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Test Stand Integration and Testing

ME 493 Final Report: Spring 2019

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Portland State Aerospace Society (PSAS) is seeking to launch a liquid bi-propellant rocket to a height of 100km. PSAS's technology development philosophy is that of incremental progress where initial designs are built, tested, broken, and iterated towards functional designs. In keeping with this philosophy, PSAS developed an undersized 2.2kN, regeneratively cooled rocket motor and pintle style injector for testing prior to developing a full scale 100km capable engine.

Several testing methods were planned for validation of the engine and injector designs. In both cases, the provided hardware failed their preliminary validation testing. The first test for the 3D printed engine was to undergo CT scanning. Analysis of the results found internal manufacturing defects inside of the regenerative cooling channels which prevented hot fire testing. A full analysis of the 3D printing process and design for manufacturing recommendations is being provided to PSAS as one of the deliverables for this project.

The pintle injector was first tested with water to determine if it met the flow rate and pressure requirements for the engine. The provided injector did not meet the requirements and required a complete redesign which was not within the original scope of the project. A new injector design which meets the flow rate requirements has been built and tested. Complete design documentation, instructions, and CAD drawings have been created as an additional deliverable to PSAS.

The design of the 2.2kN engine configured test stand was completed and construction is ongoing. A full assembly plan is being delivered to PSAS which will enable the construction to be completed over the summer along with the development and testing of.several key pieces of technology. Full documentation on all sub-component projects is being delivered to PSAS which includes, design and CAD files, as well as testing instructions and standard operating procedures for use and maintenance.

The final deliverable we are giving to PSAS is our recommendations for how to proceed with its engine development. Many lessons were learned by our team which, if followed, will greatly speed up the design and testing of rocket engines. Primary among these recommendations is that PSAS set aside its current regeneratively cooled engine design in favor of a less technically complex 'heat sink' engine. This would simplify many of the technical challenges encountered in designing and constructing the current test stand. Once PSAS has gained experience with more forgiving engine designs, that experience can be built upon to meet the additional requirements dictated by regenerative cooling.

INTRODUCTION AND BACKGROUND INFORMATION

The Portland State Aerospace Society (PSAS) is seeking to develop and launch a liquid bi-propellant rocket to 100 km. A prior capstone team designed and built a prototype 2.2 kN regeneratively cooled bipropellant (liquid oxygen and isopropyl alcohol) rocket engine and pintle type injector. This project was tasked with the challenge of testing and validation of the engine and injector. This objective includes the design and building of a rocket engine test stand which can safely deliver the propellants to the engine at the correct pressures and flow rates, provide a reliable source of ignition, and measure the results.

The Liquid Propellant Engine Test Stand (LPETS) consists of a pressurant and propellant supply tanks, a computer controlled propellant delivery system, and a welded truss structure. The LPETS Test Stand Automation and Regulation (TSAR) will allow for the test stand to be controlled remotely. It auto-sequences engine ignition, start, shutdown, pad-safing, and contingency procedures for any test exception, as well as receiving telemetry from sensors and instrumentation.

Propellant supply is accomplished using gaseous nitrogen to pressurize the fuel and oxidizer. The ignition source is a spark torch igniter. The LPETS structure is capable of safely running tests on rocket engines up to 10 kN (2250 lb) of thrust.

The test stand allows for the testing, refinement, and characterization of liquid propellant subsystems prior to flight integration. Following the initial testing of the 2.2kN engine, several additional systems are slated to be tested, including an electric feed system and low-head structural cryogenic propellant tanks.

MISSION STATEMENT

Portland State Aerospace Society (PSAS) joined the Base 11 space challenge to launch a liquid fuel rocket to 100 km, the edge of space. Prior to building a full sized engine, PSAS required testing of its half-scale, 3D printed, regeneratively cooled rocket engine and injector. The test engine and injector were designed to use liquid oxygen (LOX) and isopropyl alcohol (IPA) propellants and produce a thrust of 2.2kN (500lb). As part of the base 11 space challenge, PSAS has access to training modules, resources, and industry connections.
This challenge provided an additional motivation, however PSAS already had 100 km line in mind, with technologies that include the electric feed system, electronic nose separation (recovery system), cryogenic carbon fiber propellant tanks, carbon fiber airframe, cold gas reaction control, and a liquid fueled rocket engine by designing a liquid propellant test stand.

MAIN PROJECT REQUIREMENTS

The LPETS capstone was given 3 primary objectives which encompass all project requirements.

Objective number one was to test the engine and injector hardware provided by PSAS. The LPETS team was provided with three DMLS printed 2.2 kN engines and one pintle type injector for testing and design validation. This objective required that all testing data and any subsequent analysis be recorded and made available to PSAS.

Objective number two was the physical construction of a test stand, including the piping, valves, fittings, tanks, sensors, etc. Requirements for this objective included complete stand documentation on construction and maintenance, safety procedures, and the design, testing, and integration of all hardware necessary for the safe testing of rocket engines.

The last and most important objective was that complete project documentation be created and made available to PSAS. This requirement enables PSAS to continue its rocket engine development after the capstone team graduates and many of us go into industry. The project documentation includes, but is not limited to; CAD and design files, standard operating procedures (SOPs), testing results, data analysis, design and manufacturing recommendations, best practices, and any other information which will assist with the continuation of this project by future teams.

