Progress Report - Winter 2019

Liquid Propellant Engine:
Test Stand Integration and Testing

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1.0 Executive Summary

This progress report provides summary of the work completed by the Liquid Propellant Engine Test Stand Integration and Testing 2019 capstone team during winter quarter. The goal of this project is to Integrate a prototype liquid-bipropellant engine into a test stand as provided by the Portland State Aerospace Society. Achieving this also requires designing the test stand be suitable for the engine. The project team divided up key tasks into sub-projects which they are working on individually. These sub-projects include the Igniter, the Pintle, Engine Machining and Validation, Test Stand CAD Model, and Main Fuel and Lox Valves.

The igniter concept has been validated, and significant progress has been made toward the final design which will enter the engine through the nozzle. A detailed design for the attachment to the test stand will be finalized by April 1st, 2019 and the design will be built by May 15th, 2019. Testing of the initial pintle design determined that the design provided insufficient flow rates at the desired pressure settings. Design for the new pintle is nearly complete will be ready for manufacture by March 23rd and ready for testing by April 7th.

A design review of the Piping and Instrumentation Diagram (PID) and CAD model was completed and unnecessary components have been removed from the system. These changes also addressed concerns of fluid entrapment within the system. A second review will be conducted along with new fittings and piping by March 24th. All necessary parts will be ordered by March 31st and construction of the entire test stand will be completed by May 12th.

CT scanning of the 3D printed engines revealed internal defects which may affect the scope of our project as these defects may prevent the engines from being hot-fired. The go/no-go determination will come from future hydro testing of the engine along with a feasibility review with our sponsor.

2.0 Introduction

The liquid engine test stand team is focused on designing, building, and testing a 2.2kN liquid propellant rocket engine for the Portland State Aerospace Society (PSAS). PSAS is a collective of industry engineers, students, and rocketry enthusiasts dedicated to developing open source, low cost rocket hardware and avionics systems. PSAS is competing in the Base 11 Space Challenge (Base 11), in which university teams build and launch a liquid-propelled single stage rocket to the edge of space. Testing of the current engine design is critical path to achieve this goal. The engine implements several innovative design aspects including a fully parametric CAD design using Python and SolidWorks, direct laser sintering (DMLS) production by i3D manufacturing, and pintle injection. The liquid engine test stand is scheduled to be constructed and tested in spring 2019.

3.0 Mission Statement

The proposed project is to integrate, test, and analyze a prototype bi-propellant rocket engine. The team will integrate and test the engine and injector provided by PSAS. Engine testing will verify the performance metrics, including flow rates, thrust, cooling capabilities, and chamber pressure. Engine testing will be conducted in a reproducible manner according to a written standard operating procedures. Hot fire testing will only be conducted if the provided engine passes all qualifying tests and is deemed safe. Procedures for interacting with authorities, safety, and testing site hazard analysis will be written and used during this project. The captured data from the static fires and the analysis methods will be published under an open-source license.

Standard Operating Procedures will be formalized to meet or exceed industry standards and mitigate risk towards personnel, equipment, and property. All documentation will contain sufficient detail, background information, and operational description to enable a smooth transfer of knowledge to new project members.

4.0 Progress on Detailed Design

The Engine integration into the test stand is governed by two documents, the Piping and Instrumentation Diagram (PID), and the CAD model, Figures 1 and 2, respectively. In February, an internal design review resulted in some changes to the system layout. The layout changes included the removal of the integrated spark torch igniter. The changes to this are detailed in Section 4.1. This required the updates to the CAD model which is discussed in Section 4.4. The review also located the remaining primary hardware components to be purchased

