Hydra: Development of a Liquid Rocket Engine Test Stand and Feed System

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The design, development, manufacturing, and testing of a liquid rocket engine test stand and feed system called Hydra is presented. Hydra was developed in the student-run Liquid Propulsion Laboratory (LPL) at the Viterbi School of Engineering at The University of Southern California (USC). Hydra started as an idea in March 2017; the entirely student-built project was successfully tested and proven to work as intended on December 2nd, 2017. Many lessons were learned while designing Hydra; the flow diagrams, valve selection, electronics, control. and testing campaign are detailed along with the strategy used to successfully complete the project. Hydra is a critical milestone for LPL's capabilities and will be used as a platform to test and modify future engine and feed system ideas.

Nomenclature

q	=	flow rate in gal/min
Δp	=	pressure drop in psia
G_f	=	liquid specific gravity of the medium used
N_1	=	numerical constant
N_2	=	numerical constant
p_1	=	inlet pressure in psia
G_g	=	gas specific gravity of the medium used
T_1	=	absolute upstream temperature in °R

I. Purpose and Objectives

The Liquid Propulsion Lab (LPL) at the University of Southern California (USC) has developed manufactured and tested a liquid engine test stand and feed system named Hydra shown in Fig. 4. This paper presents the project's purpose, objectives, design and manufacturing strategy, testing campaign, static test fire, and future developments. LPL is a graduate-level research lab that focuses on developing bipropellant liquid rocket engines. The mission of LPL is to provide its members with the practical experience and the skills necessary to succeed in the aerospace industry and to position USC as a leader in liquid propulsion higher education and research. Hydra was completely student designed and built in the LPL lab located on-campus over the course of nine months using commercial-off-the-shelf parts and custom software. Its purpose is to supplement the capabilities of the lab and to test engines in a far simpler and cheaper way. The design, manufacturing, and testing of the test stand provides invaluable information. The ability to hot-fire engines, test ignition systems, and perform cold-flow tests provides a tremendous resource as a learning tool for current and future members. So far, Hydra has been used to successfully provide the test stand and feed system to two of the LPL's engines, Blue Steel 2.0 and Jessie.

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II. Design and Manufacturing Strategy

A. Design as a Test Stand

Hydra serves both as a test stand and feed system. Hydra's structure is made out of one-inch hollow stainless-steel square tubing that is welded together and mounted on four casters; there is a mounting plate welded on the back and a horizontal thrust-mount welded on the front. The size requirement is set by the trailer it gets transported in (dimensions of Hydra shown in Fig. 1 and Fig. 2).

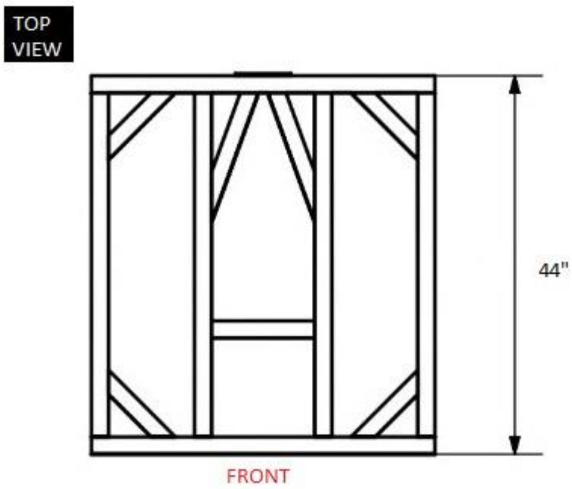

Fig. 1 Top view of load supporting structure.

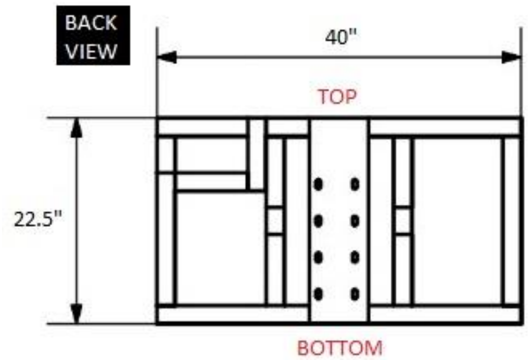

Fig. 2 Top view of load supporting structure.

The substructure, shown in Fig. 3 of the test stand consists of mounting plates for temperature/pressure transducers and several valves, a mounting cage for the pressurized fuel tank, and mounting strips for the fuel supply tank.

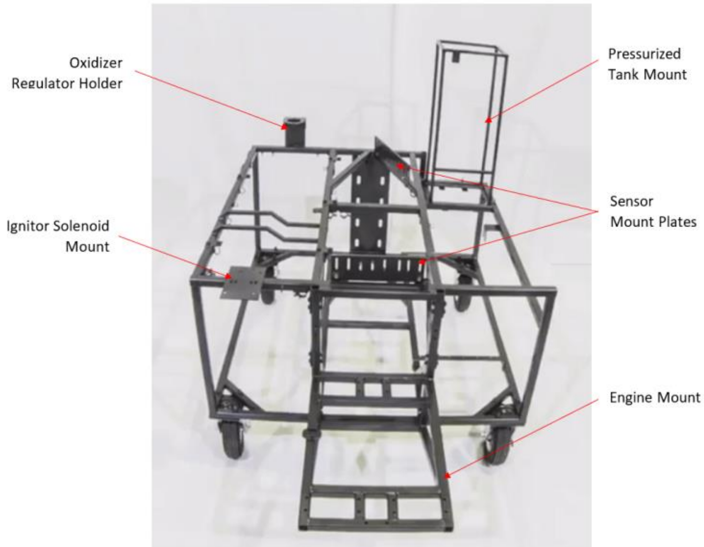

Fig. 3 Hydra's substructure.

The structure has been designed to be secured in place, transferring the thrust produced by the engine (maximum 1000 lbf), to the back of the structure or ground. Hydra can be bolted using its back plate to a vertical I-beam at the Friends of Amateur Rocketry (FAR) test site shown in Fig. 4 or bolted to a concrete floor using a set of custom plates that clamp the lower part of the structure to the ground. Any lateral movement is mitigated using counteracting ratchet straps on either side on the front of the structure.

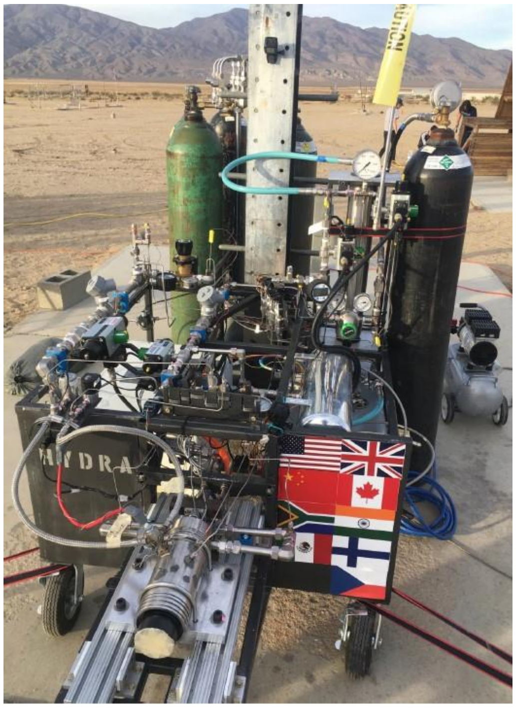

Fig. 4 Hydra mounted to I-Beam at FAR Test site in December 2017.

B. Design as a Feed System

Hydra provides a pressure regulated feed system for engines, the schematic is shown in Fig. 5. It's designed for a pressurized gaseous oxidizer, a liquid fuel, and a pressurized inert gas used for the fuel. The abbreviation format for the schematic is XX#-L where XX is the component abbreviation found on the left table, # is the number (if applicable), and L is the location: Engine (E), Fuel (F), Pressurant (P), Oxidizer (O), Fill (F), Drain (D), Ignitor Fuel (IF), Ignitor Oxidizer (IO), and Torch Ignitor (TI). The main fuel and oxidizer lines run parallel across the top of the structure from the back to the front, and the pressurant line runs vertically along the back, pressurizing the liquid fuel. The oxidizer is supplied from pressurized bottles, with a maximum of eight bottles that can be hooked up in parallel to a manifold. The fuel is stored in a supply tank located on the bottom of the structure of Hydra, and a pump inside the tank is remotely actuated to fill a pressure vessel between firings. Hydra can ignite the engine via a spark plug ignitor that uses tapped-off propellant or an e-match that burns pyrotechnic material inside the engine's combustion chamber. Hydra can also drain, purge, and prime each propellant line independently with the option to do so through flexible lines running on the outside of the stand or through the engine or test article.

