Design of a GRCop-42 Regeneratively Cooled Thrust Chamber Assembly and Feed System

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An additively manufactured thrust chamber assembly was designed and printed using laser powder bed fusion. The NASA-developed material GRCop-42 was used for its high strength and high temperature characteristics. The combustion chamber and nozzle utilize regenerative coolant channels to achieve long duration hot fire tests. Design for additive manufacturing was used to create geometries not easily attainable with traditional machining. The thrust chamber assembly was post processed to ensure print quality and verify for testing. A feed system – encompassing all propellant lines, valves, sensors, and tanks – was designed and built to enable steady state, pressure regulated testing. Pressure transducers, thermocouples, and load cells were placed to enable measurements of the propellant properties and engine performance. Venturis and orifices were used throughout the system to control the flow rates to the thrust chamber. Aside from providing propellants, the feed system provides pressure using nitrogen, and purges the lines during shutdown. The design process for this testing platform is described. A testing campaign on the hardware will be conducted by the Akronauts Rocket Design Team at the University of Akron in Spring 2023.

I. Nomenclature

A	=	area
C_d	=	discharge coefficient
C_f	=	thrust coefficient
C^*	=	characteristic velocity
D	=	tank diameter
d	=	clearance hole diameter
E	=	edge distance from hole
F	=	force
h	=	specific enthalpy
L^*	=	characteristic length
$\dot{m}$	=	mass flow rate
N	=	number of bolts
P	=	pressure
s	=	specific entropy
t	=	tube thickness
V	=	volume

Subscripts

1	=	upstream of the injector
2	=	downstream of the injector
b	=	bolt
c	=	chamber
i	=	injector
MEOP	=	maximum expected operating pressure
t	=	throat
v	=	vapor

Symbols

Δ	=	delta across injector
ρ	=	density
κ	=	non-equilibrium parameter
σ	=	stress

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II. Introduction

In 2014, a small group of students at the University of Akron founded the Akronauts Rocket Design Team to attract and inspire people interested in aerospace and give them an opportunity to have hands-on experience building rockets. In less than a decade, the team has grown from less than 10 students to nearly 70 active members. Simultaneously, the team's designs have become more complex, moving from single-stage rockets with commercial motors to two-stages with student researched and designed (SRAD) motors that have reached over 35,000 ft.

In 2021, the team expanded to develop a liquid rocket engine (LRE) program. Liquid propulsion – while being more complex than solid propulsion – offers numerous advantages such as reusability, longer burn times, controllability (can be throttled, turned off, and restarted), and can give a higher specific impulse. As a result, liquid propulsion is more commonly seen in industry, and the Akronauts Design Team's members wanted to start gaining the knowledge and skills related to it. This led to the team's first bipropellant liquid rocket engine, the Vapak-Ethanol-Nitrous-Motor 4 (VENM 4 – pronounced "Venom"). This engine was designed to generate 500 lbf of thrust and used nitrous oxide and ethanol as propellants at a mixture ratio (MR) of 4.0. It was intended to be a cost-effective thrust chamber assembly (TCA) and featured an aluminum chamber with phenolic-based ablative liner and graphite nozzle. The injector was two pieces, a stainless-steel face and aluminum manifold. The VaPak system, as described in [1], pressurized both propellants using the self-pressurizing nature of nitrous oxide. By keeping the engine design simple, the team was able to focus on developing the test stand required to test it and become comfortable with water tests and cold flows prior to hot fire testing the engine. In September 2022, about a year and a half after the project started, the Akronauts were successful in their first hot fire test of the VENM 4 engine, achieving a 5 second test duration.

Figure 1. Akronauts VENM 4 hot fire test.

Following this success, the Akronauts liquid engine program split into two projects: designing a launch vehicle for the VENM engine to fly the team's first LRE-powered rocket and developing a new engine that improved on the previous design. The new engine design's goal was to utilize steady-state, regenerative cooling to increase test duration, reusability, and performance, as well as to increase thrust. This paper details the design process for the TCA, as well as its feed system.

Figure 2. HORNET TCA rendering (left) and finished assembly (right).

