Design and Validation of the Fluids System for a Regulated Pressure-Fed Liquid Rocket Engine Test Stand

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Tartarus, the liquid rocketry project of the Space Hardware Club at UAH, has completed the design and started the fabrication of a bipropellant liquid rocket engine test stand. The test stand uses a pressure-fed, regulated cycle housed within a trailer for quick setup times. The system is split between three main subsystems: the ethanol fluids cabinet which stores and transports ethanol to the test article engine, the liquid oxygen cabinet which stores and transports liquid oxygen to the test article engine, and the engine thrust stand which sits outside of the fluids trailer where the engine is mounted and tested. The system also houses a gaseous nitrogen purge system to cleanse the ethanol and liquid oxygen run lines. The test stand has been designed to perform hotfire tests of the team's "Prometheus" engine and any future test articles created by the team. To perform this task, the system is rated to a maximum allowable working pressure (MAWP) of 1000 PSI. In addition, the engine thrust stand is rated to 1000 pounds of force (IBF) with a safety factor of 3. The up-and-coming test of the "Prometheus" engine operates the run lines for the ethanol and liquid oxygen at a pressure of 400 PSI with a pressure-fed pressure of 700 PSI with the engine producing an estimated thrust of 280 LBF. The system design and specifications will be verified with a water flow test as well as a cryogenic cold flow test with liquid nitrogen for the liquid oxygen run line. Further details on subcomponent design and pressure calculations will be covered in the paper.

I. Introduction

Tartarus is a student-led Liquid rocketry team at the University of Alabama in Huntsville with the current goal of becoming the first student team on campus to build and fire a liquid rocket engine. Starting off with a small scale LOx-ethanol pressure-fed engine known as Prometheus, the team will then move on the developing engine which can produce the thrust to weight ratio required for flight along with a variety of other technology demonstrations such as thrust vector control, different methods of chamber cooling, propellant injector designs, and in-house manufactured propellant tanks.

II. Design Constraints

The system must be able to accommodate the current scope of the Prometheus engine test campaign as well as be suited to accommodate future testing regimes with as little modification to the current design as possible, including components which can be used through a variety of conditions. The structural components of the system should be rated to test an engine of 1000 pounds of force. All

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equipment and components used for testing must be able to be transported to the testing location with the trailer currently used by Tartarus. The test stand, as well as other support equipment, should be able to be set up for a hot fire as well as other tests within a few hours of arriving at the test location. The pressure of both propellants entering the injector is set to 350 PSI. this

III. System Overview

The engine test stand designed by Tartarus, named the Mobile Test Stand, is split between five subsystems: the ethanol fluids cabinet, the LOx fluids cabinet, the engine thrust structure, the nitrogen purge system, and the muscle pressure system. Each subsystem is mounted on a series of panels which themselves are mounted onto two cabinets located in the trailer for both transport and testing operations. The entire system operates with a maximum allowable working pressure of 1000 PSI. The run lines for the propellants are ½" tubing which reduces to ¼" right before entering the injector. Every other subsystem uses ¼" lines as well. The muscle pressure system and the purge system are mounted to a panel on the back of the ethanol and LOx cabinet respectively. The engine thrust stand is beyond the subject of this paper.

