Experimental Analysis of a Student-Built Kerosene and Liquid Oxygen Rocket Engine Test Stand

Maximo A. Deiros[*], Francis V. Frazier[†], Jonatan Gonzalez [‡], Jackson Stahl[§]
Georgia Institute of Technology, Atlanta, GA 30332

The Yellow Jacket Space Program (YJSP) is a student-led liquid rocketry team at the Georgia Institute of Technology with the aim of being the first team to reach the Karman Line with a liquid-fueled rocket. The Helluva Engine Test Stand (HETS) is YJSP's mobile, pressure-fed, kerosene and liquid oxygen (Kero-LOX) engine test stand. Since its construction, it has conducted 17 hot-fire tests of various engines and injectors of up to 2500lbf of thrust, totaling to over 90 seconds of fire time. The following paper presents an in-depth experimental analysis of the test stand's performance and operation, a review of the challenges faced in its testing campaigns, and a survey of the improvements made to address them.

I. Nomenclature

C_d = coefficient of discharge
A = area
LOX = liquid oxygen
LN2 = liquid nitrogen
PT = pressure transducer
$\dot{m}$ = mass flow rate
ρ = density
ΔP = pressure change
$P_{chamber}$ = engine chamber pressure
p_t = total pressure
T_t = total temperature
γ = specific heat ratio
R = specific gas constant
LRE = liquid rocket engine

II. Introduction

YJSP was founded in 2015 with the goal of becoming the first student team to reach the Kárman Line, the edge of space, with a liquid-propellant rocket. In January 2022, YJSP launched Goldi-LOX, reaching an apogee of 5000ft. Throughout the following years, YJSP has been working on Vespula, the next-generation Kero-LOX rocket, designed to reach an apogee of over 120,000ft. The need for a reliable, future-proofed, and easy to operate engine testing stand led to the conception of HETS in the Fall of 2021. Much of HETS' design revolved around building on the lessons learned from its predecessor: Ground Feed-System (GFS). The Critical Design Review (CDR) of HETS was held in February 2023. Following CDR, procurement of components delayed construction, which took place during the Fall months of 2023, and was completed in February 2024. The test stand was then put through pressurized leak checks to validate construction quality and functionality with electronics. Inert flow testing with water and liquid nitrogen was done to characterize the pressure-fed system in preparation for hot-firing. On the 30th of March, 2024, HETS successfully conducted its first hot-fire test, gathering valuable thrust, pressure, and flow-rate data for our 800lbf sub-scale engine.

Understanding how a test stand performs and behaves is important to the testing and development process. Identifying the sources of inaccuracy in test data, and characterizing the influence of the test stand on things like engine startup is

---

[*] Chief Engineer, Aerospace Engineering, Undergraduate AIAA Member
[†] Chief Engineer (Retired), Aerospace Engineering, Graduate AIAA Member
[‡] Engine Testing Lead Engineer, Aerospace Engineering, Undergraduate AIAA Member
[§] Data Analysis Lead Engineer, Aerospace Engineering, Undergraduate AIAA Member

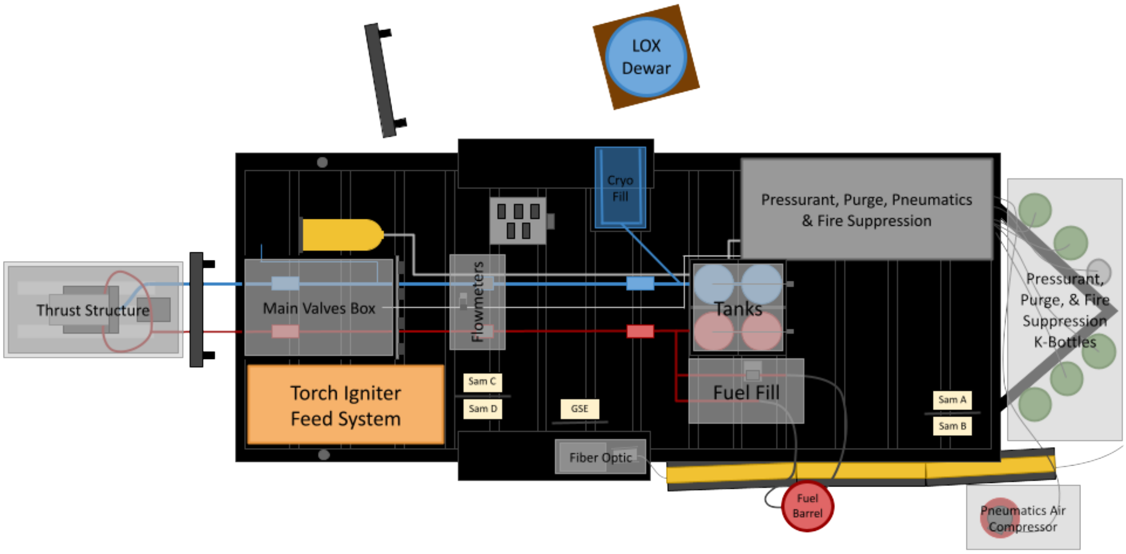


Fig. 1 Top-view of HETS. Shown are the key components and subsystems. The engine is mounted to the thrust structure which is anchored to the ground. The trailer does not bear the thrust of the engine.

necessary for a successful engine development program. The test stand's purpose is not limited to verifying the design and performance of engines and injectors. It also has the role of helping engineers reveal the optimal ways of operating an engine, feedsystem, and igniter. The test stand is able to provide insights about a propulsion system that cannot easily be predicted without physical tests. The test stand also achieves this more safely and in a lower-risk manner than if the engine was tested while integrated on a rocket. HETS has been the workhorse of the YJSP propulsion team, and has offered much valuable knowledge. In this paper, HETS' performance is assessed, and those insights are explored in data-driven discussions.