III. Thrust Chamber Assembly Design

The thrust chamber assembly, named HORNET (High-Altitude Sub-Orbital Regeneratively-Cooled Nitrous Ethanol Thruster), is part of a regeneratively cooled, bipropellant LRE. Similar to the previous VENM 4 TCA, it uses nitrous oxide and ethanol as propellants at the same chamber pressure of 400 psia, but a lower MR of 3.2. The increased flow rates and new nozzle geometry puts the designed thrust at 800 lbf at sea level. The main goal of the TCA was to achieve a 15-second hot fire test duration, which resulted in the need for regenerative cooling. Additively manufacturing (AM) the TCA was desired from the beginning of this design to benefit from the time savings, superalloys, and complex geometries that it makes possible. Figure 2 shows a rendering of the assembly as well as the printed and post process version.

A. Design for Additive Manufacturing

Design for Additive Manufacturing (DfAM) principles cover the whole manufacturing process, and all aspects – including post process and verification – must be considered at the beginning. Figure 3 below shows the major process stages, including the part design, the AM process, post processing, and assembly/testing [2]. For the design of this TCA, all printing parameters, model slicing, build layout, etc. were outsourced to the AM vendor. It was also determined very early on that for the size of the components and feature resolution required, laser powder bed fusion (L-PBF) would be the most suitable AM method [3]. For the part design, some of the additive-specific considerations were sacrificial material for build plate separation and machining, the part's build direction, no more than 30° unsupported overhangs, and especially powder removal. The injector was printed face down, requiring it to be separated from the build plate using wire EDM (electrical discharge machining) to avoid burrs covering the injector orifices. Also, the thrust chamber was designed with both an aft and forward manifold to ensure it was compatible with the current injector design. Because of this, the coolant channels were not able to be inspected to ensure there were none blocked with powder. One possible solution would be welding the manifold during post-processing, but adding another part to be printed was avoided because it would increase costs and space on the build plate. To get around this, the chamber was inspected using computerized tomography (CT) scanning to look at the cross section and ensure there was no powder.

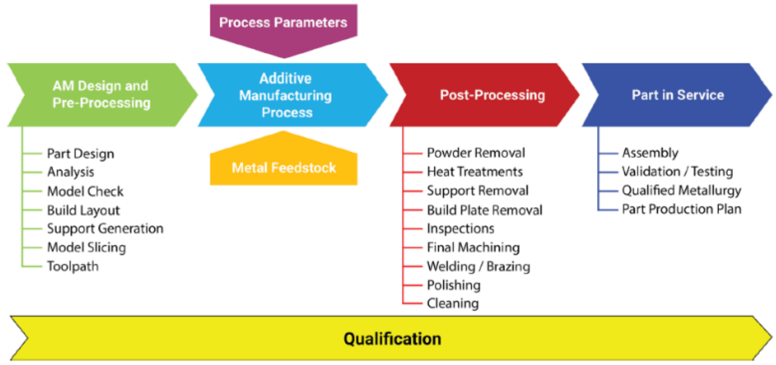

Figure 3. Generic Design for AM Process Flow [2]**.**

Following the CT scan, both the injector and chamber were heat treated with hot-isostatic-pressing (HIP) to reduce porosity in the parts, as well as acting as a stress relief for the residual stresses from printing [4]. All the sealing surfaces were then machined, and the parts were flow tested to confirm chamber pressure drop and injector flow areas. The parts were then sandblasted for aesthetics to remove the oxidation from the HIP process. For the metal feedstock, both components were manufactured from GRCop-42, a copper, chromium, and niobium alloy (Cu-4 at.% Cr-2 at.% Nb) produced by NASA. GRCop-42 is a dispersion strengthened alloy with high conductivity and high strength at extreme operating temperatures, which can reach upwards of 1,400 F for sustained durations. This, in addition to oxidation resistance, established powder supply chain, and substantial property development made GRCop-42 the preferred material for the thrust chamber and injector [4]. Various stages of hardware development are shown below in Figure 4.

Figure 4. Various stages of the DfAM process with the HORNET hardware.

B. Injector Design

The injector design was largely influenced by the previous design for the VENM 4 injector, while still taking advantage of AM. The new injector still used impinging triplets, but increased the number of elements to 12 and swapped the configuration from the previous O-F-O to F-O-F. This was a result of the change in the fuel density as a result of the regenerative circuit, but also helped to reduce the heat loads near the injector face. The ethanol orifices were designed using the single phase, incompressible (SPI) model [5], shown below in Eq. (1). In this equation, $\dot{m}$ is mass flow rate, A_i is injector cross sectional area, A_i, $C_d$is discharge coefficient, ρ_1 is upstream density, and ΔP is pressure drop.

