CV*962))^2)-(p1^2));
    if u<0
        p2=-1*(-1*sqrt(abs((G*t1*((Q/(CV*962))^2)-(p1^2))))); %flow rate equation
↪   for noncritical
    else
        p2=-1*(sqrt(G*t1*((Q/(CV*962))^2)-(p1^2)));
    end

    if p2<0
        disp('too low cv for this flow rate')
        error=1;
    end
end

%flowscript
p1=3000;
n=input('input number of valves: ');
cvs=[];
for i=1:n
    cvs(i)=input('input number %5.1 cv: ');
end

t1=70;
pees=[];

gpm1=0;
p2=p1;
while p2>1500
    pu=p1;
    for i=1:n
        CV=cvs(i);

        [p2,error,scfm]=flowcalc(pu,gpm1,t1,CV);
        if error
            break;
        end
        pees(i)=p2;
        pu=p2;
```

```
    end
    gpm1=gpm1+.1;
end

disp(pees);
fprintf(['The flow rate is %5.2f gpm at %5.1f psi and %5.2f ' ...
    'degrees F which is %5.2f scfm'], gpm1, pees(n), t1, scfm)
```

4.4.6 Testing

The operation of this system will be tested in isolation of the rest of the fluid system to ensure correct flow rates.

4.5 Purge

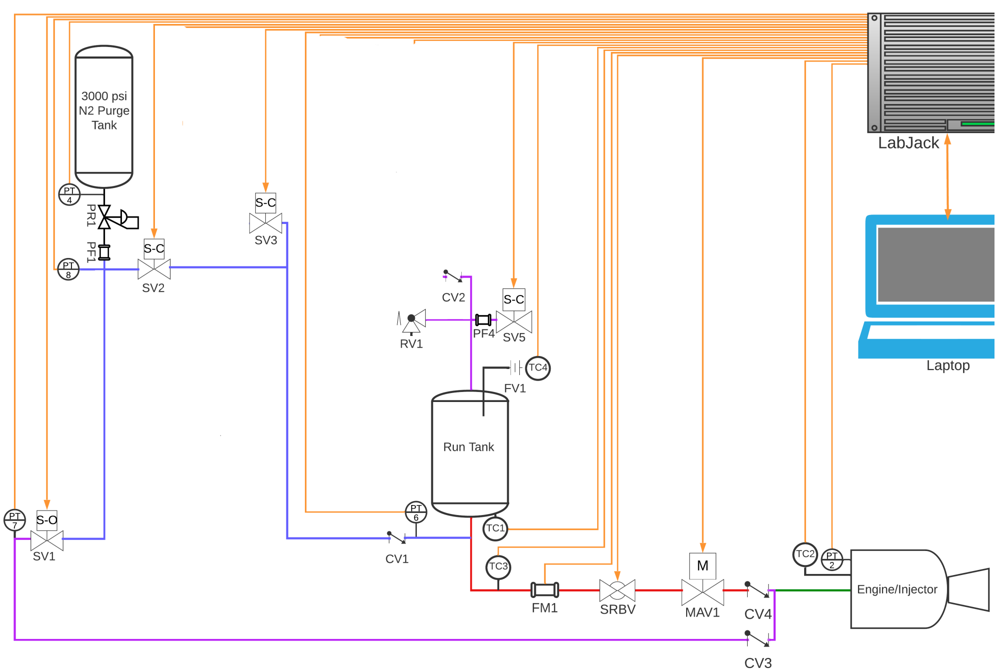


Figure 12: **Purge P&ID diagram**

4.5.1 System Function

1. Flush out water vapor from fill and hot side lines
2. Extinguish combustion post-firing
3. Clear out N2O from fluid system during shutdown procedure

4.5.2 Requirements

1. Wetted surfaces must be compatible with N2O
2. Yield pressure must be > 1.5 MEOP
3. N2 pressure must be adjustable

4.5.3 Design Choice Justification

(PR2) High Flow Regulator The regulator controls the purge pressure. It is used to change upstream purge pressure, which adjusts the N2 flow rate.

