Portland State Unversity

Liquid Fuel Rocket Engine Capstone

Final Report - Spring 2016

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Executive Summary

The design and analysis summarized in this report was commissioned to examine the viability of creating a 500 lbf thrust liquid fuel rocket engine using additive manufacturing techniques. Design specifications have been provided by the capstone team's sponsor: Portland State Aerospace Society (PSAS).

The current rocket developed by PSAS utilizes a solid fuel engine. These solid fuel engines are purchased through a third party vendor and the maximum size available for consumer use is limited. Currently, PSAS has designed their launch vehicle around the largest size solid fuel rocket engine commercially available; however, these engines do not meet their flight requirements moving forward. As a result, the design and manufacture of a liquid fuel engine is necessary for future launches.

The objective of the Liquid Fuel Rocket Engine (LFRE) capstone team is to develop and manufacture a bi-propellant liquid engine complete with performance data, and a scalable, preliminary proof of concept design capable of achieving at least 500 lbf of thrust. The static bipropellant rocket engine will aid in the ability of PSAS to cross the von Karman line in the coming years by providing a starting point for future students to continue the development and analysis of liquid fuel engines.

The proposed engine utilizes regenerative cooling channels, film cooling, and aluminum additive manufacturing processes. Additionally, off-the-shelf sealing strategies have been employed, as well as a removable pintle injector capable of alteration for testing purposes.

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1 Introduction and Background

The Portland State Aerospace Society (PSAS) is an engineering student group at Portland State University dedicated to low-cost, open-source technology development for high-powered rockets and avionics systems. The group's stated long term goal is to place a 1 kg cubesat into low Earth orbit with their own launch vehicle. One step needed to achieve this goal is to transition the current rocket design of a solid engine to a liquid fuel engine. The liquid propelled rocket engine project is being conducted as part of a mechanical engineering senior capstone project at Portland State University.

The complexity and cost of building a liquid fuel rocket engine typically makes such devices unobtainable for a majority of parties interested in their construction. Until recently, manufacturing processes and techniques limited the geometries available to the designer and rendered such engines cost prohibitive as options for inexpensive orbital space flight. Advances in additive manufacturing technologies provide the potential to prototype complex geometries on a lower budget and with shorter lead times which would be considered infeasible with traditional manufacturing methods.

Explored herein is the process of designing and testing a 500 lbf thrust bipropellant engine using liquid oxygen (LOX) and ethanol as propellants. A low cost pintle injector and accompanying regeneratively cooled thrust chamber is developed using a combination of traditional manufacturing techniques and additive processes. Design equations and tools have been created to describe the complex geometries of the nozzle contour and the sizing of other important components.

2 Mission Statement

The LFRE capstone team is to design and test a 500 lbf thrust bipropellant engine prototype using liquid oxygen (LOX) and ethanol as propellants. The engine will use additive processing technology to incorporate a geometrically complex, regeneratively cooled thrust chamber to tackle high combustion temperatures. Using GitHub and iPython Notebook, all analysis performed will be documented and easily accessible for future iterations and scaling of the engine. A prototype and all additional documentation, including designs and drawings, is to be completed by June 2016.

3 Main Design Requirements

The design requirements were created in collaboration with Erin Schmidt, the industry advisor for PSAS. Requirements have been adapted based on physical and dimensional limitations of designing a liquid fuel engine for small thrust values. The overall design requirement of this engine is to produce at least 500 lbf of thrust with a scalable and adaptable approach. The documentation supporting the design of this engine is to be compiled in a way that is easy to utilize for future work. The product design specifications (PDS) is summarized in table 1 below.

The budget for this project is \$6,000 dollars, none of which has been utilized in the design and manufacture of this engine. The 3D print of the rocket engine has been donated by i3D Manufacturing. For the injector, the team has reached out to several machinists for donations or quotes for machining and is awaiting responses. A quote from i3D showed the price of materials for such an engine usually costs about \$2,000 per print, depending on the material of the print.The print donation allows for more of the budget to go toward instrumentation and testing equipment.

Table 1 outlines the PDS requirements for the three main design components; the nozzle, injector and documentation. The key requirement for the nozzle design is to produce a thrust output of 500 lbf. Its calculations are documented on the GitHub. The nozzle has been sent out to be 3D printed with ports for necessary pressure transducers and temperature sensors. Using these sensors, calculations will be verified during static load testing. The requirements for the pintle injector is to achieve a pressure drop of 70 PSI as well as atomizing and mixing the fuel with the oxidizer to produce efficient and stable combustion that will provide the required thrust. A test annulus was designed to be machined with the pintle in order to cold and hot test the injector before firing it inside the engine. The majority of the budget was intended for purchasing the 3D printing of the nozzle and although the cost of machining the pintle is unknown, the expected overall cost will still be under budget. The third requirement

Requirement	Metric	Target	Target Basis	Verification	Achieved
Nozzle design with cooling channels	Thrust output / wall temperature	500lb / 1̃500R	Customer input	Calculations and prototype testing	Yes
Pintle injector	Pressure drop	70 PSI	External research	Calculations and cold testing	Yes
Documentation	Deadline	End of project	PSAS	Detailed iPython notebooks on GitHub	Yes

Table 1: *Main Design Requirements*

is documentation. Most of the design processes and calculations are documented in Jupyter notebooks on GitHub for the public to access. Jupyter notebooks contain equations based on input variables to allow running different iterations and will form a template for designing 3D printed engines with regenerative cooling channels. The final documentation is currently being organized and uploaded.