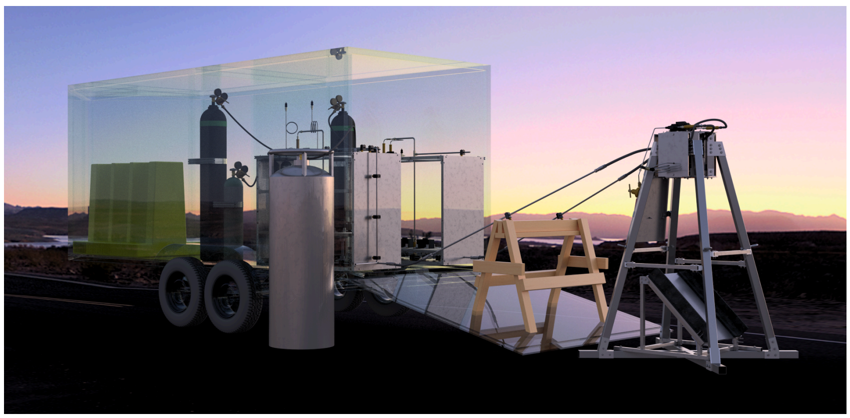

Fig. 1 CAD Model of the Mobile Test Stand with Transparent Trailer

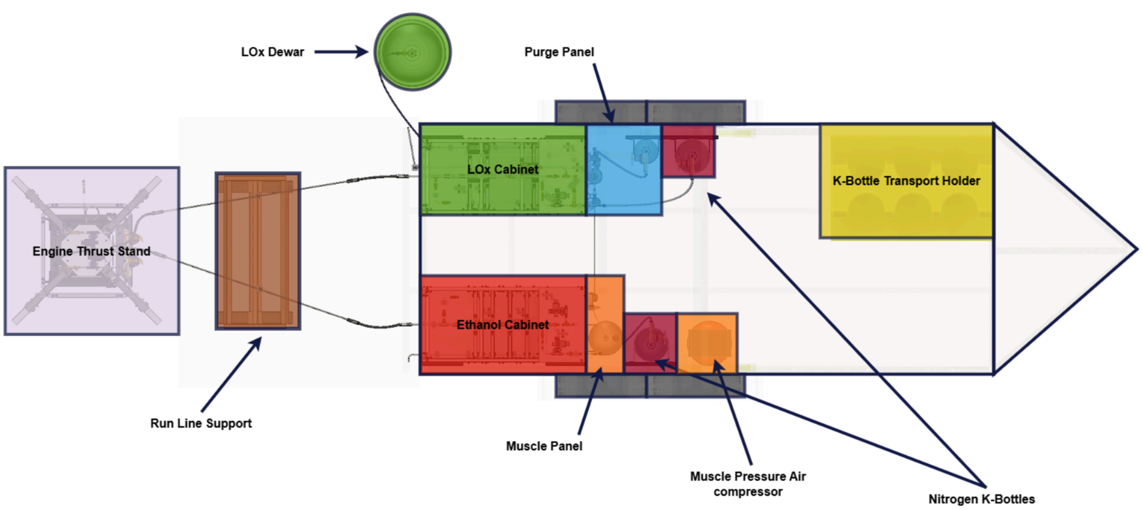

Fig. 2 Top Down View of the Mobile Test Stand

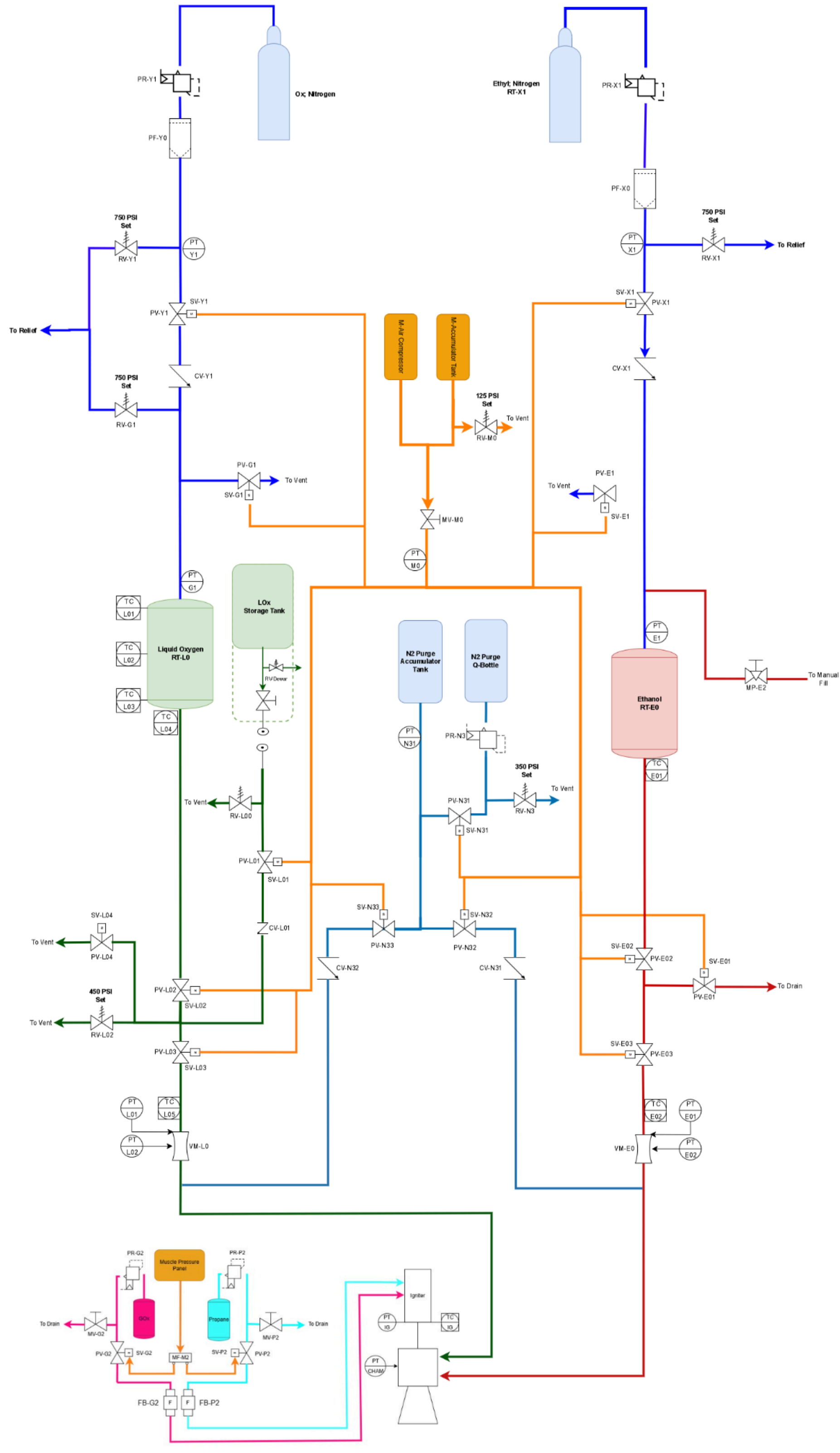

Fig. 3 Full System P&ID

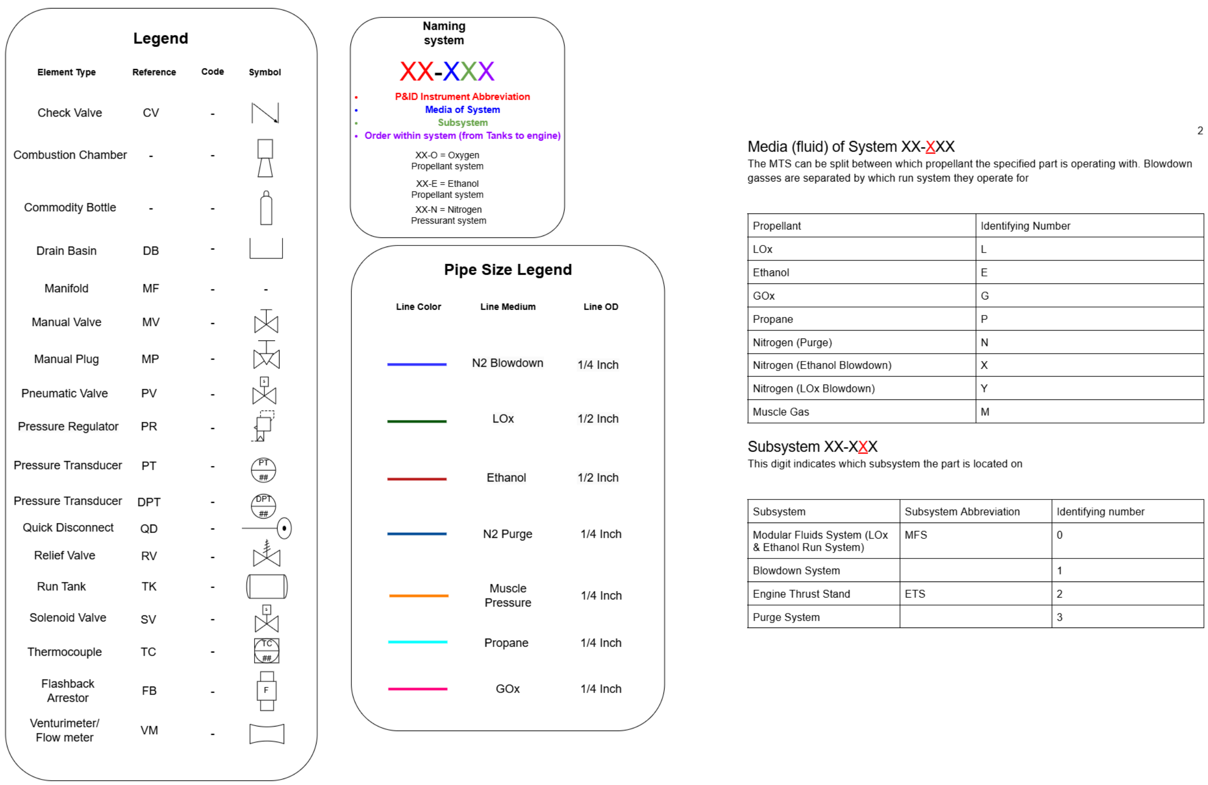

Fig. 4 Full System P&ID Legend

IV. Nitrogen Regulated Pressure System

The mobile test stand uses a regulated pressure-fed cycle of moving propellant from the run tanks to the injector. The pressure is supplied from two Nitrogen commodity k bottles running through Victor SR 4 regulators before connecting to one of two panels: one panel provides pressure to the LOx system while the other provides pressure to the ethanol system. Each panel has a run valve and a bleed valve which in the LOx's case also acts as a vent line and is directed out the back of the trailer. The regulated pressure system for ethanol operates at 685 PSI while the LOx system operates at 610 PSI with relief valves on both systems set to 750 PSI. Preliminary estimates for required regulator