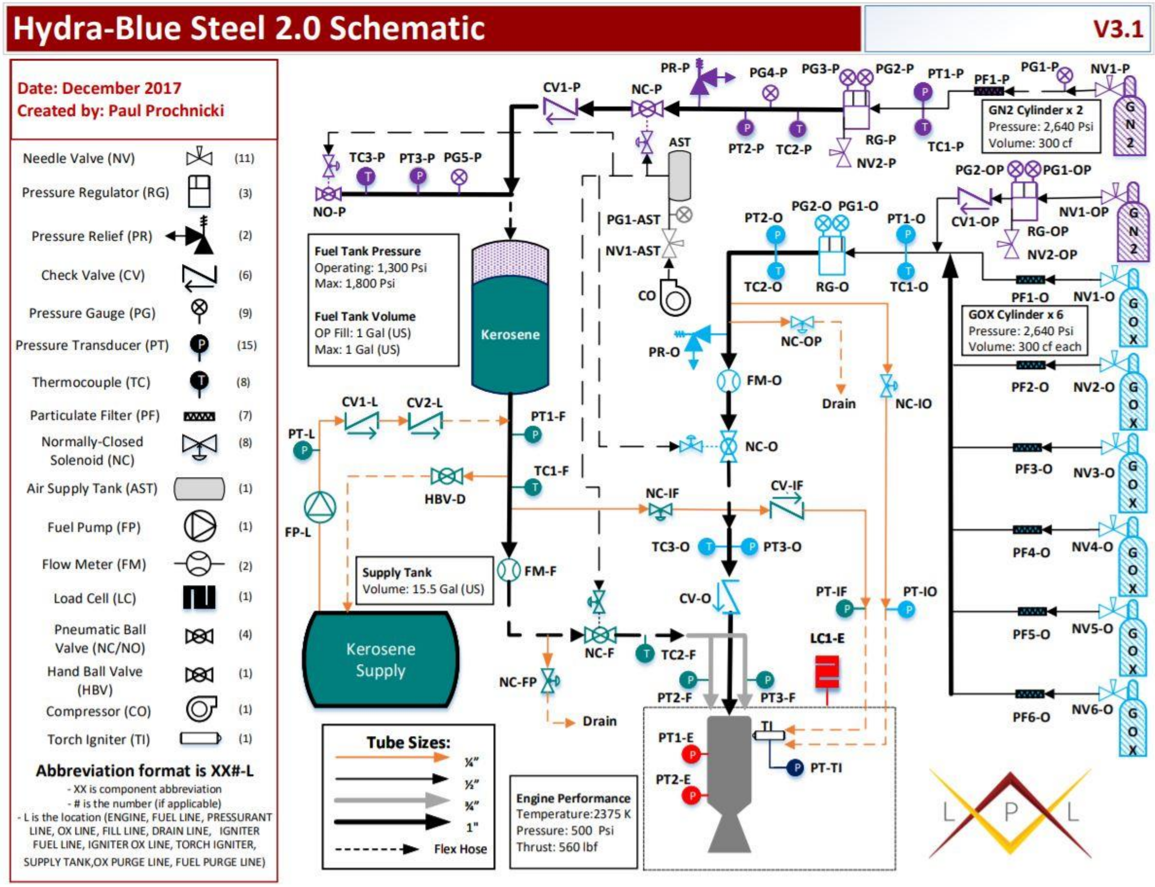

Fig. 5 Hydra-Blue Steel 2.0 schematic - Using kerosene, gaseous oxygen, and nitrogen as fuel, oxidizer, and pressurant respectively in this configuration.

The main oxidizer regulator (RG-O) and pressurant regulator (RG-P) are manually operated and preset before firing. Extensive testing is conducted prior to hot firing the engine to find the desired set point during cold-flow tests, which is discussed later in this paper. This system gives us better control than a blow-down pressure system and allows us to run tests at different pressures.

1. Design Requirements and Criteria

Hydra was designed with maximum inlet pressure of 3000 psig for the pressurant and oxidizer to accommodate commercially and widely available high-pressure bottles that can be easily rented, refilled, stored, and transported. An outlet pressure between 0-1500 psig was allocated for the oxidizer and 0-1800 psig for the pressurant. These values were targeted based on commercially available regulators with high flow coefficients (Cv), the design of the engines we were making, and cost.

Hydra was designed to only operate with non-cryogenic propellants; their added expense, volatility, and safety precautions needed presented an unnecessary challenge at the time of development to operate a liquid rocket engine. Hydra also doesn't allow the use of highly corrosive propellants, for similar reasons, the added costs in materials and the extra safety precautions required to sanitize the exposed areas was also considered nonessential. There are plenty of unique research opportunities to focus on without relying on cryogenic or corrosive propellants, such as hydrocarbons and alcohols for fuels and oxygen and nitrous oxide as oxidizers.

Line sizing calculations were conducted using the Darcy-Weisbach equation and a balance between minimizing the size (and consequently the cost) and head loss (to maximize downstream pressure availability) was achieved. Smooth-bore seamless 316 stainless steel tubing was used for all static tubing. Material compatible flexible lines were used for convenience in some locations, and for connections to the engine since it would translate during hot-firing.

Having flexible lines prevented stress in the tubing during firing and allowed for more accurate readings of thrust coming from the engine. For the sensors, 1/8 inch smooth-bore seamless 316 stainless steel tubing was also used, including for the ones mounted on the engine, they were coiled to allow for less translational resistance during firing as shown in Fig.6.

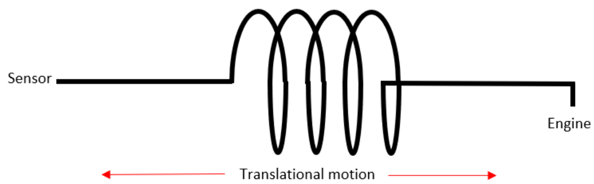

Fig. 6 Coils give the stainless tubing some flexibility to minimize stress and allow for more accurate readings.

Hydra exclusively used National Pipe Thread (NPT) and Swagelok fittings. NPT options were selected for many valves due to their widespread availability and standardization giving us more choices among manufactures to select the ideal valves and quickly buy parts as needed. Swagelok fittings were also favored due to their extensive use in oil and gas industry, catalog size and technical information, customer support, and in-stock availability.

Typically, in a pressure feed system a high-pressure fuel, an oxidizer, and a pressurant tank are supplied and then used during firing. On Hydra there is no oxidizer supply tank, to minimize infrastructure costs and increase simplicity, the oxidizer comes directly from an oxidizer manifold consisting of up to eight high pressure gas bottles. All the bottles are in parallel and equalize pressure between each other and are used to achieve the desired high flow rate and pressure. As part of the manifold, an inert high-pressure gas bottle is attached with a regulator to purge the system. The manifold assembly is attached as one large structure to the top of the bottles and the assembly is placed next to Hydra. For the fuel, the use of a single, small, one-gallon high pressure fuel tank was designed to be used. This minimized the cost and allowed us to buy a certified and tested commercially available tank. This choice also maximized safety since there is less fuel under pressure during firing, allowing for quicker venting and shorter burn duration. If the fuel needs to be purged or drained, it is a manageable quantity. Since the pressurized fuel tank during firing is small, a large supply tank with a pump is used to fill it up which can hold 15.5 gallons; it is always kept at atmospheric pressure. For similar reasons as not having a dedicated high-pressure oxidizer tank, there is also no dedicated pressurant tank that is supplied. A single high pressure inert gas bottle is transported independently from Hydra and ratcheted to the side of the test stand connected via flexible tubing to the high-pressure fuel feed system.

Apart from these main tanks, a commercially available compressor is used to supply air to the pneumatic valves. It is also transported independently and kept outside of Hydra due to size restrictions. To make sure there is a sufficient supply all the time and since the regulator on the compressor cannot keep up with the flow rate demands of the valves, the compressor supplies air to a buffer tank on Hydra via a flexible tube. All the pneumatic valves use the air from this tank during operation also via independent flexible tubes, and the compressor fills this tank intermittently. All the tanks in reference to the test stand are shown in Fig. 7.

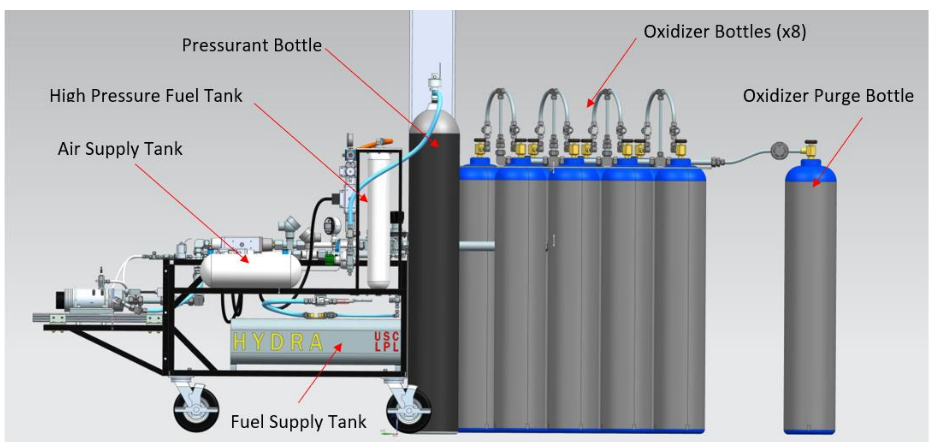

Fig. 7 CAD of the fuel, oxidizer, pressurant, and air tanks and bottles.

2. Pressurant Flow

Shown in Fig. 8, the pressurant flow begins with the high pressure inert gas bottle (maximum pressure of 3000 psi) followed by NV1-P. This valve is the manual valve that comes with all commercial high-pressure bottles to open and close the outlet of the bottle. Using the corresponding Compressed Gas Association (CGA) fitting, an analog pressure gauge, PG1-P follows to closely monitor the pressure in the line (and bottle when opened). The gauge serves a safety measure to make sure there is no pressure in the line when removing the bottle, allows us to quickly determine if the bottle has enough pressure for firing, and serves as a back-up to the digital pressure transducer PT1-P. Followed, is a particulate filter, PF1-P, to filter out any contaminants that could have been in the bottle or in the line when the bottle was not installed. RG-P is the main regulator for the pressurant and consequently the fuel for Hydra. It is a single stage pressure reducing manual regulator designed for a maximum inlet pressure of 6000 psi and outlet pressure of 0-2000 psi. Two small analog gauges are mounted on the body (PG2-P and PG3-P), followed by a larger analog gauge PG4-P and digital pressure transducer PT2-P to monitor the outlet pressure of the regulator.