PINTLE

One of the primary pieces of hardware to be tested was a pintle style propellant injector. The injector employs a LOX centered pintle design. In this style of injector, LOX flows through the center of the pintle and is sprayed outward in a radial pattern. The fuel enters a chamber surrounding the base of the pintle and enters the engine through the annular gap between the outer radius of the pintle and the engine. (See Figure 1) Inside of the combustion chamber the two propellants impinge upon each other at right angles, which creates a cone shaped spray of well mixed fuel and oxidizer.

PSAS provided an aluminum version of the pintle injector which had been designed by a previous capstone team which needed to be tested prior to integration with the engine. Initial testing with water determined that the current injector design does not meet the engine requirements. (See Table 1) The total volumetric flow rate required for both propellants is 67 liters per minute of water at a pressure between 345 and 485 kPa. When tested the combined flow rates were found to be 16 liters per minute within the required pressure range.

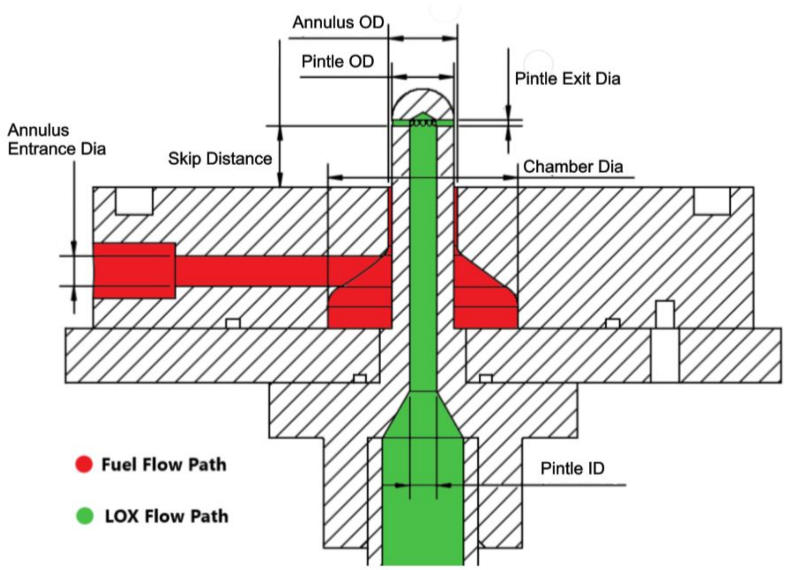

Figure 1: Cross section of pintle injector. LOX flow path shown in green and fuel flow path shown in red.

Table 1: Flow rate results for Pintle testing. Tests show that the current design of the pintle does not obtain the needed flow rates.

Pintle				
Requirement	**Measured**		**Target**	
Pressure	386	kPa	345-485	kPa
Flow Rate	0.07	kg/s	0.405	kg/s
Annulus				
Pressure	421	kPa	345-485	kPa
Flow Rate	0.15	kg/s	0.526	kg/s

Once it was determined that the current injector design did not meet the requirements, research was performed to locate the original calculations used for the initial design. The documents found did not give sufficient details to check the calculations and methods used to arrive at the initial design. This prompted an external search into injector design, manufacturability, and relevant pressure loss calculations.

From this external search an initial mathematical model was created as a tool to check the previous design and to be used as a starting point for an updated design. The model provided information about which flow geometries were creating the largest resistance to flow. After locating problem areas, the model was used to explore several possible design changes. The geometry sizes used for the models selected based on standard drill sizes to ensure manufacturability.

The new designs were next analyzed and refined using Computational Fluid Dynamics (CFD) software. Flow simulations confirmed that the changes in the geometry should be sufficient to achieve the required flow rates and located some potential issues with inconsistent exit velocity. The V2 pintle was next machined in aluminum and hydro tested. The example results from the testing the loss coefficient for the pintle are shown in figure 2 along with a side by side comparison of the V1 and V2 pintle injectors.

