Development of a Mobile Liquid Rocket Engine Test Bed

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This paper details the design process of a mobile test stand for Tartarus, a student-led liquid rocket engine research and development Space Hardware Club project at the University of Alabama in Huntsville. Since the system is so complex, extensive setup and testing is required to ensure the safety and reliability of test equipment. Considering that so much testing is required and the test stand would take multiple hours to set up, we devised a mobile test stand design. The primary tasks of this mobile firing system is to house and protect critical fluid equipment, ensure stability during firing, and provide swift and straightforward setup and breakdown. In order to meet these requirements, the test stand will be built in an enclosed trailer. All system components will have been assembled prior to firing which means that the only items that need setup are the trailer stabilization system and controls. As for the fluid system, it will be designed to operate at a maximum pressure of 1000 psi. The first engine only calls for 300 psi which allows for higher thrust engine designs to be tested with no need for altering the fluid system. The firing structure inside the trailer, specifically the one that supports the engine, will be rated to 800 pounds of force for the same reason. Externally, the trailer will be secured with a steel cable tie-down system. The cables will be attached to ground anchors to ensure that the structure remains stationary during firing. For fueling, two dolly-type carts will be built to provide easy and safe transportation of our propellants. Fuel will then be transferred to the fluid system via flex tubing and quick disconnects. All of these features will work together seamlessly to create a thorough and effective engine test system.

I. Introduction

Tartarus is a student-led, liquid rocketry research and development project at the University of Alabama in Huntsville. The project is part of the Space Hardware Club within the university. The purpose of the project is to provide opportunities for hands-on experience in developing small-scale liquid rocket propulsion systems. As of now, the project has undergone a rescope of its vision and goals including elements related to safety, overcomplexity of the original build, and setup procedure difficulty. Due to this rescope, a brand-new firing system setup is needed. The original liquid-rocket design was determined to be dangerous due to several issues found through a professional development review with current UAH faculty. The current plan is to start by building a small, simple, low power engine with about 200 pounds of thrust. We will then use the lessons learned and expertise gained from this small engine to build a larger, more powerful engine, with up to about 1500 pounds of thrust.

II. The Old System

Tartarus' previous test stand was a completely different setup. It powered an 800 pounds of thrust engine operating on liquid nitrous oxide and ethane. It employed a supercharge blowdown cycle using nitrogen gas at an operating pressure of 800 psi. The supercharge cycle functioned by adding extra nitrogen gas into the ullage volume of the propellant run-tanks after fueling. On the nitrous oxide side, some self-pressurization was utilized to assist in propellant loading and pressurizing. Even though the system operated as intended, it fell victim to many issues that shall not be carried over to the new test stand. The primary issue was that the test stand had too many fluid equipment

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pieces required for its assembly. This reduced the team’s ability to work on the stand greatly, as it took more than three hours to assemble each time a test was performed. Equally, it took almost as long to disassemble. Furthermore, the large quantity of parts meant that transportation of the test stand was logistically difficult as multiple vehicles were required for part storage. With such a multitude of parts, this meant that a higher number of possible propellant leaks could occur. This is unacceptable due to the safety hazards this presents to test operators. These failures and setbacks of the previous system have guided us into making our new specifications and requirements to make sure these errors are not repeated.

Figure 1. The complexity of an old test stand panel proved to be very tedious to set up and looked very haphazard.

Figure 2. This unnecessary fitting “train” was a large, reoccuring source of leaks during testing.

III. New System Overview

The primary features of this test stand are its mobility and simplicity. All of the equipment shall be designed for use in an enclosed trailer. We decided to use an enclosed trailer over a flatbed trailer for the simple reason that all of the fluid equipment will be protected during harsh weather. Having the pre-built system installed to a mobile platform decreases setup and break-down time significantly. When the test stand is fully built, we will have the ability to pull the trailer to our test site and begin testing within the timeframe of an hour as little assembly will be required.