4 Top Level Design Considerations

There are a multitude of considerations for the design of components of a liquid fuel engine such as cooling channel geometries, expansion bell geometries, collection chambers, instrumentation, material selection, and fuel injection strategies. All available options have certain strengths and weaknesses which are necessary to take into consideration for the performance of the engine.

4.1 Nozzle Geometry

Many rocket nozzles are of the converging/diverging 'De Laval' type. The diverging section of the nozzle is important for performance due to high fluid velocities in this section of the rocket engine. Several types of nozzles exist, however, the most common are conical and bell shaped nozzles. Specialized geometries such as the 'spike' and expansion deflection (E-D) geometries, pictured in Fig. 1, are possibilities, however the difficulty in manufacturing such a nozzle place them well outside the scope of this project.

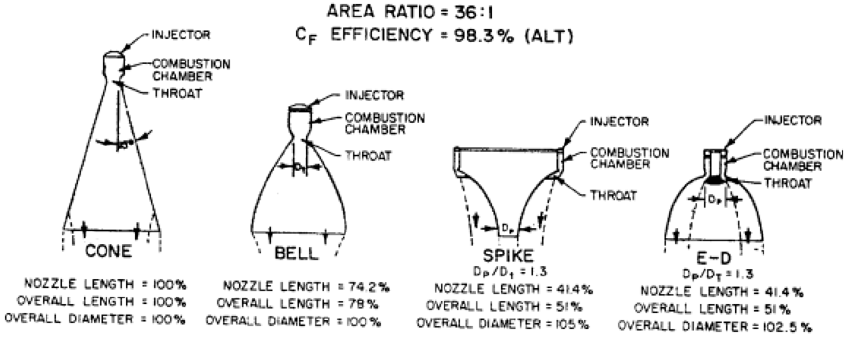


Figure 1: *Overview of rocket nozzle geometry types with performance characteristics and relative dimensions compared to conical nozzles. CF represents thrust efficiency of a conical nozzle. Area ratio is the flow area of the nozzle exit compared to the area of the converging section at its smallest radius (throat). (Huzel 1992)*

The available options for the capstone were the conical and bell nozzles. Conical nozzles offer an easy to manufacture solution, however due to the geometry, the flow velocity leaving the nozzle has a non-axial component, which reduces the thrust efficiency. The bell nozzle offers improved combustion efficiency at a ∼26% reduction in overall length compared to a conical nozzle, which allows for lower material costs when utilizing additive manufacturing.

4.2 Material Selection

The rocket engine was initially designed for Inconel 718 materials, however high stresses due to thermal expansion required the selection of an alternate material for a rocket of this size. AlSi10Mg was chosen as its replacement due to its high thermal conductivity, and low relative cost. With heat transfer properties taken into consideration aluminum is more suitable to the available cooling capabilities though it reduces the maximum possible combustion temperature. For large engines with better cooling capabilities it is more typical to compromise thermal conductivity for material strength.

4.3 Injector

There are several possibilities for the selection of the injector. Most injectors types are capable of atomizing the fuel in a stable and efficient manner so performance characteristics are not the driving factor in design selection. A 500 lbf thrust has low fuel mixing requirements, as long as the mass flow rates and momentum ratios are satisfied, many different design ideas will work. Swirl injectors, as well as impinging jet injectors were concepts included in considerations; however, these designs are not modular. For testing purposes it would be necessary to redesign and reprint the nozzle for every iteration of the injector or deal with the complexity of sealing the injector at the regenerative cooling channel interface. As a result a more modular design was selected. A pintle injector is fixed to the engine via bolts or machine screws, so if alterations are necessary for test procedures it is relatively easy to remove and replace. Additionally, pintle injectors are less susceptible to combustion instabilities and are potentially throttleable; features that will benefit future larger engine designs. The major injector components will be machined on a lathe in a timely manner, and sent out to machinists for finishing details such as fluid ports. Since the slots on the pintle are 0.02" × 0.035", they must be machined by wire EDM for tighter tolerancing.

5 Final Design

The general arrangement drawings in Fig. 2, 3, and 4 detail the features of the final liquid fuel engine design. The engine is 3D printed in aluminum and is equipped with regenerative cooling channels as well as film cooling ports in the combustion chamber. These features ensure that the strength lost due to the heat generated by combustion is mitigated as much as possible. The fuel inlet at the bottom of the nozzle transports the fuel up through the cooling channels in red. A small amount of fuel is removed in the manifold to be used for film cooling. The small film cooling holes in the combustion chamber create a barrier of gaseous fuel to protect the wall from high combustion temperatures. The majority of the fuel is then expelled through a small annulus near the pintle injector where it collides with liquid oxygen and is ignited to produce the required thrust. The cooling channels are sized to maintain constant cross sectional area and limit the pressure loss of the fluid in the channels.