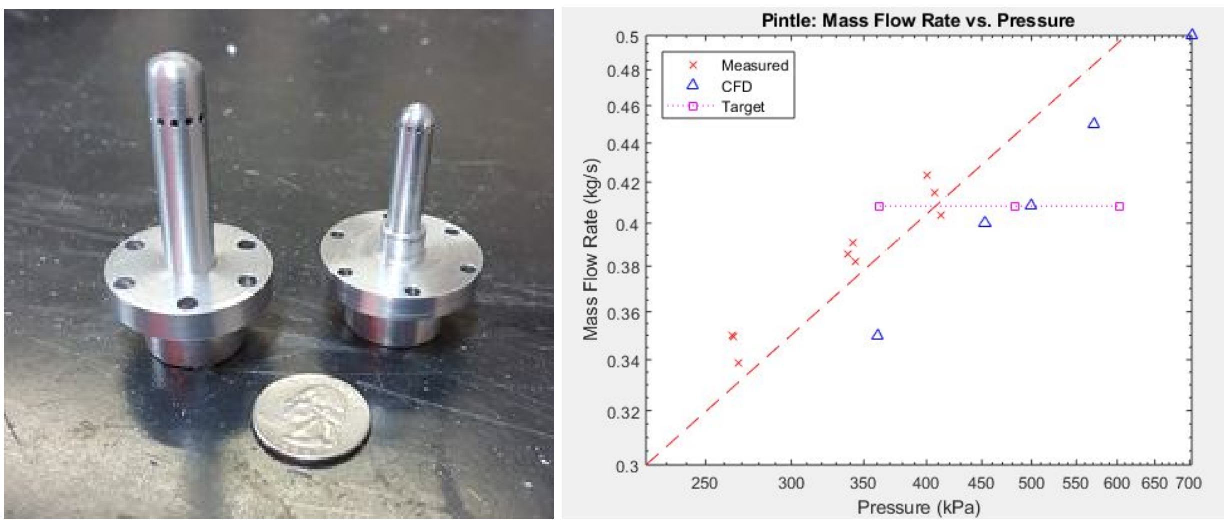

Figure 2: Left image: comparison of V1 and V2 pintle injectors. Right image: Hydro testing results from V2 pintle injector. The horizontal dotted line with square points indicates lower and upper pressure requirements and target mass flow rate. The blue triangles are the predicted results from the CFD model. The red x's are the experimental results, and the dashed line is the projected mass flow vs pressure curve using the measured pressure loss coefficient. This graphs shows that the pintle design does meet the mass flow rate and pressure requirements.

While testing the V2 injector, it was noted that it produced non uniform flow out of the annular orifice (Fig 3). To resolve this issue a new injector base plate was designed with multiple flow paths leading into the fuel reservoir at the base of the pintle. This new design was then 3D printed on a multijet printer by 3D Systems. Multiple copies of this injector were printed and hydrotested with good results. As expected from the prior testing, the flow rates were within the required ranges and the updated fuel flow path design produced uniform flow. When tested for spray angle, the design performed as intended. Fine tuning of the design still needs to take place prior to manufacturing a hot fire testable injector.

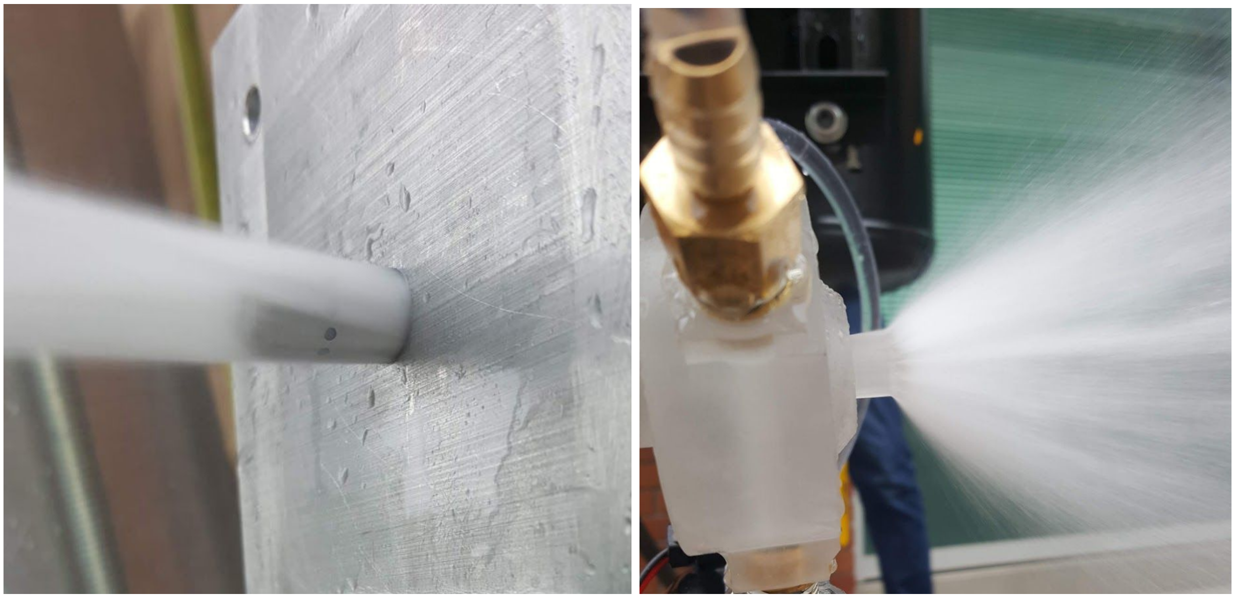

Figure 3: Left image: Hydro test of V2 fuel flow path with visibly non-uniform exit flow through annulus. Right image: Hydro test of V3 design with flow through both fuel and LOX flow paths. This design produces the correct spray angle with good droplet formation.

As a deliverable to our customer, we are providing thorough documentation on pintle injector design. This includes explanations of all equations, calculations, and python scripts used for the design, complete CAD and CFD models, detailed instructions on how to perform hydro testing for future injector designs. Additional work was also done on the preliminary design for a scaled up injector which will be needed by PSAS for its 100 km rocket. All details and documentation on this along with our recommendations for design and manufacturing improvements are also being delivered to PSAS.