III. HETS System-Level Design

The HETS test stand is a pressure-fed system mounted on a trailer with the engine's thrust structure anchored to the ground behind the trailer. Nitrogen K-bottles are mounted to the side of the trailer to provide pressure for the propellant tanks, which are filled with kerosene and liquid oxygen when firing an engine (Fig. 1). HETS is comprised of a tank pressurization system, pneumatics system, fire suppression system, purge system, and propellant feed-system. The pressurization and purge systems use nitrogen to pressurize the tank and to purge the engine of residual propellants after firing, respectively. The pneumatics system uses compressed air with a backup nitrogen supply and is used to control valves on the system. The fire suppression system uses carbon dioxide to suppress any fires after engine shutdown. The propellant feed-system delivers fuel and oxidizer to the engine from the tanks. The test stand is instrumented with propellant flowmeters, pressure transducers, and thermocouples to gather data remotely. Valves on the system can be operated remotely using the YJSP's custom data acquisition circuit boards and control software, with the exception of some redundant hand-isolation valves to provide protection from system pressurization in the event of a software/electronic failure. Vents for small volumes are also hand valves.

The design of HETS began after the team had acquired valuable lessons from the club's previous engine test stand, GFS. The main issues that required improvement were the difficulty to transport GFS from our workspace on campus to the test site, the pressure regulators for the propellant tanks which are inherently unable to maintain a precise pressure, and the vertically oriented thrust structure. As a student club, we are limited on resources and infrastructure for maintaining and transporting a test stand. When major maintenance was needed for GFS it had to be disassembled completely and moved to campus, which drove us to choose to build HETS on a trailer for ease of mobility. We then considered other architectural changes of the actual system.

The pressure-regulation system is important in meeting flowrate requirements and so was reassessed for HETS. The pressure regulators used on GFS were susceptible to effects such as droop when regulating the pressure of flowing gas, which changed the pressure of the propellant tanks while the engine was firing. This is obviously not desirable, as the flowrate of propellant to the engine will change as the pressures change. This influenced the choice to pursue an active control system with “bang-bang” valves.

A vertical thrust structure was used for GFS, but was reconsidered for HETS. The two most valuable advantages of the vertical design to YJSP are the ability to replicate flight-like conditions and mitigation of propellant pooling. However, vertical thrust structures also have challenges that make them less practical for student teams. Vertical thrust structures are bulkier and more difficult to work on than horizontal structures. GFS required operators to use ladders to access the engine plumbing. On a vertical test stand, the engine has to be held up while mounting to the engine interface, which may require a gantry for larger engines. Along with the practical issues, a vertical thrust structure is not as compatible with a horizontal test stand mounted on a low trailer, such as HETS. Having propellant lines traveling against gravity while moving up a vertical structure would eat into the pressure budget and create problems with line bleed-in. For these reasons, a simpler horizontal thrust structure was selected.

IV. Feed-System Analysis

In a pressure-fed feed-system, determining the propellant tank pressures necessary to feed propellants at the appropriate mass flow rates and pressures is crucial to engine performance and safety. Over/underestimated target tank pressures can lead to excessive or insufficient chamber or injector pressure, high or low combustion temperature, and off-nominal mixture ratios (MR), all of which can negatively impact performance and could be dangerous.

C_dA is a parameter inherent to the particular flowpath between two points on a fluids system, and will change if any part of the plumbing is altered. It is a measure of fluid admittance, where an increased $\dot{m}$ will increase ΔP, and a higher value of C_dA will produce a lower ΔP for a given $\dot{m}$. Equation 1 shows this relationship for liquids. Equation 1 can be used to determine the pressure drop from tank to injector. It can be used with Eq. 2 to derive the target tank pressure required to achieve the desired mass flow rate of propellant. This ‘pressure ladder’ is also illustrated by Fig. 2 and Fig. 3.