(PF1) 50 Micron Particulate Filter This in line particulate filter is used to protect the downstream solenoid valve from potential particulate contaminants.

(SV1) Solenoid Valve A direct acting solenoid valve was chosen, because there may be a negative pressure differential present at the valve.

(CV3) Check valve The check valve prevents back-flow from the feed lines into the purge system. This prevents a large quantity of N2O from accumulating in the purge line, which would defeat the purpose of the purge.

1/2" Stainless Steel tubing Larger diameter is required to maintain high N2 flow rates.

4.5.4 Analysis

This script determines what pressure to set the purge regulator for a desired flow rate

```
function p = regset(p2,t,cv,f)
    f=f/(7.48052/60); %convert gpm to cubic feet per hour
    f=f*((p2+14.7)/14.7); %convert from actual volumetric flow rate to standard
↪   (ACFM to SCFM)
    pt1=sqrt(((f/(962*cv))^2)*(.967*(t+460))+p2^2); % solve for upstream pressure
    p=pt1;
end

f=input('Enter the desired flowrate in gpm: ');
p2=input('Enter the pressure downstream: ');
%t=input('Enter the temperature : ');
t=70;
cv=input('Enter the CV : ');
regulatorset=regset(p2,t,cv,f);
fprintf('Set the regulator to %5.1f psi for %5.1f gpm flowrate', regulatorset, f)
```

4.5.5 Testing

The operation of this system will be tested without the run tank to ensure the proper operation of the solenoid valve.

4.6 Electronics

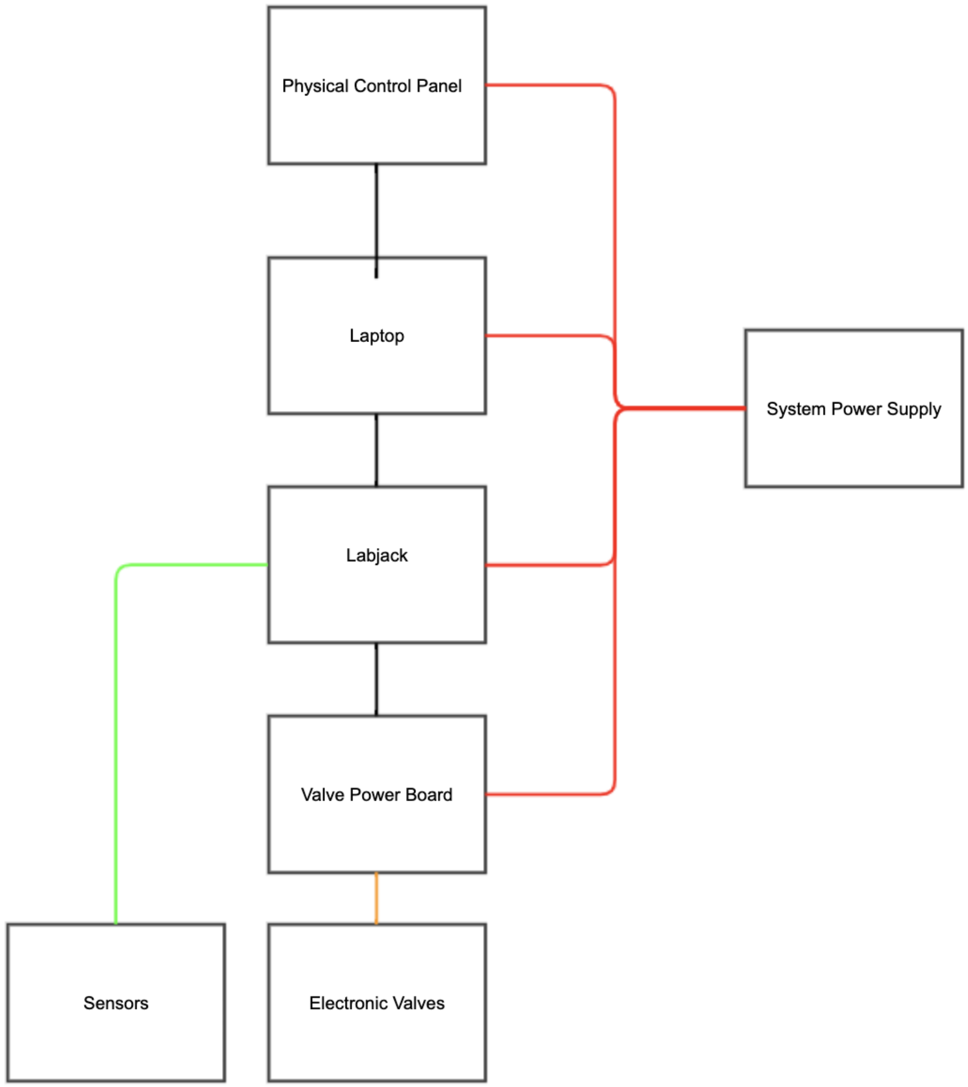


Figure 13: **Electronics Conceptual Diagram**

4.6.1 System Function

1. Read Sensor inputs,
2. Collect Data
3. Control Firing Procedure
4. Graphically display system status

4.6.2 Requirements

1. Emergency shutdown must be controlled by physical button

2. System must return to failsafe upon error/power loss
3. GUI must display current operating conditions: tank pressures, thrust, temperatures, supply voltage, valve positions, N2O vent status, potential faults

4.6.3 Design Choice Justification

Physical Control Panel A physical control panel is used to provide immediate control over the operation of the test stand

Labjack The labjack is required to host the fluid system operations firmware

5 Testing

The fluid system will be tested in the following sequence:

- Leak test
  - Pressurize the system to a low pressure, to determine if there are leaks
- Cold Flow test
  - Operate test stand as intended with CO2 in the minimum viable operational mode
  - Operate test stand with Supercharge System activated
  - Operate system as intended with N2O without firing the engine.