$$\dot{m}_{SPI} = A_i C_d \sqrt{2\rho_1 \Delta P} \tag{1}$$

The nitrous oxide flow area was determined using the Dyer model, also known as the Non-Equilibrium Non-Homogenous (NHNE) model [6]. This is required because the chamber pressure is lower than the vapor pressure of nitrous oxide, resulting in vapor bubble formation within the orifice. It combines the SPI model with the Homogenous Equilibrium Model (HEM) which assumes constant entropy across the injector orifice. The HEM is shown in Eqs. (2)-(3) below, where s is specific entropy and h is specific enthalpy. The NHNE model uses a non-equilibrium factor, κ, to combine the two models, shown in Eqs. (4)-(5).

$$\dot{m}_{HEM} = A_i C_d \rho_2 \sqrt{2(h_1 - h_2)} \tag{2}$$

$$s_1 = s_2 \tag{3}$$

$$\kappa = \sqrt{\frac{\Delta P}{P_v - P_c}} \tag{4}$$

$$\dot{m}_{DYER} = A_i \left(\frac{\kappa}{1+\kappa} \dot{m}_{SPI} + \frac{1}{1+\kappa} \dot{m}_{HEM} \right) \tag{5}$$

However, due to the HORNET injector's high manifold pressure, high injection velocity, and the orifices length-to-diameter ratio, the difference in predicted flowrate between the two models is not as remarkable as noticed in the VENM 4 engine. Both models are used to predict the injector pressure drop for a given mass flow rate and are verified through water and nitrous oxide blowdowns prior to hot fire testing.

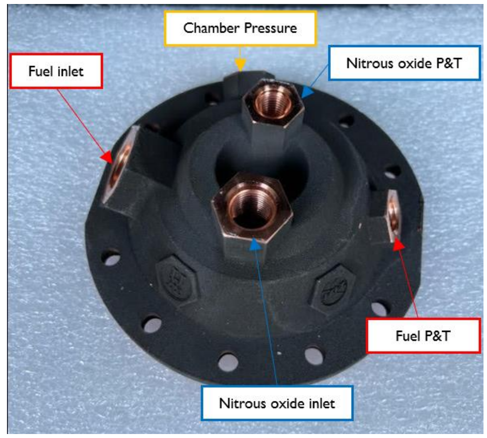

Figure 5. HORNET injector ports (post HIP and machining).

The largest design change with the HORNET injector was with the manifolds. Previously the injector was composed of two parts: an injector face and a manifold, which were bolted together and used 3 O-rings to seal between each fuel and oxidizer section. The new design reduced the injector assembly to one part with no seals (other than port seals) and has walls separating the fuel and oxidizer. The main considerations with this design feature were ensuring the walls were thick enough to hold the manifold pressure as well as not having any unsupported overhangs within the injector. With AM, it was also simple to add sensor ports for the injector manifolds to measure propellant pressure and temperature right before injection into the chamber, as well as a port for a chamber pressure measurement for measuring engine performance. These can be seen identified in Figure 5.

C. Thrust Chamber Design

As mentioned previously, the thrust chamber was designed to operate at the same pressure as the VENM 4 thrust chamber, which was 400 psia. Using NASA's Chemical Equilibrium with Applications (CEA) software, various mixture ratios were looked at to determine an ideal operating condition. The combustion efficiency and combustion gas temperature were examined to compare the performance to the heat load that the coolant would see. It was determined, as shown in Figure 6, that the gas temperature could be reduced about 10% with only a 0.5% drop in characteristic velocity (C^*). Additionally, there was only a 1% drop in specific impulse (I_{sp}), so it was decided to target a 3.2 mixture ratio for initial tests. By using CEA, several performance parameters were calculated for the thrust chamber design, such as C^* and thrust coefficient (C_f). These parameters were then used to determine the thurst chamber 's throat area to achieve our desired pressure, given by Eq. (6) below, where A_t is throat area, F is thrust, P_c is chamber pressure, and C_f is thrust coefficient [5].