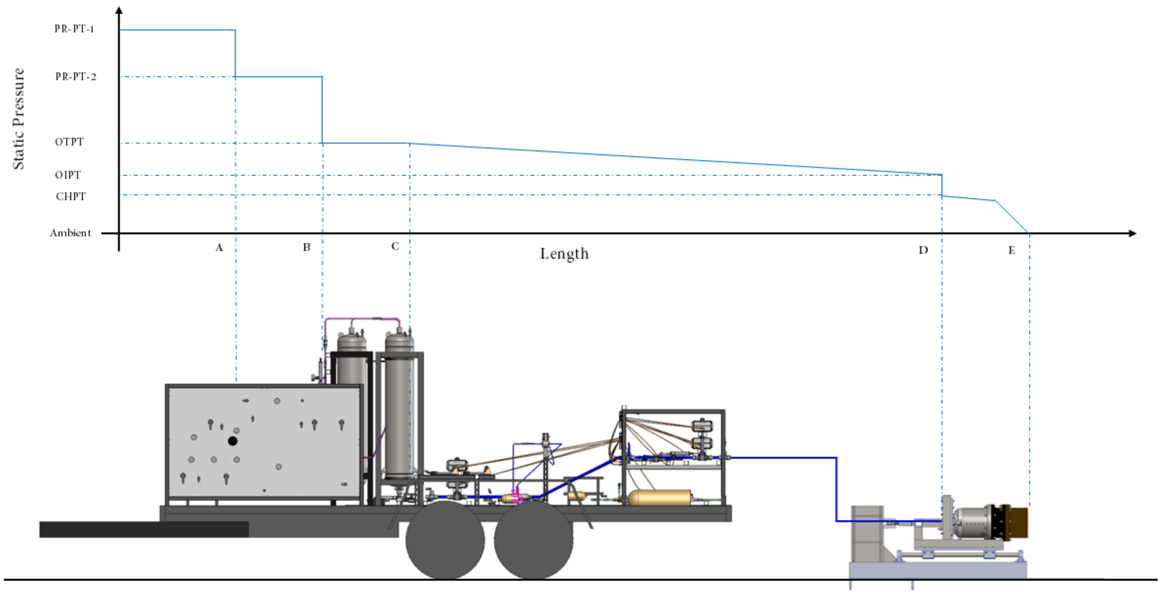
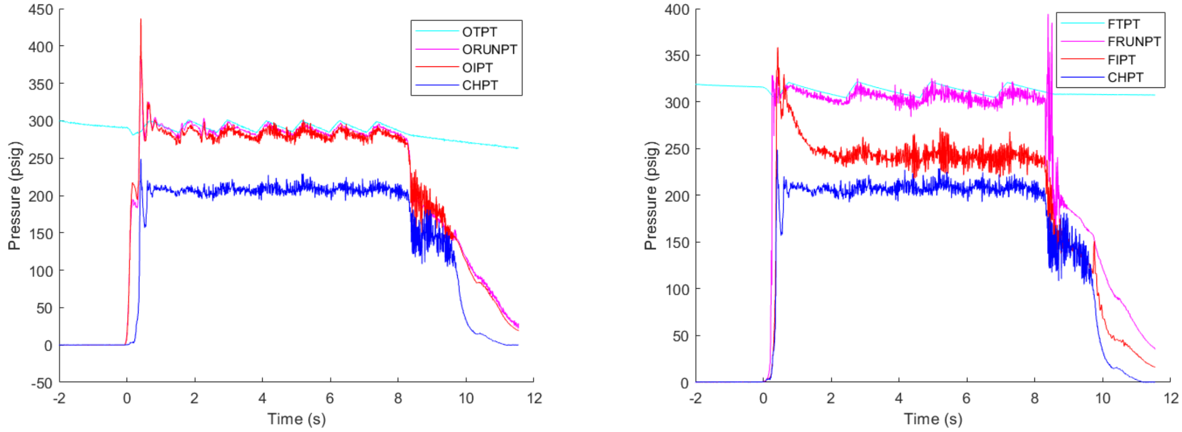


Fig. 2 Pressure Ladder for LOX-side: K-bottle pressure stepped down by a regulator (A), then by Bang-Bang valves (B). Gradual decrease in pressure between tanks and injector (C-D), pressure drop through injector (D), and expansion through engine nozzle (E).



(a) **(b)**

Fig. 3 LOX (a) and fuel (b) Pressure Ladders for HETS. 'RUN' PT's are placed between the tank and injector, after the main valves.

$$C_dA = \frac{\dot{m}}{\sqrt{2\rho\Delta P}} \tag{1}$$

$$\text{Tank set pressure} = \Delta P_{system} + \Delta P_{injector} + P_{chamber} \tag{2}$$

System C_dA (C_dA_{sys}) must be determined experimentally for the most accurate results during either a hot-fire or inert flow. One method of determining C_dA_{sys} involves placing an in-line mass flowmeter and using pressure transducers (PTs) on the propellant tank and at the entrance of the injector. Direct measurements of $\dot{m}$ and ΔP can be plugged into Eq. 1 to solve for C_dA. Another method involves using a calibrated flow orifice, the engine injector itself (with C_dA_{inj}), or any flow restricting device with a known C_dA to measure mass flow rate. A PT can be placed directly upstream and downstream of the flow restricting device, and pressure drop across it can be used with Eq. 1 to back out mass flow rate.

C_dA_{sys} and C_dA_{inj} can both be used with ΔP readings from PTs to calculate the mass flow observed during a hot-fire. In-line mass flow meters can also directly measure $\dot{m}$. HETS measures $\dot{m}$ using all three methods to determine a more reliable estimate for mass flow rate and compare accuracy between the different methods. (Fig. 4).

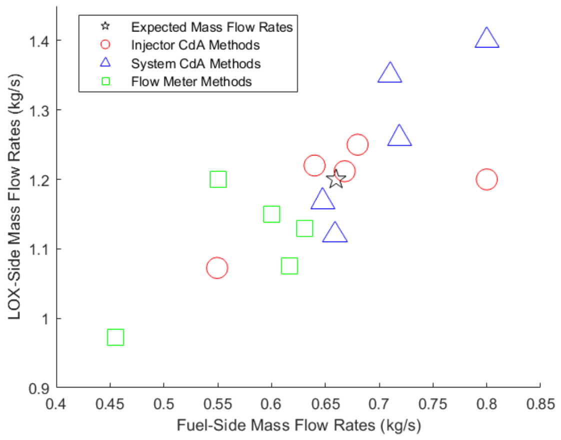


Fig. 4 Measured average mass flow rates using 3 different measurement methods for 5 different subscale hot-fires. Each data point represents the mass flow rates measured with a given method.