ENGINE

Three additive manufactured engines were provided by PSAS from the 2016 MME capstone. These engines were designed to be regeneratively cooled and prints were donated by a local

DMLS company (i3D) out of AlSi10Mg. Two of the three engines fabricated underwent a non-destructive evaluation via CT scanning (Donated by Delphi Precision Imaging). The scans revealed internal manufacturing and design defects in the 3D printed engines. The regeneratively-cooled wall dividers that separate the channels were designed near the bottom limit for manufacture recommended wall thickness. Visually analyzing the virtually reconstructed 3D scan and slices it was determined that the DMLS printer recoater blade collided with the thin regeneratively-cooled walls. These collisions damaged the walls causing them to fracture and form foreign object debris that have the potential to damage or plug the engine during hot fire. An interesting observation that contributed to arriving at this conclusion and also gave an approximation to the direction of travel for the recoater blade is the fact that the damage occured approximately 180 degrees from one another. It was determined that the recoater blades direction of travel is perpendicular to the damaged regions. The final decision is that the design caused warping due to it being too thin and unsupported and then the recoater damaged them.

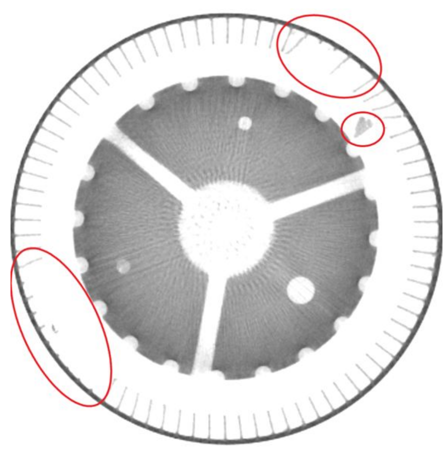

Figure 4: Horizontal CT scan slice of the engine near the flange. The larger circles highlight the regions that showed damage and the small circle highlights a broken section that can become dangerous.

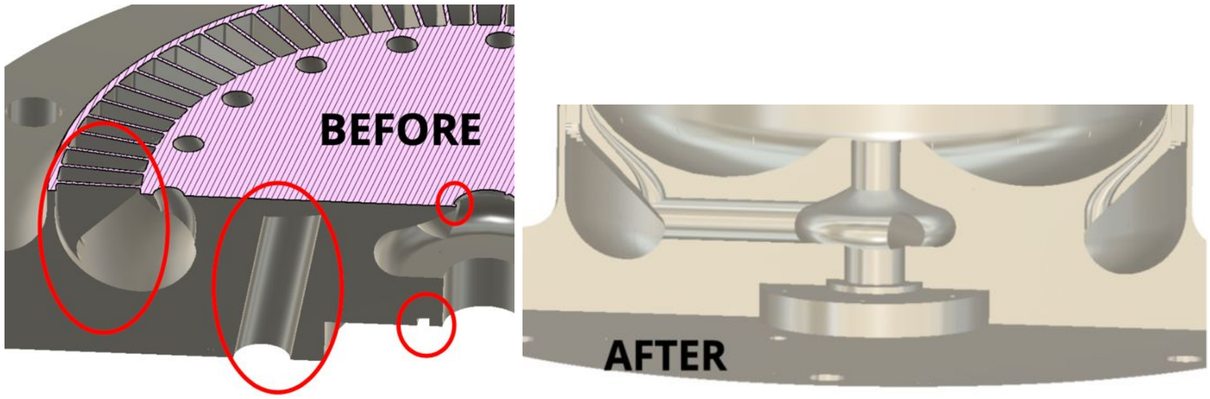

Figure 5: On the left is the CAD model of the engine with features that need to be changed circled. On the right is the simple changes made to CAD to remove features and improve manufacturability.

Figure 6: Welded fixture to post machine the printed engine where it interfaces with the test stand.

MAIN FUEL & LOX VALVES

The main pressurant valves consist of the main fuel valve and the main oxidizer valves. Both valves are responsible for the delivery of two pressurized liquids. Both valves are required to have a system that would allow for manually controlled on/off actuators that will turn the ball valves at pressures of up to ~1000 psi. The configuration of the actuator went through many iterations and ended with the elbow design shown in Figure 7 and 8. The purpose of the elbow is to provide a method of gathering information of the ball valves position. Both designs for the LOX and fuel valve actuators are very similar in nature. The only difference between them are the valves themselves and the types of brackets used to connect the actuators to the valves. To crack open and close the valves, a 12V 23 rpm DC motor is used, which will get the valve to open in about 1.25 seconds. The frame, motors, and supports are all commercial off the shelf and readily available. The brackets were made in house using sheet metal for the MFV and a square tube for the LOX valve.

