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Technical Report

Deepti Kousik [DJK298]
Cornell Rocketry Team
Liquid Fluid Systems
Propulsion

Cornell University
Sibley School of Mechanical and Aerospace Engineering
124 Hoy Road
Ithaca, NY 14850

INTERNATIONAL ROCKET ENGINEERING COMPETITION

1 Nomenclature

- **APG** - Analog Pressure Gauge
- **COPV** - Composite Overwrapped Pressure Vessel
- **CV** - Check Valve
- **Cv** - Coefficient of Flow
- **E-Reg** - Electronic Pressure Regulator
- **FOD** - Foreign Object Debris
- **HP** - Hand Pump
- **LC** - Load Cell
- **LV** - Launch Vehicle
- **MV** - Manual Valve
- **MFM** - Mass Flow Meter
- **MAV** - Mechanically Actuated Valve
- **OF Ratio** - Oxidizer-Fuel Ratio
- **P&ID** - Piping and Instrumentation Diagram
- **PF** - Pressure Filter
- **PR** - Pressure Regulator
- **PRV** - Pressure Release Valve
- **PT** - Pressure Transducer
- **SV** - Solenoid Valve
- **SS** - Stainless Steel
- **TC** - Thermocouple
- **TCA** - Thrust Chamber Assembly

2 System Overview

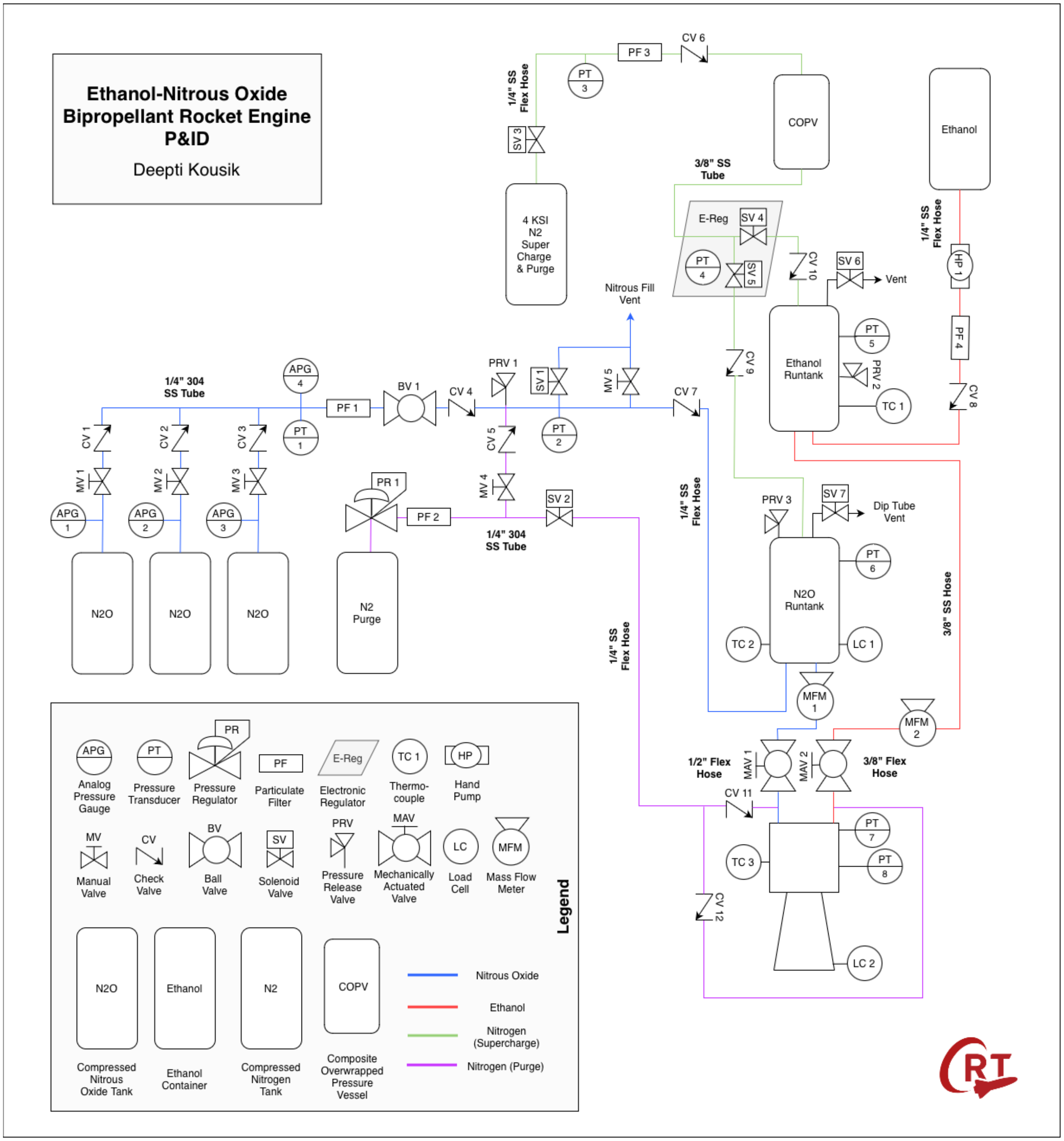


Figure 1: **System Diagram**

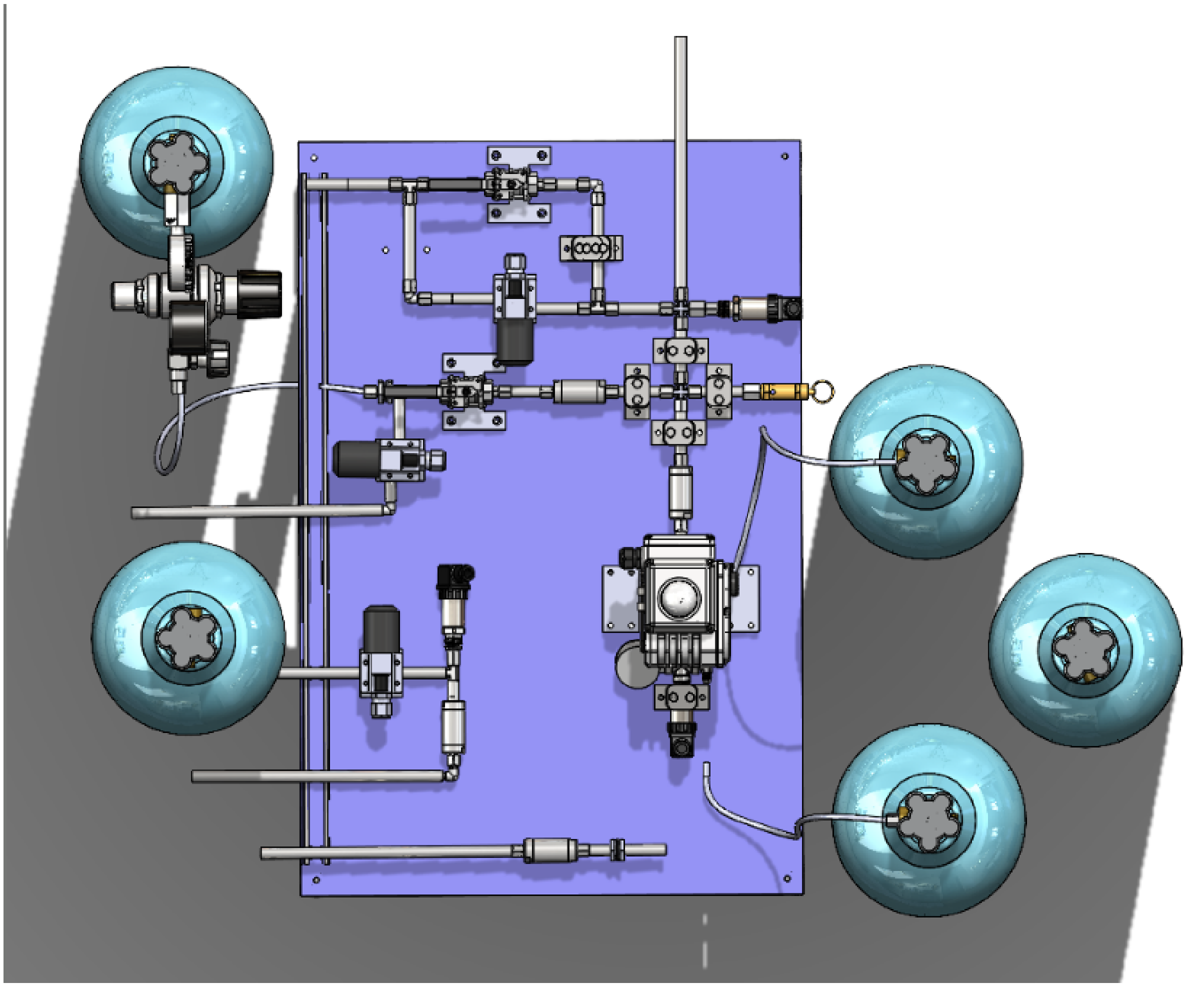


Figure 2: **Fill Station CAD**

2.1 System Purpose

The primary function of the liquid fluid systems are to deliver oxidizer (Nitrous Oxide) and fuel (Ethanol) to the TCA. This system shall involve filling a COPV, Oxidizer Tank, and Fuel Tank. The system involves multiple subsystems that aid in filling, purging, and more to ultimately create combustion in the TCA and create thrust. Additionally, this system seeks to enable the functions of a liquid bipropellant rocket while preserving the fill station's ability to fill Nitrous Oxide for hybrid procedures.