The new fluid system will employ a regulated blowdown pressure cycle. Instead of injecting extra nitrogen into the run-tanks, it will now be constantly run throughout the entirety of the firing time. We switched to this method due to the reliable and constant thrust values that this system will provide unlike the previous one. The fluid system will also be upgraded to withstand a maximum operating pressure of 1000 psi. This will allow future teams to test new engine designs without the need of altering the entire fluid system for each new engine variant. This will reduce the cost of engine development significantly and remove the difficulty of repeated system modification. The new system will also be built with fewer parts, decreasing the probability of leaks during testing. The previous system was made with an unnecessary amount of adaptors and fittings. To rectify this, we shall use fittings only whenever necessary, make longer pipe segments, and use fluid equipment that is already a standardized size like the rest of the system. Stainless steel 316 ½-inch diameter piping is the tubing of choice as its large size decreases the flow velocity of the propellants, which decreases the likelihood of liquid oxygen flow instability. All cryogenic lines shall be insulated to reduce the boiling off of liquid oxygen.

Inside the trailer, all the fluid equipment shall be mounted on two separate 80/20 channel frames. These frames will only need to support the weight of the equipment and nothing else. In order to mount the engine, another steel tube frame shall be built by the back doors of the trailer, separate from the fluid equipment frames. The engine mount frame shall resist a maximum thrust value of 800 pounds while supporting the engine at a 45 degree angle. The angle ensures that there is no buildup of excess propellants during and/or after firing. Both internal frames shall be mounted directly to the steel frame of the trailer at multiple connection points. To keep the trailer stable, a custom tie-down system shall be installed to the bottom frame of the trailer. It will be made up of four steel cables anchored in the ground. Each cable will be attached at 45 degrees relative to the corners of the trailer to support the system in all directions of horizontal and vertical motion. Wheel chocks shall be employed alongside the tie-downs to add another level of stability.

In order to load the propellants into the run tanks, we developed two propellant carts or prop carts for short. These carts hold all the necessary plumbing required for filling as well as line purging. There shall be a cart for each propellant for the sake of safety as storing both propellants on one cart would be an accidental detonation waiting to happen. Each cart shall be fitted with its own nitrogen bottle. For the ethanol cart, the nitrogen will be used to push the fuel into its respective run tank and then purge the line once filled. The LOX cart's nitrogen bottle shall only be used to purge the line since we can use the pressure of the LOX's container to move it. Both carts shall have a dolly configuration, meaning that there are two wheels on the back of the cart so the operator can tilt it up and roll it to its destination. They shall have all the required securing hardware to keep all propellant tanks and nitrogen bottles safe and stable during transport. To connect to the test stand, we shall use quick connect/disconnects to attach to the fluid system. These connects shall be fitted onto flexible tubing to allow for easier manipulation.

The team has some additional, non-crucial future plans for the stand. We plan to install cameras inside the trailer to allow for an easier, remote viewing of operations inside during tests. We also plan to install an independent power source such as a rechargeable battery. In the next sections, the fluid system, structural system, and the prop carts will be discussed in detail. Some images of the test stand can be found in the appendix.

IV. Fluid System

Before the team started designing the fluid system, they first needed to ascertain all of the most important specifications that the system would need to conform to. The first of these requirements is the operating pressure. The students working on the engine design deemed that it needed an operating pressure of 300 psi, much lower than the maximum system pressure of 1000 psi. This relatively low pressure value increases the safety during tests as the equipment will be put under a lower amount of pressure stress. The next requirement is the choice of propellants. The team had the propellant choice already selected going into the redesign: liquid oxygen and ethanol. Ethanol poses no extra threats besides flammability, reducing the complexity of the equipment used in this side of the system. Liquid oxygen (LOX), however, is much more difficult to handle as it is a cryogen. Due to its volatile nature, special cryogen-rated equipment must be used anytime LOX interacts with the system. For example, there are special valves designed for cryogens as they have internal pressure relief devices. After the specifications were laid out, the team could continue to system layout. Our system's piping and instrumentation diagram (P&ID) is shown in Figure 4. It shows how all of the equipment is connected and shows how they all interact with one another.