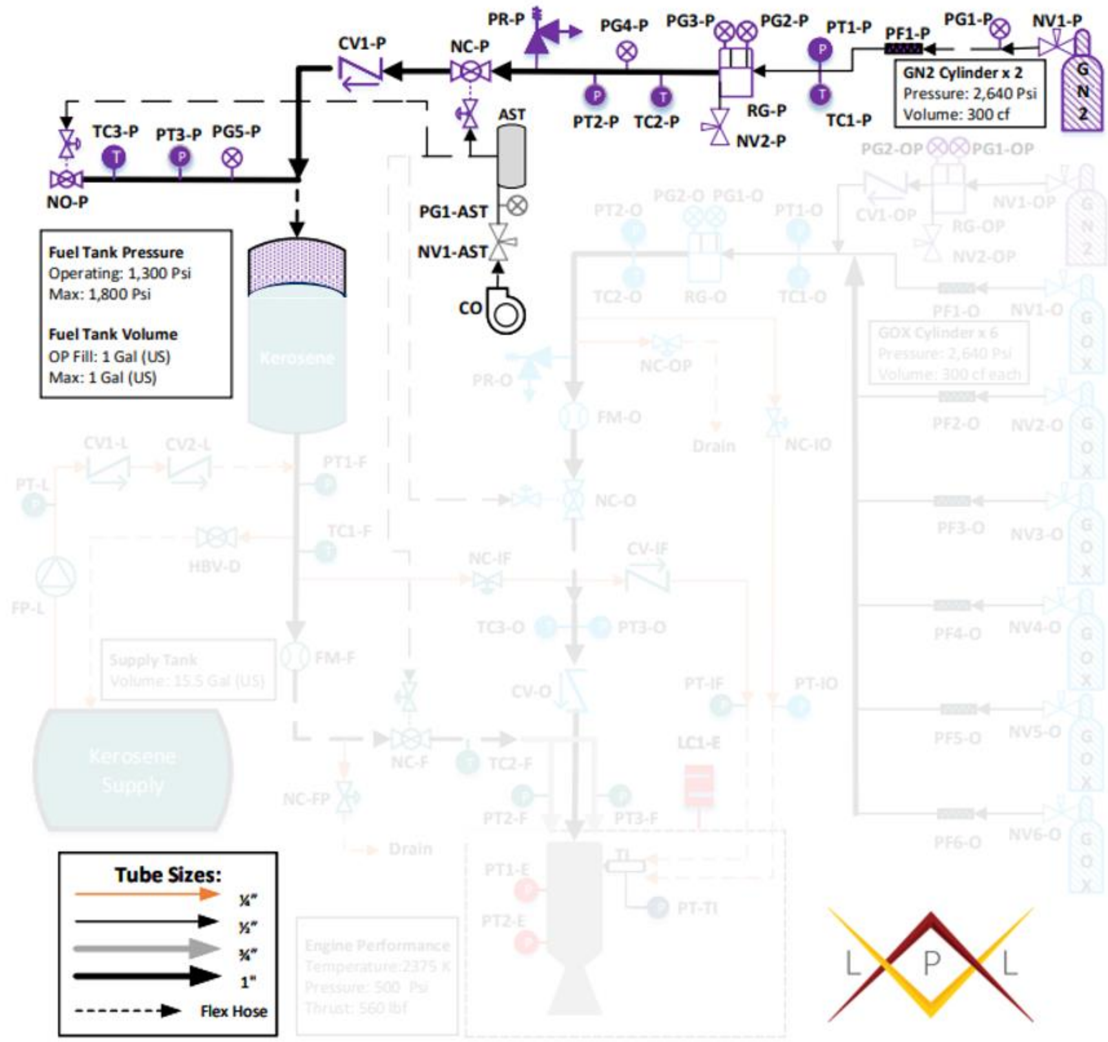

Fig. 8 Schematic of Pressurant flow.

NC-P is the normally closed (spring-return) pneumatic ball valve that is remotely controlled. Via a solenoid, air from the Air Supply Tank (AST) pressurizes the valve stem to turn the ball appropriately. This pressurizes the fuel up to the Main Fuel Valve (MFV) before the engine. The valve pressurizes the fuel from the top and the valve is forced to open slowly to prevent slamming the fuel with a column of gas, this however doesn't prevent the valve from closing fast, this mechanism is shown in Fig. 9.

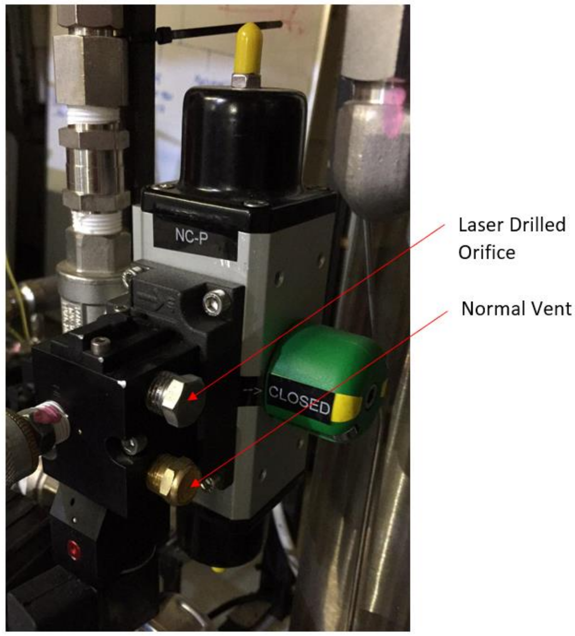

Fig. 9 NC-P with an orifice on one of the two vents. The pneumatic part of the valve has two chambers, since it is a spring return valve, only side is pressurized to open it. Two vents are located on each chamber to vent the air from the contracting side. To make the valve open slowly an orifice was used to replace the vent to constrict the flow coming out, hence turning the stem slowly, however, since the other vent is not tampered with, the valve closes with normal speed.

PR-P is a relief valve and burst disk assembly used to protect all the downstream components. If the regulator if set higher than the maximum allowable set pressure, the relief valve will crack open and then re-seat itself after the pressure goes back down. However, in a case where there is too much pressure and it is rapidly building up, the burst disk will open and vent the gas at a much a higher flow rate. The check valve, CV1-P, also serves a similar purpose, to ensure flow is always directed downstream to the fuel; even if a catastrophic failure upstream were to occur prior to the check valve to ambient pressure, the valve will seat and prevent any backflow if the system was already pressurized.

NO-P is one of the more critical safety mechanisms built into Hydra, this normally-open pneumatic ball valve, is operated remotely similar to NC-P and must be closed to start pressurizing the fuel tank and must remain closed during the entire firing. Its large Cv allows the relatively small volume of pressurized gas in the fuel tank and lines to be quickly vented. If there is a power loss in the control system, the valve will open and vent any high-pressure gas in contact with the fuel. For the system to be safe, no power is required since the valve will spring-return-open, preventing and venting and pressurization.

Temperature probes, TC1-P, TC2-P, and TC3-P are set to monitor temperature fluctuations in different parts of the pressurant feed system. They mainly play a role for research and educational purposes and are placed in different parts of the feed system to see how different flow rates and pressures affect the flows temperature.

3. Fuel Flow

Shown in Fig. 10, the fuel flow starts with the fuel tank; it is a stainless-steel tank with mounted vertically on Hydra. The tank is filled with fuel remotely using an electric pump (FP-L) that fills the tank from the 15-gallon supply tank located underneath, this is verified by the pressure transducer PT-L. The fuel is filled from the bottom across a pressure transducer and two check valves CV1-L and CV2-L. There are redundant check valves to ensure there is no possibility of high pressure gases reaching the fill tank as it is not rated to hold any pressure. The supply tank is constantly being vented; the port acts as a means of filling the tank once at the firing range and prevents the tank from pressurizing or pulling a vacuum when the pump is operational. A manual ball valve, HBV-D, is the only other path to the supply tank, which is used to drain the fuel from the lines and pressurized tank if needed.

Followed after the pressurized tank, a pressure and temperature transducer, PT1-F and TC1-F, measure data from the outlet of the tank. The tapped-off line for the fuel side of the ignitor is located at this point as well. A turbine flow meter measures the volumetric flow rate right before the MFV, NC-F. This normally closed valve is a pneumatic valve also controlled remotely using a solenoid and air from the on-board AST. A drain line consisting of a solenoid (NC-FP) and a long flexible hose is located right before NC-F. The high-pressure gas before the fuel, allows the entire fuel feed system before the engine to be completely drained through this line after a firing. Before a firing, this line also acts as the means to prime all the fuel lines up to the MFV. The solenoid valve and flexible hose are positioned in a way so that the fuel lines must be filled with fuel and the solenoid closed before the rest of the fuel tank can be filled. The flexible hose coming out of the drain line is open to atmospheric pressure and is securely placed inside a container outside of Hydra to dispose or recycle the fuel. The outlet of the line can be monitored visually from a remote location.

When the MFV, NC-F, is open, fuel temperature and pressure are measured with transducers, TC2-F, PT2-F, and PT3-F and is then injected into the test article. Depending on the configuration required, a manifold can split the fuel injecting it in two different locations.