- Hot Fire
  - Conduct a full test of the system, including igniting and running the engine

PPE:

- Long Sleeved Clothes
- Close Toed Shoes
- Face Shield
- Hearing Protection
- Latex Gloves

Equipment:

- Torque wrench
- Cylinder Grabber

- Cylinder Dollies
- Laptop

Procedure:

- Safety Procedures
  - Mark off both sides of the area between the warehouse with yellow caution tape
  - All personnel shall stand behind wall in adjacent room, except for operator who will stand behind test 10 meters from test stand behind polycarbonate shield
    - The polycarbonate shield is a precaution to prevent any contact with cold vented gases and contain any debris
  - The test stand should only be approached when run tank pressures are below 20 PSI (14.7 is atmospheric)
    - In the event of electronics failure, the test stand may be approached after 45 minutes, or after venting out of dip tube is finished, whichever takes longer
- Preliminary procedures
  - Perform visual inspection of all systems to ensure there is no visible damage or loose connections
  - Using tank grips, lift CO2 cylinder onto load cell and secure with chain
  - Install purge and supercharge tanks
  - Ensure that the test stand is secured to the ground with sandbags or anchors
  - Ensure that there is proper ventilation, and that there is a 10ft radius clear area around the test stand
  - Power on system I & II electronics by flipping battery switch I & II
    - Ensure that all data readings are at nominal values
    - Actuate solenoid valves in order from 1-5, confirming that they are functioning
    - Actuate MAV1
    - Set spring return valve to open position then press emergency stop
    - SRBV should snap shut, ensuring failsafe functionality
    - Power OFF system II electronics by flipping battery switch II
  - Remove dust caps from fluid system connections
  - Connect tanks and torque CGA fittings to 35 ft-lbs
  - Enter ready mode
    - SV1 must be receiving power and in the closed position
  - Put on face shield, long sleeves, gloves
    - All observers must remain in a secured area

- Slowly open N2 purge tank, ensuring that there are no audible leaks.
  - Verify that N2 tank pressures are nominal
- Set purge regulator to 300 psi
  1. Turn regulator to adjust pressure
  2. Open SV1 for 0.25 seconds
  3. Repeat steps 1 and 2 until desired downstream (PT8) pressure is maintained
- Power ON system II electronics by flipping battery switch II
- Slowly open N2 Supercharge tank, ensuring that there are no audible leaks.