set pressures were made by first assuming the volumetric flow rate of the propellants in the tank would be the same as the pressurant gas in the tank. Then, this volumetric flow rate was used to calculate major and minor head losses throughout the system. These pressure losses were added to the required run tank pressures, discussed in Section VI, to determine the required regulator set outlet pressures.

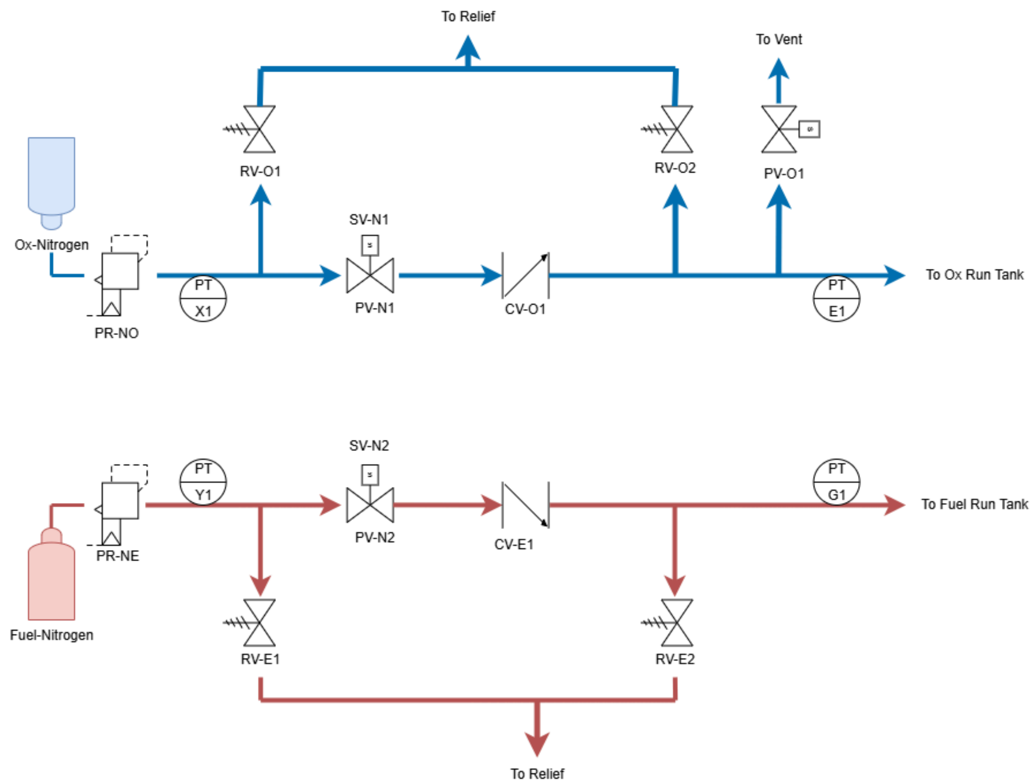

Fig. 5 Regulated Pressure System P&ID

V. Muscle Pressure System

There are 13 different solenoid valves to actuate the ball valves throughout the Mobile Test Stand. These valves actuate with a pressure of 100 PSI, which is released into the actuator by solenoid valves opened by the controls system. The valve pressure is calculated to allow every valve to actuate at once. This includes 8 Swagelok actuators at 1.5 in^3 volume required, three AVCO cryogenic actuators at 2.5 in^3, and 2 Morin actuators at 55 in^3. This requires a total volume of 126 in^3 of air. Due to the positioning of the valves, approximately 8.25 ft of tubing is needed.

In our system, the air compressor is directly connected to an accumulator tank, making the total of the stored pressurized volume 11 gallons. Additionally, there is a 125 PSI relief valve off of that connection as a precaution against too much pressure in the system. Separating the tanks from the solenoid valves is a manual valve which will be released when the system is at pressure. In order to get the total time it will take to pressurize the 11 gallons worth of tanks, the total volume is summed with the total volume of tubing. This would result in roughly 2540 in^3 of volume that needs to be filled. Dividing this by the 2.5 SCFM (Standard Cubic Feet per Minute) converted to CFM (Cubic Feet per Minute), it will take roughly 235 seconds to fully pressurize the entire system aside from the valves. Once this is done, using ideal gas, the time required to actuate all the valves themselves was calculated to be roughly 0.29 seconds.The presence of a 5 gallon accumulator tank provides an extra buffer in case of sudden pressure loss in the system.