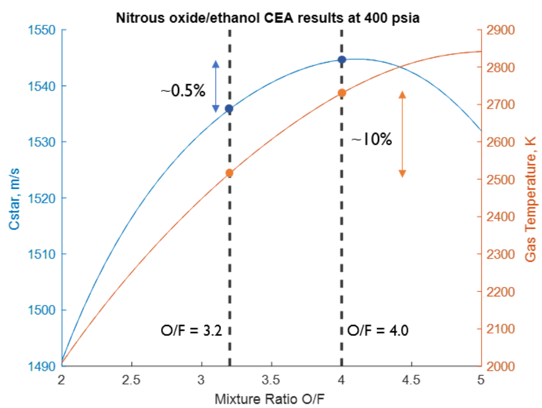

Figure 6. Nitrous oxide/ethanol CEA results at 400 psia.

$$A_t = F P_c C_f \tag{6}$$

The length of the barrel section of the chamber was determined by designing to a recommended characteristic length (L*) of 30 to 120 inches [Sutton]. Equation 7 shows it below, where L^* is characteristic length and V_c is chamber volume. To account for the significant chamber radii, the chamber volume was approximated by calculating the volume of the frustrum of a cone at various points and summing the results. The characteristic length of the thrust chamber was kept close to 30 in. to reduce part length and weight, as well as print costs. The barrel diameter was constrained by the injector geometry but still resulted in a subsonic area ratio within the recommended 2-5 [7]. The chamber contour was designed based on typical rocket design criteria, while accounting for the limitations of AM.

$$L^* = \frac{V_c}{A_t} \tag{7}$$

The nozzle geometry was initially calculated using the method of characteristics to produce a minimum length, ideally expanded nozzle, as described in [8]. Then it was shortened to remove weight at the expense of negligible performance decreases, producing what is known as a Truncated Ideal Contour nozzle (TIC) [9]. Later, it was decided to slightly truncate the design further to reduce material costs and part length.

The chamber's coolant channel geometry was designed based on predicted heat fluxes using Bartz heat transfer correlations [7]. The thrust chamber used rectangular channels and the width and height were varied to minimize pressure drop and have a near-linear coolant temperature increase. The normalized output temperatures are shown in Figure 7.

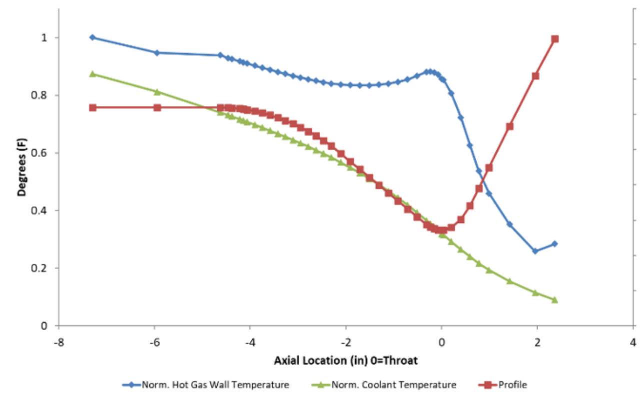

Figure 7. Regenerative circuit coolant temperatures.

IV. Test Stand Design

A. Tank Design

The main design constraints on the tanks were to withstand 1.5x the maximum expected operating pressure (MEOP) of 1600 psi with a factor of safety of at least 2, as well as hold enough volume for a 15-s burn time. However, between water tests, cold flows, and hot fire tests, the desired test duration could be anywhere from 5 s up to 15 s. Following a test, all remaining nitrous oxide and nitrogen are vented. To avoid wasting propellant in shorter tests, the oxidizer tank's length was designed to be adjustable by using modules. The ends of the tanks are sealed by bulkheads. Couplers were designed to fit in between sections of Al 6061 tube stock and seal when using more than one module. Using this method, the oxidizer tank can be 24", 48", or 72" long and hold up to 5 s, 10 s, or 15" s of nitrous oxide, respectively.

Figure 8. CAD of Fuel tank (left) and machined fuel and oxidizer tank (right).

Both tanks have ports that are outlets to the feed system and ports that are inlets to the nitrogen system for pressurization. Also, the oxidizer tank holds a pressure relief valve (PRV) that actuates when the pressure goes beyond a set value between 1,600-2,000 psi, a port that connects to the nitrous fill system, and a solenoid vent valve. The vent valve serves to empty the tank at the end of the test, as well as reduce pressure to allow for filling of more nitrous oxide. The vent is also connected to a dip-tube within the tank to ensure a portion of the tank is kept empty for ullage. When the nitrous tank fills up to the dip-tube, the vent cloud turns a thick white color that signifies the tank is full. The fuel tank is simpler: on top it has a hole for filling with ethanol by hand before being plugged and a nitrogen inlet for pressurization; on the bottom it has a drain valve and fuel outlet. Both tanks have one load cell on the bottom to measure the weight in the tanks during testing. The tank weights are used to measure the mass flow of the propellant during testing. For the load cells to properly measure the weight of the tanks, there needs to be one degree of freedom in the vertical direction, so that the only thing applying force to the load cell is the weight of the tanks and the propellant in them. To achieve this, stainless steel flexible hoses are used on either side of the tanks to connect them to the fill cart and to the rest of the feed system.