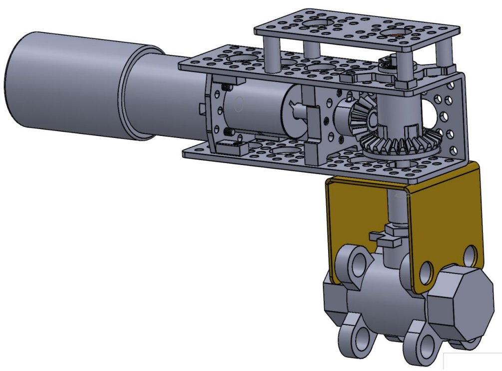

Figure 7: Main valve

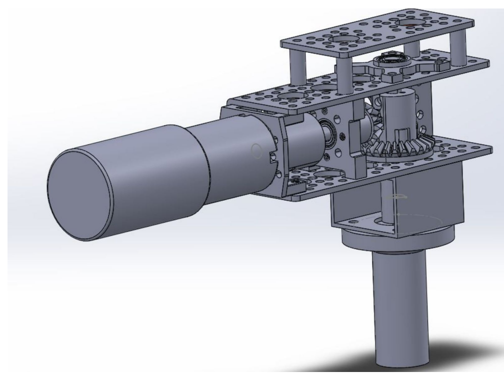

Figure 8: Main LOX valve

During the design process a typical issue that needed to be addressed, related to the main LOX valve, was its tendency to freeze shut. Since liquid oxygen is a cryogenic fluid, the LOX valve requires to have a system designed to prevent frost from accumulating and freezing the valve shut. An experiment was done to analyze this situation. It should be noted that this experiment was done prior to our knowledge of how exactly the valve froze shut. Our initial theory was that the mere exposure of the valve to a cryogenic fluid would cause a change in the torque required to open the valve. The experiment consisted of using liquid nitrogen, which is much safer to handle and a bit colder than liquid oxygen, to simulate cryogenic flow. Shown in figure 9, the MFV was dipped in liquid nitrogen for a certain amount of time. After taking it out, the valve was measured by a force meter attached to a lever arm, which provided us with a reading of torque. Figure 10 shows the torque graph from the data that was gathered. After observing the torque required to open the valve at room temperature and then at cryogenic exposure, both graphs were identical and a conclusion was made that the cryogenic flow was irrelevant.

Figure 9: Main LOX valve was put into liquid nitrogen to simulate cryogenic conditions.

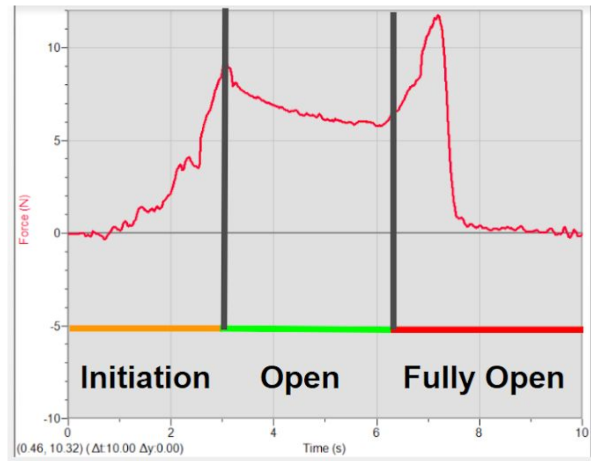

Figure 10: Graph showing the results from torque testing. All graphs were very similar to each other.

After talking to professional rocket engineers at the space conference in california, we were informed that our experiment was not accurate to what happens during actual test fire. During the period of having the valve contain LOX, the humidity in the air condenses in and on the valve just like on a cold water bottle on a hot day. The frost slowly builds up on itself until the valve frozen shut and inoperable. During the experiment this phenomenon was noticed and is shown in figure 11 but wasn't accounted for. Future PSAS students will need to design a system that dehydrates the air around the valve. A simple technique to achieve this is bleeding nitrogen into a bag that covers the valve and prevents moisture build up. Documentation is provided to PSAS on all procedures that need to be done as well as design recommendations to successfully integrate the main valves into the test stand setup.

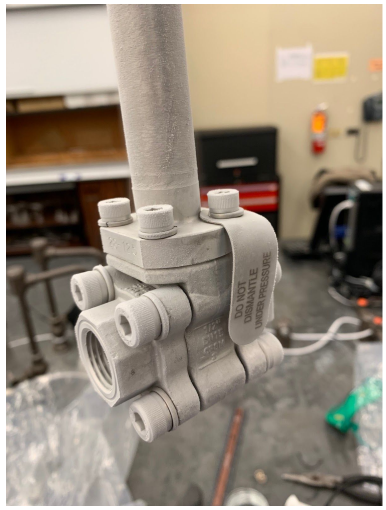

Figure 11: Frost buildup on ball valve. Growth of frost is observed after a certain time exposure to the ambient air in the room.

IGNITER SYSTEM

The engine that was designed for PSAS has a pilot hole in the back of it for an augmented spark torch (AST) igniter. This was the initial plan for igniting this engine, but as the 2.2kN engine is so small, it became clear that in order to mount the pintle with the correct pressure taps, it was going to be extremely difficult to fit the igniter.

Discussing this with the engine capstone team, it was determined that the igniter hole in the back of the engine was put in place to give the option of using an internal AST Igniter, but this type of igniter was not required to light the engine. Because of this, an external ignition system was designed and implemented. Figure 12 shows the old and new position of the igniter.

The new design of the test stand gives the option for use of an external igniter, via a spring-loaded armature. A CAD mockup of this arm is shown in figure 12. This arm is designed to be able to hold an external ignition source in the correct position, until engine ignition, at which point the arm will be “blown” away from the engine. If the 2.2kN engine is tested on the stand, this armature will provide the ignition source, and it gives engine designers of future iterations of the engine an option of using an internal or external ignition source.

The actual ignition of the engine was to be a modified version of the AST igniter, based on an off-the-shelf brazing torch. However, this design was not validated, and the arm was designed with provisions for using a simplified pyrotechnic ignition source if the torch igniter didn't work.