Starting at the top half of the P&ID, all the equipment for fueling and temporary propellant storage is shown. Starting from the nitrogen Q-bottles (high pressure bottle), the nitrogen then travels through a solenoid valve. This type of valve opens when a small pressure of 90 psi is pumped into the valve body. These valves are actuated electrically from our control setup. The valves immediate to the nitrogen bottle stop the flow of the gas until it is time to fire. The gas then travels through a check valve and into the run tanks. Check valves are unidirectional valves that are used to regulate flow direction. The check valves are placed here so that no gasses from the run tanks can flow past the relief valves and burst disks. The two valves mentioned are discussed in "System Safety" later in the paper. After flowing through the run tanks, any stored propellants will travel past drain valves before arriving at the run valves. The drain valves are also discussed in "System Safety." Run valves are the final valves before the engine. They separate the propellants from the engine until firing. These two run valves are incredibly important to the system. The time that each valve opens is crucial to preventing a hard-start which can destroy the engine. Throughout the system are pressure transducers and thermocouples to monitor the pressure and temperature of the propellants throughout testing. In the middle of the P&ID is an isolated bottle of nitrogen gas. As mentioned earlier, all solenoid valves require a small amount of pressure to actuate also known as muscle pressure. This bottle is what provides the nitrogen gas to all of the solenoids in our system. We did this because we did not want to risk borrowing nitrogen gas from other parts of the system and risk losing pressure in the solenoids. The solenoids are connected to the nitrogen using plastic, flexible tubing. Immediately before the run valves are the quick connects/disconnects. These points are where the propellants are pumped into the system. Check valves are placed after the quick connects to ensure that the propellants do not flow out of the system during operations.

All of the fluid equipment is made from 316 stainless steel in order to resist corrosion caused by liquid oxygen. This material is also one of the most common materials our suppliers use to manufacture the equipment. The fluid elements connect to the tubing and each other with built-in Yor-Lok fittings shown in Figure 3. These fittings create a self-sealing connection when screwed together, reducing the probability of leaks at connection points. With all of the fluid equipment in place, we can now discuss how and where the fluid system is mounted to the trailer.

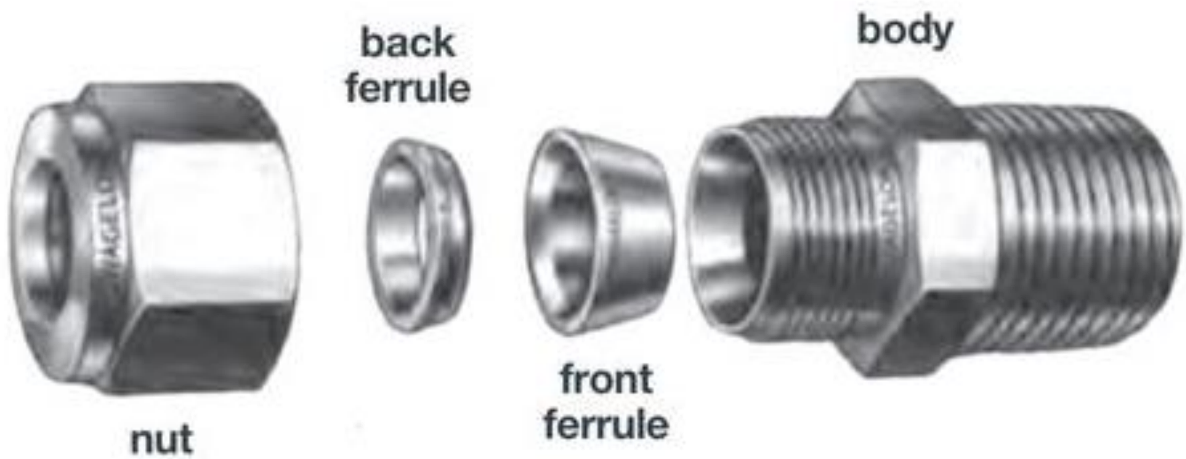


Figure 3. Yor-Lok fitting separated into all of its components.