The pintle injector pictured in Fig. 3 is responsible for delivering the liquid oxygen to the combustion chamber. The oxygen travels down the center of the pintle and leaves the small LOX holes in the tip at a 90 degree angle to the original direction of travel. The liquid

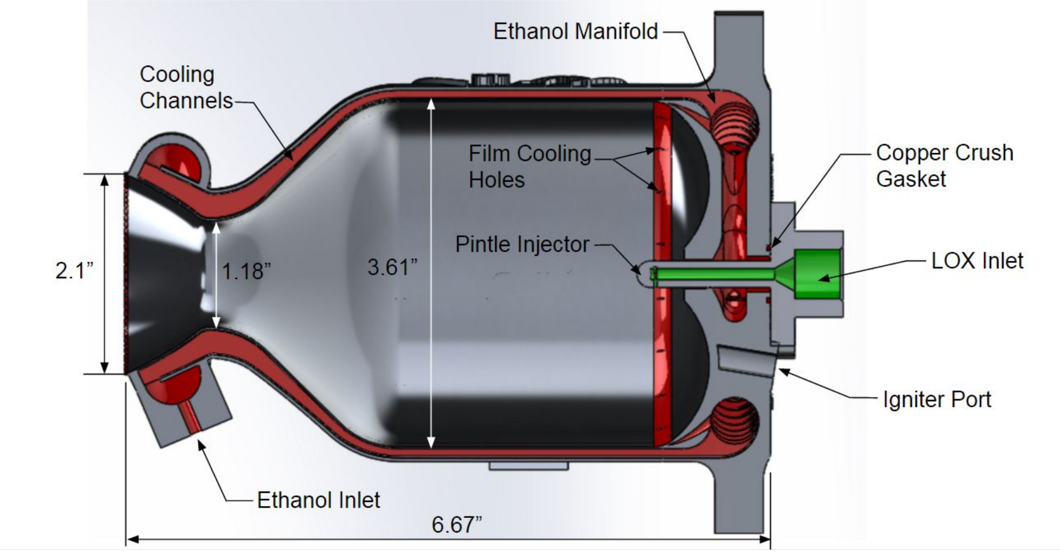


Figure 2: *Final assembly cross section drawing of the rocket engine to be printed. Areas in red show the regenerative cooling channels and the pat the fuel takes through the engine. Areas in green are the liquid oxygen flow path.*

oxygen leaving the pintle collides with the fuel and creates an atomized mixture. The oxygen and fuel ports have been sized to ensure the momentum of the fuel and oxygen are similar and the trajectory of the mixture is ∼45 degrees.

The bell contour pictured in Fig. 4 is a parabolic approximation of a converging-diverging De Laval type nozzle. By using a bell nozzle, the expansion of the hot gas to atmospheric pressure is accomplished in a greatly reduced length and at higher efficiencies when compared to a conical nozzle. The purpose of any nozzle is to convert enthalpy to kinetic energy. The throat and the bell are the crucial components in accelerating the exhaust gasses to supersonic speeds. Minor changes in bell geometry and area ratios at the throat and exit of the nozzle have a significant impact on the thrust and overall efficiency of the engine. The specific geometries have been selected to produce 500 lbf of thrust while working within the temperature limits of the selected material. Validation of bell and nozzle geometry is summarized in Appendix A.

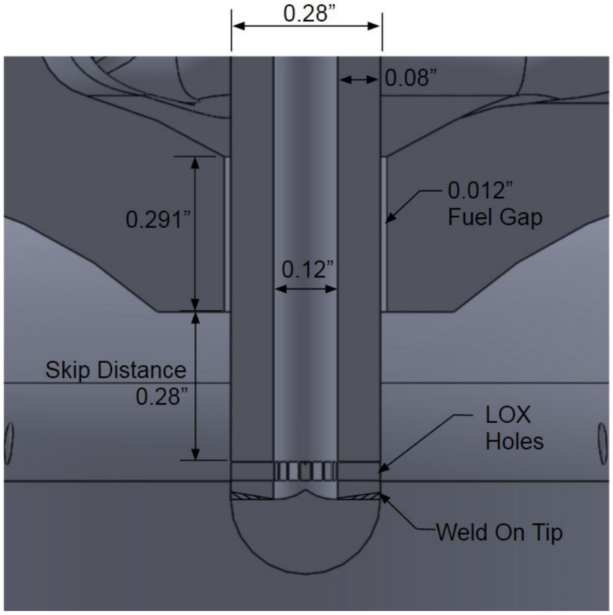


Figure 3: *Final design cross section drawing of the pintle injector to be manufactured. Liquid oxygen (LOX) leaves through the holes in the tip of the injector. The tip is manufactured in two parts and assembled after machining to achieve desired geometry.*

Figure 4: *Final design cross section drawing of the nozzle bell to be printed, the nozzle and fuel manifolds are manufactured as a single part. The nozzle is a parabolic approximation of a De Laval converging-diverging nozzle.*

6 Design Analysis

A hot-fire test of the rocket engine is expected to be completed in August of 2016. Validation of CFD models generated in lociCHEM and/or STAR-CCM+ will follow after test data has been compiled.

Theoretical models for pressure, temperature, heat transfer coefficient, and Mach number have been prepared in Fig. 5 which show the general trends at discrete locations along the nozzle contours. These values are useful for determining critical heat transfer areas and show the general fluid properties as the exhaust gas moves through the converging-diverging nozzle. All trends are computed in terms of current design geometry. All fluid analysis is completed using a Python notebook detailed in Appendix A.