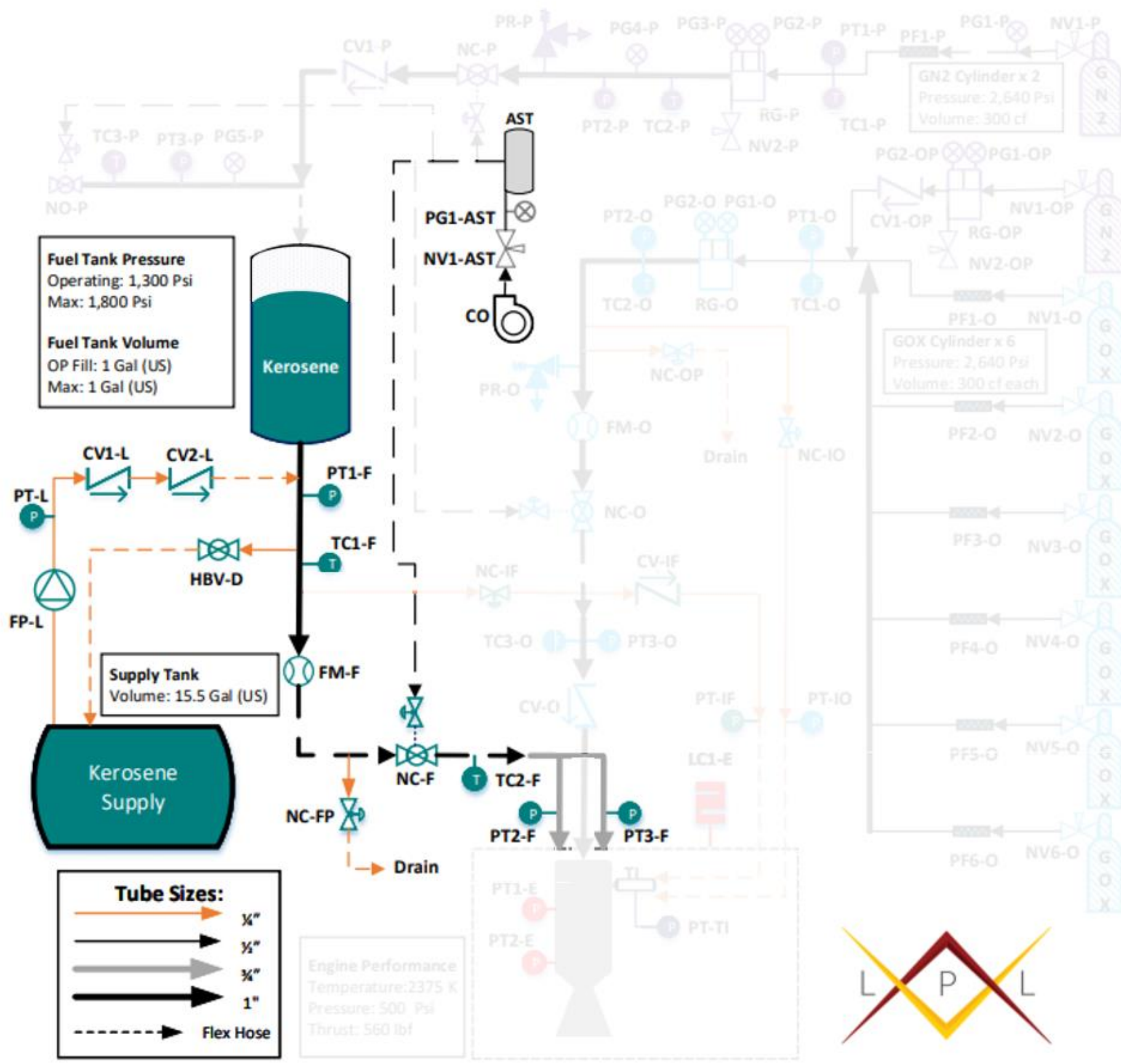

Fig. 10 Schematic of Fuel flow.

4. Oxidizer Flow

To supply a high flow rate, six or eight oxidizer bottles can be hooked up in parallel in a manifold, shown above in Fig. 11 is the six-bottle manifold configuration. After each oxidizer bottle, there is a manual needle valve that comes with all commercial high-pressure bottles to open and close the outlet of the bottle. After using the corresponding CGA fitting to connect the bottle to the oxidizer manifold, a particulate filter to filter out any contaminants that could have been in the bottle or in the line when the bottle was not installed, is used. On the same manifold, an inert gas bottle is installed with a regulator and check valve. This line is attached to the manifold but doesn't allow oxidizer through because of the check valve. The purpose of the line is to push out any oxidizer gas to purge the feed system and test article. Depending on the situation, if the engine needs to be purged, it is much easier to do so using this purge line rather than using the pressurant gas. If the fuel is in the lines or tank, the fuel would need to be drained to use the pressurant gas, since the oxidizer is a gas, the purging is much simpler coming from the oxidizer manifold. The regulator, RG-OP for the purge is used to decrease the potentially high pressure from the bottle.

The manifold, bottles, and purge line are mounted externally from Hydra. Once connected, flow goes through the main oxidizer regulator, RG-O, and pressure and temperature are measured before and after the regulator (PT1-O, TC1-O, PT2-O, TC2-O). Two analog gauges PG2-O and PG1-O are mounted on the body of the regulator to finely adjust the pressure of the manual valve.

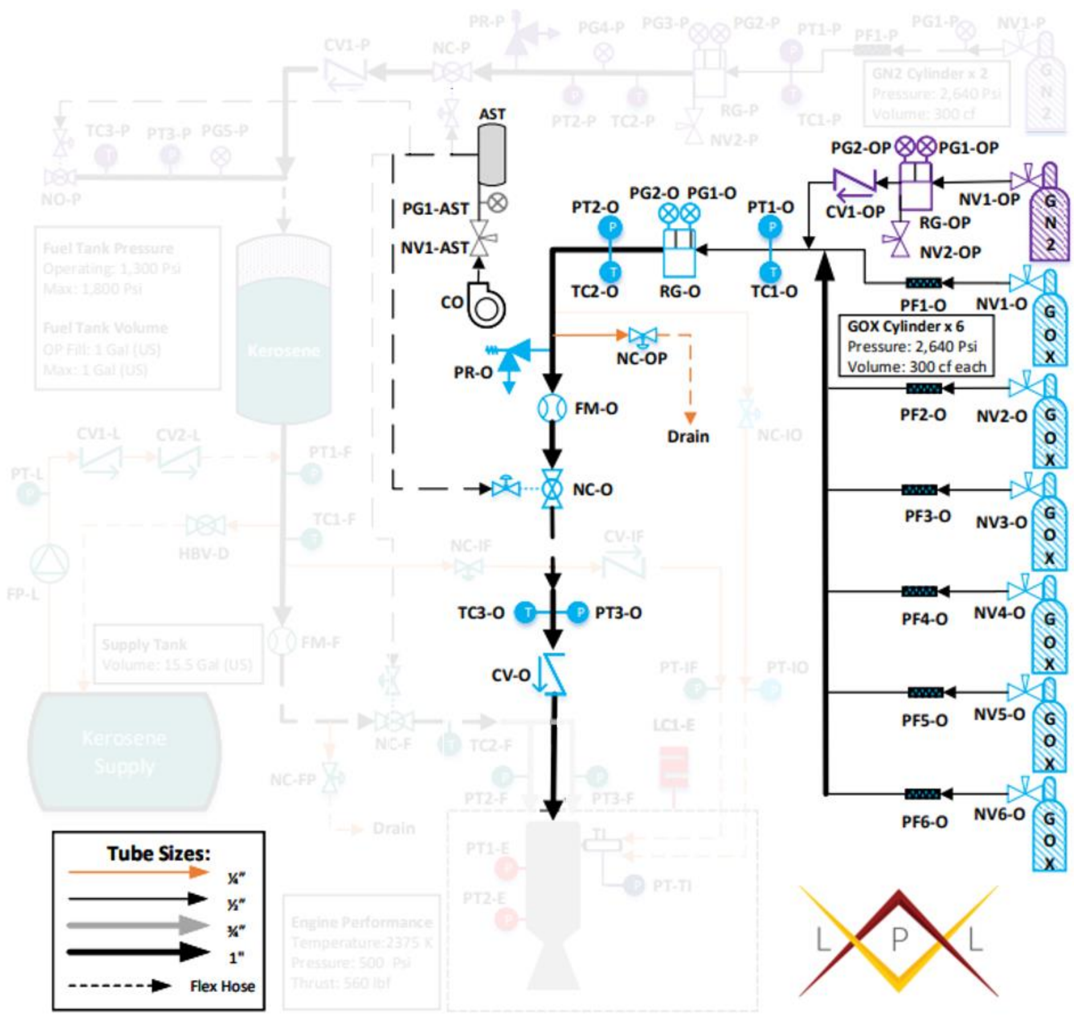

Fig. 11 Schematic of Oxidizer flow.

Similar to the fuel line, a drain line with a solenoid (NC-OP) is used to prime and drain the oxidizer gas and a tapped-off line for the oxidizer side of the ignitor is located at this point as well. Since the oxidizer is a gas, it is not critical to have the prime/drain line as close as possible to the Main Oxidizer Valve (MOV), for convenience it is located after the regulator RG-O, next to the ignitor line.

Like the pressurant flow, a relief valve and burst disk assembly (PR-O) is used to protect all the downstream components after the drain and ignitor lines. This is followed by a turbine flow meter to measure the volumetric flow rate right before the MOV, NC-O. NC-O is a normally closed pneumatic valve also controlled remotely using a solenoid and air from the on-board AST. After the MOV, a pressure and temperature transducer provide data right before the test article. A check valve, CV-O is the last component before the test article. The check valve function is to prevent any backflow of the combustion gases or fuel into the oxidizer feed system.

5. Ignitor

Shown in Fig. 12, Hydra's feed system taps off from the main fuel and oxidizer lines after the regulators to enable the user to utilize a constricted (through orifices) amount of propellant as an ignitor. After being taped off, the lines go to independent normally closed solenoids (Fig. 13) that are controlled remotely and then through a check valve to prevent any back flow from the high chamber pressure inside the engine. Alternatively, an e-match can be used which can ignite a pyrotechnic charge to ignite the engine.