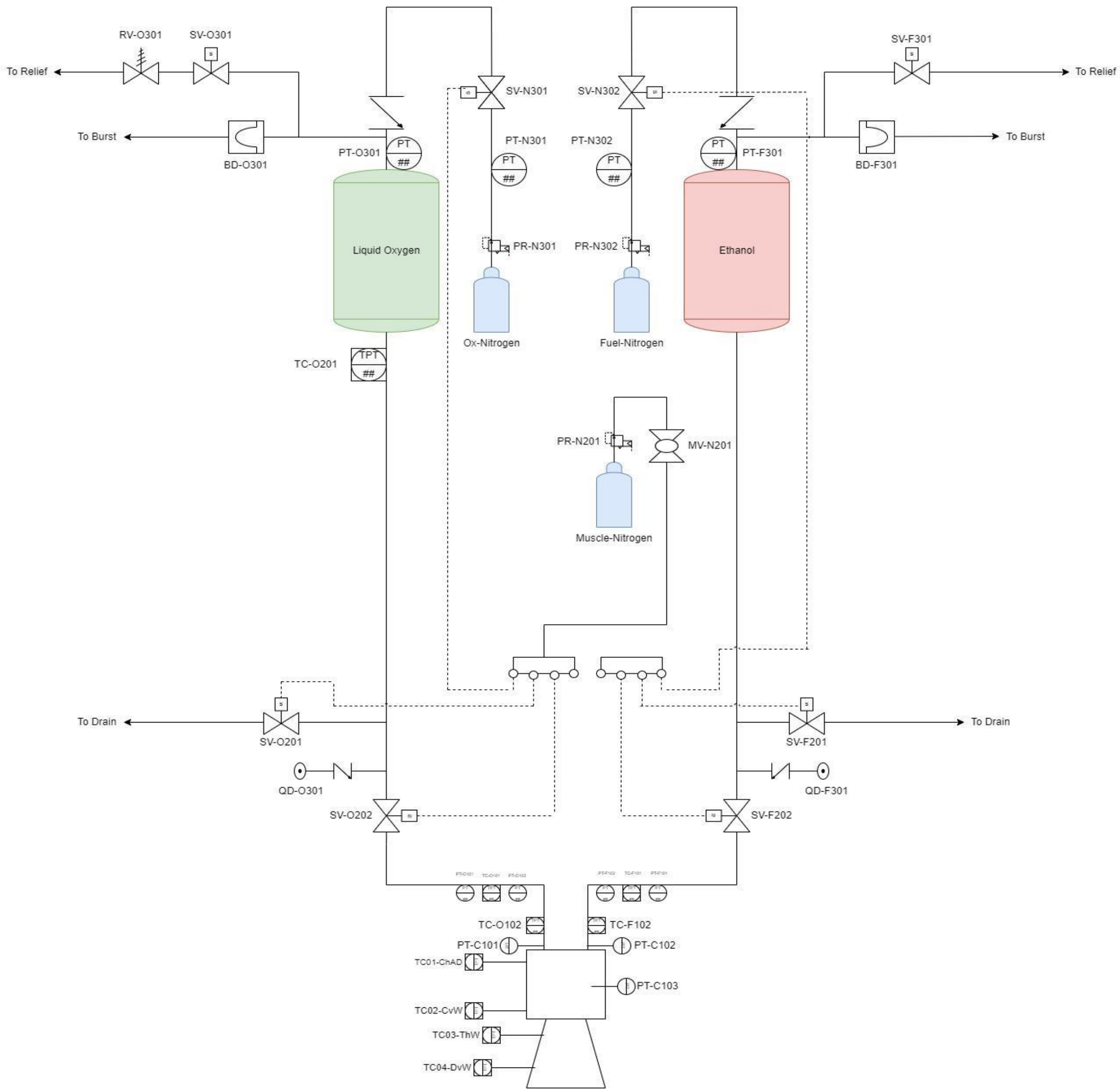
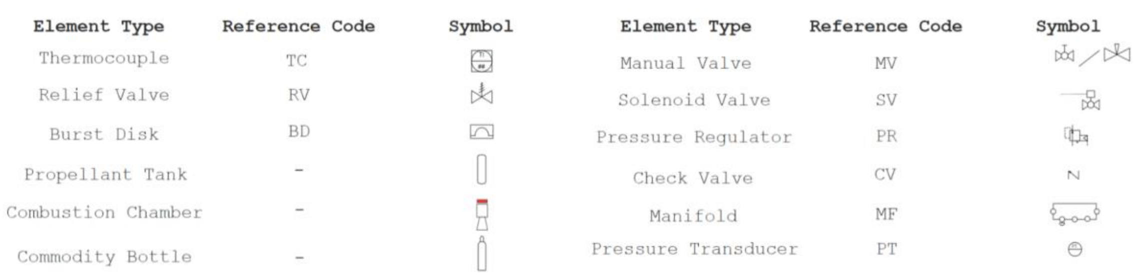


Figure 4. P&ID of our current fluid system for the mobile test stand.



Element Type	Reference Code	Symbol	Element Type	Reference Code	Symbol
Thermocouple	TC		Manual Valve	MV	
Relief Valve	RV		Solenoid Valve	SV	
Burst Disk	BD		Pressure Regulator	PR	
Propellant Tank	-		Check Valve	CV	
Combustion Chamber	-		Manifold	MF	
Commodity Bottle	-		Pressure Transducer	PT	

Figure 5. Legend for P&ID above.