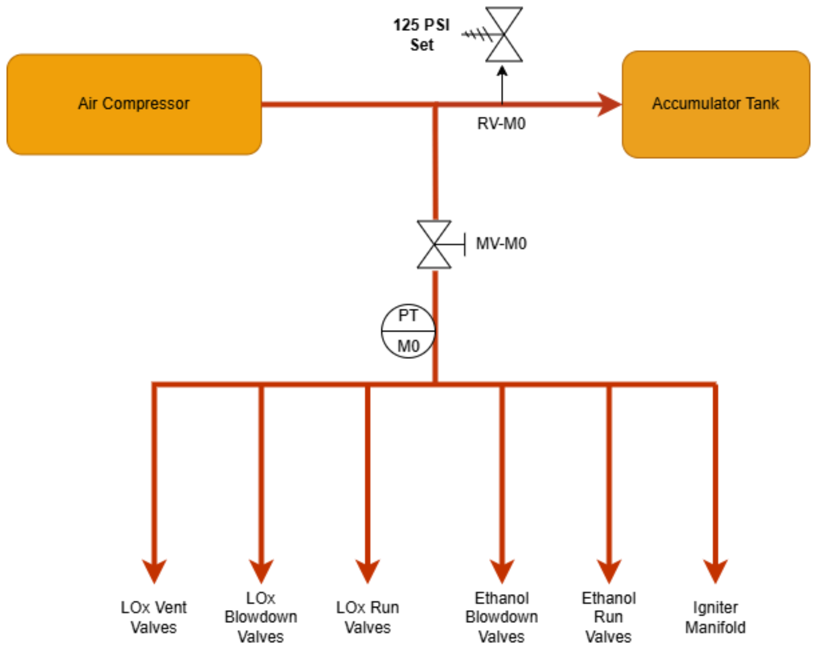

Fig. 6 Muscle Pressure System P&ID

VI. Ethanol Run Line

The Ethanol Run Line is centered around the ethanol fluid cabinet. The ethanol run line will pass through the entire fluid cabinet before being routed to the engine. The system will maintain an operating pressure of 415 PSI. The run valves in the system will use Swagelok 60 Series Ball Valves and drain lines will use Swagelok SK Series Ball Valves. The system is filled manually at a plugged t-off that routes to the run tank where the fuel for the system will be stored. A thermocouple monitors the temperature of fluids being routed from the tank. The line then routes through two run valves that will allow the system to be isolated from the engine. A double run valve setup was chosen as it allows for a redundant method of closing the run tanks if either of the run valves fails to actuate closed. In between the two run valves, a bleed valve will be present to allow remaining ethanol to be drained after firing. After the run valves, a venturi-meter is present to monitor the flow rate; pressure transducers and thermocouples are also present to monitor temperature and pressure. At the last stage before entering the engine, another thermocouple and a pressure transducer are present to again monitor temperature and pressure.

The major head loss through the ethanol line was calculated using the Churchill approximation of the Darcy-Weisbach equation to be 43 PSI. Taking into account the bends and other minor head loss caused by bends and components, which was calculated to be 21 PSI, there is an estimated 64 PSI pressure drop across the ethanol run line from the run tank to the injector. Finding the sum of the head loss as well as the required pressure entering the injector of 350 PSI gives an operating pressure for the ethanol run line at 415 PSI.