2.1.1 Parents & Partners

- Liquid Launch Vehicle (in the future)
- Liquid Test Stand
- Fill Station
- Liquid TCA

2.1.2 Subsystems

- Nitrous Oxide Fill
- Ethanol Fill
- Nitrogen Purge
- Nitrous Oxide & Ethanol Supercharge
- Electronic Pressure Regulator
- Ethanol Fuel Tank
- Nitrous Oxide Run Tank
- Ethanol MAV
- Nitrous Oxide MAV
- Liquid Quick Disconnects

2.2 Competition Requirements

- 5.2.3.1: A liquid engine is an engine designed with stored fuel and stored oxidizer in the liquid state.
- 5.2.3.2: All liquid propellants must be non-toxic as defined in Section 5.3.
- 5.2.3.3: All liquid engines shall be static fired, well characterized, and tested as per section 5.16.
- 5.10.1: Hybrid and liquid propulsion systems shall implement a means for remotely controlled venting or offloading of all liquid and gaseous propellants.

2.3 Internal Requirements

- Ethanol & Nitrous Oxide must have separate purges
- Ethanol & Nitrous Oxide must never mix until the TCA
- System shall be capable of remote operation
- Pressurized system shall not require personnel intervention in event of failure
- System shall be capable of delivering 2.5788 kg/s Nitrous Oxide to injector
- System shall be capable of delivering an OF Ratio of 3.8

2.4 Primary Functions

2.4.1 Nitrous Oxide & Ethanol Fill

One of the main purposes of this system is to fill the run tank and the fuel tank. The Nitrous Oxide fill system remains very similar to the hybrid fill system and utilizes the same valves. This involves a motorized ball valve, a way to vent the fill lines, and ideally the quick-disconnect to mimic flight architecture as closely as possible. The primary difference