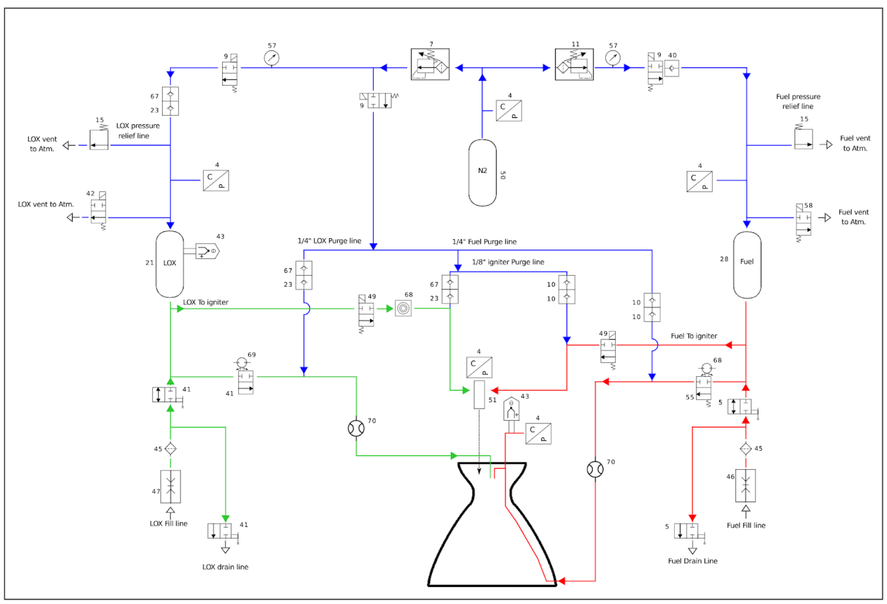


Figure 1: Piping and Instrumentation Diagram prior to current revision

The system architecture was broken into the relevant subsections and reviewed in detail. For each subsection, the review began at the pressure inlet and followed the fluid flow through flow path. This piece-wise examination of the system resulted in the modifications shown in Fig. 2.

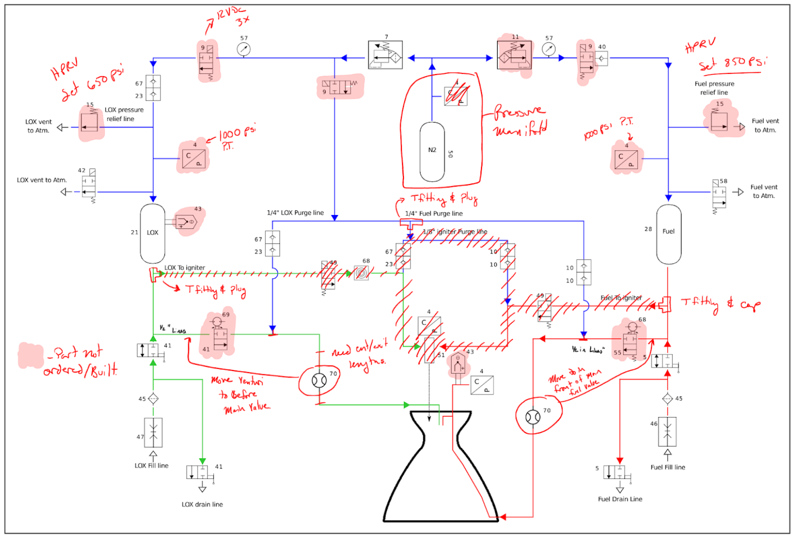


Figure: 2 PID Update with redlines

Relevant changes include the pressure regulator for the fuel side, the solenoids to control the flow from the pressure section, the pressure transducers throughout the system, and the thermocouples to be used on the lox tank and engine. Also added to the stand requirements is a pressure reservoir consisting of several nitrogen tanks manifolded together. The order of the main valves and the venturi meters was reversed. Taps will be made in the system for the igniter but will be capped off until later versions of the engine are tested.

Another significant concern regarding hardware which was observed is corrosion. Several weeks after water testing, the pintle test hardware has begun showing signs of significant corrosion. To counter this, stainless AN37 Flare hardware and stainless tubing was found to be preferred for the LOX system and aluminum AN37 Flare with Aluminum tubing for the fuel and pressure lines. This will allow us to disconnect dissimilar metal components more reliably than brass swaging hardware will when the system is stored.

Additionally ,the design revision provides specifications to the PSAS team building the control computer for the test stand. All electronic sensors need to interface with the Test Stand Automation and Regulation system (TSAR) for data logging and operational protocol.