V. Structural Systems

As mentioned earlier in the paper, there shall be three main frames inside the trailer: an ethanol equipment frame, a LOX equipment frame, and an engine mount frame. Each frame has its specific purpose, material, and configuration that are crucial to the operation of the system.

The fluid equipment frames are the simplest of the frames. They shall be made of 1.5” x 1.5” 80/20 extrusion framing. The dimensions of both frames shall be seven feet long by two feet wide. They will be built in a rectangular configuration. The internal sections of the frames are where we plan to mount all of the system equipment. The 80/20 material is extremely convenient to work with since the only actions needed to alter the frame or attach mounting points is to install a small notch with a screw. An example of the 80/20 extrusion framing in construction is shown in Figure 6 below.

In comparison to the fluid equipment frames, the engine mounting frame is a lot more complicated. Since the frame needs to support a maximum thrust value of 800 pounds, a stronger material must be used. We decided to use 1” x 1” steel tubing. The reason we went with this material is that it is commercial-off-the-shelf, strong, and able to be drilled through. To build the frame, we will be bolting all connection points to ensure that the construction is sturdy and rigid. The team debated welding the frame together, but that was quickly dismissed due to lack of experienced welders in the club. The point where the engine attaches to is pivoted at a 45-degree angle. This was done to prevent LOX buildup in the combustion chamber. If the previous issue were to happen, then we run the risk of accidentally starting a fire. An issue we had to resolve was the movement of the engine mounting frame. Even though the firing structure will be secured to the steel frame of the trailer, the mounting stand will still move a noticeable amount. The issue arises with the hard tubing we would connect to the engine. Since the fluid system is not capable of moving, the tubing would break or separate from the engine if it were under stress long enough. To solve this problem, we decided to use flexible lines between the frames. Stainless steel flex lines are readily available from *McMaster-Carr* and are rated for the maximum operating pressure of 1000 psi.

During firing, the trailer will be subjected to the full force of the engine. Even though the trailer weighs around 2000 pounds, additional measures must be taken to keep the system as immobile as possible. For this, we designed a 4-point cable tie-down system. How the system works is at each corner of the trailer’s bottom frame will be a galvanized steel cable. These cables will be about 8 feet long and be connected to tire-downs in the center. At the ends of the cables will be ground anchors. These anchors will be driven into the ground and then lifted up until they are locked in the soil. After the anchors are fully secured, four team members will tighten the tie-down until the trailer is completely stationary. Steel cable with a diameter of ¼-inches can withstand a working load of 1,400 pounds and will break at 7000 pounds. These cables are commercial-off-the-shelf and support our needs well. In addition to the cable system, four RV stabilizer jacks will be installed at each corner of the trailer to provide a flat and equally distributed contact point with the ground. We will also make use of wheel chocks to make sure the tires do not roll during firing. All of the structural components in combination will make a sturdy, effective, yet simple stability system for our needs. Pictures of the frames and stability structure can be found in the appendix.

Figure 6. An example of how an 80/20 extrusion channel assembles.

VI. Propellant Carts

One of the most difficult tasks that we have to prepare for is fueling. This combines a multitude of issues that can be detrimental to the system equipment and the personnel. These issues include propellant storage, transportation, and plumbing. It is generally known that liquid oxygen constantly decomposes, releasing oxygen gas into its surroundings and increasing internal pressure of whatever vessel it is stored in. Special vessels or dewars are the required storage containers for LOX, or any cryogen, as they relieve all pressure with built-in relief valves. Even though the dewars are safe, their storage location still remains an issue. Since they vent pure oxygen gas to their surroundings, this creates an area that is highly toxic and flammable if in large quantities. This means that having bulk storage of our LOX in the trailer is simply impossible. It is also very difficult to transport since dewars are generally very heavy. Additionally, it would be tedious to connect hard lines from the dewar to the trailer every time we wanted to run a test. Luckily, we were able to solve all of the previous problems with one solution: propellant carts.