is that the Nitrous Oxide will be supercharged (next section), which means it will be filled at a much lower pressure than in hybrid. Ethanol will be filled from a large container and pumped into the fuel tank using a hand pump in order to maintain precise fill.

2.4.2 Nitrogen Purge

The purge lines serve as a method to purge the system using Nitrogen, effectively helping to cleanse and remove FOD. This is also crucial to ending hot-fires. The Nitrogen lines must have the capability to purge the Nitrous Oxide lines, run tank, fuel tank, MAVs, and TCA. Thus, there is a valve on the fill station allowing for the purge of the Nitrogen lines and subsequently the quick disconnect. The Nitrogen supercharge lines are connected to the run tank and fuel tank, and so the supercharge lines can double as purge for those as needed. Finally, a line connects a Nitrogen compressed gas cylinder to the TCA, allowing for easy purge at the end of tests

2.4.3 Supercharge

We are choosing to supercharge both our Nitrous and our Ethanol. Supercharge simply refers to pressurizing an inert substance (such as Ethanol, which will be at atmospheric pressure) using another fluid at a high pressure. In this case, a 4 ksi compressed gas cylinder of Nitrogen will fill a COPV to 3 ksi and this will then be regulated down using the E-Reg to pressurize the run tank and fuel tank each to 1000 psi. Nitrous Oxide is self pressurizing, which is how we currently pressurize it for hybrid, but supercharging will allow us more optimal blowdown curves and reduce the risk of decomposition. It will also ideally make fill more reliable and controllable, allowing for repeatable effective procedures.