  - Verify that N2 Supercharge tank pressures are within expected bounds
- Set purge regulator to 1000 psi
  1. Hold SV5 open during purge setting
  2. Turn regulator to adjust pressure
  3. Open SV4 for 0.25 seconds
  4. Repeat steps 1 and 2 until desired downstream (PT1) pressure is maintained
- Power OFF system II electronics by flipping battery switch II
- Slowly open CO2 tank, ensuring that there are no leaks
  - Verify that CO2 tank pressures are nominal
- Retreat to a safe distance then power ON system II electronics by flipping battery switch II
- System is now ready to flow
- (FIRING) Run through the firing sequence, pausing between each stage to confirm normal operation
  - Purge tank and lines
  - Engine purge
  - CO2 (N2O) fill
  - Pre-fire Supercharging
  - Firing
  - Shutdown
- (SHUTDOWN) When pressures return to ambient, Power OFF system II electronics by flipping battery switch II

  - After run tank pressure reaches below 20 psi, Approach system, shut off all tanks, beginning with CO2 tank
  - Power off system
  - System is now completely shutdown
  - Inspect all components of the test stand
    * Inspect system and read results
    * If results satisfactory, test failure states
  - CO2(N2O) DUMP
    * Repeat preliminary procedures
    * Run through the firing sequence up until after N2O (CO2) fill
    * Perform N2O (CO2) dump paying close attention to temperatures
    * Perform shutdown procedure
  - (EMERGENCY STOP)
    * Run through normal testing procedure, but push red button to initiate emergency stop 2 seconds after MAV1 is opened

Results:

- Pressure and Temperature Data
- Load cell data
- How long does it take to fill run tank?
- How much CO2 is vented during the fill procedure?
- Leak test
  - Pressurize system to low pressure 100psi and check for leaks Ideal procedure: Replace orifice fitting with solid plug. Close all v