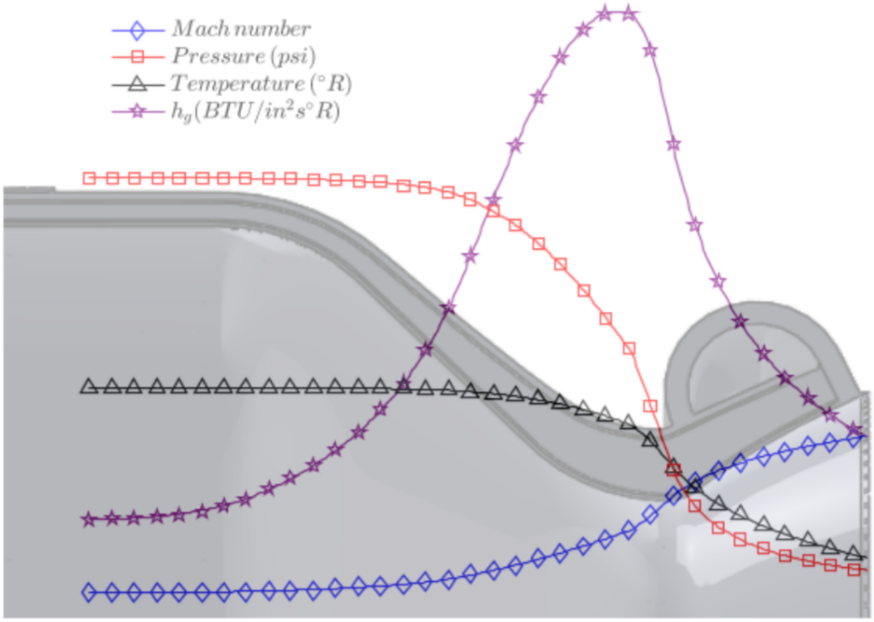


Figure 5: *Scaled profiles of the Mach number, pressure, temperature, and heat transfer coefficient at the wall as a function of x along the length of the nozzle.*

7 Conclusions and Recommendations

The design currently satisfies all major PDS requirements; however, the design is limited in functionally to a proof of concept. The design should include more temperature and pressure reading points along the nozzle contour to further validate the theoretical models prepared. Due to the risks associated with testing this nozzle many of those sensors have been omitted from the design. It is in the team's best interest to ensure the engine is "explosion proof" to a reasonable degree of certainty before investing in expensive sensors which may be destroyed in the test process. The sensors currently included in the design measure chamber temperature and pressure as well as LOX and fuel inlet temperature.

Design alterations are necessary to ensure the current nozzle geometry and pintle are the best way to achieve the required thrust with the highest combustion efficiency. The nozzle outlined in this document is only one possible solution to a complex problem. Compromises have been made in the design process which sacrifice efficiency for design feasibility and material availability.

Currently, the tip of the pintle is designed to be welded on. For future iterations, it is recommend that the pintle tip has the ability to be removable. This will allow for interchangeable testing of tips with various number and sizes of slots or holes. A unique advantage to the pintle design is the ability to throttle the combustion exhaust gasses. This feature has not been implemented in this design iteration but would be interesting to explore in future work.

Additionally it has been observed in the theoretical models that the cooling capacity required in this size engine is difficult to achieve. A cooling strategy which has yet to be validated has been employed. Though it may be necessary to explore this problem further in future iterations. A possible solution is move the cooling channel inlet to the areas with highest cooling requirement to increase heat transfer in critical areas.

Finally, the intention was to have CFD and FEA models to validate the integrity of the nozzle before having the nozzle 3D printed. The models have been started and will be completed by August 2016 and included in the American Institute of Aeronautics and Astronautics (AIAA) paper.

References

Gill, G. S., W. H. Nurick, Russell B. Keller, and Howard W. Douglass. *Liquid Rocket Engine Injectors.* Cleveland: National Aeronautics and Space Administration, Lewis Research Center, 1976. Print.

Huzel, Dieter K., David H. Huang, and Harry Arbit. *Modern Engineering for Design of Liquid-propellant Rocket Engines.* Washington, D.C.: American Institute of Aeronautics and Astronautics, 1992. Print.

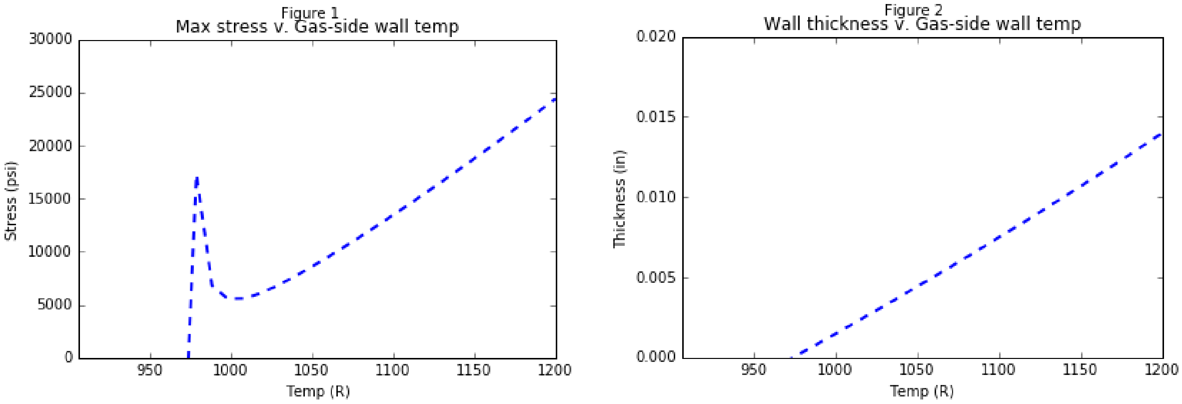
Krzycki, Leroy J. *How to Design, Build and Test Small Liquid-fuel Rocket Engines.* China Lake, CA: Rocketlab, 1967. Print.

8 Appendix A

In order to complete the extensive calculations required for bi-propellant engines in a timely manner relevant equations have been compiled into a calculation notebook programmed in Python (Huzel 1992). The notebook accepts inputs from the user and calculates all relevant parameters of a rocket engine to satisfy strength, cooling, thrust and geometry requirements for an engine of a desired size.