3 Design

3.1 Design Considerations

The design choices were made based on the following:

3.1.1 Safety

Safety is the number one priority when designing. Flying a liquid bipropellant rocket is an ambitious undertaking for CRT and testing should be approached in the safest way possible. All of the SRAD subsystems will be designed with large factors of safety as they are intended for testing, failure mode effect analysis has been done, and normal states of all valves are communicated with Electrical and Software to ensure that in the event of a failure all consequences are minimized.

3.1.2 LV Architecture

The main purpose of these fluid systems are to be used with the liquid test stand, which will facilitate hot-fires and cold flows. Despite this, and to minimize integration challenges later on, this design aims to mimic the flight architecture as closely as possible. This way, issues are caught onto early in the process and we characterize the fluids' behavior as it would behave in a flight configuration.

3.1.3 Efficiency

It also important to consider the bandwidth available on a student collegiate team and design with realistic deliverables. There is no reason to make a design needlessly complex, but it should still be a reliable system. Many of these subsystems can grow in the future as CRT continues to grow and shift goals.

3.2 Ethanol Fill Trade Study

There are several ways to fill Ethanol: simply pouring it in, using a pump, or using a valve (this could be a needle valve, a manual valve, etc.). These methods are summarized below:

Pouring in:

- Simple
- Easy
- No purge required
- Can fill precisely
- Can contain contaminants
- Must fill prior to assembly, or create a fill opening
- Lots of risks if not filling on the pad

Pump:

- Allows for fill while fully assembled
- Reliable and precise fill levels
- Increases complexity

Valve:

- Allows for fill while fully assembled
- Could potentially control from far away (although this is currently unnecessary)
- Purge likely required
- Overly complex

Based on this comparison, the decision to use a pump was made, balancing complexity with accuracy. Using a valve adds unnecessary complexity to the system, but simply pouring the ethanol in could have a lot of different negative effects in practice. Thus, a simple hand pump will be used to ensure a thorough procedure for fill that is not overbuilt.

3.3 Ethanol Line Trade Study

There are 2 main options when looking to create a line from the fuel tank to the Ethanol MAV. The line can either run outside of the Nitrous Oxide run tank, or it can go through the run tank in some sort of through-hose. A hose through the run tank adds benefits of being more compact and easier to integrate with an LV. However, this is dangerous and could be catastrophic if there are any leaks. Additionally, with CRT's current bulkhead design, it can be difficult to ensure the bulkheads are completely aligned once torqued. Running piping outside of the run tank is significantly more safe, but will inevitably lead to complications down the line as the tubing outside of the tank is not ideal in an LV configuration. Due to this being CRT's first time attempting liquid and the primary focus of this design on fluid systems for testing purposes, we chose to run rigid tubing outside of the run tank. The tubing has a diameter of 3/8" (justification for diameters is provided later), and thus will not be detrimental to LV integration in the future. Additionally, there is a possibility of adding a pass-through in the future, but we are prioritizing safety with this iteration of the design.

3.3.1 Supercharge Pressurant

There are two main pressurants one could choose to supercharge this system - Nitrogen and Helium. Helium is industry standard and has a lower molecular weight, meaning we would use a smaller mass of Helium, but it is also very expensive and can tend to be leaky. Nitrogen does have a higher molecular weight, but we have previously characterized its behavior as we use it in our hybrid systems and it is much cheaper than Helium. Therefore, for the first iteration of our liquid design, we are using Nitrogen as it is inexpensive, which is optimal for rigorous testing, and we are more familiar with its behavior.