Structural considerations of the pressure vessel design included bolt shear stress, tube tensile stress, bearing stress on bolt clearance holes, and tube shear stress as referred to as bolt tear-out stress [10]. The critical failure mode for this design was the bolt tear-out stress and is calculated using Eqs. (8) – (9). In these equations, $D_{i,tube}$ is the inner diameter of the tank tube, N is the number of bolts, F_b is the force on each bolt, t is the thickness of the tank tube, d is the bolt clearance hole diameter, and E is the distance between the hole center and end of the tube. Table 1 below shows these calculations with the tank design as well as the tank's smallest safety factor.

$$F_b = \frac{\frac{\pi}{4} D_{i,tube}^2 \times P_{MEOP}}{N} \tag{8}$$

$$\sigma_{tear-out} = \frac{F_b}{\left(E - \frac{d}{2}\right) \times 2t} \tag{9}$$

B. Feed System

The feed system of the test stand carries the fuel and oxidizer from the tanks to the TCA. It also controls the mass flow rate of the propellants to achieve the ideal mixture ratio when the fuel and oxidizer mix after traveling through the injector. Figure 9 shows the piping and instrumentation diagram (P&ID) of the current test stand configuration. The green lines show the path of the oxidizer, the yellow shows the path of the fuel, and the blue shows the path of the nitrogen gas.

Table 1. Tank bolt tear-out stress calculation.

Bolt tear-out stress		
Max Operating Pressure	2400	psi
Do, tube	6.00	in
Di, tube	5.54	in
Number of bolts	24	bolts
Force per bolt	2409	lbs
Bolt clearance hole diameter	0.35	in
E, tube shear thickness	0.50	in
Min shear thickness	0.33	in
Tube thickness	0.25	in
Stress, tear out	14826	psi
6061 shear strength	30000	psi
FS, tear-out	**2.02**	

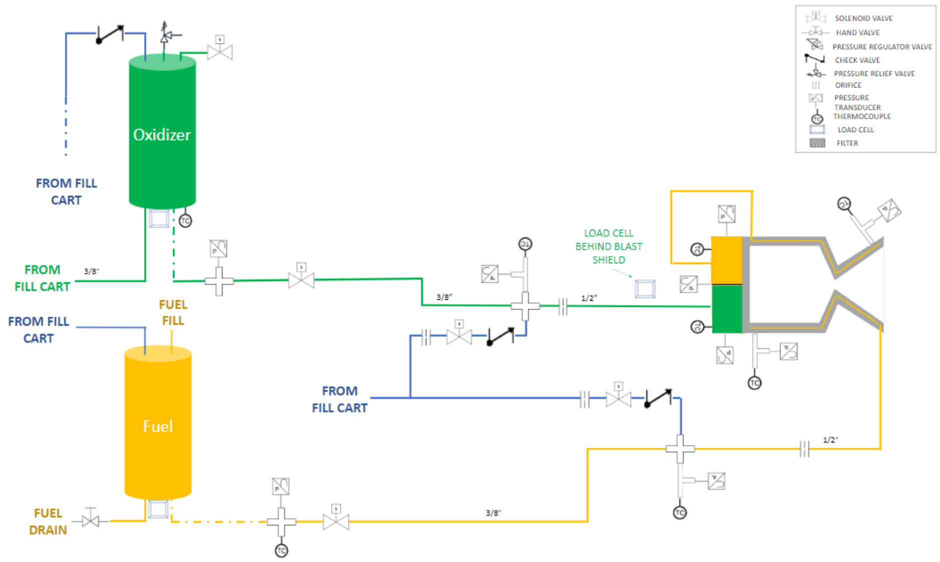

Figure 9. P&ID of the HORNET Test Stand

The feed system was designed to have the shortest possible line to the TCA while keeping one degree of freedom for the load cells on the tanks and blast plate to take propellant weight and thrust measurements. The TCA is mounted to a sled that has a horizontal degree of freedom and pushes against a load to measure the thrust output of the engine. This sled has a cage-like structure that connects the mounted TCA to the blast plate that sits against the load cell. All valves for the feed lines and purge system are mounted to the blast plate, on the opposite side of the TCA, as seen in Figure 10. The assembly of the feed system ensures one degree of freedom for the load cells by using flex line tubing from the tanks to the feed system.