However, off-nominal behavior in the injector or chamber PTs can introduce error into these $\dot{m}$ readings. Determining which method is the most accurate is difficult to do without knowing the actual propellant $\dot{m}$, which can only reliably be done with industrially calibrated flow meters. System and Injector C_dA values, if not obtained with accurate flow metering devices, contain error which can propagate. HETS is equipped with a COTS (Commercial Off the Shelf) turbine flow meter for the fuel side, and a custom-machined Venturi flow meter for the LOX side – both were calibrated with a Coriolis flow meter. Generally, values from the Venturi flow meter and Injector C_dA are taken as the most accurate values for LOX-side and fuel-side, respectively. The fuel-side turbine flow meter has exhibited some behavior that has led us to question its accuracy (such as the outlying data point in Fig. 4), which is why injector C_dA is trusted more.

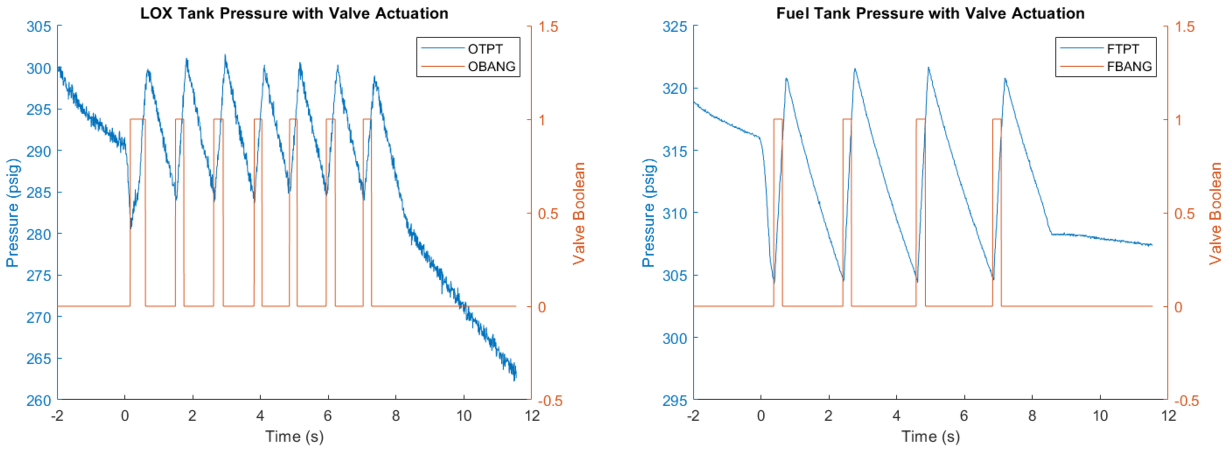
These results present a key insight that must be considered when designing and operating an engine testing stand: an accurate way of measuring $\dot{m}$ is critical. Figure 4 shows that the methods which utilize System and Injector $C_d A$ tend to overshoot the measurement of $\dot{m}$ compared to the other methods. This indicates that the values for $C_d A_{sys}$ are overestimated. The flow meters indicate a slight undershooting of $\dot{m}$, which further reinforces this idea. As tank pressures are calculated using $C_d A_{sys}$, an overestimated $C_d A_{sys}$ will lead to using insufficient tank pressure, producing lower $\dot{m}$. An accurate method of $\dot{m}$ measurement, such as a high-quality COTS flow meter, would increase the accuracy of $C_d A$ values, and would allow for more consistent and accurate feed system performance.

When using inert flows to determine $C_d A_{sys}$, a potential source of error is using a flow setup that is non-identical to what it would be during a hot-fire. For example, using a flow orifice instead of the injector itself can result in a $C_d A_{sys}$ error of up to 10%, which corresponds to an error in calculated tank pressures of up to 21%. This is due to the difference in flowpath upstream of the primary flow restriction. Additionally, using dissimilar fluids (such as water instead of kerosene and LN2 instead of LOX) can introduce error due to the altered Reynolds number for the same mass flow rate [1]. To minimize the error from these two sources, it is recommended to use the engine injector itself to perform inert flows, and to tune flow rates to match Reynolds number. However, in the case of vehicle testing, it may be desirable to size orifices to match the volumetric flow rates of propellants ($\dot{V}$) instead of $\dot{m}$ to characterize pressurant system response and quantify things like pressurant adiabatic cooling and ullage collapse. Fuel side flows can be performed with kerosene instead of water, provided that a safe and water-tight method for capturing the fuel is implemented. This will yield more accurate $C_d A_{sys}$ values for fuel side. Performing flows with LOX is not recommended as high injection velocities in an oxygen-rich environment can lead to auto-ignition of loose particles/debris. The thrust structure on HETS is close to the ground, which can expose loose particles to high velocity gaseous oxygen. If a test stand places the engine far above the ground, minimizes potential debris exposure, and contains no flammable materials in the vicinity, LOX flows could be justified.

V. Pressurant System Analysis

An active tank pressurization control system was a major requirement for HETS, which was put in place due to the problems GFS had with passive regulation. The "bang-bang" valves used by HETS are fast-acting pressure-piloted solenoid valves. The valves are controlled by a custom-programmed auto-sequence, which allows pressurant gas to enter each propellant tank in intervals, keeping tank pressures within ±10 psig of the target value (Fig. 5). A choking orifice is placed downstream of these valves primarily to limit pressurant gas flow for better pressure control and lower relief valve requirements.