    Actual procedure followed:
  - Pressurize system to MEOP using N2

6 Supply Chain

Omega Sponsored Items: all delivered

1. Omega Turbine Flow meter SYS/FTB-105/FLSC-C1-LIQ
2. SAPC-RTD-4-100-A-80 RTD temperature sensors
3. PRTDCAP-1KA-2-P098-050-T-40 Vent temperature sensor

Marotta Ordered Items: all delivered

1. PLV-34 Solenoid Valve
2. Check Valve
3. MAV-524 Pilot Operated Solenoid Valve

Sponsorships

1. Marotta
2. Omega
3. Valworx
4. Titan

A Appendix

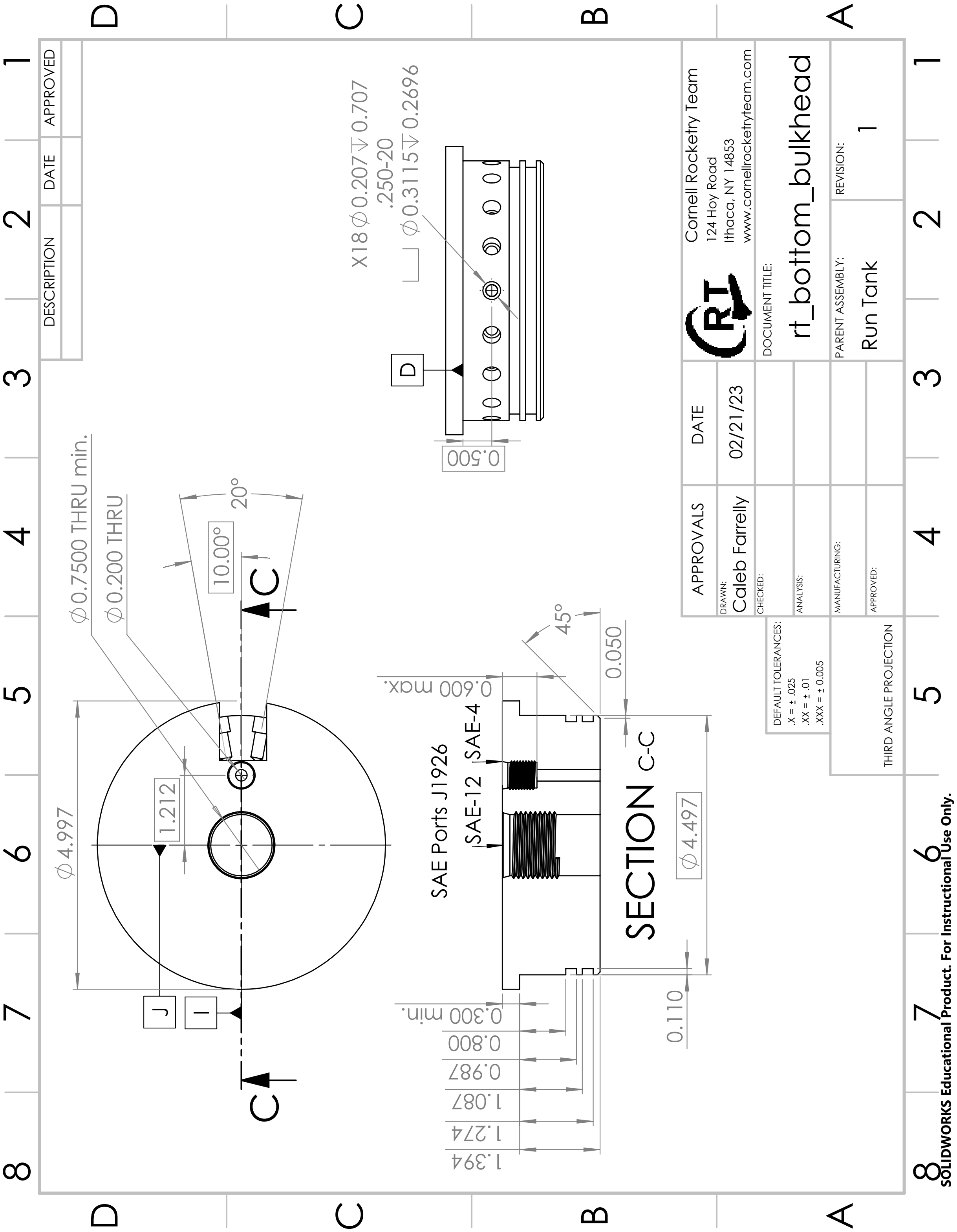


Figure 14: Run Tank Bottom Bulkhead Drawing

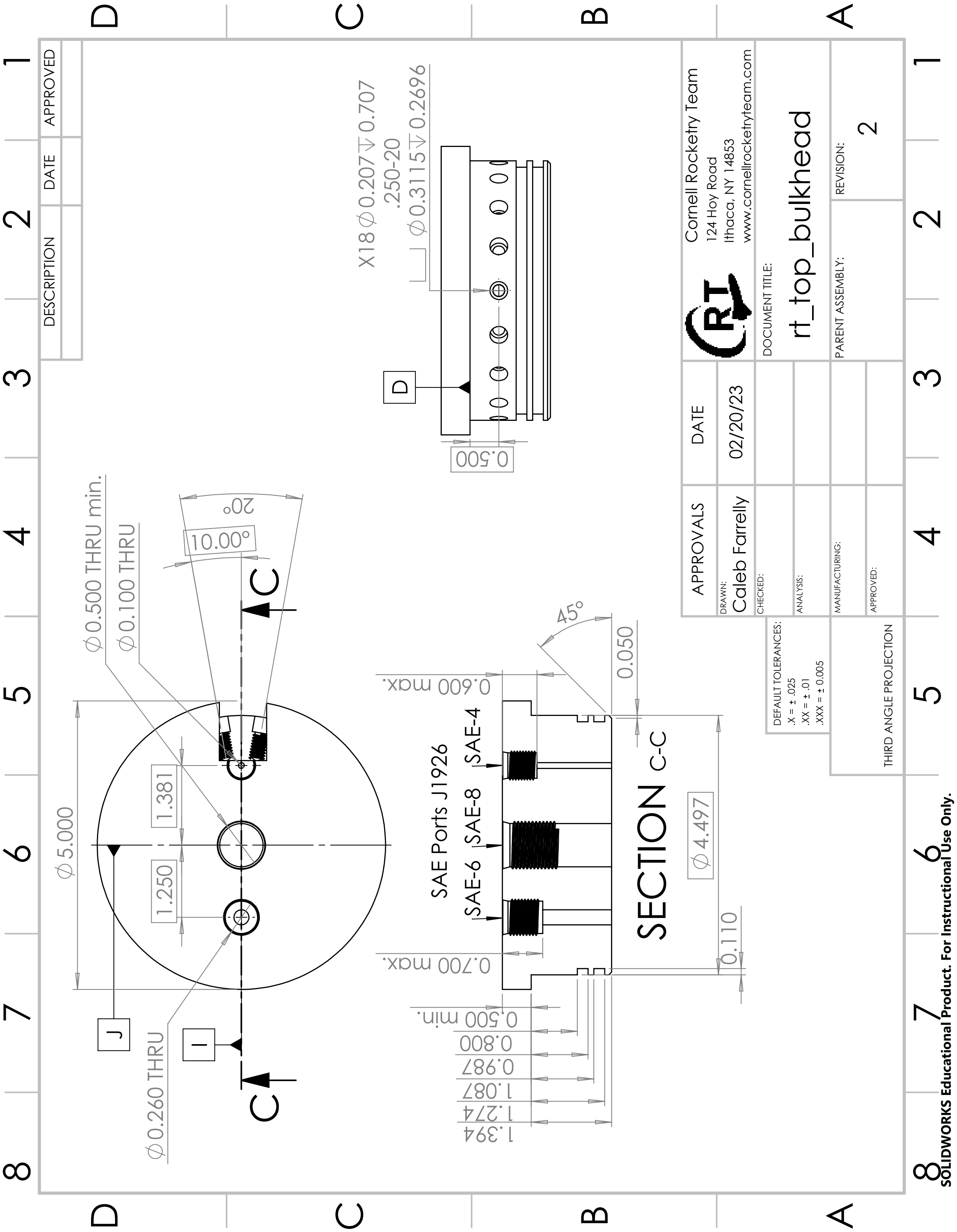


Figure 15: Run Tank Top Bulkhead Drawing

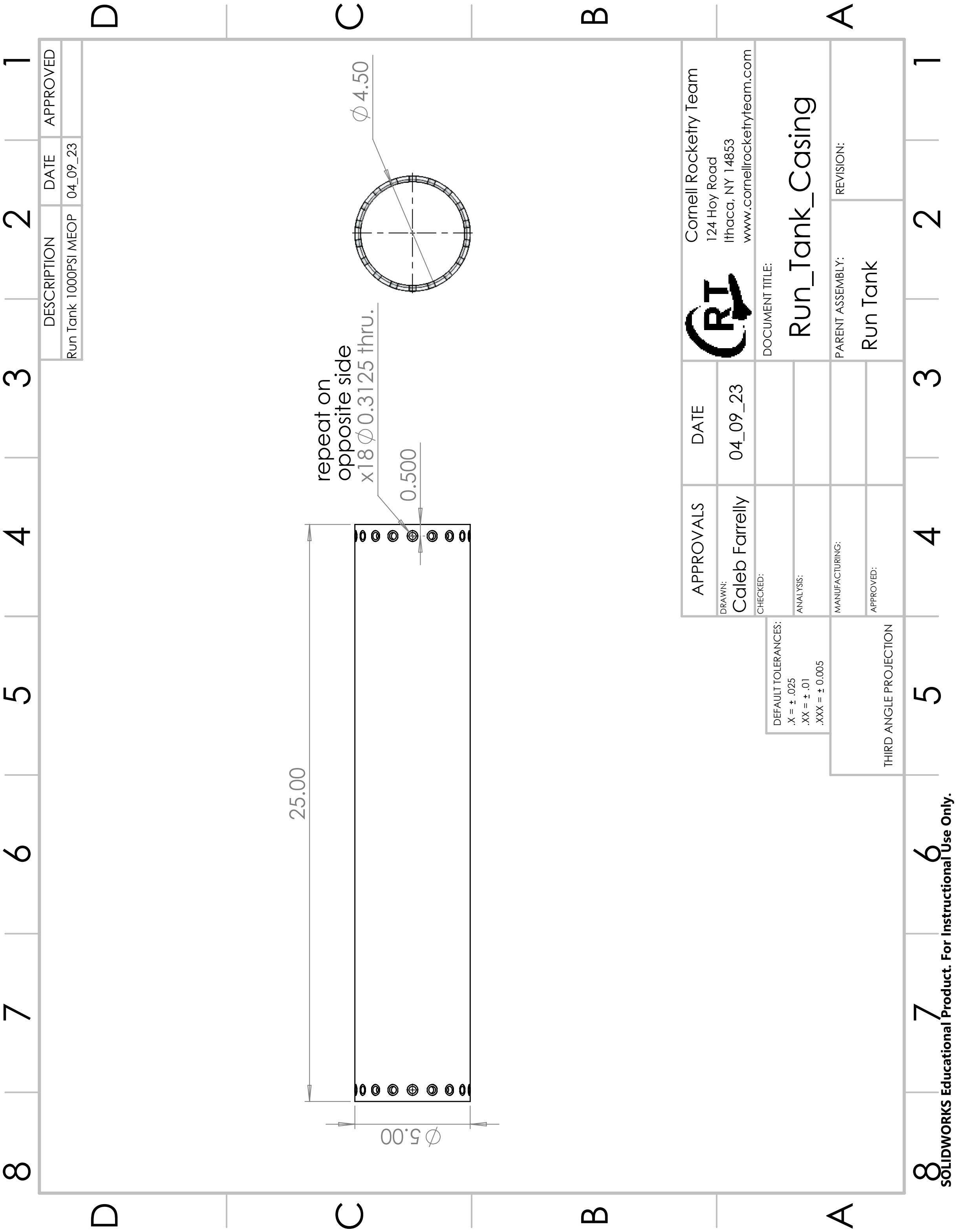
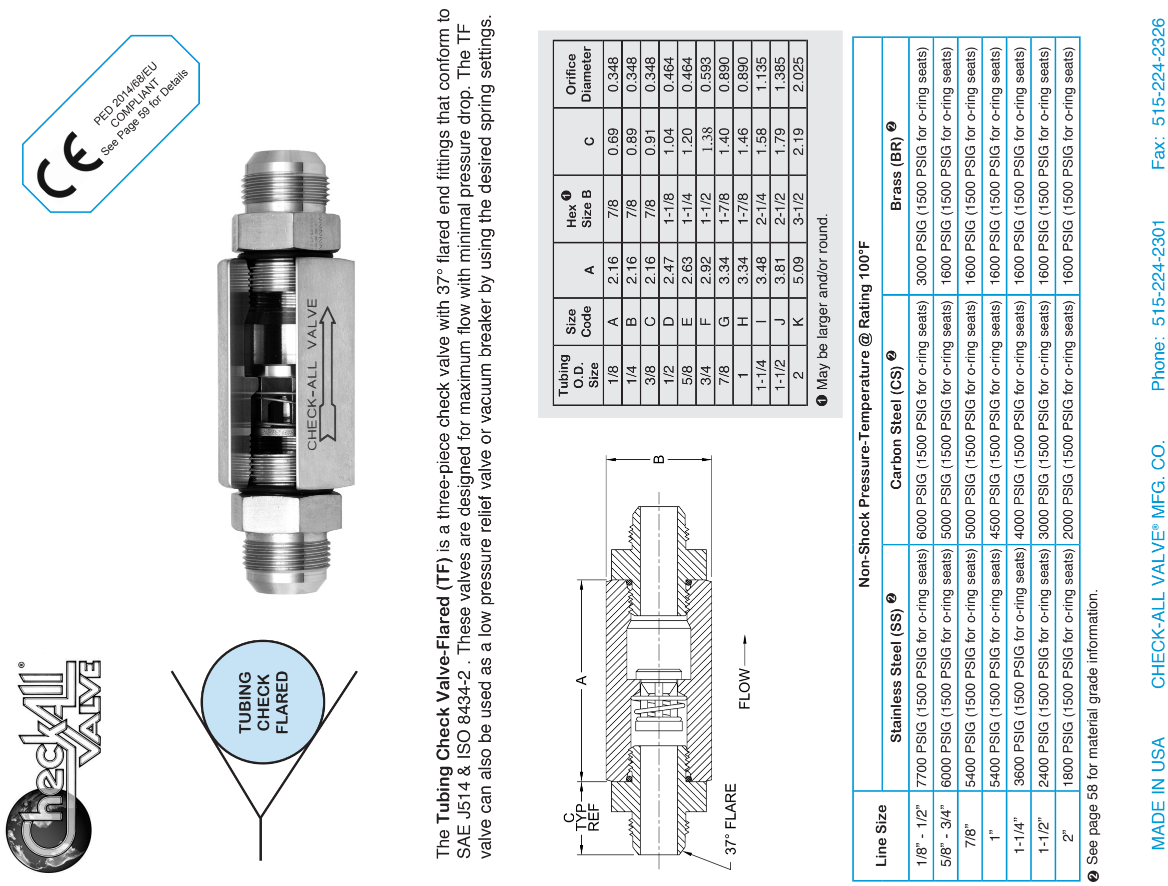


Figure 16: Run Tank Casing Drawing



TUBING CHECK FLARED

PED 2014/68/EU COMPLIANT See Page 59 for Details