A valve is located on each feed line between the tanks and the purge fittings. These valves control the flow of propellant to the injector; they are placed there to cut off the flow right before the purge lines, so that any propellant past the valve is purged from the system. Pressure transducers and thermocouples are located at multiple locations across the feed system to measure the pressure and temperature to calculate propellant density.

The mass flow rate of the propellants is calculated by deriving the flow rate from the pressure differential across a pipe restrictor [11,12]. The HORNET test stand uses venturi flow meters as the pipe restrictor. Its purpose is to partially obstruct the flow to build up a pressure differential between the upstream and downstream flow [11,12]. The venturis on the test stand are placed as close to the TCA as possible to mitigate the pressure loss due to the frictional head loss in the pipe or minor head loss through bends in the piping. Figure 10 (middle) shows the venturis placed on the cage portion of the test stand.

Figure 10. Test Stand CAD Model (left) Cage (middle) and Blast Plate (right).

Valves control the flow of nitrous oxide through the system. The only hand valve is on the top of the nitrous oxide bottle. The other valves across the system, which are actively used during the filling procedure, are solenoid actuated to be controlled remotely and avoid the risks of pressurizing the system with an operator present.

C. Nitrogen Gas Pressurant System

The external pressurant and purge system (EPPS) is used to pressurize the tanks and move the propellants through the system. The purge lines were designed to connect to the fuel and oxidizer feed lines right after the valves to remove any remaining propellants from the system after complete combustion. Nitrogen was chosen to be the pressurant and is held in an external fill cart. The EPPS line is routed from the nitrogen gas bottle and split into three lines. One line connects to the purge lines and the other two connect to the tanks. Figure 11 (left) shows the P&ID of the EPPS along with the nitrous oxide fill bottle. Two nitrogen bottles are used to increase the volume and mass flow rate and to the system.

The EPPS design includes a pressure relief valve to increase the safety of the system. The pressure relief valve opens at a set pressure to relieve pressure from the feed system so that it does not over-pressurize and potentially explode or damage components. All tubing and fittings are rated to a minimum of 3,000 psi, and the pressure relief valve is set to 2,000 psi. Figure 11 (right) shows the EPPS assembly, holding two high pressure bottles: one for nitrous and one for nitrogen. The additional nitrogen bottle will be chained to the other two cylinders and stand up next to the stand in future tests.

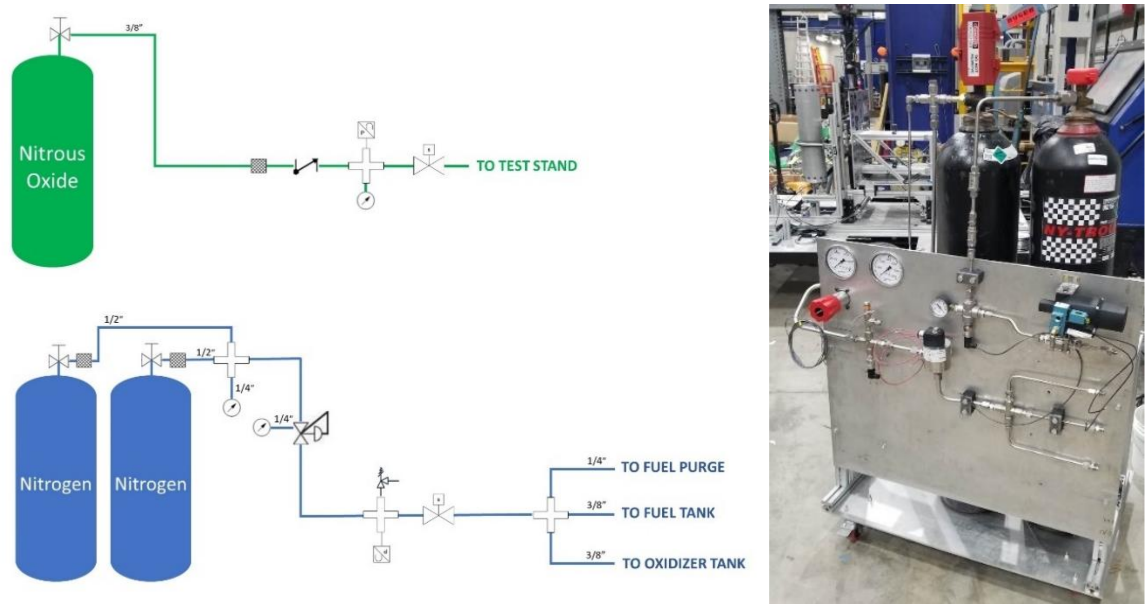

Figure 11. P&ID of the fill cart (left) and assembly (right).