The igniter armature was completed by the end of the capstone, but the actual ignition system not built yet. Similar to the documentation left for the pintle and main fuel valve design, a document containing igniter research, design decisions and CAD, was created as a deliverable for PSAS.

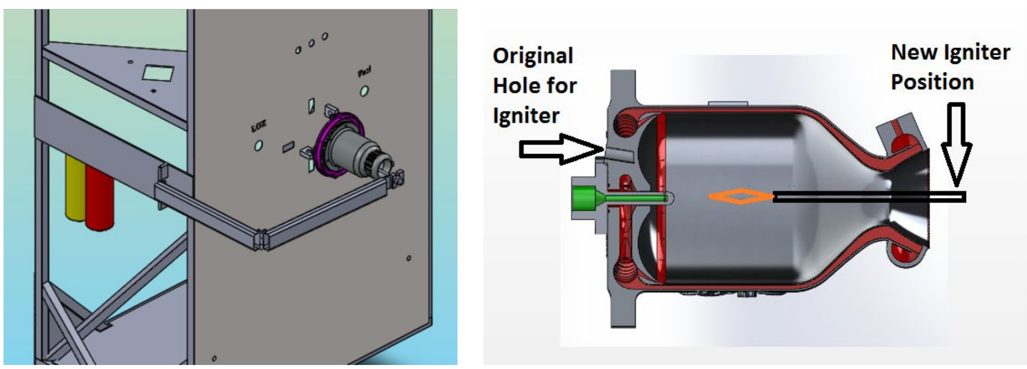

Figure 12: Solidworks model of new igniter system attached to the test stand model (left). Igniter position change in the engine (right).

TEST STAND

The test stand is a vital component to testing new engine designs as the test stand was designed to conduct multiple tests, incorporate new components, and withstand tests of up to 10 kN of thrust. The new test stand design was built upon the framework from the 2015 capstone. Components, plumbing, and control systems were designed and integrated into the new test stand frame.

As with designing any product having a good idea of what components are needed and where they go are essential. While evaluating the computer generated model left by the previous capstone team it was clear that it did not accurately reflect what was planned as some components were not up to date and some were missing. As shown in Fig 13 the test stand was heavily re-designed to better represent what was going to be constructed.

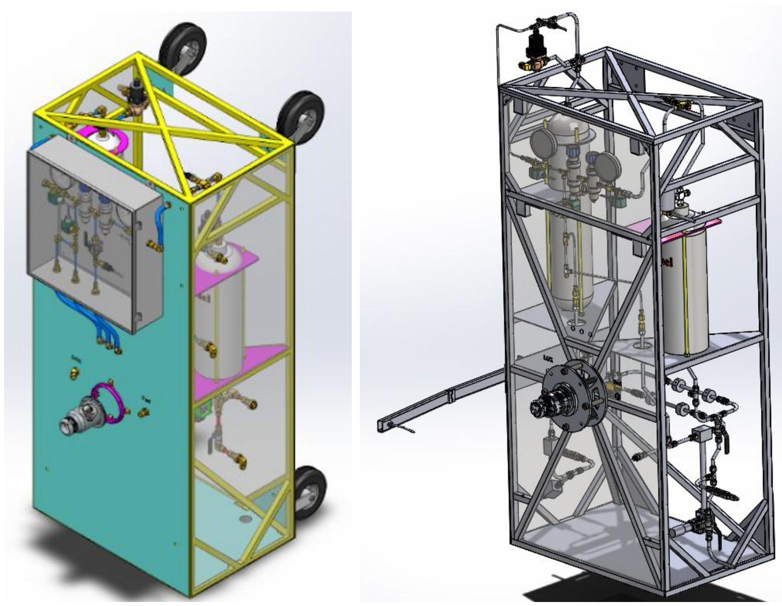

Figure 13: Solidworks test stand model from 2015 capstone (left) and the new revised test stand model (right).

Most of the fittings for both the fuel and LOX side have been switched from swagelok to AN 37^{o} fittings. This is because AN fittings perform well under vibration, high pressures, and cryogenic conditions. The sleeve used to back up the flared end of the tube ensures tube alignment with fitting axis, reduces mechanical strain on tube, and compensates for vibrations. The flared end has a minimal change in geometry compared to swagelok resulting in negligible pressure losses. The threads for AN fittings are coarser which provides individual threads with more strength and resists cross-threading, a common issue with the fine-threaded swagelok fittings.

The stand had been designed with fittings wherever tubing needed to change direction. Fittings give the tubing a discontinuous internal surface and create very large losses on direction changes. To reduce pressure requirements tube bending replaced most of the fittings. Bent tube has near-negligible pressure loss and are more robust with geometry changes due to high pressure or extreme temperature.

The original design called for a mixture of stainless steel, brass, and aluminum fittings. Under the redesign the stand now has three distinct sections, each with its own material selections. The pressure panel is built out of swagelok brass fittings and aluminum tube. Aluminum tube was used as brass fittings were available and seal well with aluminum. The fuel side of the stand, below the fuel tank, will consist of aluminum materials only except for valves. Currently it is a mixture of brass and aluminum. The oxidizer side is made from stainless steel. This will allow for better maintenance of the system as each section can be pulled apart for storage reducing corrosion. Stainless steel was used for the liquid oxygen transport as it works well at cryogenic temperatures and is not significantly reactive with oxygen. Eventually brass and aluminum should be eliminated from the system. Aluminum is extremely subject to attack by corrosion and brass becomes brittle as galvanic corrosion pulls zinc from the alloy.