4.1 Igniter

Liquid propellant rocket engines require a high energy ignition source. An inadequate source of ignition can lead a hard start, or the engine failing to ignite entirely. A hard start occurs when two combustion wavefronts exist in the combustion chamber due to pooling of the propellant mixture. In the best case scenario, a hard start means rapid expulsion of gas from the engine resulting in a flameout. The worst case scenario is catastrophic engine failure.

The standard ignition sources for liquid-bipropellant rocket engines are pyrotechnic ignition, and hypergolic slugs, augmented spark torch igniters. A pyrotechnic ignition system lights a premixed solid fuel/oxidizer (i.e. gunpowder) which then ignites the primary rocket fuel. This type of ignition system is inexpensive and easy to manufacture but is not as reliable as other types. Hypergolic slugs use two hypergolic propellants to create a short, high intensity flame in the combustion chamber. Hypergolic propellants, or hypergols, are substances that spontaneously ignite when combined. There was a highly enjoyable book written on the topic in the nineteen-seventies.[1] Hypergols are commonly used and very reliable, but can only be used once per test set-up and are extremely poisonous. The augmented Spark torch igniter acts like a very small rocket within the larger rocket. The small combustion chamber is ignitable by a high energy spark. The small exhaust ignites the larger rocket's mixed propellants.

The test engine has been designed to work with a spark torch igniter inserted into base of the engine (internal ignition). The engine was printed with a blind hole in the base plate for such an igniter, as shown in Fig. 3. However, the bore is too close to other features to be machined easily. After a review of the options available for igniters, it was decided that an external ignition source would be the easiest and most reliable option.

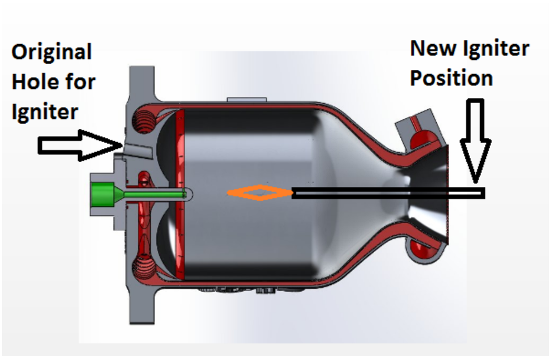


Figure 3: Cross-section of engine, showing igniter position

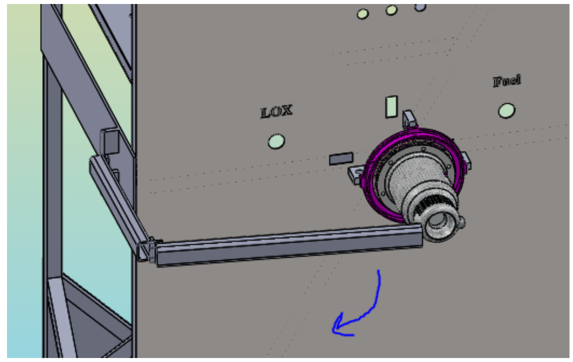


Figure 4: Cad Mockup of Igniter Arm

The current design optimizes for simplicity by modifying an off-the-shelf miniature oxy/mapp brazing torch. The ignition source will be a spark plug which will be used to light the torch remotely. The fuel and oxygen supply for the torch will be controlled via solenoid valves.

The torch, ignition system, and solenoid valves have already been sourced and purchased and the concept has been tested. Currently the team is working on designs for how the igniter will attach to the test stand and engine. The latest design iteration, shown in Fig. 4, involves a hinged arm connected to the stand. The arm positions the igniter in the nozzle of the engine. The arm will be magnetically held in place. When the engine ignites it will blow the igniter and arm away from the engine and clear of the exhaust.

4.2 Main Fuel/LOX Valves

The fuel and liquid oxygen flow to the engine is controlled by the main propellant valves. Both LOX side and fuel side will use actuated ball valves which are controlled remotely. The actuator, control system, and valve housings were initially designed for use with the fuel valve. After the design is validated a modified version will be adapted for the LOX valve.