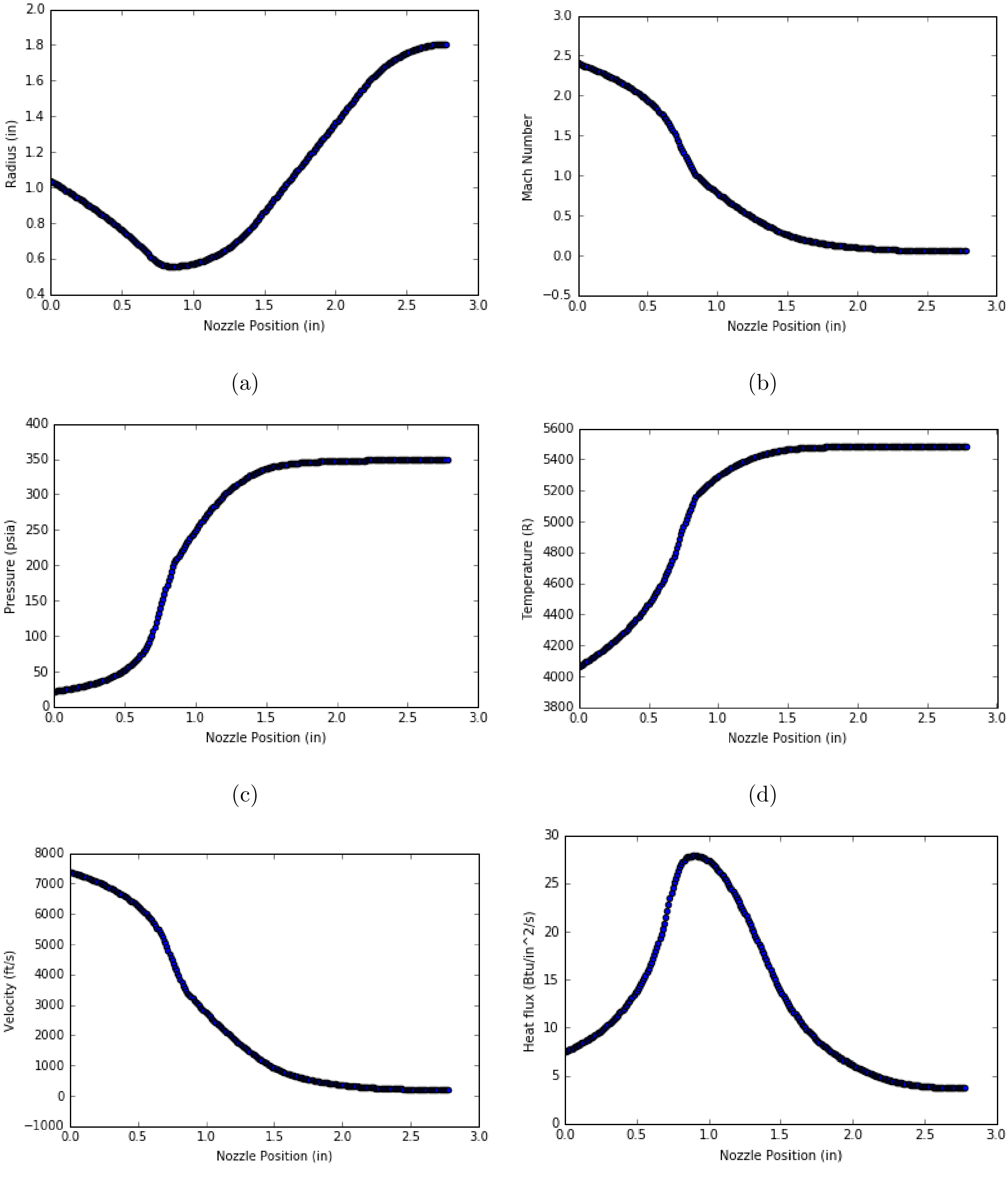
All of the production and calculation details are too extensive to include in the body of this report, but the iPython Notebook is available in its entirety at the link below:
https://github.com/psas/liquid-engine-capstone-2015/blob/master/Nozzle_Construction/LFRE.ipynb

Below are excerpts from the boiling analysis section of the iPython notebook.



(a) (b)

Figure 6: *(a) Maximum stress as a function of temperature and (b) Wall thickness as a function of temperature.*



(a) (b)