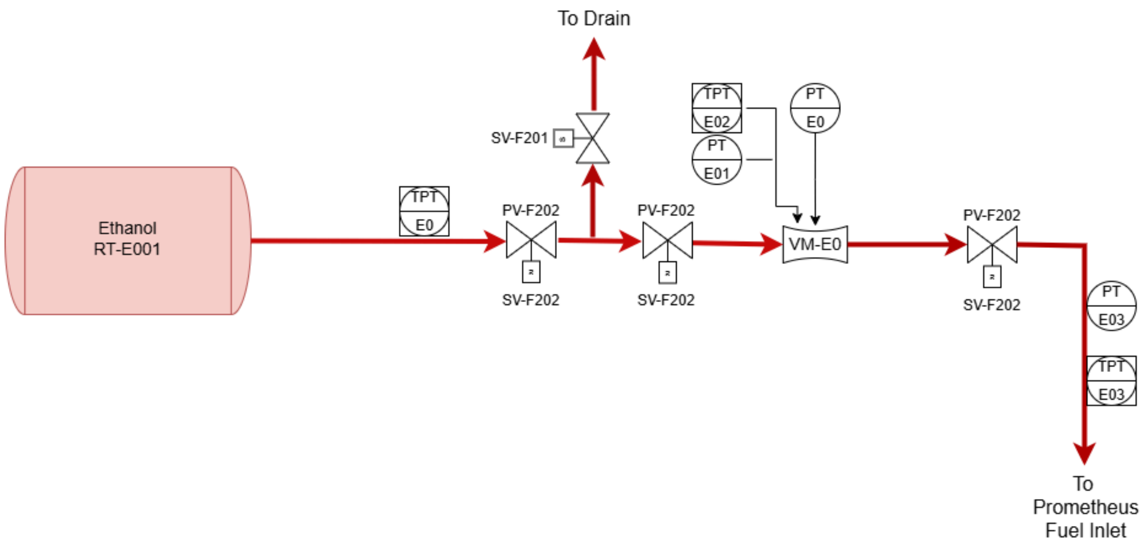

Fig. 7 Ethanol Run Line P&ID

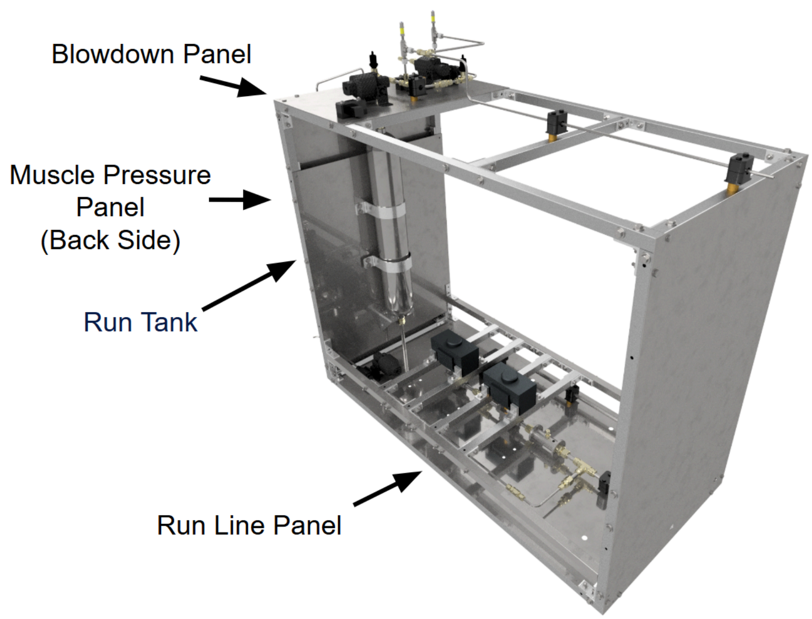

Fig. 8 Ethanol Cabinet CAD

VII. LOx Run Line

The run line for the LOx cabinet takes up the bottom panel of the cabinet itself, being the central section that the rest of the system is designed around. The run line connects from the Nitrogen regulated pressure and the run tanks, where the Liquid Oxygen is stored in the system during a test. From the run tank, the LOx run line first encounters a tee-off. This tee-off is used in filling the run tank from the bottom up through a quick disconnect that runs to the storage dewar. The LOx is initially stored in a dewar located outside the trailer, which can be remotely opened and closed for filling. By bottom-filling the LOx it is able to vent out the top port of the run tank and through a line to the back of the trailer, preventing both GOx build up and obscured visibility of the test stand due to any exhaust gas. Following the fill tee off are the two run valves with a bleed and relief valve between them, similar to the ethanol run line. For the LOx run line, a relief valve is also present between the run valves to prevent a BLEVE (Boiling Liquid Expanding Vapor Explosion) event in the case of the bleed valve failing to open. Finally, the run valves are followed by a venturimeter similar to the ethanol run line before travelling to the injector. The run lines are wrapped in polyethylene foam and aluminium tape. All instrumentation for the LOx lines are mounted on the end of one foot stagnation tubes to prevent freezing.

The LOx's Pressure head loss was calculated via the same method as the ethanol system, with the major head loss being calculated at 43 PSI and the minor head losses from bends and components at 21 PSI. Summing the head losses with the pressure required for the injector as done before gives an operating pressure of 415 PSI, the same operating pressure as the ethanol system.