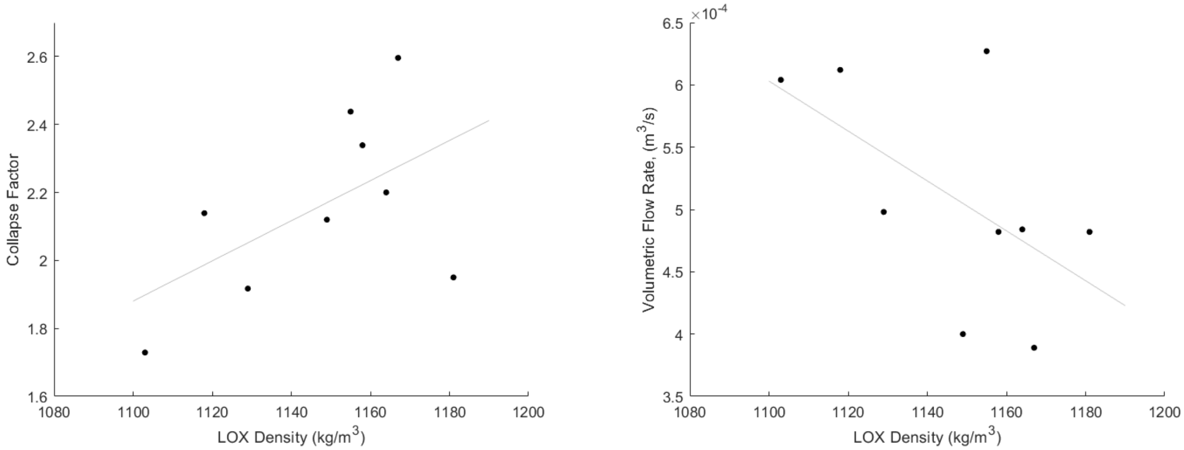
Designing a bang-bang pressurized feed-system requires accurate knowledge of the LOX tank ullage collapse. Collapse is a phenomenon in cryogenic propellant tanks where heat transfer from the pressurant gas to the cryogenic



(a)

(b)

Fig. 5 LOX (a) and Fuel (b) Tank pressurization scheme using Bang-Bang valves. Valve Boolean indicates when each Bang-Bang valve is on (1) and off (0). Tank pressure continues to increase for a short time following the valve close command due to valve actuation time.



(a) **(b)**

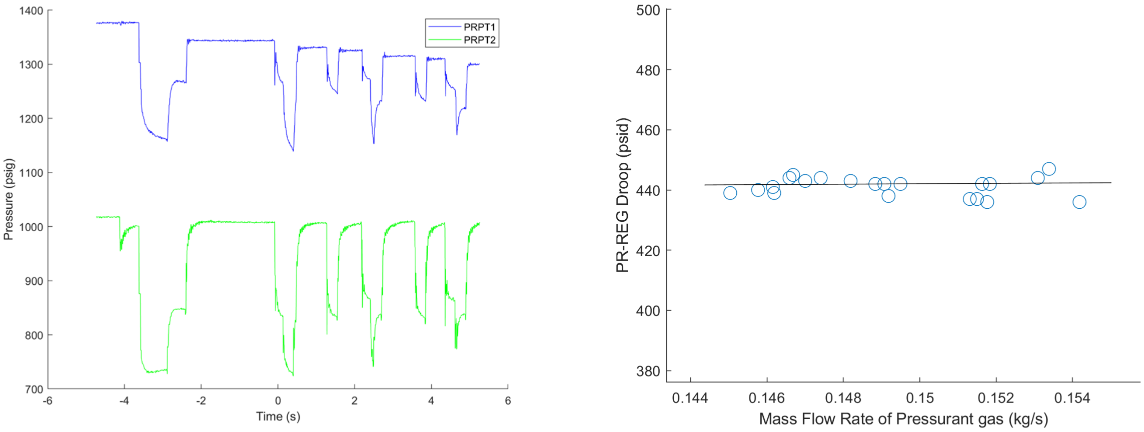
Fig. 6 LOX tank ullage collapse factor vs. density (a) and pressurant consumption vs. density (b). LOX temperature is directly correlated with density and pressure.

liquid increases the density of the gas and by extension the pressurant mass flow required into the tank [2]. The choking orifice must be sized to provide enough flow-rate of pressurant to balance tank pressure against the outflow of both propellants, and pressurant collapse inside the LOX tank. Initial estimates were placed at a collapse factor of 2, which was thought to be conservative. It should be noted that while lower LOX temperatures cool pressurant gas more intensely – increasing collapse factor (Fig. 6a), colder LOX is more dense, which lowers the volumetric flow rate of propellant, reducing the amount of pressurant gas needed (Fig. 6b). This characteristic reveals the importance of cryogenic propellant conditioning. HETS fills LOX from cryogenic dewars which come in a range of pressures. Since lower pressure LOX is colder and denser [3], low-pressure dewars are desirable. If these are not available, high-pressure dewars can be used to fill the tank. These high-pressure dewars can be vented of pressure in advance to allow for cooling of the stored liquid. HETS will vent dewars down to 50psig if they are delivered at too high a pressure. Alternatively, a waiting period can be implemented to allow the warm LOX to boil partially and cool down. This may take significant time, especially with insulated propellant tanks.