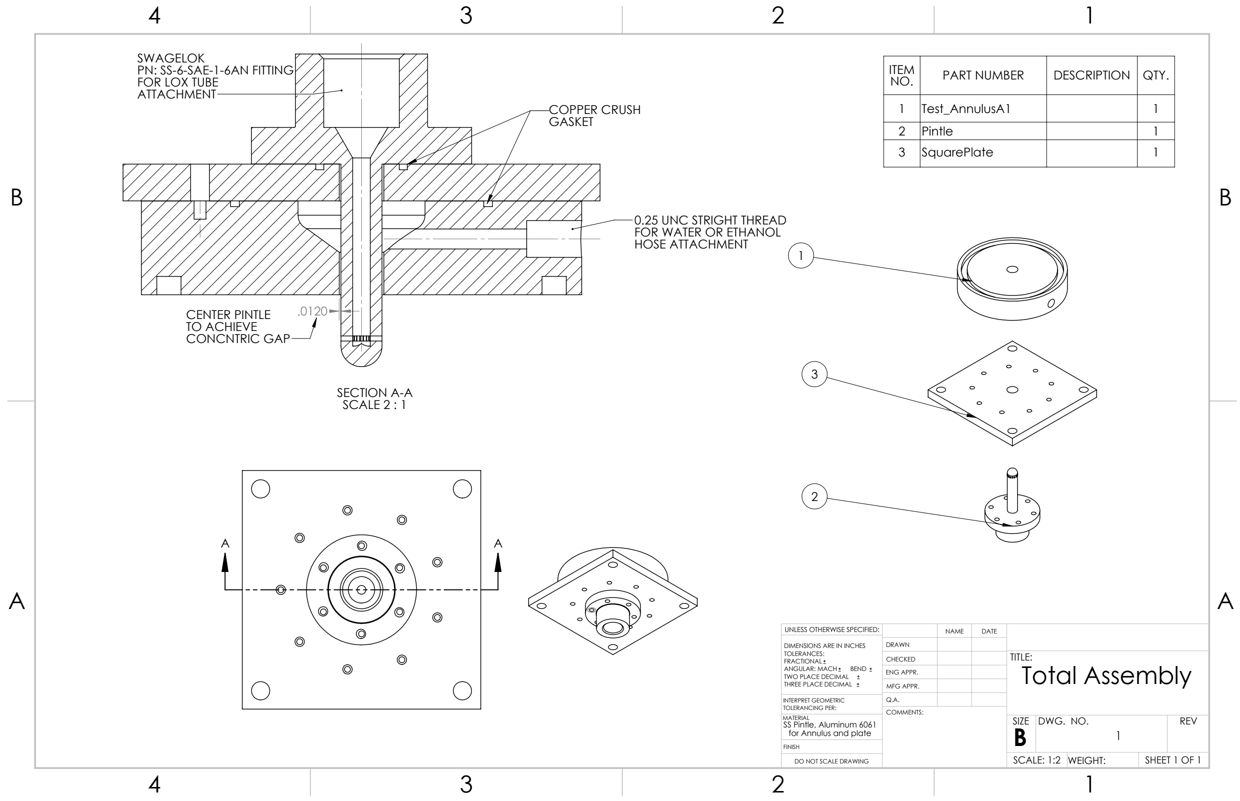
(c) (d)

(e) (f)

Figure 7: *Radius, Mach number, pressure, temperature, velocity and heat flux as a function of horizontal position along the nozzle are shown in figures (a) through (f), respectively.*

9 Appendix B

Below are the design assembly drawings for the pintle testing unit assembly.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Test_AnnulusA1		1
2	Pintle		1
3	SquarePlate		1

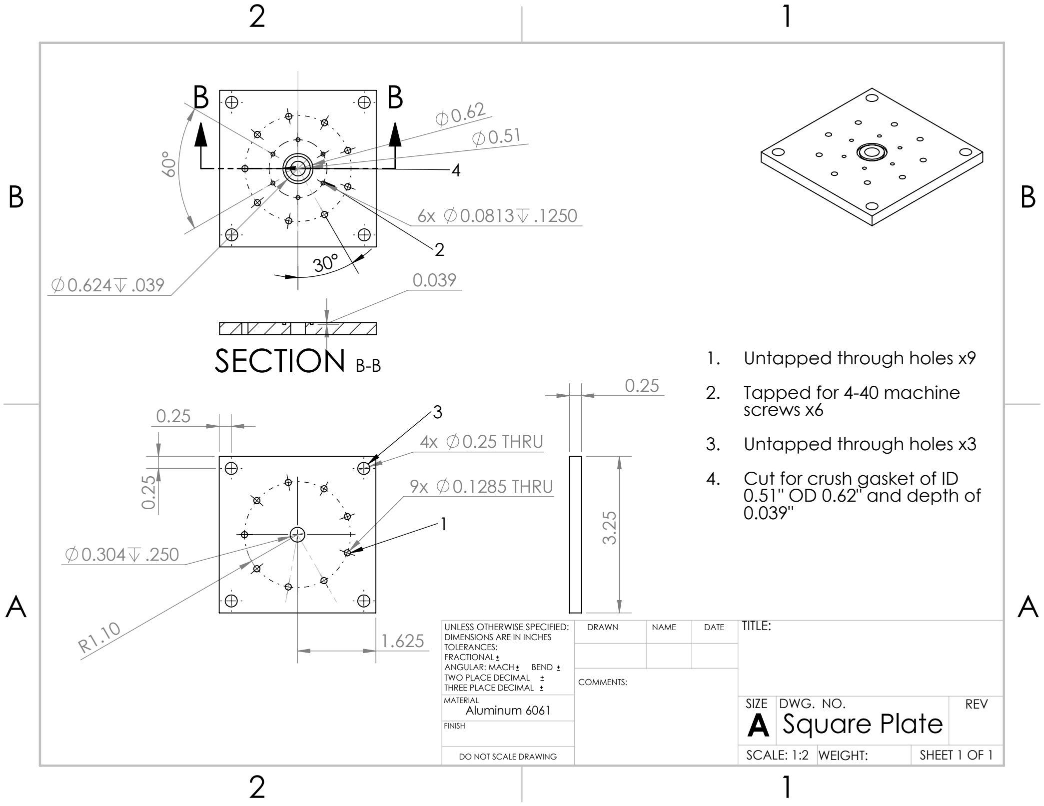
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
SS Pintle, Aluminum 6061
for Annulus and plate
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