4 Calculations

4.1 Ethanol & Nitrous Oxide

There are a few numbers provided by Caleb Farrelly's Senior Design Report that specify requirements of the TCA:

- Nitrous Oxide Mass Flow Rate - 2.57 kg/s
- Ethanol Mass Flow Rate - 0.86 kg/s
- OF Ratio - 3.8

The maximum length the run tank can be is 46 inches, so this is the limiting variable in calculations to determine the mass and volume of Ethanol needed. We assume the thickness of the run tank is 1/4″, the diameter is 6″, the density used is at boiling point, and 10% of the tank is left as ullage. The following can be done:

$$V = l \cdot \pi \cdot (r - t)^2 \tag{1}$$

This gives a volume of 17.8 L possible in the run tank, 10% of which will be ullage. Thus, about 16 L of Nitrous Oxide will be used. This is equivalent to 24 kg, and using the mass flow rate given of 2.57 kg/s, the max burn time can be determined to be 9.35 seconds. This number will be rounded up to 10 for the sake of safety and scaling.

Next, similar equations can be applied to find the volume/mass of Ethanol used.

$$m = \dot{m} \cdot t \tag{2}$$

$$V = l \cdot \pi \cdot (r - t)^2 \tag{3}$$

The thickness is assumed to be 3/8″ (although it has been changed to 1/4″ now), giving a mass of about 8.5 kg. This is equivalent to 11 L, and the total volume of the fuel tank will be 12 L, which means it will need to be around 0.874 meters or 34 inches long.

4.2 COPV

These calculations are helpful in determining the sizing of the COPV. The orifices attached to the COPV will be decided by the owner of the E-Reg. A Matlab script is currently in development to simulate blowdown and give a more specific estimate of the volume of the COPV. For the time being, the volume was calculated by comparing all of CRT's values to Imperial College London, who are a well respected collegiate rocketry team that have successfully flown a bipropellant liquid rocket. Comparing our burn time, mass used, and volume used, we can discern that we should use around 2x the amount of Nitrogen as they do, which yields 6L of Nitrogen for supercharge.

4.3 Losses Across Piping

Whenever fluid travels through a pipe, there are losses due to the frictional force at the viscous boundary layer. Most of the time, these losses are negligible in this system as Ethanol and Nitrous Oxide are being pressurized to very high pressures. However, these losses can be non-negligible at small diameters and long distances of piping, which could be detrimental. Calculations were done to size diameters and check the change in pressure across lines, especially those going from the tanks to the MAVs. The following equations for Reynolds Number, flow rate, velocity, and change in pressure were used:

$$\dot{m} = 0.86 \text{ kg/s}$$

$$L = 55 \text{ in} \quad (\text{Run tank is } \sim 46 \text{ in}) \approx 1.4 \text{ m}$$

$$T = 30°\text{C}$$

$$\rho = 781 \text{ kg/m}^3$$

$$\mu = 0.001074 \text{ kg/(m}\cdot\text{s)}$$

$$\Delta P = f \frac{L}{D} \frac{\rho v^2}{2}$$

$$\text{Re} = \frac{\rho v D}{\mu}$$

$$f = \frac{64}{\text{Re}}$$

$$v = \frac{4Q}{\pi D^2}$$

$$Q = \frac{\dot{m}}{\rho}$$

$$\Delta P = \frac{64\mu}{\rho v D} \frac{L}{D} \frac{\rho v^2}{2}$$

$$\Delta P = \frac{64\mu L v}{2D^2}$$

$$\Delta P = \frac{64\mu L}{2D^2} \left(\frac{4Q}{\pi D^2} \right)$$

$$\Delta P = \frac{128\mu L \dot{m}}{\pi D^4 \rho}$$

$$\Delta P = \frac{128(0.001074)(1.4)(0.86)}{\pi D^4(781)}$$

$$\Delta P = \frac{0.000692}{D^4}$$

$$D = \frac{1}{4}'' \quad \Rightarrow \quad \Delta P = 62 \text{ psi}$$

$$D = \frac{3}{8}'' \quad \Rightarrow \quad \Delta P = 12 \text{ psi}$$

$$D = \frac{1}{2}'' \quad \Rightarrow \quad \Delta P = 4 \text{ psi}$$

These equations were used to estimate losses of 12 psi for the Ethanol tubing running along the outside of the run tank when using a 3/8" diameter stainless steel tube. This is the smallest the diameter could be sized without experiencing larger pressure losses - the next standard size, 1/4", yielded a pressure drop of about 62 psi.