The general idea of the propellant carts is that each propellant is stored separately on two mobile dollies. Each cart shall have its own nitrogen gas Q-bottle for plumbing and purge pressure. The carts will also have their own plumbing equipment installed to their framing. With these carts, we can fill their internal propellant tanks from bulk storage tanks, reducing the amount of weight and propellants we have to move to the trailer and back. To move the carts, two rubber wheels will be installed on one side of the cart while two support legs will be installed on the other side, much like a cargo dolly. Two operators will be placed on each cart to ensure that they do not fall over during transport and propellant filling. The frames of the carts will be custom made with sheet steel and aluminum. Steel will be used for the crucial weight-bearing sections of the cart while the aluminum will be used for side paneling. All the valves on the carts will be manually actuated to allow for total control of the fueling process. Also, running cables to each solenoid valve would be a difficult and unnecessary task. When it comes time to fuel the test stand, the carts will interface with the fluid system with flexible lines and quick connects/disconnects. Flex lines are crucial to the fueling interface since the prop carts cannot be parked in the same location, relative to the trailer, every time. They allow for our operators to be able to easily manipulate the lines to their spot. The quick connects also allow for easy and swift interfacing with the fluid system since they do not have to be attached with tools. Once fueling is complete, all the operators have to do is purge the fueling lines and roll the cart away from the trailer. These carts will make testing much easier to complete as they fall in line with the idea of a fully mobile and preassembled test set-up as they have the same qualities. Below are the P&IDs for each cart along with the basic structure that each cart will share.

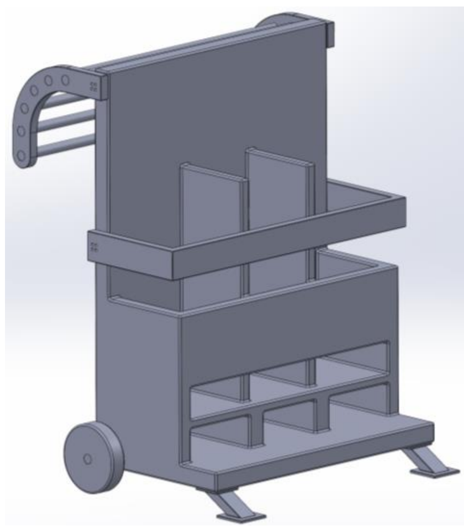


Figure 7. Assembly of the prop cart's structure.