One concern raised during the valve design is the possibility of the LOX valve freezing shut due to the cryogenic flow. If frozen, the motor on the actuator will need to output enough torque to force the valve to the desired position. An experiment was conducted where the LOX valve as submerged in liquid nitrogen to subject it to cryogenic temperatures. Liquid nitrogen has a boiling temperature of $-210^{\circ}C$ to $-196^{\circ}C$, which is colder than Liquid Oxygen at ($-183^{\circ}C$). The LOX valve was tested at room temperature and after being submerged for an extended time in liquid nitrogen. A moment arm and force meter were used to determine actuation torque and a thermocouple was used to measure valve temperature. Through varying time intervals of the valve being submerged the torque was found to vary as seen in Fig. 5 and Fig. 6.

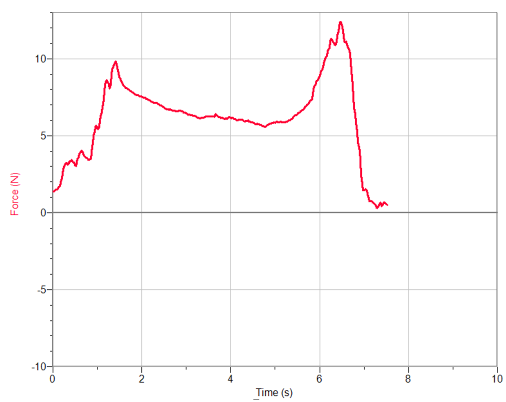


Figure 5: Valve at room temperature. First peak (2.35 ft lb) is the valve starting to open, followed by a second peak when the valve is fully open

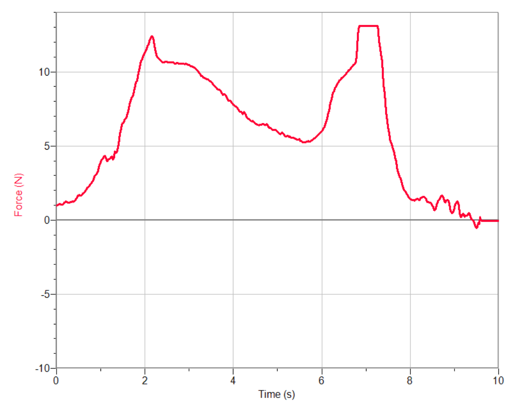


Figure 6: Valve at first exposure to cryogenic temperature. First peak (3.03 ft lb)

The valve requires an increase of 0.68 ft lbs in torque when it was first exposed to the cryogenic temperature shown in figure 6. The valve itself underwent a temperature change of -74.5 C° and maintained an average temperature of - 93.2 C°. After the initial exposure, the valve went back to the same torque range as the room temperature one shown in figure 5. From the data gathered it was concluded that using a motor with about 3.5 ft lbs of torque is optimal. To make things simpler and easier to build, both fuel and LOX side actuators will use the same design housing design with custom brackets and interfaces.

4.3 Pintle Injector

The engine was designed to employ a liquid oxygen (LOX) centered pintle design. In this design, 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. Inside of the combustion chamber, the two propellants impinge upon each other at right angles creating a cone shaped spray of atomized and well mixed propellants.

PSAS provided an aluminum version of the pintle injector which had been designed by the 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 mass flow rate required for both propellant flow paths is 14.8 gallons per minute (gpm) of water at a pressure between 53 and 70 psig. The combined flow rates were found to be 3.5 gpm.

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		
Average Pressure	56	psig
Average Flow Rate	1.07	gpm
Target Flow rate (water)	6.47	gpm
Annulus		
Average Pressure	61	psig
Average Flow Rate	2.41	gpm
Target Flow rate (water)	8.33	gpm

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. Table 2 shows a simple comparison matrix between several of the designs explored. For both the Pintle and Annulus, design B has been selected as our Pintle version 2.

Table 2: Comparison of CFD results between the original pintle design two alternate designs. For the simulation the mass flow rates were set to those required by the engine in order to determine the pressure drop. Exit velocities were considered uniform if they were within 5 m/s of the average exit velocity.

	Pintle Design			Annulus Design		
Design	Orignial	A	B	Original	A	B
Pressure Drop (psi)	1447	151	68	394	64	66
Uniform Exit velocity (y/n)	y	y	y	y	n	y

New CAD models have been created are being reviewed. Once the drawings are ready, a new pintle and annulus test jig will be machined. The second version of the pintle is expected to be ready for testing early in spring term.