4.4 Nitrogen Fill

Finally, many calculations were done to characterize filling a COPV with Nitrogen. The first decision was whether to fill with a compressed gas cylinder of 3 ksi or 4 ksi. The pressure in the COPV must be more than 2 times the downstream pressure (1000 psi) to maintain choked flow, so the COPV must be able to fill to 2000 psi in both cold and hot conditions. This is an important distinction, as testing is done in the freezing cold in Ithaca while competition is typically in a desert in the summer. Filling the COPV also needs to take long enough that we can fill to a precise pressure as there is no PR that fulfills our requirements, so it is our responsibility to regulate the pressure we fill to manually. It also cannot take too long to reach a high enough pressure, or it will result in testing delays.

I used the following equation for gaseous subsonic flow to estimate the equalized pressure between the COPV and 3 ksi vs 4 ksi compressed gas cylinders at cold and hot temperatures. This maintains the assumption that the transfer is isothermal, which is idealized but reasonable enough to get an accurate estimation.

4000 PSI Tank:

$$\frac{(4000 \text{ psi})V}{293 \text{ K}} = \frac{(147)(703296)}{288.7 \text{ K}}$$

$$V = 43 \text{ L}$$

$$P_{\text{eq}} = \frac{P_1V_1 + P_2V_2}{V_1 + V_2}$$

$$P_{\text{eq}} = \frac{(4014.7)(43) + (14.7)(6)}{49}$$

$$P_{\text{eq}} = 3525 \text{ psi}$$

4000 PSI - Cold Temperature:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$\frac{4000}{293} = \frac{P}{260}$$

$$P = 3549 \text{ psi}$$

$$P_{\text{eq}} = \frac{(3563.7)(43) + (14.7)(6)}{49}$$