D. Instrumentation and Controls

The instrumentation used in the HORNET test stand and fill cart are crucial for ensuring not only proper and safe operation but also accurate measurements of performance. The current configuration includes a control box that houses the relays, DAQs, and connections to the power supply. A LabJack T7 is used as the controller for the system and a LabJack T7 Pro is used as the DAQ. E- and K-type thermocouples are used in various points throughout the system. The pressure and temperature of the propellant is measured at the tanks, valves on the feed lines, injector manifolds, and at the inlet and outlet manifolds of the regen-cooling channels in the TCA.

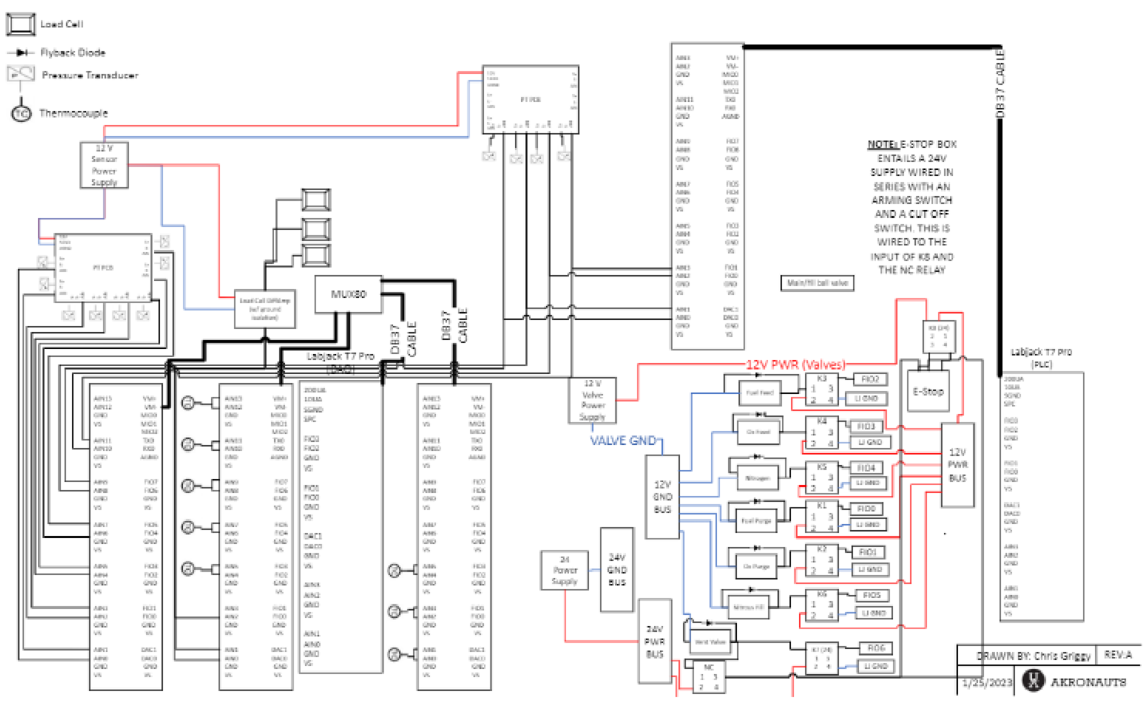

Figure 12. Wiring diagram of instrumentation and controls.

There are also pressure transducers on the fill cart to measure the pressure at the PRV and nitrous line between the nitrous bottle and the valve. A wiring diagram of all the components is shown in Figure 12. A load cell board was designed and added to the controls of the test stand to amplify the load cell inputs to better read the data. A custom-written software, called HIVE, controls the controller and DAQ from an external computer. HIVE directly relays data to a user interface (UI) for live graph output and saving during testing. HIVE has the capability of reading all the sensors on the test stand and provides a user-friendly interface for various controls such as actuating valves manually, the hot fire sequence, and sequences in the instance of an emergency stop.