4.4 Test Stand CAD and hardware

Material compatibility between liquid oxygen and certain metals is crucial. Brass is susceptible to corrosion where the zinc is drawn out leaving the remaining copper fragile. This process is called dezincification and is caused by the presence of electrolytes.

Other design requirements are keeping costs low and eliminating pressure losses. By limiting elbow joints and unnecessary fittings, cost and pressure loss were reduced. This also simplified the overall system design as seen in Fig. 7. The relief valves for both the fuel and liquid oxygen (LOX) systems also needed to be repositioned to eliminate pooling of liquids in pipes when venting. To protect the pressure control components from engine rich combustion, the pressure panel was moved inside the test stand frame as seen in Figure 9.

Due to time constraints and ease of implementation a new initial igniter system design was required. The previous igniter system was removed from the computer aided design (CAD) to simplify the overall system by making it a separate system as detailed in the igniter section. However, the fittings for the original igniter system were capped for future implementation of a integrated igniter system if necessary.

Separate Stainless steel and aluminum tubing and AN style fittings were chosen as they can handle the pressures required and are more reliable than brass swages. Stainless steel is also commonly used to store liquid oxygen. Due to changes to several components within the CAD model, new parts are being purchased to fulfill these new requirements.

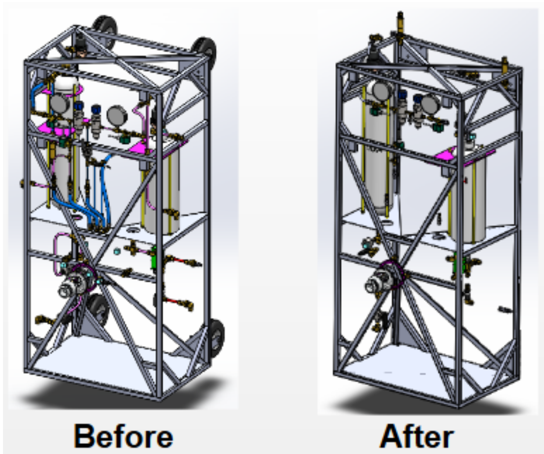


Figure 7: Before and after of the test stand shows the simplifications made.

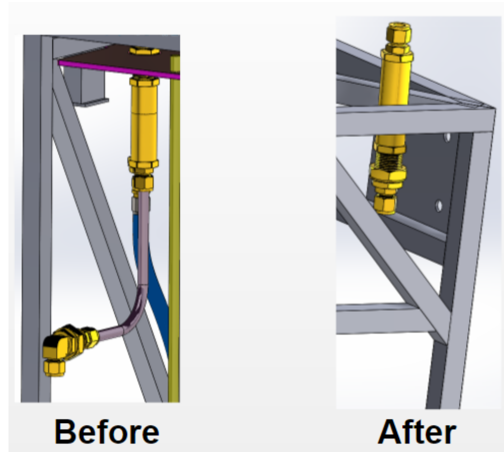


Figure 8: Before image shows potential to pool liquid. After image, relocates the pressure relief valve to prevent pooling

In the previous design the relief valves were positioned below the tanks and coming out the sides. The main concern was liquid pooling in the pressure section which was located below the top of the tanks. By repositioning the relief valves above the storage tanks and piping out the top of the fittings on the tanks,as shown in Fig. 8, the possibility of liquid pooling in the tubes can be reduced.