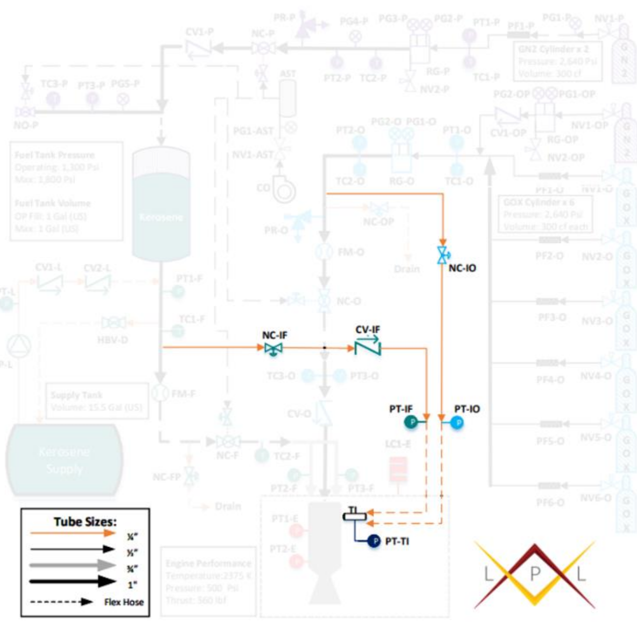

Fig. 12 Ignitor Schematic.

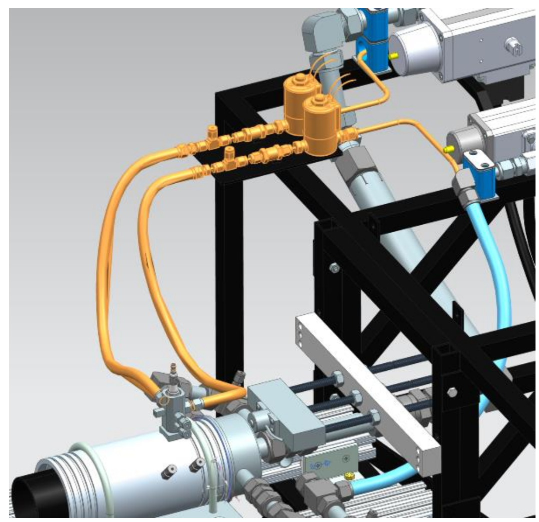

Fig. 13 CAD of ignitor lines.

6. Electronics and Controls

The electronics control and data acquisition (DAQ) hardware is enclosed in a box which is integrated into the bottom of the chassis of Hydra, opposite to the fuel supply tank. The box includes power distribution for all sensors and valves, a printed circuit board (PCB) for data input and output, and DAQ hardware.

The interface between the DAQ and the controls unit is provided by connectors on the back side of the electronics box where dust and waterproof circular connectors are located. These connectors can only be installed in one orientation; this ensures proper installation and avoids damage to the sensors caused by incorrect wiring. Because of the high vibration caused by the engine during the hot static fire, every sensor has additional locking features to maintain proper connection for the duration of the test. The locking features are threaded and bayoneted connection.

Communication between Hydra and the bunker where the main computer is located is enabled by a 100-foot-long USB cable. It is a two-way communication channel: from the main computer to Hydra, communication includes signals to actuate valves, abort signal, etc.; while in the other direction Hydra is sending information about the valve state and sensor readings including pressure, temperature, flow rates, and thrust measurements.

The control code is written in LabVIEW; this program was chosen because it comes with plug and play hardware that enables easy integration of the electronics with the main computer. Additionally, the user can easily design user interface panels where buttons and sensor readings can be monitored. There are three user panels that have been designed which the operator can use.

The first one, "Parameters", is used to set all important parameters as pressure maximum and minimum limits to ensure safe operation. The operator can then set the timing for the firing sequence including the time for ignition, opening MOV, and opening MFV. The operator can also set how much fuel to pump from the fuel supply tank to the pressurized fuel tank between firings (shown in Fig. 14).

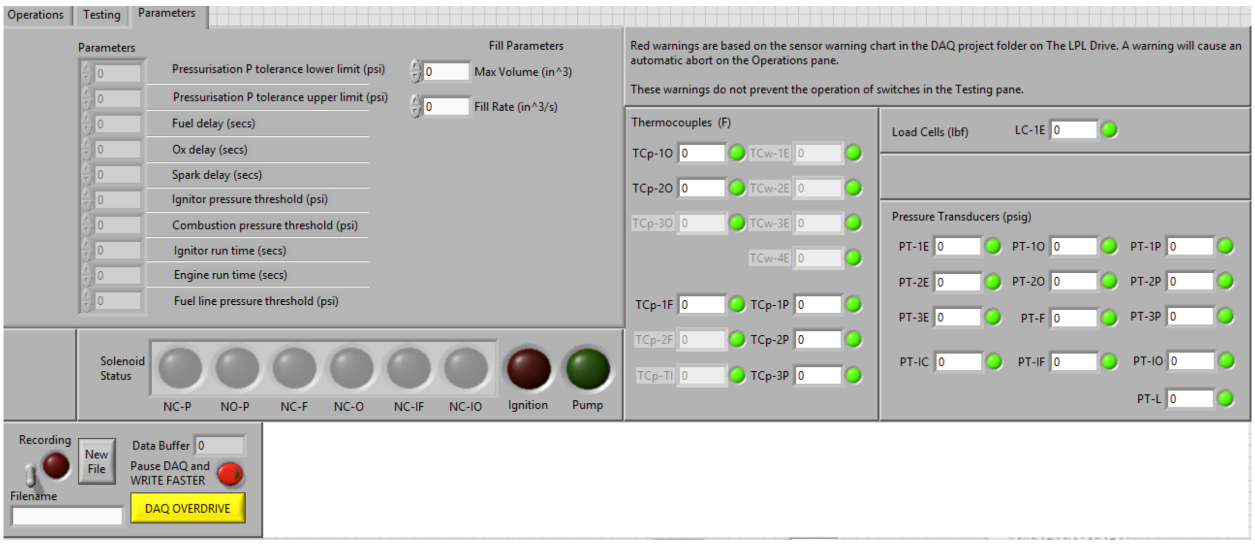

Fig. 14 Parameter panel in LabVIEW.

The second panel, "Testing", is used during testing where the user can actuate each valve individually. This is used for initial testing such as proof and leak tests where the operator can isolate different sections of the feed system. By doing this, the operator can locate possible leaks in the system and diagnose certain issues that may arise without conducting a full test (shown in Fig. 15).

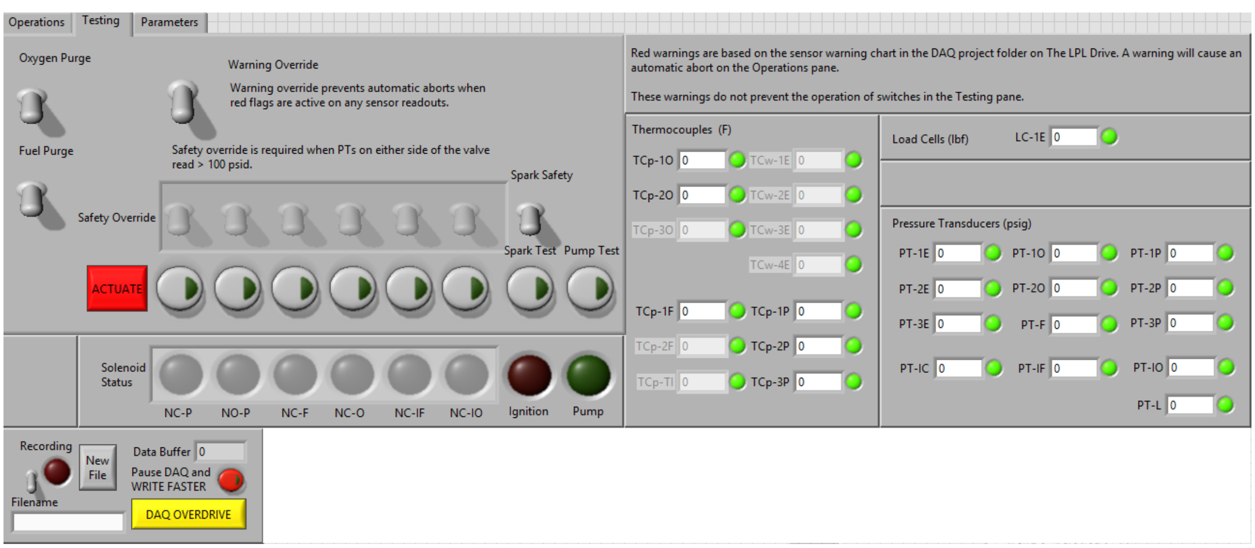

Fig. 15 Testing panel in LabVIEW to operate individual valves.

Finally, the "Operation" panel is used during timing test and the static fire. The operator can fill the fuel tank, pressurize the system, initiate the firing sequence, and purge the system. Every step needs two actions: arm the toggle button and then start the task by selecting a pushbutton (shown in Fig. 16).

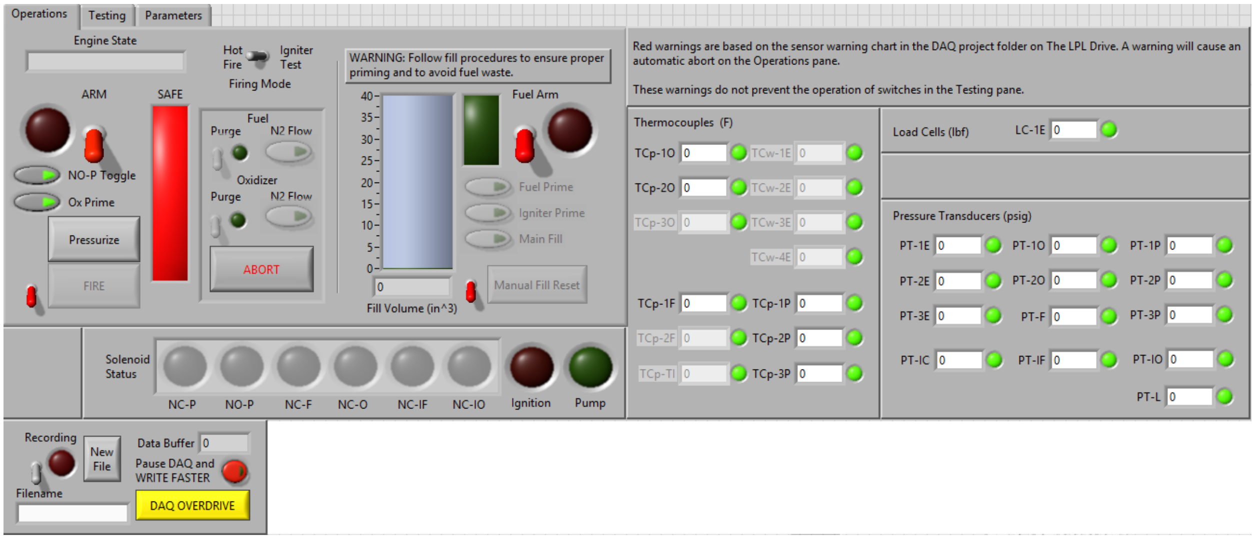

Fig. 16 Operations Panel in LabVIEW.