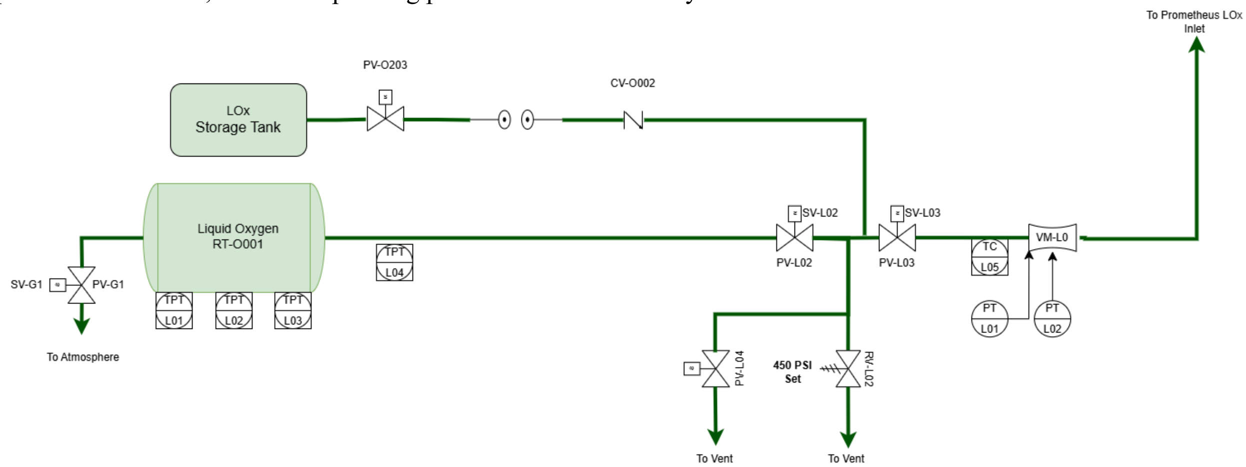

Fig. 9 LOx Run Line P&ID

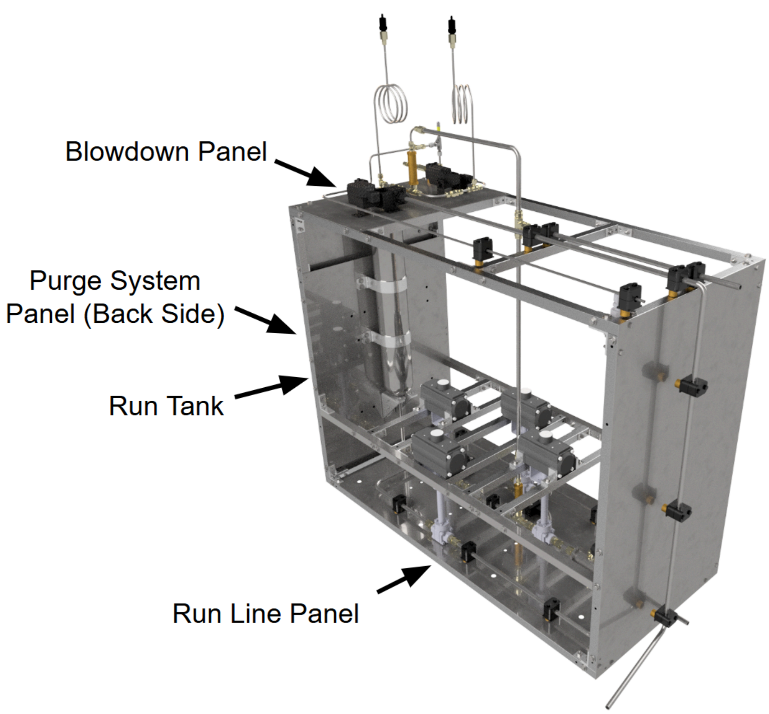

Fig. 10 LOx Cabinet CAD

VIII. Nitrogen Purge System

The nitrogen purge system allows the run lines to be cleared of residual propellant and removes oxygen from the system before and after hotfire. The pressurized nitrogen is supplied from a commodity Q bottle to a panel located on the back of the LOx cabinet. A tee branch-off leads to a DOT-3AL2015 accumulator tank, which stores the required pressurized volume of 0.37 gal which matches the volume calculated through ideal gas law assuming density and temperature are constant. past the purge system run valve, the line splits into two lines that connect to each propellant run line at a tee located after each venturi meter. The purge system will start off once opened at 280 PSI and run until the accumulator tank reaches atmospheric pressure. Past the isolation valve for the Q bottle there is a relief valve set to 350 PSI.