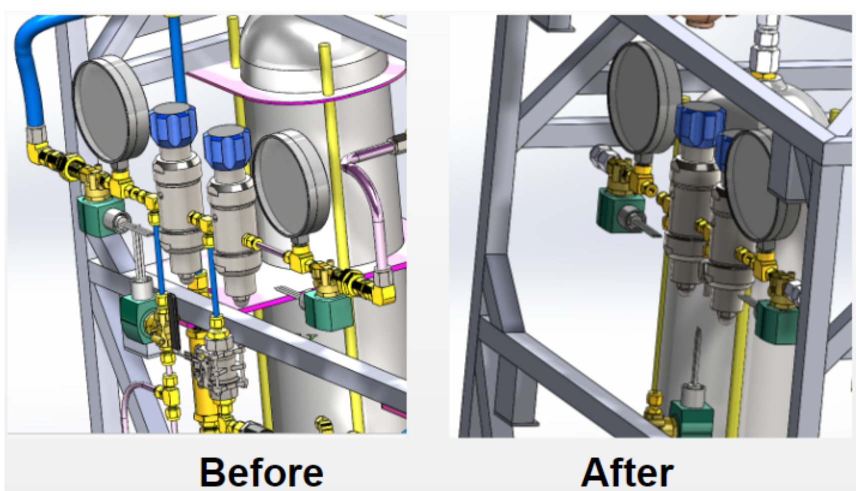


Figure 9: Before and After shows simplifications made as well as having the components moved inside the test stand in order for the blast shield to be installed

By keeping the original fittings for the igniter system the ability for future integration of an igniter system is possible. This will also include replacing previous brass swagelok fittings on the LOX side with stainless steel AN37 fittings and the fuel side with aluminium. After all the new components have been implemented a new piping layout will be added to the CAD. Missing parts are being ordered and will be integrated to the stand as they arrive.

4.5 Engine and Machining

Three 2.2kN rocket engines were designed and sent out for fabrication by the 2016 capstone team. They were fabricated with a process known as direct metal laser sintered (DMLS). The engines are comprised of fused aluminum powder, about 80% by weight, and cost around $2k each. The engines were kept by PSAS with the goal of test firing them. Before a hot-fire can be done, they require cleaning and post-processing.

One of the best sources of information for post-processing work required was from direct communication with members of the 2016 capstone team. They provided changes that need to be made to the initial printed design and features that will need to be machined away. They also had some ideas for fixture designs. A machinist is currently helping to determine the technical requirements and process.

The manufacturer mentioned that the printed material machines like cast aluminum, which will determine machining parameters like tool speed, feed rate, etc. Information about the 3D printed material was found via Material Data Sheets and research papers. Comparison of the selected material vs other common print material was presented on the capstone team's final report, and on a report from a University of Southern California team. Fixture materials were chosen with the assistance of local metal providers and welding forums.

A fixture for the engine is needed to machine the engine because it has complex geometry and an unstable base. The engine's nozzle is delicate and could get damaged if too much force is applied to it when machining. To prevent damage to the nozzle, the fixture holds the engine supported by its flange as shown in Fig. 10. The fixture was designed around the preexisting CAD model for the engine.

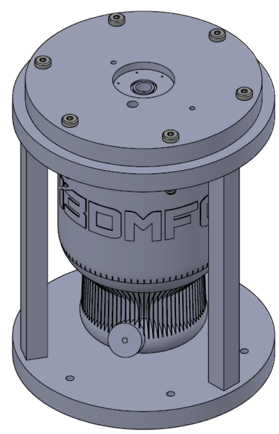


Figure 10: CAD model of engine and jig for machining

Two out of three engines have been CT scanned. Both scans have revealed internal defects, meaning it is likely that the last one has similar defects. Hydro testing one of these engines is required to determine how much of an impact these defects have on the flow rate and if these defects break-up and become particulates that could clog the pintle injector.

Pin gaging revealed that the printed holes are not the correct size specified in the design. Most of the holes are more than 0.0037" undersized. For machining, this changes the size the pins needed for alignment. The bolt holes also have a taper to them. However, this should not affect the machining as the holes will need to be widened to the correct size anyway.

Moving forward, the CAD drawing for the fixture has been reviewed and changes are to be made to accommodate the results from pin gaging, and process changes. Material for the fixture was ordered and has arrived on campus. Machining of the fixture and accompanying pieces are slated to begin by the 17th of March as a welding source is still to be identified.

5.0 Conclusion

The project team has been making progress on the major technical milestones needed for validating PSAS's engine design. After significant redesign of the entire system, several key challenges remain. CT scans of both of the engines have come back showing defects inside the engines' internal passageways causing concern over the quality of the printed engines. This may lead to a delay in hot firing the engine pending a review of the issues with our sponsor. Furthermore, there are concerns over the safety regulations and logistics of finding a suitable location to test the engine. More planning needs to be done to confirm our current prospective location is suitable. In spite of these challenges the team is on track to meet our project requirements.