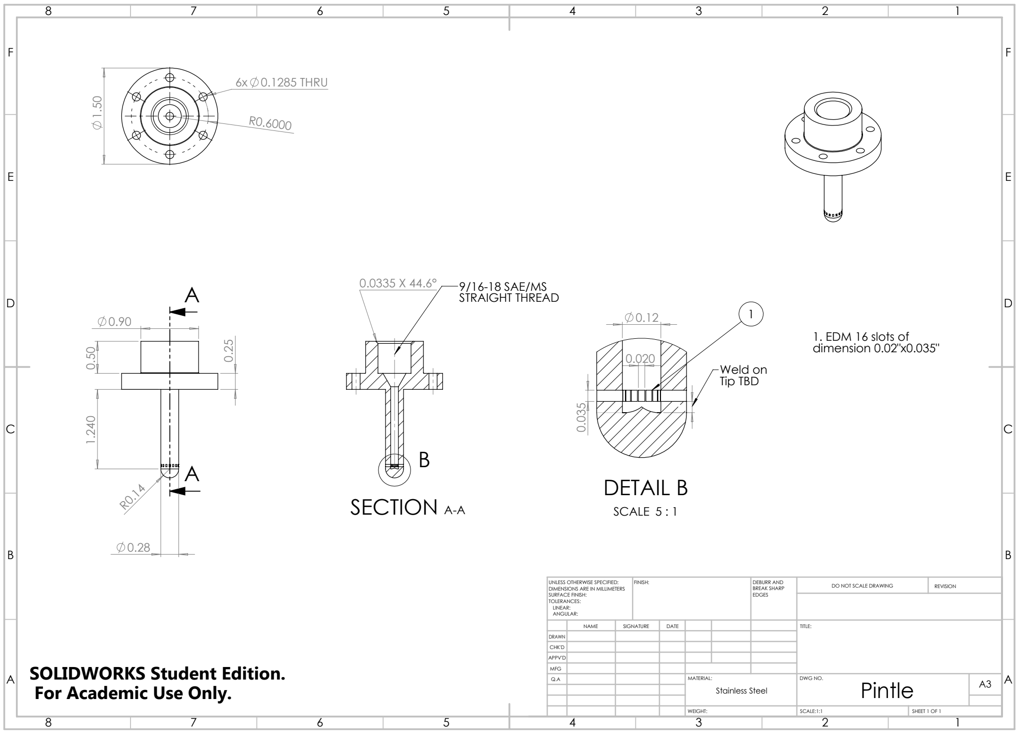
COMMENTS:

TITLE:
Total Assembly

SIZE B
DWG. NO. 1
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1



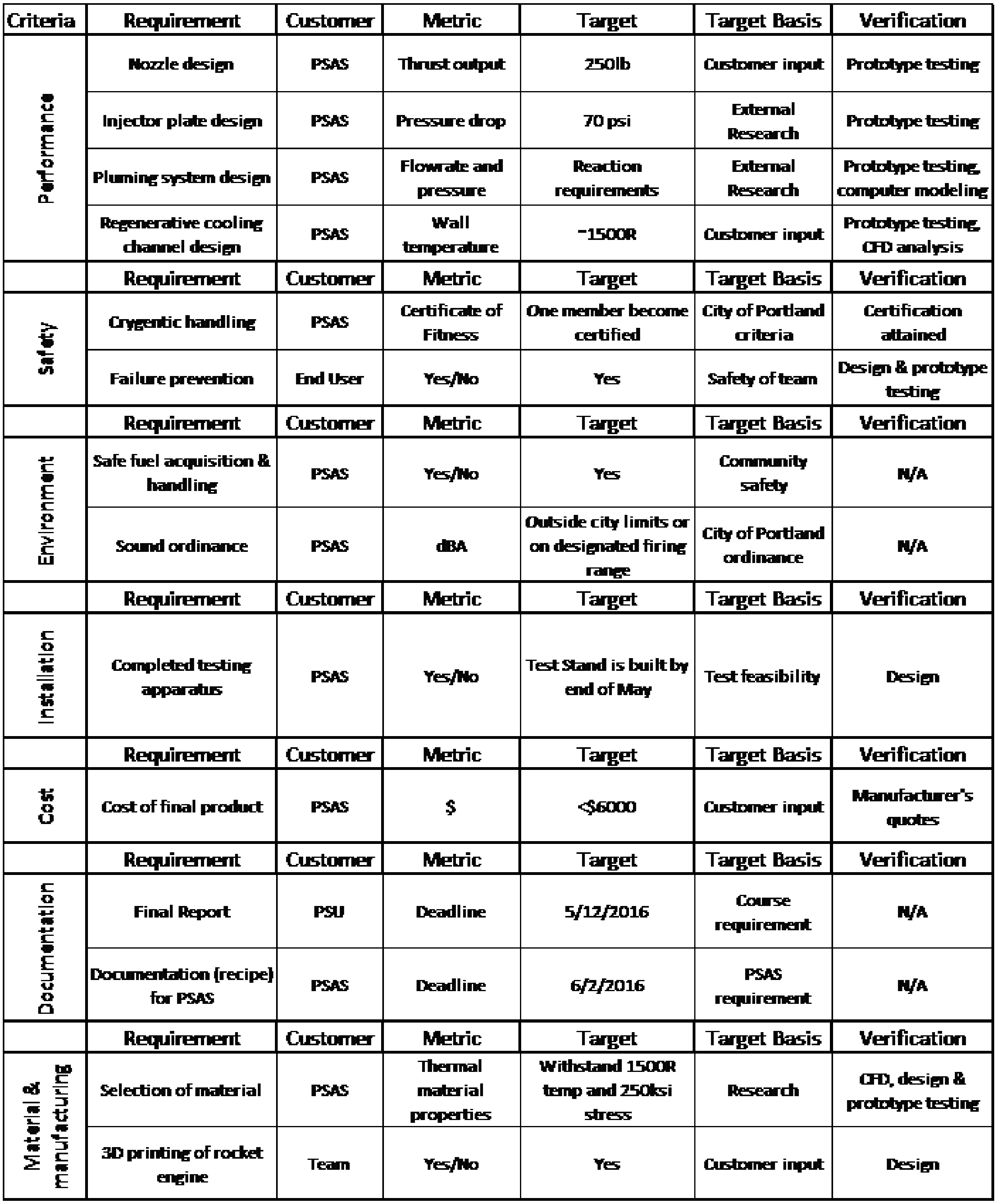
1. Untapped through holes x9
2. Tapped for 4-40 machine screws x6
3. Untapped through holes x3
4. Cut for crush gasket of ID 0.51" OD 0.62" and depth of 0.039"