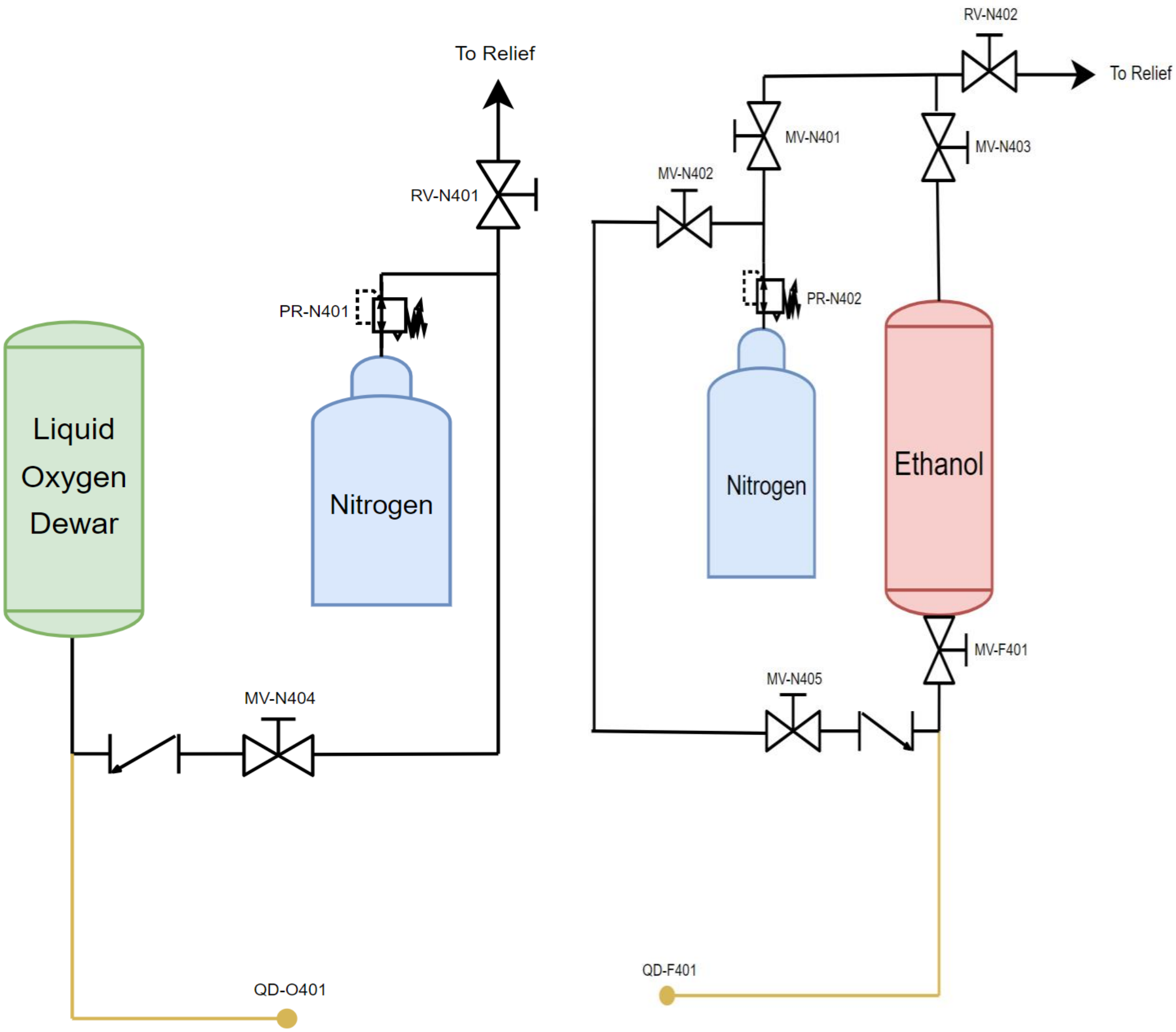


Figure 8. LOX Propellant Cart (Left) and Ethanol Propellant Cart (Right). Refer to legend in Figure 5.

VII. System Safety

Perhaps our largest hurdle is ensuring the safety and reliability of our mobile test stand. Fitting an entire system for a liquid oxygen fueled engine in a trailer is extremely dangerous, so we have taken every measure to ensure the safety of the crew and equipment. This includes the inclusion of pressure relief devices, drains, and a system-wide abort state. One of, if not the most, dangerous difficulties with LOX is its constant decomposition. In a matter of minutes, there can be an uncontrollable boiling-liquid-expanding-vapor-explosion event (BLEVE event); therefore, it is crucial that we have ways to relieve said pressure without direct intervention. The first way we prevent pressure buildup is the incorporation of mechanical relief valves. Instead of manually monitoring and calculating the inconsistent decay of LOX, we will instead be using a spring-powered relief valve. When a certain system pressure is achieved, the spring in the valve will compress, moving the cap off the valve and allowing the gas to escape. This way, we do not have to spend time intricately venting oxygen and we can spend more time running the test. The second way we prevent pressure buildup is by incorporating a burst disk. This is a last-resort relief method as it is an emergency contingency. The burst disk operates by housing a thin sheet of metal rated to a specific pressure. When it reaches that pressure, that seal brakes allowing any gas in the system to escape. We shall have a burst disk on each propellant side of the fluid system. We shall also make use of drains near the end of the system. In the event of an emergency, we will have the ability to drain all liquid propellants from the system with the switch of two solenoid valves. The propellants will then drain into two external basins. If we were to experience an emergency, we would make use of the abort state. The abort state combines the relief valves and drains throughout the entire system. In an active abort state, all the run valves would close, the drains would open, and paths to the relief valves would open. This would mean that all gaseous and liquid propellants would exit the system until empty. With all of these safety precautions in place, testing will be much safer and no damage to the test stand will occur.

VIII. Testing

We have made a tentative testing plan for our various systems over the next year. Once cryogenic hardware is acquired, we shall perform a valve cryogenic compatibility test to ensure that our parts can actually withstand the operating conditions of cryogens. For this test, we will create a small apparatus involving all used hardware: dewar, manual and solenoid valves, piping and insulation, and relief valves. Next, we will perform a valve actuation timing test to ensure that our run valves acuate and open in the correct time frame. In order to prevent a hard-start of the engine, the run valves must open at very specific times (within a span of seconds). When we are further along in development of the test stand, we will perform a leak check before running a low pressure integration test. For the leak test, we will use water at very low pressures before slowly increasing said pressure to ensure total fluid equipment rigidity. When we are ready, we will perform a high pressure integration test to ensure that our system is capable of withstanding operational pressure without failing. Then, we will do a prechill and cryogenic integration test for our entire system. This test will be the critical moment in deciding if the test stand is clear to progress to hot fire. If there are any failures in this test, we will have to return to the redesign phase until every component is proven to withstand all failure conditions.