Appendix

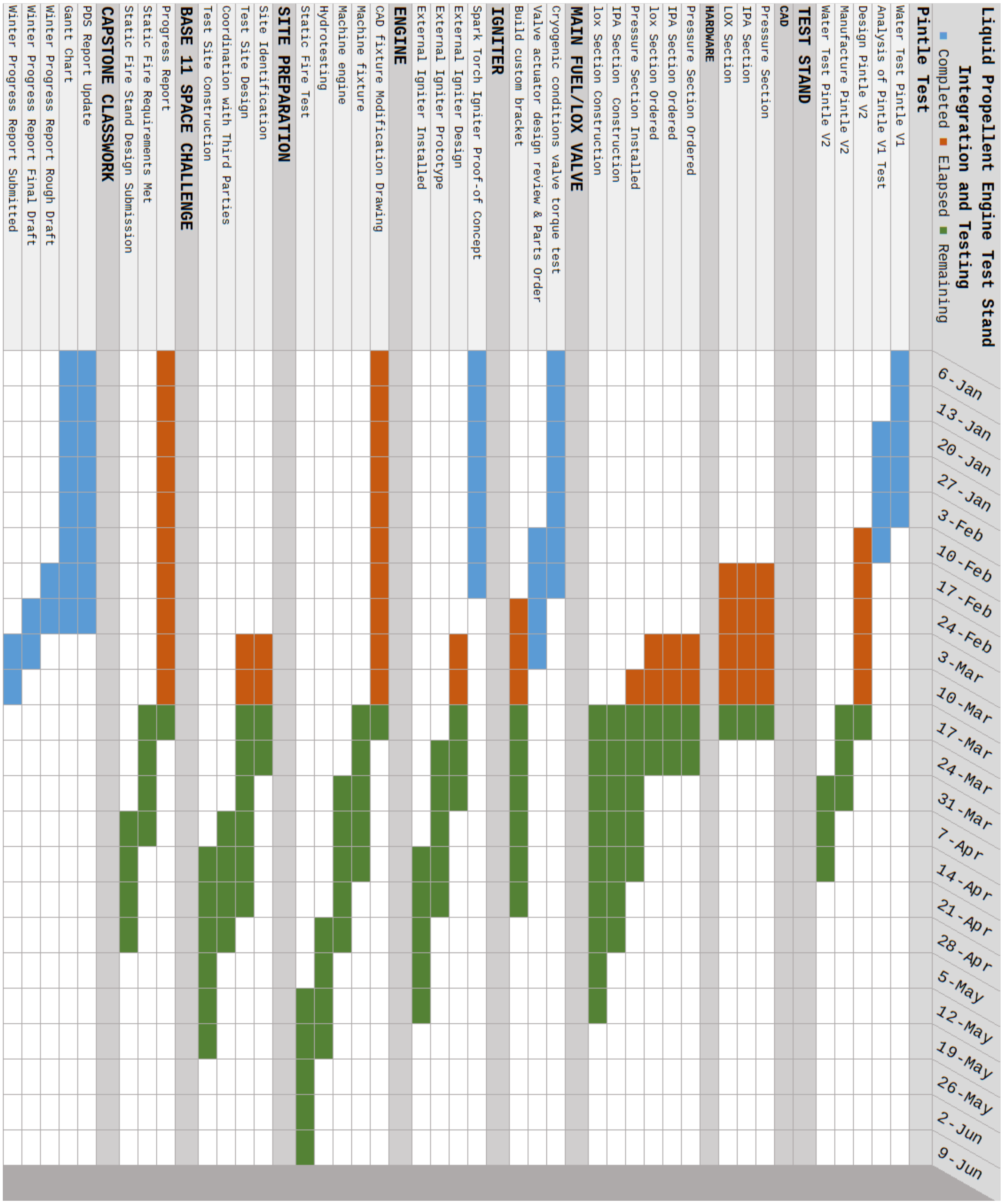
PDS Report

Criteria: Performance, Safety, Environment, Cost, Documentation, Material & Manufacturing