The engine provided did not have enough supporting material around the pre-existing igniter port for one to be installed. Instead, to simplify machining and avoid the issue, an external ignition system was devised. The next iterations of the engine will rely on advances in printing technology or on post-processing to provide a tap for the igniter.

The new design of the test stand gives the option for use of an external igniter, via a spring-loaded armature. This arm is designed to be able to hold an external ignition source in the correct position, until engine ignition, at which point the arm will be “blown” away from the engine. If the 2.2kN engine is tested on the stand, this armature will provide the ignition source, and it gives engine designers of future iterations of the engine an option of using an internal or external ignition source.

Since pipes have a high coefficient of thermal expansion, cryogenic temperatures will cause the tubes to contract which can result in leaks at fittings where pre-load is lost. Adding joggles to long sections of tube relieve this by allowing the tubes extra length to straighten out instead of losing pre-load.

New models have been integrated into the CAD to better represent the dimensions of the components that will be installed. These models include new LOX valves for size and flared fittings, main LOX valve for actual dimensions, and main fuel valve for actual dimensions. Most models are rough volume estimates purely for dimensioning.

The pressure panel section has been moved behind the firewall to better protect it from unscheduled engine structure integrity checks. This also allows for a modular firewall to be installed on the front of the stand without need for pressure panel mounting.

The previous CAD did not match the test stand “as built” due to warpage from welding and other imperfections in fabrication. The CAD was updated to match the physical stand. Hold-down plates and other precision components including the teflon tank cushions were designed using the updated dimensions.

A guide detailing the changes made to the test stand was also created as a deliverable to PSAS for assisting anyone who may need more information on the test stand. This guide also includes a tubing guide that outlines the process to make tubing for the test stand and the restrictions that come with it.

Possibly the most Ad-hoc part of the project, mounting hardware consists of channel strut and related hardware. Aluminum tubing was bent in-house and installed. Stainless steel tubing is being manufactured by a local steamfitting apprenticeship. Where strut-channels do not have an appropriate anchor, all-thread and electrical straps are used. Anywhere heavy components are mounted, teflon spacers are used to prevent chafing/fretting and absorb some shock.

Figure 14: Physical construction of the test stand design.

To finish the project off, documents were written outlining the research, and progress of several key components to the test stand. Documentation was created for the pintle injector, test stand, igniter, and main propellant valves. The purpose of these documents is to give successors of the project a good understanding of the progress, design decisions, and lessons learned of the project.

CONCLUSIONS AND RECOMMENDATIONS

A great deal of information was learned during the course of this project. Our supplemental documentation which goes lessons learned and our detailed recommendations is our most valuable deliverable. For clarity and space, summaries of our recommendations have been divided up between the engine, injector, and test stand.

The 2018-19 LPETS Capstone team recommends the following;

ENGINE

Much of the complexity encountered in the initial design and construction of the test stand surrounded the decision to attempt regenerative cooling for the first engine design. Regenerative cooling requires a specific mass flow rate of propellant be pushed through the cooling channels in order to prevent the engine from melting, but the exact pressure required to maintain that mass flow rate is not known until the engine is tested. Additionally, the internal cooling channels can not be inspected without special CT scanning equipment, which adds time and cost to an already expensive process.

For these, and other technical reasons, we recommend that PSAS not pursue regenerative cooling at this time. We propose a relatively quick redesign of the current engine to convert it into a ‘heat sink’ type engine. This design relies on thicker material with a higher heat capacity combined with short duration hot firing tests to keep from melting. It is far less sensitive to issues surrounding the propellant mixture ratio and mass flow rates than a regeneratively cooled engine. Once PSAS has gained experience with hot fire testing an engine of this nature, it will be better positioned to revisit regenerative cooled engine designs.

PINTLE

The current pintle design should function within the the mass flow rates and pressure requirements for our recommended engine redesign. It is recommended that as part of the redesign a better interface between the pintle injector and engine be used to allow for easier machining, assembly, and inspection.

Moving forward, the current injector design will not scale up to meet the requirements for a 100km engine. Initial analysis of this was performed and showed serious design issues with this approach. Several options to address the known issues exist with the most promising design being to inject the LOX into the chamber through a single radial sheet, rather than using orifices. This design along with several other proposed changes have begun being investigated in conjunction with rising ME seniors who are interested in taking the project over for the 2019-2020 capstone year.

TEST STAND

The test stand as built requires pressurant control valves with a higher flow coefficient for any test. It is recommended that PSAS acquires lower pressure solenoid valves with a higher flow coefficient. Implementations of the Electronic Fuel System (EFS) for testing engines larger than 2.2kN would reduce the pressure requirements on solenoid valves and reduce overall test-stand costs allowing PSAS to allocate more resources to cryogenic propellant tanks and electric feed system projects which are more oriented to LV4 progress. Further improvements on the test stand include a complete stainless steel fluid system and construction of a support structure for the stand which will increase it’s second moment of inertia and hold pressurant gas.