7. Sensors

The main purpose of Hydra is to conduct tests and record data. To get data, various sensors in different location around the feed system are used. These sensor values are used to characterize performance of the feed system and the test article, along with providing safety checks throughout each test.

Most of the sensors are used to measure pressure in the lines. There are pressure transducers on each line, starting downstream of the oxidizer manifold and downstream of the pressurant bottle. Generally, the first transducers verify if there is enough pressure to conduct any test. The other pressure readings are downstream of both pressure regulators in the system on the oxidizer and pressurant lines. These pressure transducers are used to characterize pressure droop and measure outlet pressure of the pressure regulators.

Additionally, there is a pressure transducer in the high-pressure fuel tank line to verify the fuel level supplied by the pump in the fuel supply tank is met, and later to verify pressurization of the tank. The rest of the pressure transducers are used at the engine injector and chamber to determine engine performance. Each pressure transducer in the feed system is paired with a thermocouple to measure temperature on critical sections of the feed system.

In addition to the pressure and temperature sensors, Hydra also has two flow meters. They are located upstream of the MOV and MFV. The flow meter in the fuel line is provides mass flow rate directly (given density). For the flow meter in the oxidizer line, the mass flow rate calculation requires data from three sensors. The flow meter provides the volumetric flow rate and the pressure transducers and thermocouples in the oxidizer line described above provide pressure and temperature of the flowing gas. Utilizing these three values, one can calculate the mass flow rate using ideal gas law.

C. Strategy

Most design decisions made on Hydra were focused to minimize the time and cost while maximizing the safety and reliability of the stand. To maximize its future potential, parts were designed and selected to be easily repairable and replaceable. The sensors located throughout were placed to further characterize and understand the operation of Hydra and to contribute to diagnosing any issues that may arise.

To decrease the time it took to build and test Hydra, the lead times of critical components were taken into consideration and the amount of custom machining or hardware was kept to a minimum; most of the components were commercially available off the shelf. Another method to make sure Hydra was completed in a timely manner, included careful planning and a full CAD model of all the components and tubing to make sure everything would fit and there were no conflicts.

To keep costs down all the cleaning, assembly, and testing was conducted in-house. The minimal parts that needed to be machined were also done in-house. Most components selected were not “aerospace” grade, however; careful examination of the technical information for each component was taken into consideration in their selection to meet the requirements for the system. The decision to have a small pressurized vessel and an unpressurized supply tank also significantly decreased the price of Hydra.

Another cost cutting decision was to not have an independent pressurized pressurant or oxidizer tank. Whether we would have used the compressed bottles as a direct supply to the feed system or not, we would have needed them to fill an independent pressurized tank initially and a separate system would have needed to be made to transfer the gases from the bottles to the two independent tanks. Substituting the main oxidizer and pressurant tanks with compressed gas bottles directly as the to the feed system eliminated a lot of unnecessary infrastructure. This also provided high reliability since the tanks are commercially available and filled with high pressure prior to receiving them and are made to be transported.

The selection of using a hybrid of both manual and automated valves enabled us to keep the simplicity and cost low while taking sufficient safety measures to operate Hydra in its most critical stages remotely. To keep safety high, the components and fittings were mostly from the oil and gas industry and were made for high pressure, high vibration, and a high number of cycle applications. Hydra has been built with a set of software and hardware safety mechanisms including secure mounting, power loss protocols, venting and purging hardware, excess safety factors for high-pressure components, remote pressurization, relief valves and burst disks, and sensor values that trigger abort. To ensure proper installation, the burst pressure and expected operating pressure were noted, and a proof pressure in between was selected and hydrostatically tested; the parts were later torque stripped after leak checking. In the feed system itself, there are many programmed safeguards and abort scenarios in place, however, mechanically the use of a normally-open ball valve vent, the use of both relief and burst disks, and a purging system are examples of safety measures put in place and implemented from the initial design. Another safety feature was adding long vertical tubes on the outlets of the relief valves and main vent, to allow any vented high-pressure gas to be redirected upwards and away from any operator. The tubes also have a small flag that can be seen from a distance only moving when gas is being vented.

Since Hydra needs to be able to fit inside a trailer and to minimize the setup time, most of the feed system is mounted on Hydra. To set up Hydra for testing, the pressurant and oxidizer bottles must be connected, the oxidizer manifold must be connected to Hydra, and the air compressor must be connected to the AST. These are the only high-pressure gas connections that must be made and removed whenever Hydra is setup or transported. The fact there is a minimum number of connections increases the reliability of the system and allows us to remain confident that the system will hold the necessary pressure over many tests. Given a limited lab space, size, and weight, Hydra was designed to be easily maneuvered in the lab and transported in a trailer to test sites. The system requires minimal assembly to optimize the time necessary to set up for tests and hot fires.

III. Testing Campaign

During the construction phase of Hydra, all parts and materials were procured, fabricated and verified to fit and operate nominally. A two-month rigorous testing campaign was performed to validate that all hardware operated as expected and to confirm Hydra’s functionality worked as planned. During the testing campaign, Hydra was completely disassembled, ox-cleaned, inspected, and reassembled. A systematic hydrostatic proof test was performed to ensure the feed system could hold pressures above standard operating conditions. Afterwards, a gas leak inspection was conducted to ensure fittings were bubble-tight above standard operating conditions as well. The last testing campaign milestone was a set of cold flow tests using water and nitrogen gas to validate the operations and evaluate the performance characteristics.

D. Oxygen Cleaning

It is important to follow cleaning standards to ensure safety for oxygen-enriched systems. Oxygen itself will not burn, but it will vigorously support combustion of other materials. Ignition hazards must be avoided, which includes heat from mass impact, heat from particle impact, organic compound contamination, etc., [2]. The LPL has developed a procedure to clean for oxygen usage in reference to ASTM G93, [1], and NASA Safety Standard for Oxygen and Oxygen Systems, [2]. The procedure includes using an all-purpose degreaser, an acetone pre-clean, an isopropyl-alcohol wipe down, and precision cleaning using an ultrasonic cleaner with isopropyl-alcohol. Visual inspections are done to find any particulate matter larger than 50 micrometers, and any moisture, oils, or grease. There are two steps of inspection, before and after the precision cleaning. If the components are not visibly clean, they will be sent through the process again until clean. Each component is documented with inspection pictures. The components are then dried by using filtered air or nitrogen. To minimize particulates introduced during this process, cleaning supplies used must be foam-tipped swabs and low lint chemical wipes.

8. Hydrostatic Proof Testing

Hydrostatic proof testing is a procedure to qualify a test article and prove that it will maintain and hold operating pressures during nominal operation. This test is conducted using deionized water and a hydrostatic pump. It is safer to proof a system using water rather than gas because it is incompressible and contains less energy when pressurized in a given volume. It has less potential energy hence damages are mostly limited to the nearby area. Using water instead of a compressed gas minimizes the quantity distance Proof pressure was stated to be 150% of the operating pressure. This provides a safety factor in the case of over pressurization during operation. Prior to proof testing, the maximum operating pressures of all components must be above the set proof pressure. The test is conducted in stages by dividing the proof pressure by five. The first stage is the lowest pressure and each following stage increases until the fifth stage, which is proof pressure. If a leak resulting in a pressure loss is found during any of the stages, the system is depressurized, and the component is tightened. This test is completed when the fifth stage is reached and there are no visible leaks or loss of pressure. Once the test article is proof tested, it is qualified for leak testing.

E. Gas Leak Inspection

The gas leak inspection test uses nitrogen, a smaller particulate medium than water, to locate further sources of leaks. The maximum pressure used for leak testing is 110% the operating pressure. The leak testing uses a similar staging process to proof testing by dividing the leak pressure by five and increasing pressure each stage. Major leaks are found using a leak detection fluid. If major leaks are detected, the system is depressurized, and leaks are fixed by torquing fittings or reassembly and alignment. For each stage, the supply pressure is shut off and the leak rate is quantified for five minutes. This leak rate is documented for each stage. A test article has passed the gas leak test when there are no major leaks and the leak rate is acceptable at the maximum leak pressure. Torque stripping is then applied to leak tight fittings to verify if components shift and become un-torqued throughout the testing phase or shipment of the test stand.

F. Cold Flow Testing

After qualifying the engine and test stand through pressure testing, a cold flow campaign is completed to find the operational system parameters for each static fire. These parameters and operating conditions vary with different engines and components. Cold flow tests are conducted to find the Cv of the injector for both fuel and oxidizer sides and to find the pressure to set the pressurant and oxidizer regulator during a static fire. After these tests are completed to characterize how the system will be set for operation, a timing test is conducted to find the optimal timing for ignition, fuel flow, and oxidizer flow. Deionized water and nitrogen are used for the fuel and oxidizer lines respectively.