$$P_{\text{eq}} = 3129 \text{ psi}$$

3000 PSI Tank:

$$P_{\text{eq}} = \frac{P_1 V_1 + P_2 V_2}{V_1 + V_2}$$

$$P_{\text{eq}} = \frac{(3014.7)(43) + (14.7)(6)}{49}$$

$$P_{\text{eq}} = 2647.4 \text{ psi}$$

3000 PSI - Cold Temperature:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

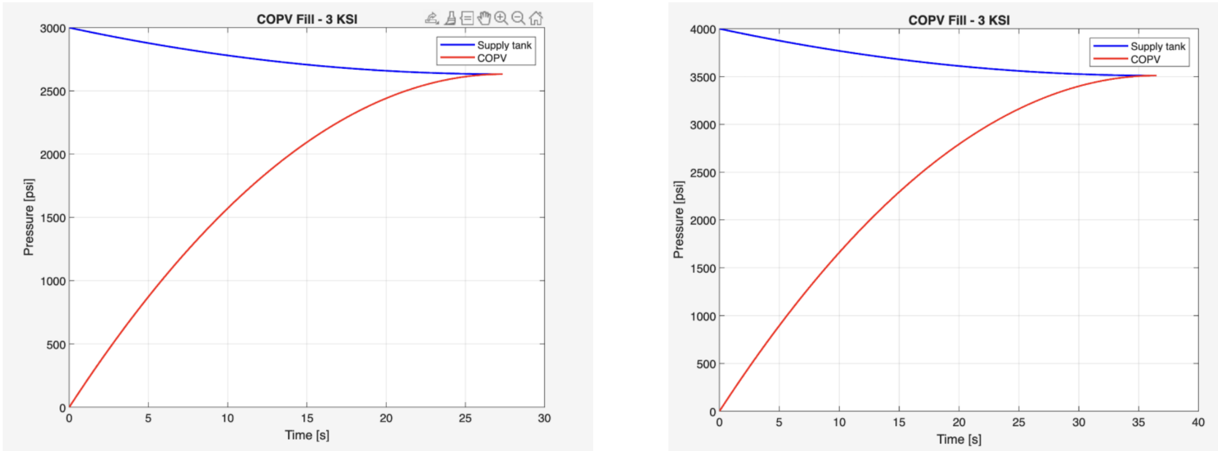
$$\frac{3000}{293} = \frac{P}{260}$$

$$P = 2662 \text{ psi}$$

$$P_{\text{eq}} = \frac{(2662 + 14.7)(43) + (14.7)(6)}{49}$$

$$P_{\text{eq}} = 2351 \text{ psi}$$

I also created a Matlab script to simulate filling the COPV with Nitrogen to check my calculations and estimate the time it would take for the pressure to equalize. I modeled this using the Cv of components selected to make the simulation as realistic as possible to what the actual restrictions on the flow would be. The results are shown below, first comparing 3 ksi vs 4 ksi tanks, and then showing the system with all of the component specifications.



Equalizes at t = 27.35s
P = 2,632.7 psi

Equalizes at t = 34.68s
P = 3,510.2 psi
Reached 3,000 psi at t = 22.6s

Figure 3: **3 ksi vs 4 ksi Fill**

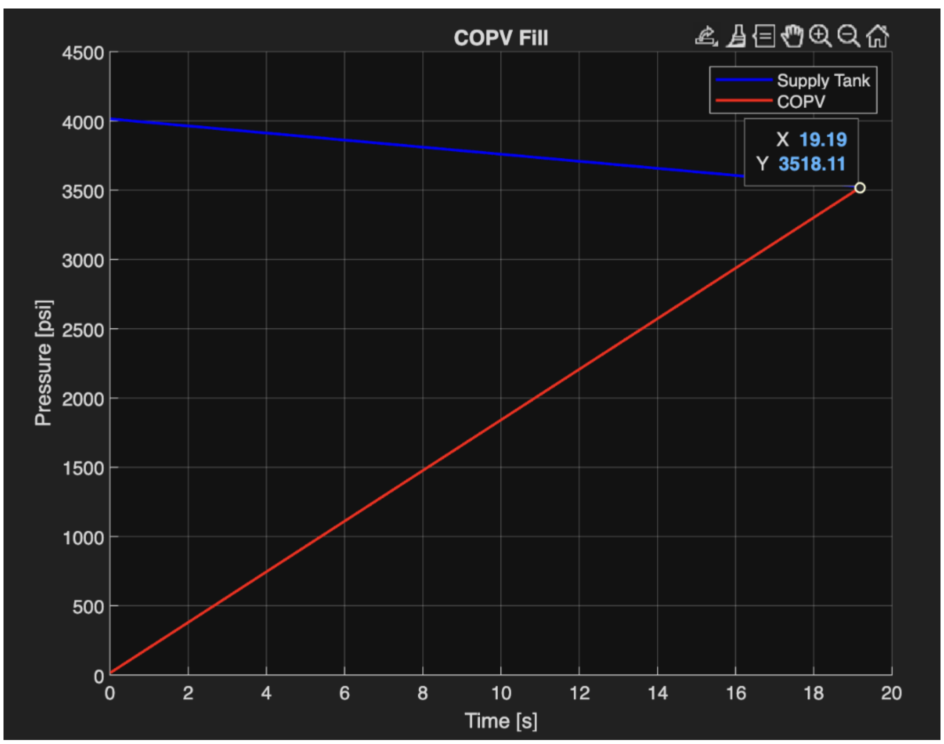


Figure 4: **Final Fill Characterization - 4 ksi**

Based off of this, I chose to proceed with a 4 ksi compressed gas cylinder of Nitrogen. This will reasonably fill within a minute and can achieve a pressure of >3000 psi in the COPV, which gives flexibility with supercharge.

5 Components

Shown below are the components selected for these systems. Their titles in the table correspond to their titles in the original P&ID.