Though the main tank pressure control is performed by the bang-bang valves, a large pressure regulator (PR-REG) was placed upstream to help keep bang-bang inlet pressure somewhat constant. The nitrogen K-Bottles have a start of life (SOL) pressure of ~2300 psig, and PR-REG steps that pressure down to between 1000-1500 psig. Due to the nature of regulators, however, droop heavily influences the output of PR-REG (Fig. 7a) . Droop is the drop in a regulator's outlet pressure below the set point, caused by increasing flow rate through the regulator[4]. PR-REG fails to keep its outlet pressure at it set value (~1015psig in Fig.7a), but manages to keep outlet pressure constant for a given pressurant flowrate fairly well between bang-bang valve actuations. The pressurant mass flow rate when each bang-bang valve is open can be calculated by taking the pressure upstream of the choking orifices and using Eq. 3 (assuming isentropic flow).

$$\dot{m} = \frac{A p_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma + 1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \tag{3}$$

Figure 7b shows that PR-REG has a relatively constant value of droop across a small range of mass flow rates. Over a larger range of flowrates, regulator droop scales with pressurant $\dot{m}$ non-linearly. For a small range of pressurant $\dot{m}$, simplification of the system can be achieved by replacing the regulator with an appropriately sized orifice. This can reduce system cost and complexity. For large ranges of pressurant $\dot{m}$, using an orifice will require the bang-bang valves to widely vary their duty cycle, and may not be able to support the required flow rate when the nitrogen supply pressure drops below a certain amount.



(a) **(b)**

Fig. 7 (a) Pressurant supply showing regulator droop during each bang-bang actuating interval. (b) Pressurant regulator droop remains fairly constant over a small range of pressurant mass flow rates.

VI. Engine Startup Analysis

A smooth engine startup requires many elements of the test stand to be precisely calibrated such as initial injector pressures, valve timings, and igniter hardware. An anomaly in any of these could result in ‘hard-starting’ the engine: this occurs when engine startup contains a sudden detonation rather than a smooth ramp-up, and is usually identified by large spikes in chamber pressure (Fig. 8) which could destroy hardware. Hardstarts are most often the result of propellant accumulation in the chamber prior to ignition [**p.355**, 5]. Over the years, YJSP has collected evidence that there are two main causes of hard-starts:

1) Mistimed valves which results in a very long LOX-lead
2) Weak or insufficient igniter energy to immediately ignite propellants, resulting in their accumulation or external ignition

When starting an engine, it is most desirable to have both propellants enter at approximately the same time; however, more consistent startup behavior can be achieved by choosing one propellant to be injected shortly before the other [**p.321**, 5]. All engine fires on HETS have aimed for a LOX lead of 100-300ms on startup. A LOX lead was chosen over a fuel lead for many reasons. Liquid oxygen has a lower risk of pooling in the chamber compared to kerosene because of its tendency to boil off. HETS uses fuel-rich solid-rocket motors for igniters, which can react with the initial stream of vaporized LOX and prevent accumulation. Additionally, kerosene’s low volatility and its higher heat capacity means that more energy needs to be transferred into the fuel to start the reaction, which can extend the delay before complete ignition, allowing more time for unburned propellants to accumulate in the chamber. Literature indicates some precedent for fuel-leads in LREs [6, 7], but many of these engines work with more volatile fuels like hydrogen or use hypergolic propellants, which do not need to vaporize prior to combustion or require an ignition source. The length of the LOX lead is driven by the uncertainty in main valve timings, which is discussed below. The duration was chosen to minimize the LOX lead while ensuring a normal deviation in valve timings would not produce a fuel lead.

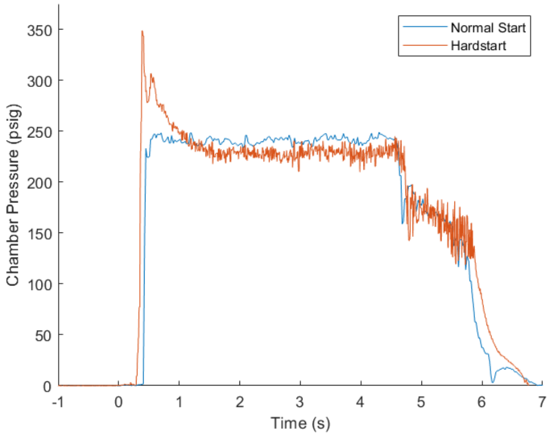


Fig. 8 Chamber Pressure (CHPT) readings for two startups.

The majority of hard-starts on HETS are suspected to be due to inconsistent valve timings. This variability can be primarily attributed to inconsistent pneumatic pressure (Fig. 9), though the spring-return nature of the main valves and changing environmental conditions which can affect the friction between the valve ball and seat can also have an effect. All of YJSP's engines are fuel rich. Excessively long LOX leads (>400ms) can create a heavily oxygen-rich environment (and with potentially pooled LOX), which can detonate when fuel is introduced [8].

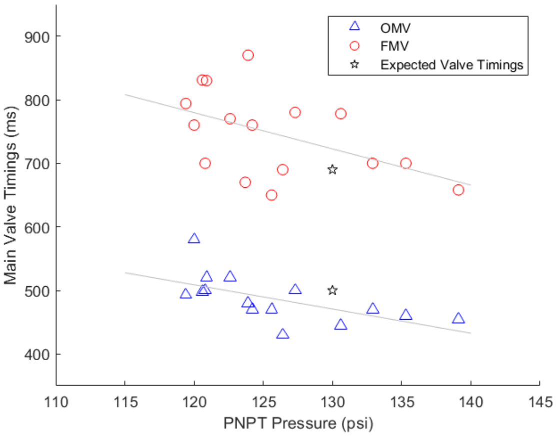


Fig. 9 Oxygen Main Valve (OMV) and Fuel Main Valve (FMV) actuation times dependent on pneumatics pressure (PNPT) compared to expected timings.