IX. Conclusion

Building a cryogen-rated system from scratch is no easy task. Such a design takes a lot of time, effort, and review to ensure that safe and long-term use of this test system is achievable. Incredible amounts of safety and forethought have been put into this project. As we continue with this process, we hope that we can help improve the knowledge base of liquid bipropellant systems for undergraduate teams. In designing this test bed, we aspire to create a strong foundation that future Tartarus members can utilize while designing stronger and more efficient engines. Despite the fact that the previous system's failures set the team back, it has given us a much better idea of failure conditions and risk mitigation, and we believe that we are still on track to see a hotfire next year.

Appendix

Figure 9. Isometric view of trailer.

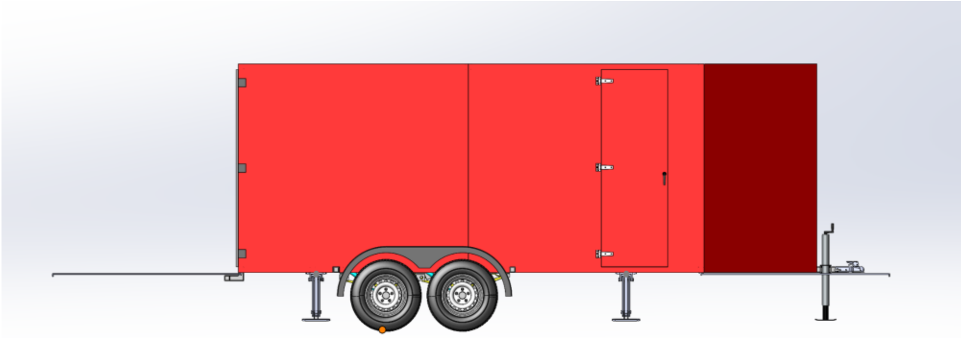


Figure 10. Side view of trailer.

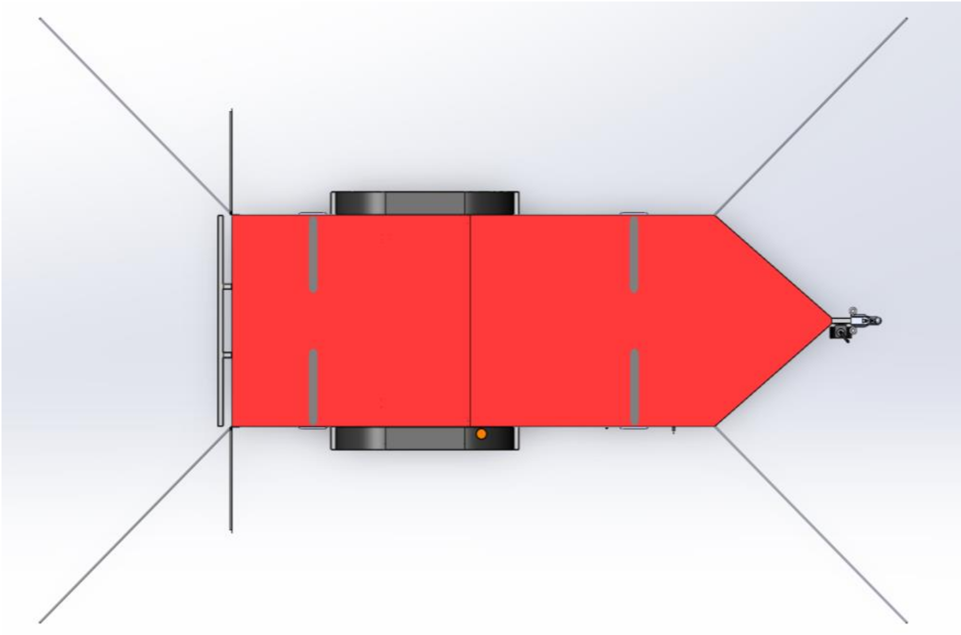


Figure 11. Top view of trailer.

Figure 12. Fluid and engine frames.

Acknowledgments

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