Customer Need	Primary Category	Secondary Category	Variable	High	Low	Desired
PSAS, NASA						
Formal Failure Modes and Effects Analysis (FMEA)	Documentation	Safety	FMEA	1	0	1
Deliverable Document: Safety S.O.P.	Documentation	Safety		1	0	1
Deliverable Document: Operations S.O.P.	Documentation	Documentation		1	0	1
Deliverable Document: Post Firing Analysis of Engine with suggestions for larger engine	Documentation	Analysis		1	0	1
Safety Procedures Known and Followed	Safety	Safety		1	0	1
Fuel: Isopropyl alcohol	System	Safety		1	0	1
Oxidizer: Liquid Oxygen	System	Safety		1	0	1
Pressurant: Nitrogen (gas)	System			1	0	1
Incorporation of PSAS Supplied DAQ (From TSAR)	System	Safety		1	0	1
Test Engine: 2.2kN engine supplied by PSAS	Hardware	System		1	0	1
Participation in any mandated safety Training (multiple customers)	Safety			1	0	1
Minimum human interaction with the test stand during operation	Safety	System		1	0	1
No person(s) are to approach Test Stand while system is pressurized	Safety	System		1	0	1
Redundant system to prevent accidental pressurization of System	Safety	System		1	0	1
Funds available from PSAS should not exceed $2,000 without prior approval	Budget		Money	2000	0	2000

Funds available from NASA grant (UTEAP)	Budget		Money	3938	0	3938
Deliverable Document: Background, Research & Theory of Operation	Documentation			1	0	1
Deliverable Document: Training Materials	Documentation			1	0	1
Deliverable Document: System Maintenance	Documentation			1	0	1
Deliverable Document: Test Site Management	Documentation			1	0	1
Deliverable Document: Transportation of Test Stand & propellants	Documentation			1	0	1
Deliverable files: Full Solidworks CAD model of Test Stand Assembly	Documentation			1	0	1
Software: All technical documents and files are to be regularly pushed to git	Documentation			1	0	1
Software: All other test stand administrative files to be stored on PSAS Shared google drive	Documentation			1	0	1
Deliverable Document: Bill of Materials	Documentation			1	0	1
Fully Constructed Test Stand (or whatever is left of it)	Hardware	System		1	0	1
Engine Chamber Pressure	System		psi	375	325	350
Fuel Mass Flow Rate	System		lbm/sec	unk	unk	1.16
Propellant Mass Flow Rate	System		lbm/sec	unk	unk	0.09
Injector spray angle	System		degree	unk	unk	45
Injector Pressure Drop	System		psi	53	70	70
Capstone Advisor						
Weekly meeting to discuss project and progress	Administrata					
Capstone Class						
Deliverable Document: Project Design Specifications	Documentation					

Gantt Chart



Liquid Propellent Engine Test Stand Integration and Testing
Completed
Elapsed
Remaining
Pintle Test
Water Test Pintle V1
Analysis of Pintle V1 Test
Design Pintle V2
Manufacture Pintle V2
Water Test Pintle V2
TEST STAND
CAD
Pressure Section
IPA Section
LOX Section
HARDWARE
Pressure Section Ordered
IPA Section Ordered
lox Section Ordered
Pressure Section Installed
IPA Section Construction
lox Section Construction
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Build custom bracket
IGNITER
Spark Torch Igniter Proof-of Concept
External Igniter Design
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External Igniter Installed
ENGINE
CAD fixture Modification Drawing
Machine fixture
Machine engine
Hydrotesting
Static Fire Test
SITE PREPARATION
Site Identification
Test Site Design
Coordination with Third Parties
Test Site Construction
BASE 11 SPACE CHALLENGE
Progress Report
Static Fire Requirements Met
Static Fire Stand Design Submission
CAPSTONE CLASSWORK
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Winter Progress Report Rough Draft
Winter Progress Report Final Draft
Winter Progress Report Submitted
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2-Jun
9-Jun

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[1] Clark, J. D., 1972, *Ignition!*, Rutgers university Press, New Brunswick NJ.