Hard-starts on HETS have also resulted from igniter faults. HETS utilizes a small solid rocket motor (SRM), installed either on a movable arm pointed up the throat, or in the injector faceplate for larger engines. The flame is intended to come in contact with and ignite propellants as soon as they emerge from the injector. During one fire, the SRM was knocked off-center from its housing, and the flame was deflected by the nozzle (Fig. 10), causing external ignition.

The influence of injector pre-chill on hard-starts is still being determined. For many early HETS fires, a trickle-chill procedure was performed to lower the temperature of the injector LOX manifold and preceding run lines. As a result, the oxidizer lead for these fires was mostly LOX, as opposed to GOX (gaseous oxygen). The injector pressure trace on startup for a hot-fire with and without pre-chilling the injector is shown in Fig 11a The discontinuity in the slope of the no-pre-chill graph is predicted to be the GOX/LOX transition. However, for more recent fires, the injector chill-in was removed to test if a GOX lead would produce smoother startup and lower the chances of a hard-start. It was also done due to the inability for a vehicle to conduct a trickle-chill to conserve propellant and to "Test Like You Fly" (TLYF). After seeing hardstarts in both cases, it is plausible to believe that injector chill-in improves startup characteristics. Leading with GOX as opposed to LOX could result in poor mixing and atomization of fuel in the injector. [9]. This can result in pooling of unburned, unmixed fuel which can detonate upon introduction of LOX.

It is important to question the reliability and accuracy of sensors on any test stand, especially sensors which are exposed to extreme environments such as the engine chamber PT (CHPT). In several instances, CHPT has read data which appears strange or anomalous. Figure 8 shows a chamber pressure trace with a slow ramp-down from the initial CHPT spike down to nominal pressure. For this fire, no anomalous behavior was be observed in the injector manifold pressure traces, which would be expected if chamber pressure was significantly above injector pressure for an extended period of time. This points towards the possibility that CHPT in Fig. 8 was not reading actual chamber pressure. The ramp-down phenomenon could be the result of high-pressure detonation-combustion gases filling the volume of the CHPT connecting line and choking through the small port in the chamber once chamber pressure stabilizes [9]. These high-pressure gases in the CHPT line could have also been produced from a local fuel ignition, as it is possible for fuel to accumulate in the CHPT line. Figure 11b illustrates this mechanism.

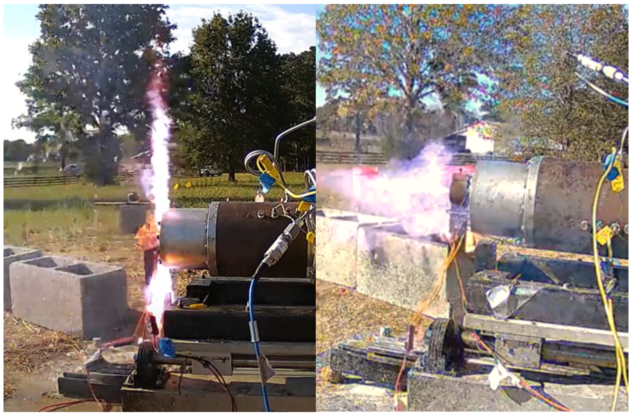
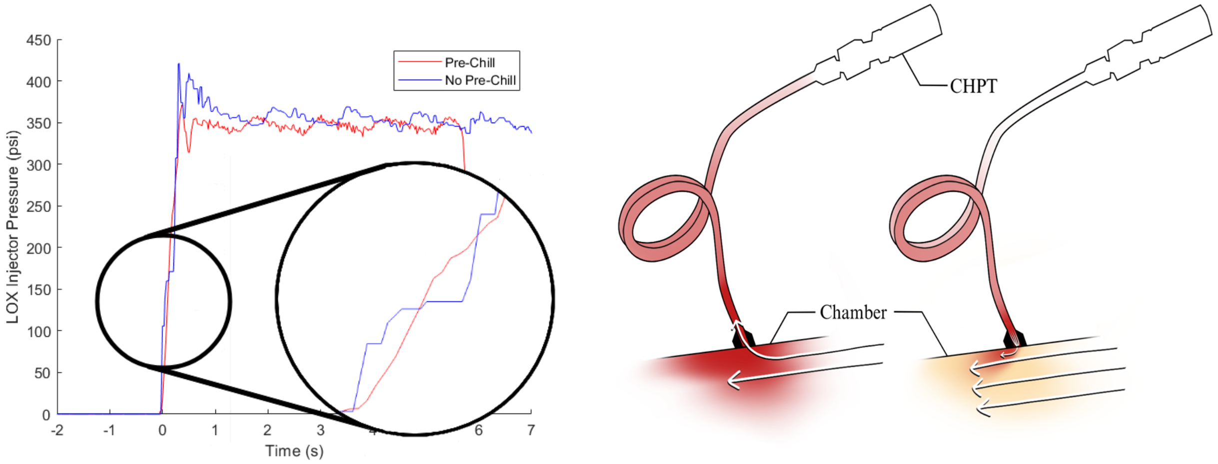


Fig. 10 Comparison of an anomalous igniter start (left) and nominal igniter start (right). The anomalous igniter fails to direct the flame towards the injector, causing propellants to ignite at the nozzle.

Another possibility is that insufficient data collection rates might not pick up the rapid spike of a hardstart. In some hot-fires such as Fig. 8 above, the highest spike of the hard-start is only occupied by two datapoints. Hard-start detonations can occur in the order of 1ms [10]. Data collection on HETS can peak at about 130Hz, which is almost 10x slower than the detonation wave. Identifying hard-starts can be made easier with high data rates and redundant sensors.