9. Fuel Line

To characterize the fuel line for the static fire, one test was designed to find the pressure drop over the fuel side of the injector and another test for finding the value to set the pressurant regulator to. The setup for these tests consists of connecting the fuel line of Hydra to the fuel side of the injector. Cold flow tests using water to simulate fuel are then conducted.

For each injector test, data are gathered for the flow rate and pressure drop over the injector. Using Eq. (1) for liquid flow, the Cv for the injector is found by [3]:

$$q = N_1 C_v \sqrt{\frac{\Delta p}{G_f}} \tag{1}$$

The Cv found from each test is averaged to find the pressure drop over the injector during operating conditions also by using Eq. (1). The designed flow rate and specific gravity of fuel are used. This pressure drop is used as a starting point for the following test.

To determine the set pressure of the pressurant regulator, a needle valve is used to simulate the pressure drop that occurs over the engine during static fire. The needle valve is connected to the end of the fuel line on Hydra in place of the injector. The pressure drop over the needle valve is set to match the pressure drop over the engine during a static fire, which is equal to the designed chamber pressure plus the pressure drop over the injector (found in the previous test).

Equation (1), is used to determine the Cv of the needle valve necessary to provide a pressure drop equivalent to the engine. The needle valve Cv is set to the calculated value by using a curve provided by the needle valve supplier for Cv versus number of turns open. The initial pressurant regulator setting is determined by using flow curves for pressure droop given by the regulator supplier. These curves give the pressure droop as a function of flow rate, inlet pressure, and outlet pressure. An initial value is chosen to give an outlet pressure near the pressure drop expected over the needle valve. Iterative testing is used with adjusting the number of turns to open the needle valve (corresponding to a given Cv) and changing the regulator pressure. The outlet of the pressurant regulator is found when the pressure drop over the needle valve is equal to the engine pressure drop and the operational flow rate is achieved, verified by flow meters. The test is repeated to ensure the test is giving correct data.

10. Oxidizer Line

It is also important to characterize the oxidizer line to find the pressure drop over the injector and what value to set the oxidizer regulator to for the static fire test. These values were found simultaneously by conducting an orifice test. The test setup includes the full engine assembly minus the nozzle. The orifice is placed in the engine instead of the nozzle to provide the needed pressure drop that will be experienced by combustion during static fire. The orifice is sized using Eq. (2) for choked gaseous flow [3]:

$$q = 0.471 N_2 C_v p_1 \sqrt{\frac{1}{G_g T_1}} \tag{2}$$

This test is repeated until the designed flow rate and pressure drop over the orifice corresponding to the chamber pressure of the engine is achieved.

11. Timing test

The timing test is conducted to determine the parameters for starting the oxidizer flow, fuel flow, and lighting the ignition source. Finding the time delay for each line to enter the engine after electronic actuation is critical for a safe ignition sequence. For best replication of the system prior to ignition, Hydra is set to operate at the conditions selected for static fire from the testing campaign. The proper ignition sequence is to light the ignition source first, followed by oxidizer flow, and then fuel flow. Once the ignitor is lit, the oxidizer flow will increase the temperature of the burning flame of the ignitor which will make the fuel ignite at the instant it enters the engine. The delays between each actuation should be on the order of milliseconds.

The timing test should be verified using slow motion video and referencing the data obtained from the sensors. Ensuring that oxidizer is timed to be inside the chamber prior to the fuel avoids a hard start because the oxidizer will escape the chamber and cannot accumulate like the liquid fuel. Also, leading with oxidizer ensures that once the fuel is introduced, combustion will immediately occur because of the high temperature of the ignitor burning vigorously in an oxygen-enriched environment. Several iterations of the timing test are conducted to find the timing needed for the static fire (Fig. 17). The time delays found through this test are then implemented into the parameters pane of the DAQ software.

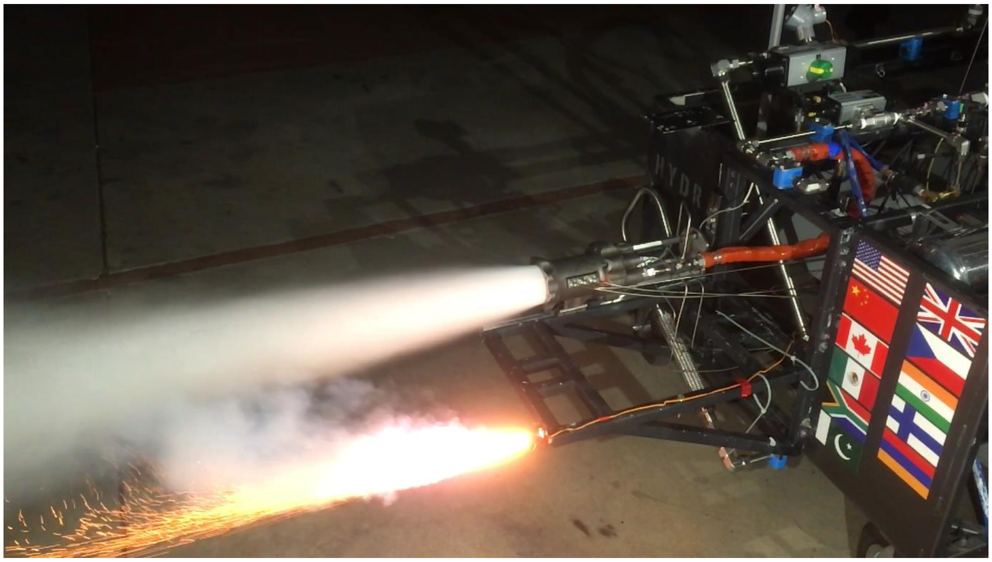

Fig. 17 Image of slow motion video showing the timing test conducted for the Jessie engine.

IV.Static Test Fire

G. Teams for Test Firing

To perform a static test fire, Hydra requires a Test Coordinator and three teams: Setup, Bunker, and Operations. The Setup team is responsible for general logistics and assistance needed throughout the day, including communications, equipment distribution, inventory control, and safety protocols. The Bunker team is responsible for Hydra's DAQ system, power, programming, operations of electronic valves, and data communication (this team is located in the Bunker shown in Fig. 18). The Operations team is responsible for inspecting, fueling, and opening/closing and setting manual valves (this team is located in the Hydra Mounting Location shown in Fig. 18 during setup). The Test Coordinator oversees and directs the teams through all procedures, clearing each action and solving any immediate problems.

Fig. 18 FAR test site aerial view.

H. Operations

The operations to test fire an engine using Hydra are separated into three main procedures; Pre-Fire Checklist, Firing Sequence, and Post-Fire Checklist.

The Pre-Fire Test document highlights the steps taken, in proper order, to take the system from its stable state during transport to a successful static fire.

The main steps are:

- Unload everything and bolt Hydra to the ground or I-Beam
- Setup the oxidizer manifold
- Connect all the compressed gas bottles
- Connect power and check communication from the DAQ to the control bunker
- Check for leaks in any of the connections
- Fill the AST
- Mount the cameras
- Check that the valves are at their starting and default position
- Fill the fuel supply tank
- Open the compressed gas bottles
- Set the outlet pressures of the regulators
- Prime the system
- Start recording for the cameras

The Firing Sequence document highlights the steps taken, in proper order, to perform initial, recycle and final shutdown firing sequence. The recycling sequence considers whether the system was previously successfully fired or was aborted. The steps are all conducted remotely; the system is pressurized, a countdown is announced, the data recording begins and the MFV and MOV are opened for the duration of the firing unless an abort is triggered.

This Post-Fire checklist document highlights the steps taken, in proper order, to take the system from its final shutdown firing sequence to a successful tear down to transport Hydra. The information is saved, and all the oxidizer bottles are closed. The system is then drained, purged, and de-pressurized. At this point the components that need to be removed can be removed safely.

I. Static Test Fire Results - Blue Steel 2.0 Engine - December 2nd, 2017

On December 2nd, 2017, the Hydra integrated test stand and Blue Steel 2.0 engine was successfully fired (shown in Fig. 19), validating the functionality of the system and its future potential. Each team's performance played a vital role in the successful testing and firing of Hydra.

Fig. 19 Blue Steel 2.0 Engine (Kerosene and GOX, 500 lbf thrust, 6 second duration).

Even though Hydra performed as expected, the Blue Steel 2.0 suffered an O-ring failure that was able to be diagnosed, detected, and analyzed using the data Hydra collected from the engine and feed system shown in Fig. 20 and Fig.21.

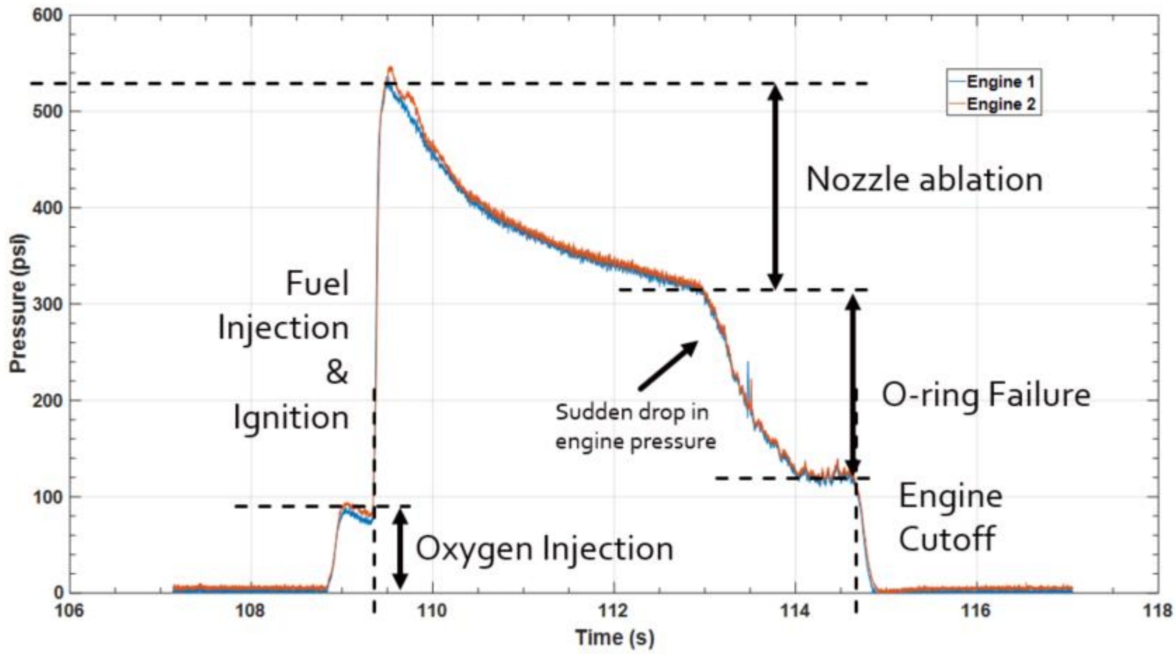

Fig. 20 Data from two-pressure transducer channels inside the combustion chamber of Blue Steel 2.0.