E. Proof Testing

Before doing any large testing campaigns, the feedlines and tanks needed to be proof tested to the highest expected pressure to ensure the safety of the hardware and to catch any leaks or inconsistencies in the system early on. The proof test is executed by filling the feed lines and tanks with water and pressurizing them with a water pump up to the operational pressure with a safety factor of 2.5. The testing is done by ramping up to the final expected pressure in increments. For example, if the end tested pressure is 2,000 psi, the operators of the test would first pressurize the system to 500 psi, then 800 psi, then 1,200 psi, then 1,600 psi, and finally 2,000 psi. This is done so that any minor leaks or potential problems in the system can be caught and fixed at lower pressures first. In between each increment, the test operators hold at the pressure for 5-10 minutes to make sure no system failures occur while a pressure is held. The pressure relief valves are also set during proof testing. The pressure these valves will open at cannot be determined without a pressurized fluid running through them to check. Each pressure relief valve was set to 2,000 psi during proof testing.

V. Conclusion and Future Work

A regeneratively cooled, additively manufactured thrust chamber and injector were designed and printed using GRCop-42. The engine was designed to produce 800 lbf using nitrous oxide and ethanol and withstand test durations up to 15 seconds. Design for additive manufacturing principles were followed through the design, printing, postprocessing, and testing stages. The test stand previously used for testing of the VENM 4 engine was upgraded with new tanks to contain higher pressures and hold more propellant, new feed lines and instrumentation, new control systems and software, and a nitrogen system that provides regulated pressure to the system. The next actions include a series of water and nitrous oxide blowdowns pressurized with nitrogen to collect data on the flow rates, pressure drops, and the performance of the nitrogen system. Then, after assessing all needed changes, the system will be ready for a series of hot fires, the first being anticipated to happen in the beginning of April.

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References

[1] Ewig, R. *Vapor Pressurization (VaPak) Systems History, Concepts, and Applications*. 2009.

[2] Gradl, P., Tinker, D. C., Park, A., Mireles, O. R., Garcia, M., Wilkerson, R., and Mckinney, C. "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components." *Journal of Materials Engineering and Performance*, Vol. 31, No. 8, 2022, pp. 6013–6044. https://doi.org/10.1007/s11665-022-06850-0.

[3] Gradl, P., Mireles, O., and Andrews, N. *Introduction to Additive Manufacturing for Propulsion and Energy Systems*. 2021.

[4] Gradl, P. R., Protz, C., Cooper, K., Garcia, C., Ellis, D., and Evans, L. "GRCop-42 Development and Hot-Fire Testing Using Additive Manufacturing Powder Bed Fusion for Channel-Cooled Combustion Chambers." *55th AIAA/SAE/ASEE Joint Propulsion Conference*, 2019. https://doi.org/10.2514/6.2019-4228.

[5] Sutton, G. P., and Biblarz, O. *Rocket Propulsion Elements*. John Wiley & Sons, Inc., Hoboken, New Jersey., 2017.

[6] Waxman, B. S., Zimmerman, J. E., Cantwell, B. J., Zilliac, G. G., and Wells, E. C. *Mass Flow Rate and Isolation Characteristics of Injectors for Use with Self-Pressurizing Oxidizers in Hybrid Rockets*. 2013.

[7] Huzel, D. K., and Liang, D. H. H. *DESIGN OF LIQUID PROPELLANT ROCKET ENGINES NASA SP-125*. 1967.

[8] Anderson, J. D. *Modern Compressible Flow*. 2003.

[9] Arbos, S., Co-Supervisor Oriol, T., and Dalmases, L. *Study of Minimum Length, Supersonic Nozzle Design Using the Method of Characteristics*. 2019.

[10] Sennott, A., and Sharp, C. *How to Design Pressure Vessels, Propellant Tanks, and Rocket Motor Casings*.

[11] Liu, X., Lao, L., and Falcone, G. "A Comprehensive Assessment of Correlations for Two-Phase Flow through Venturi Tubes." *Journal of Natural Gas Science and Engineering*, Vol. 78, 2020. https://doi.org/10.1016/j.jngse.2020.103323.

[12] Ghassemi, H., and Fasih, H. F. "Application of Small Size Cavitating Venturi as Flow Controller and Flow Meter." *Flow Measurement and Instrumentation*, Vol. 22, No. 5, 2011, pp. 406–412. https://doi.org/10.1016/J.FLOWMEASINST.2011.05.001.