1. EDM 16 slots of dimension 0.02"x0.035"

10 Appendix C

A detail version of the PDS document.



Criteria	Requirement	Customer	Metric	Target	Target Basis	Verification
Performance	Nozzle design	PSAS	Thrust output	250lb	Customer input	Prototype testing
	Injector plate design	PSAS	Pressure drop	70 psi	External Research	Prototype testing
	Pluming system design	PSAS	Flowrate and pressure	Reaction requirements	External Research	Prototype testing, computer modeling
	Regenerative cooling channel design	PSAS	Wall temperature	~1500R	Customer input	Prototype testing, CFD analysis
	Requirement	Customer	Metric	Target	Target Basis	Verification
Safety	Crygentic handling	PSAS	Certificate of Fitness	One member become certified	City of Portland criteria	Certification attained
	Failure prevention	End User	Yes/No	Yes	Safety of team	Design & prototype testing
	Requirement	Customer	Metric	Target	Target Basis	Verification
Environment	Safe fuel acquisition & handling	PSAS	Yes/No	Yes	Community safety	N/A
	Sound ordinance	PSAS	dBA	Outside city limits or on designated firing range	City of Portland ordinance	N/A
	Requirement	Customer	Metric	Target	Target Basis	Verification
Installation	Completed testing apparatus	PSAS	Yes/No	Test Stand is built by end of May	Test feasibility	Design
	Requirement	Customer	Metric	Target	Target Basis	Verification
Cost	Cost of final product	PSAS	$	<$6000	Customer input	Manufacturer's quotes
	Requirement	Customer	Metric	Target	Target Basis	Verification
Documentation	Final Report	PSU	Deadline	5/12/2016	Course requirement	N/A
	Documentation (recipe) for PSAS	PSAS	Deadline	6/2/2016	PSAS requirement	N/A
	Requirement	Customer	Metric	Target	Target Basis	Verification
Material & manufacturing	Selection of material	PSAS	Thermal material properties	Withstand 1500R temp and 250ksi stress	Research	CFD, design & prototype testing
	3D printing of rocket engine	Team	Yes/No	Yes	Customer input	Design

11 Appendix D

External Search

Designing the engine required extensive research from publications by NASA and other sources. The following resources were utilized in the design process.

Huzel and Huang- Heat transfer analysis is being conducted to determine the type of metal to be selected for the nozzle and cooling chamber, most likely a high-temperature steel such as inconel. Stress analysis is used to determine nozzle, combustion chamber and cooling channel geometries.

Rocket Lab's "How to Design, Build and Test Small Liquid Fuel Rocket Engines"- Initially used to calculate general nozzle geometries by utilizing a simplified overview of how a liquid fuel rocket engine is built. It laid out the foundation for the preliminary nozzle dimensioning and design.

SpaceX Advisory Meetings- PSAS connected the capstone team with an advisor, Armor Harris, an engineer at SpaceX. Armor advised the team with initial decisions and design parameters as well as giving us a better understanding of the intricate aspects of building a liquid rocket engine.

NASA- Primarily used for injector research because of the multiple options of injector types. Using sources such as NASA's "Liquid Rocket Engine Injectors", the pintle injector was chosen based on ease of machinability and combustion stability. In order to achieve a simple and easy to manufacture pintle injector design, the regenerative cooling channel interface, fuel manifold and most of the injector plate will be part of the additively manufactured combustion chamber.

Internal Search

Propulsion Classes: Because of the complexity of the scope, and without having previous classes on propulsion and combustion, propulsion classes are held once a week led by PSAS president Erin Schmidt. The class is open to anyone but aimed primarily toward building a knowledge base for the production of the liquid rocket engine.

Github: PSAS uses GitHub to broadcast their data and encourage members to collaborate. Using GitHub allows for open source ease and collaboration by creating repositories of work that, if warranted, is accessible to the public. All pertinent work done by the capstone team on the bi-propellant engine will be uploaded to GitHub for ease in the design of future iterations.

Jupyter iPython Notebooks: Within GitHub, work is displayed using Jupyter iPython Notebooks. The notebooks are a useful method for collaborating and combining inputs and equations into one document. The calculations for the nozzle geometry, heat transfer and stress analysis and pintle injector design are currently being transcribed into an iPython Notebook. By doing this, one could input new quantities and use the abilities of iPython to obtain values based on existing equations. This feature allows for ease of the iterative process of the current model as well as future dynamic models in the years to come.