Table 1: Liquid System Components

Component	Description	Link	Pressure Rating	Temp. Rating	Cv (Flow)	Connect. Type	Price
SV 2	Marotta MV74LT	Link	3,000 psi	-65°F - 140°F	0.145	–	Sponsored!
SV 3	MV130	Link	6,000 psi	–	0.596	–	Sponsored!
SV 4	E-Reg (Up to Verena)	–	–	–	–	–	–
SV 5	E-Reg (Up to Verena)	–	–	–	–	–	–
SV 6	Marotta MV74LT	Link	3,000 psi	-65°F - 140°F	0.145	–	Sponsored!
CV 6	3/8″ N_2 Supercharge Check Valve	Link	7,700 psi	100°F	1.6	-6 AN	$300
CV 8	1/4″ Ethanol Check Valve	Link	7,700 psi	100°F	0.7	-4 AN	$300
CV 9	1/4″ N_2 Supercharge Check Valve	Link	7,700 psi	100°F	0.7	-4 AN	$300
CV 10	1/4″ N_2 Supercharge Check Valve	Link	7,700 psi	100°F	0.7	-4 AN	$300
CV 11	1/4″ N_2 Purge Check Valve	Link	7,700 psi	100°F	0.7	-4 AN	$300
CV 12	1/4″ N_2 Purge Check Valve	Link	7,700 psi	100°F	0.7	-4 AN	$300
PT 3	4000# G2 Pressure Transducer	Link	4,000 psi	–	–	1/4″ NPT	$150
PT 4	4000# G2 Pressure Transducer	Link	4,000 psi	–	–	1/4″ NPT	$150
PT 5	1500# G2 Pressure Transducer	Link	1,500 psi	–	–	1/4″ NPT	$150
PT 6	1500# G2 Pressure Transducer	Link	1,500 psi	–	–	1/4″ NPT	$150
PT 7	1500# G2 Pressure Transducer	Link	1,500 psi	–	–	1/4″ NPT	$150

Component	Description	Link	Pressure Rating	Temperature Rating	Cv / Flow	Connect. Type	Price
PT 8	1500# G2 Pressure Transducer	Link	1,500 psi	–	–	1/4″ NPT	$150
TC 1	Thermocouple	Link	–	-50°C to 250°C	–	1/4″ NPT	$152.09
TC 2	Thermocouple	Link	–	-50°C to 250°C	–	1/4″ NPT	$152.09
TC 3	Thermocouple	Link	–	-50°C to 250°C	–	1/4″ NPT	$152.09
TC Fitting	Threaded Thermocouple Fitting	Link	–	–	–	1/4″ NPT	$13.88
HP 1	Non-drip Hand Pump	Link	–	35°F to 110°F	–	2 NPT	$381.96
PF 3	1/4″ In-line Particulate Filter	Link	6,000 psi	-320°F to 600°F	150 SCFM	-4 AN	$274
PF 4	1/4″ In-line Particulate Filter	Link	6,000 psi	-320°F to 600°F	150 SCFM	-4 AN	$274
PRV 2	Model 30 Pressure Relief Valve	Link	60–4000 psi	-20°F to 300°F	–	1/4″ NPT	$210.46
						TOTAL	**$5,012.75**

6 Failure Analysis

Most of the failures associated with this system result in rupture, unintended combustion, and extreme damages. The following failure modes were identified: leaks, improper sealing, nitrous oxide decomposition, blockages, contaminations, valve failures, and backflow. This is not an exhaustive list, but gives a good idea of what challenges the system can face.

To avoid these, intensive cleaning procedures will be implemented and be verified through leak checks, integration tests, and integrated cold flows. This will help to verify that there is not debris in the system, all of the valves can be electronically actuated successfully, and catch issues before we move to hot-fire tests. Sealing procedures involving PTFE tape and SECO seals, PRVs, and check valves will all als be used to mitigate the chances of failure.

References

[1] Aerospace Fluid Component Designers Handbook Volume 1

[2] Huzel, Dieter K. Huang, David H. - Modern Engineering for Design of Liquid-Propellant Rocket Engines-American Institute of Aeronautics and Astronautics, 1992

[3] University of Waterloo Project Report, 2024

[4] Imperial College London, Team 12 Technical Report to the 2024 EuRoC, 2024

[5] Youngblood, Stewart H. Design and Testing of a Liquid Nitrous Oxide and Ethanol Fueled Rocket Engine

[6] Farrelly, Caleb. Spring 2025 Masters Design Report, 2025

[7] Dizinno et al. Design of a High Pressure Fluid System For a Bipropellant Liquid Rocket Engine, 2024

[8] Rennels, Donald C. and Hobart M. Hudson - Pipe Flow, A Practical and Comprehensive Guide-Wiley, AICHE, 2012