Appendix A

All drawings, CAD files, and project documentation are located on the PSAS Github page and on Google Drive. The specific repositories and drive folder can be found at:

https://github.com/psas/liquid-engine-test-stand

https://github.com/psas/pintle-injector

https://drive.google.com/drive/folders/1tH_0L8DlW5AworlBcEfvvbSp9V3l-4ee?usp=sharing

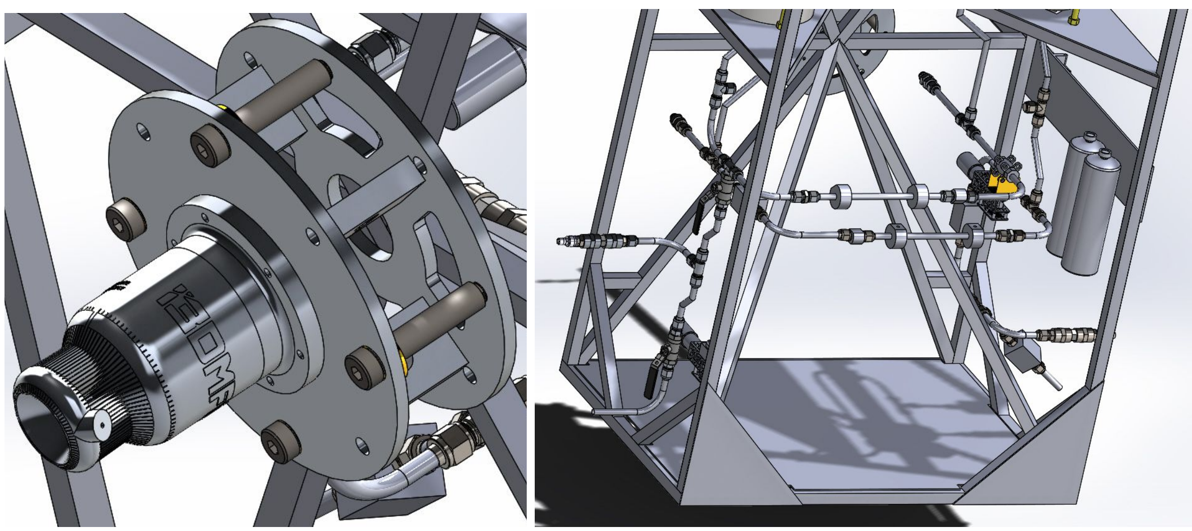

Fig 1. Pictures of the test stand Solidworks model showing the engine on the thrust plate (left) and the lower fuel and LOX sections (right).

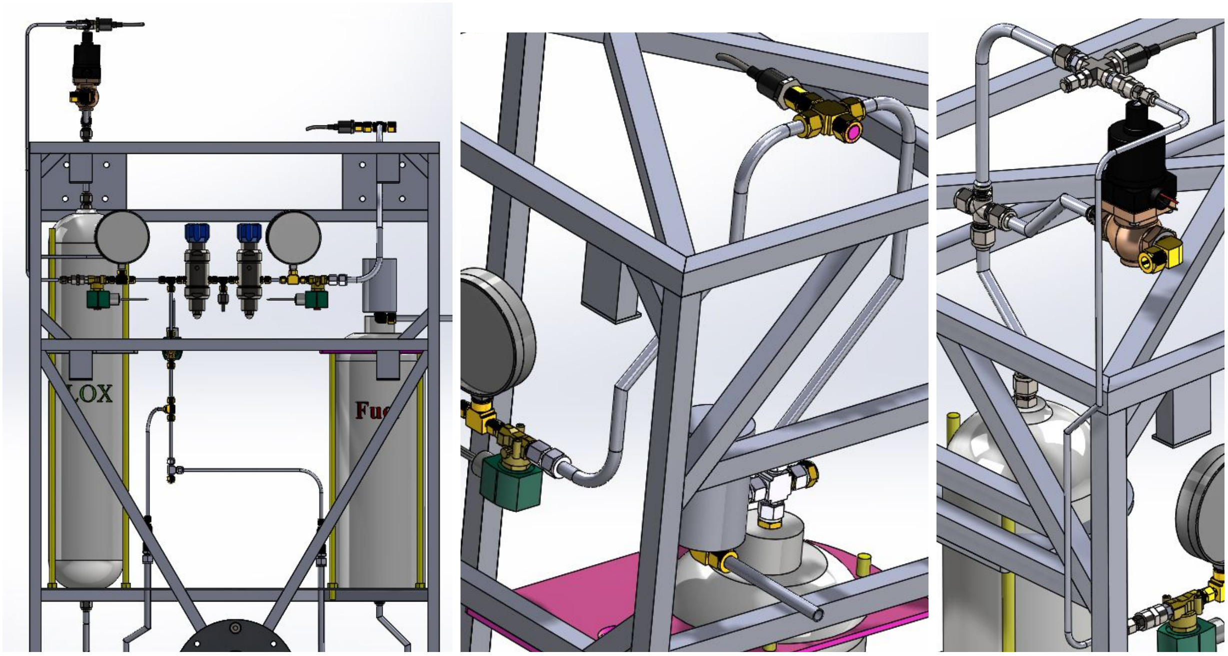

Fig 2. Pictures of the test stand Solidworks model showing the pressure section (left), the upper fuel section (middle), and upper LOX section (right).