(a) (b)

Fig. 11 (a) Injector manifold pressure behavior with and without chill-in. (b) Hard-start choking mechanism in CHPT line that could be producing a ramp-down pressure trace.

VII. Conclusion

HETS has proven itself to be a reliable and versatile Kero-LOX engine test stand. The generous margin added during its design has allowed it to work well across a large range of engine sizes. The oversized trailer has provided ample space for seamless construction, maintenance, and upgrades. The ease of operation and refined test procedures have allowed the HETS team to more than double the number of hot-fires done in YJSP history in the span of a month. An emphasis is placed on the lessons learned throughout the HETS testing campaigns.

Future work on HETS involves testing new engine types, such as ablative and regeneratively cooled engines. An electric pump-fed system is currently in development for implementation on HETS and will allow fine throttling control. More research will be done into how to mitigate hard-starts, such as injector atomization tests to investigate the role of pre-chill on initial propellant mixing. Additionally, many upgrades are in progress to improve the performance, reliability, and test cadence of HETS. For example, new fast-acting actuators are being designed to cut down on valve-timing variability and improve the consistency of LOX-leads. The thrust structure is also undergoing a redesign, which will increase its load-bearing capacity for use with more powerful engines and will accommodate the main valves and pumps to reduce the length of the run lines. This configuration is also consistent with TLYF.

Acknowledgments

YJSP would like to acknowledge Dr. Wenting Sun, Dr. Adam Steinberg, Dr. Mitchell Walker, Dr. David Wu, and Kristopher Manion for their continued support and advocacy towards YJSP's success and growth. YJSP would also like to extend gratitude to Pamela Lohr Hendrix and Sarah Kamal for generously providing their land for us to safely and comfortably perform tests. The names of current and former members who substantially contributed to the design, construction, and operation of HETS are listed below.

Noah Robinson
Carson Kamal
Sasha Callaway
Saaketh Ramoju
Mohammed Al-Mahrouqi
Dakota Basista
Matthew Blawat
Tyler Cummings
Matthew Dalton
Sparsh Desai
Daniel Elliot
William Ewles
Daniel Gilliland
Nicolas Gutierrez
Cheyenne Halverson
Aaron Hammond
Taylor Hampson
Ethan Heyns
Andrew Heyward
Aiden Hu-Lowenthal
James Jutras
Braden Kerstin
Vineet Kulkarni
Emma Li
Daniel Luo
Callum MacDonald
Schuyler McCaa
Veronica Mok
William Putaansuu
Jeff Shelton
Laura Uhlig
Joanna Xiao
Kieran Yarberry
Dario Zaccagnino
Justin Zhang

References

[1] Sutrisno Salomo Hutagalung. “Effect of Release Coefficient of Orifice Plate on Water Fluid Flow Systems”. In: *Journal of Physics: Conference Series* 1230 (July 2019), p. 012086. doi: `10.1088/1742-6596/1230/1/012086`.

[2] Laurence De Quay and B. Keith Hodge. “A History of Collapse Factor Modeling and Empirical Data for Cryogenic Propellant Tanks”. In: *AIAAaSME/SAE/ASEE Joint Propulsion Conference* (2010).

[3] Bahman Zouri. “Physics of Cryogenics: An Ultralow Temperature Phenomenon”. In: Elsevier, 2018. Chap. 14.

[4] Dimitrios Tzetzis Asterios Kosmaras and Panagiotis Kyratsis. “Finite Element Analysis and Experimental Validation of a Novel Oxygen Pressure Regulator”. In: *Academic Journal of Manufacturing Engineering* 15 (2017), p. 67.

[5] George Paul Sutton and Oscar Biblarz. *Rocket Propulsion Elements: An Introduction to the Engineering of Rockets*. John Wiley Sons, 2000.

[6] A. R. Casillas. “Combined cycle engine research in Japanese HYPR program | Joint Propulsion Conferences”. In: *Joint Propulsion Conferences* (2024). doi: `10.2514/MJPC98;subPage:string:Abstract;csubtype:string:Conference`. url: `https://arc.aiaa.org/doi/epdf/10.2514/6.1998-3278` (visited on 02/04/2025).

[7] Hongjae Kang, Eunkwang Lee, and Sejin Kwon. “Suppression of Hard Start for Nontoxic Hypergolic Thruster Using H2O2 Oxidizer”. In: *Journal of Propulsion and Power* 33 (Feb. 2017), pp. 1111–1117. doi: `10.2514/1.b36510`. (Visited on 02/11/2025).

[8] Soon-Young Park, YoungJun Kim, and Eun-Whan Jeong. “Optimization of the Startup Sequence of a Liquid-propellant Rocket Engine”. In: *7th European Conference For Aeronautics and Space Sciences (EUCASS)* (2017). doi: `10.13009/EUCASS2017-293`.

[9] Kohji Tominaga et al. “Estimation of Hard Start Mechanism by Visualization Test of Hypergolic Bipropellant Thruster”. In: *7th European Conference for Aeronautics and Space Sciences (EUCASS)* (2023). doi: `10.13009/EUCASS2023-712`.

[10] Yoshiki Matsuura et al. “Investigation on Suppression of Hard Start Phenomena in Hypergolic Bipropellant Engine”. In: *AIAA Scitech 2024 Forum* (2024). doi: `10.2514/6.2024-1394`.