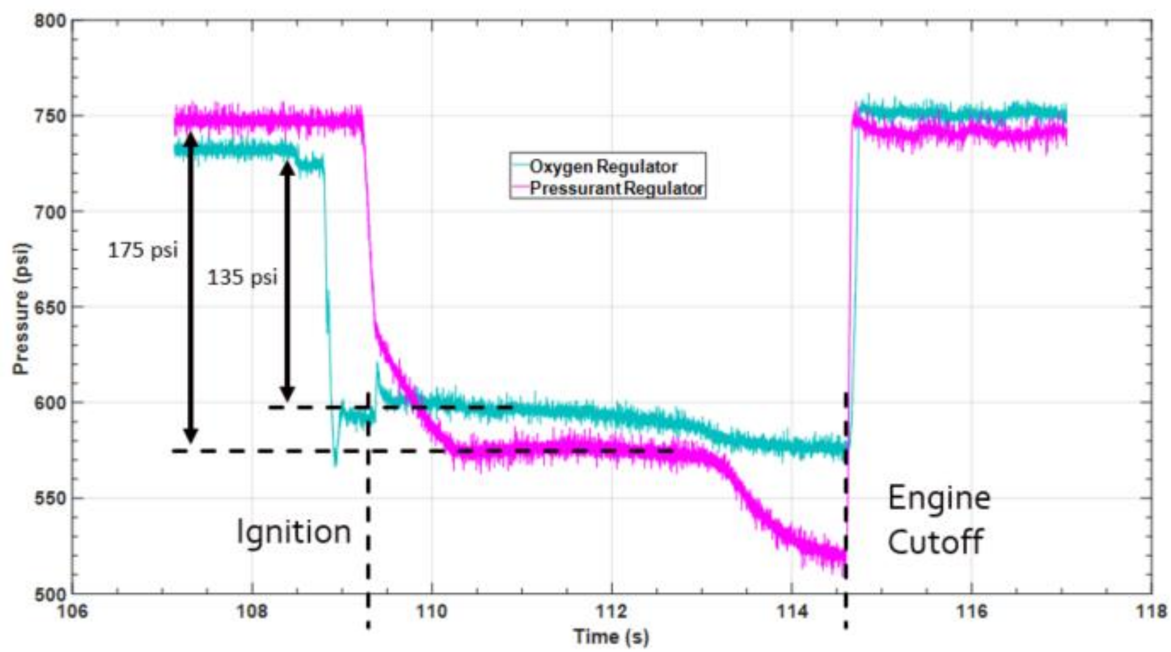

Fig. 21 Outlet regulator pressure note the pressure drop during firing.

Hydra was able to help determine the root cause of the failure to not be linked to the feed system but rather an error in the Geometric Dimensioning and Tolerancing of the component.

J. Static Test Fire Results - Jessie Engine - June 2nd, 2018

On June 2nd, 2018, exactly 6 months from the Blue Steel 2.0 static fire test, the Hydra integrated test stand and Jessie engine was successfully fired (shown in Fig. 22). Although the engine itself suffered a failure, Hydra successfully supported the new feed system requirements (shown in Fig. 23).

Hydra played a key role in determining that the root cause of the failure originated from selecting the fuel to be introduced into the engine first (due to ignitor restrictions) rather than the oxidizer, causing the engine to hard start; Hydra was undamaged.

Fig. 22 Jessie Engine (Kerosene and GOX, 3D printed, 750 lbf thrust, 1000 psi chamber pressure).

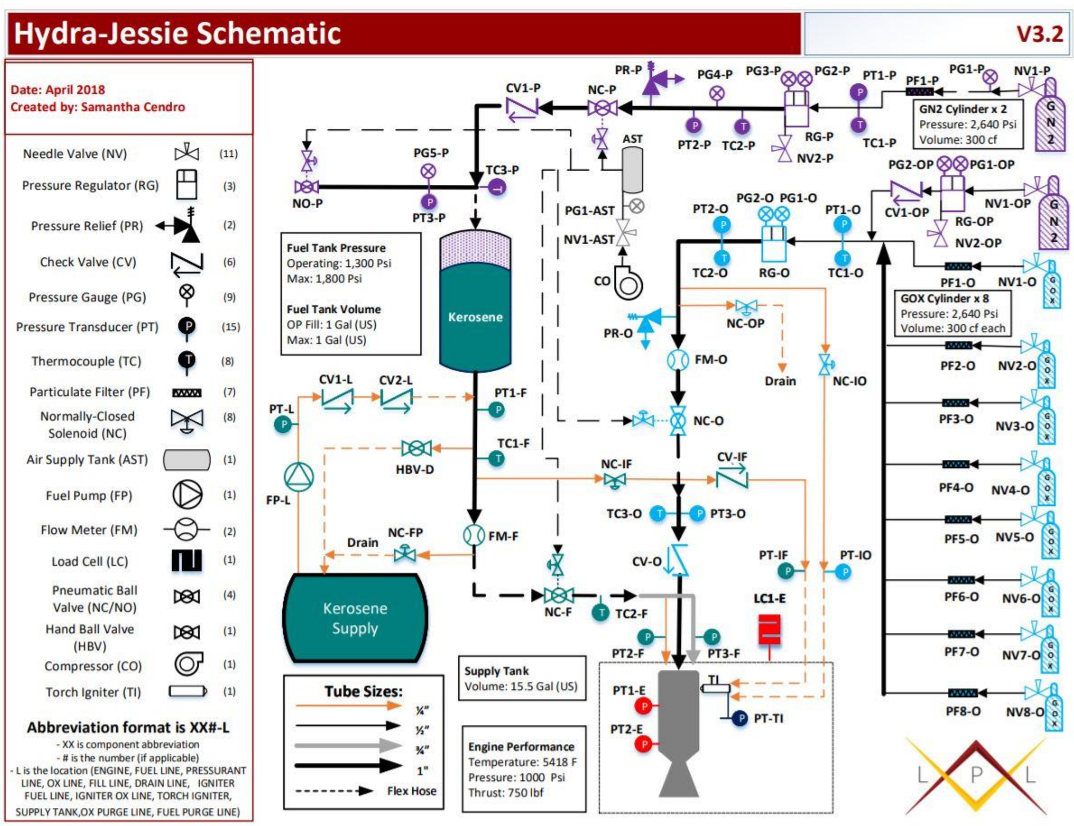

Fig. 23 Hydra - Jessie schematic - To support the Jessie Engine, Hydra was modified to use eight oxidizer bottles. Jessie uses kerosene, gaseous oxygen, and nitrogen as fuel, oxidizer, and pressurant respectively in this configuration.

V.Future Developments and Lessons Learned

Hydra was designed to be easily modified and enhanced for future uses. Hydra was designed with versatility in mind: sensors can be easily added, the software can be modified, various engines/ignition systems can be accommodated, different pressures can be set effortlessly, and various fuels (liquid) and oxidizers (pressurized gas) can be used. A modification to add more sensors and cameras to collect more data and automating all valves so that all the positions can be set remotely, including the opening and closing the high-pressure gas bottles is being considered. The possibility of switching from a back pressure regulated to a Dynamic Pressure Regulated (DPR) system is also being considered to simulate flight conditions and test throttling capabilities for rocket engines.

During the designing, building, and testing of Hydra, several important lessons were learned which will help future groups when undertaking similar projects:

- Design the system such that it can be easily primed by minimizing the vertical bends in tubing and having bleed ports at all high points (except for small lines where gas entrapment is deemed acceptable); sensor ports should generally be pointed downwards so bubbles escape
- Measure all parts when they arrive to make sure they match the model and technical information
- Design the system with testing in mind, any added ports for inlets and outlets should be part of the design and plugged when not in use
- NPT fittings should be avoided where orientation is critical
- Limit the amount of NPT fittings to a minimum; the Teflon tape required is installed manually, varying from person to person. This creates an unnecessary risk and often delays for critical components
- Make sure component materials (including interior parts) are compatible with cleaning chemicals and water (IPA, Acetone etc.)
- Make the electronics enclosure and anything else on Hydra waterproof or able to be easily protected from water for cold flow and hydrostatic testing
- Make data and power cables robust and safe against tugging and breaking
- If the maximum pressure is achieved or there is no power, the feed system should be able to vent autonomously and mechanically
- Analyze the structure for all load cases, not just nominal/steady state (startup transients, hard-start, etc.)
- A rigorous cleaning and inspection process should be conducted and logged

These design choices along with the others described in this paper maximize Hydra's capabilities and ensure it can be repeatedly used to conduct quick turnaround tests and supports LPL's educational goal for its current and future members. The success of the project proves LPL's ability to design, manufacture, and test aerospace-grade hardware in university lab environment. For more information about Hydra and other projects please visit our website at usclpl.com

Acknowledgements

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