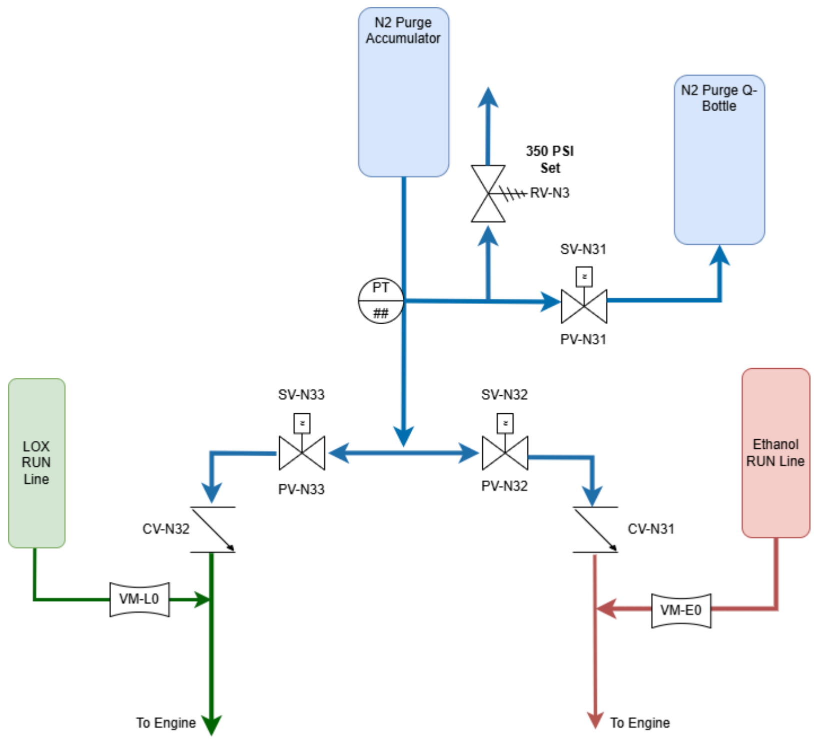

Fig. 11 Purge System P&ID

IX. Validation

A number of tests to safely verify all of our equipment in a step by step process have been devised. First, a number of pre-fabrication tests on our equipment were conducted. The first test was a low pressure "cold flow" injector test, where dyed water ran through an early design of our injector to verify mixing and propellant discharge. Next, an Igniter system test to verify that ignition was capable of reaching temperatures required for combustion. Finally, venturi meter flow test to verify that the in-house venturi meter accurately measured propellant flow.

After the test stand has been fabricated, a series of integrated tests will be conducted before cryogens and propellants are loaded into the system. These tests include an integrated controls test to verify the entire controls system actuates and reads instrumentation data correctly, a low pressure hydrostatic leak test to ensure that fittings are sealed and that no leaks are present in the system, a water flow test without the injector to verify pressure losses between the Trailer and Test Stand, and a water flow test with our injector to prove that our injector still works with our system.

After this is complete, full system high pressure tests will begin. These tests serve as dress rehearsals for the team as well as rigorous testing of our equipment. First, a high-pressure integration test, where the system will run from start to finish at the intended pressure with water instead of propellant. This ensures that our system can function at the intended operating pressures of 415 PSI for the run lines and purge lines as well as 680 PSI for the regulated pressure systems. Next is the cryogenic wet dress rehearsal, where the system is loaded with water for the ethanol line and LN2 for the LOx line, the entire hotfire procedure is run through with the propellant simulants being flowed through the injector.

X. Conclusion

Through this paper, we hope that it serves as a valuable resource for future teams looking to design and build an engine test stand within the limitations, budgetary or otherwise, of a student team. By documenting our design process, key decisions, and challenges faced, we aim to provide a practical framework that another team can adapt and improve upon to suit their specific needs. Our goal is to contribute to the body of knowledge within student-led programs like ours, helping teams with a benchmark to build upon instead of spending the money and time that we have creating a stand from scratch.

Acknowledgments

The authors would first and foremost like to thank Dr. Gang Wang and Dr. Richard Tantaris for their mentorship to The University of Alabama in Huntsville's Space Hardware Club. We would also like to thank Dr. Xu for representing AIAA at The University of Alabama in Huntsville. We are also very grateful to the MAE department at UAH and Mr. Jon Buckley in particular for the use of their machine shop. The Alabama Space Grant Consortium and the University of Alabama in Huntsville have graciously given us the resources necessary to fund this project through the Space Hardware Club. Thank you especially to AVCO for giving insightful technical feedback and providing cryogenic valves for the Modular Fluids System. Finally, we would like to thank all members of Tartarus for their continued support and dedication to the project.

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