The **Tubing Check Valve-Flared (TF)** is a three-piece check valve with 37° flared end fittings that conform to SAE J514 & ISO 8434-2 . These valves are designed for maximum flow with minimal pressure drop. The TF valve can also be used as a low pressure relief valve or vacuum breaker by using the desired spring settings.

Tubing O.D. Size	Size Code	A	Hex ❶ Size B	C	Orifice Diameter
1/8	A	2.16	7/8	0.69	0.348
1/4	B	2.16	7/8	0.89	0.348
3/8	C	2.16	7/8	0.91	0.348
1/2	D	2.47	1-1/8	1.04	0.464
5/8	E	2.63	1-1/4	1.20	0.464
3/4	F	2.92	1-1/2	1.38	0.593
7/8	G	3.34	1-7/8	1.40	0.890
1	H	3.34	1-7/8	1.46	0.890
1-1/4	I	3.48	2-1/4	1.58	1.135
1-1/2	J	3.81	2-1/2	1.79	1.385
2	K	5.09	3-1/2	2.19	2.025

❶ May be larger and/or round.

Line Size	Non-Shock Pressure-Temperature @ Rating 100°F		
	Stainless Steel (SS) ❷	Carbon Steel (CS) ❷	Brass (BR) ❷
1/8" - 1/2"	7700 PSIG (1500 PSIG for o-ring seats)	6000 PSIG (1500 PSIG for o-ring seats)	3000 PSIG (1500 PSIG for o-ring seats)
5/8" - 3/4"	6000 PSIG (1500 PSIG for o-ring seats)	5000 PSIG (1500 PSIG for o-ring seats)	1600 PSIG (1500 PSIG for o-ring seats)
7/8"	5400 PSIG (1500 PSIG for o-ring seats)	5000 PSIG (1500 PSIG for o-ring seats)	1600 PSIG (1500 PSIG for o-ring seats)
1"	5400 PSIG (1500 PSIG for o-ring seats)	4500 PSIG (1500 PSIG for o-ring seats)	1600 PSIG (1500 PSIG for o-ring seats)
1-1/4"	3600 PSIG (1500 PSIG for o-ring seats)	4000 PSIG (1500 PSIG for o-ring seats)	1600 PSIG (1500 PSIG for o-ring seats)
1-1/2"	2400 PSIG (1500 PSIG for o-ring seats)	3000 PSIG (1500 PSIG for o-ring seats)	1600 PSIG (1500 PSIG for o-ring seats)
2"	1800 PSIG (1500 PSIG for o-ring seats)	2000 PSIG (1500 PSIG for o-ring seats)	1600 PSIG (1500 PSIG for o-ring seats)

❷ See page 58 for material grade information.

MADE IN USA CHECK-ALL VALVE® MFG. CO. Phone: 515-224-2301 Fax: 515-224-2326

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Figure 17: Check Valve Catalog

References

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