PORTLAND STATE UNVERSITY

Liquid Fuel Rocket Engine Capstone

PROGRESS REPORT - WINTER 2016

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Executive Summary

The detailed analysis, design, prototyping and testing of a bipropellant rocket engine project has been proposed by a Portland State University senior capstone team. Design specifications and safety precautions were provided by the team's sponsor, Portland State Aerospace Society (PSAS), and have been documented in the product design specification (PDS) document. A final prototype, analysis of the engine and detailed documentation of all calculations, references, decisions and why they were made, etc. will be provided to PSAS. 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 analyzing liquid fuel engines. The static engine, constructed by the capstone team, will strive to be as scalable as possible with the time constraints provided.

Contents

1 Introduction

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 motor 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. This project is on track to being completed by June of 2016.

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 decreased budget and with shorter lead times which would be considered unobtainable with traditional manufacturing methods.

Explored herein is the process of designing and testing a 250 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. Equations have been determined to describe the more complex geometries of the nozzle contour and the sizing of other important components.

2 Mission Statement

The objective is to design and test a 250 lbf thrust bipropellant engine prototype using 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 will be documented and easily accessible for future iterations and scaling of the engine. A prototype and all documentation, including testing procedures and results, is to be completed by June 2016.

3 Project Plan

A project plan is generated to ensure the product is delivered on time. Figure 1 shows a timeline of the assignments and milestones of the project to establish clear deadlines that need to be met throughout the school year. Currently the capstone team has completed concept development and selection and is in the detailed design and analysis stage. Prototyping and testing of the nozzle and injector plate will start the last week of March. Refer to Appendix A for detailed Gantt chart.

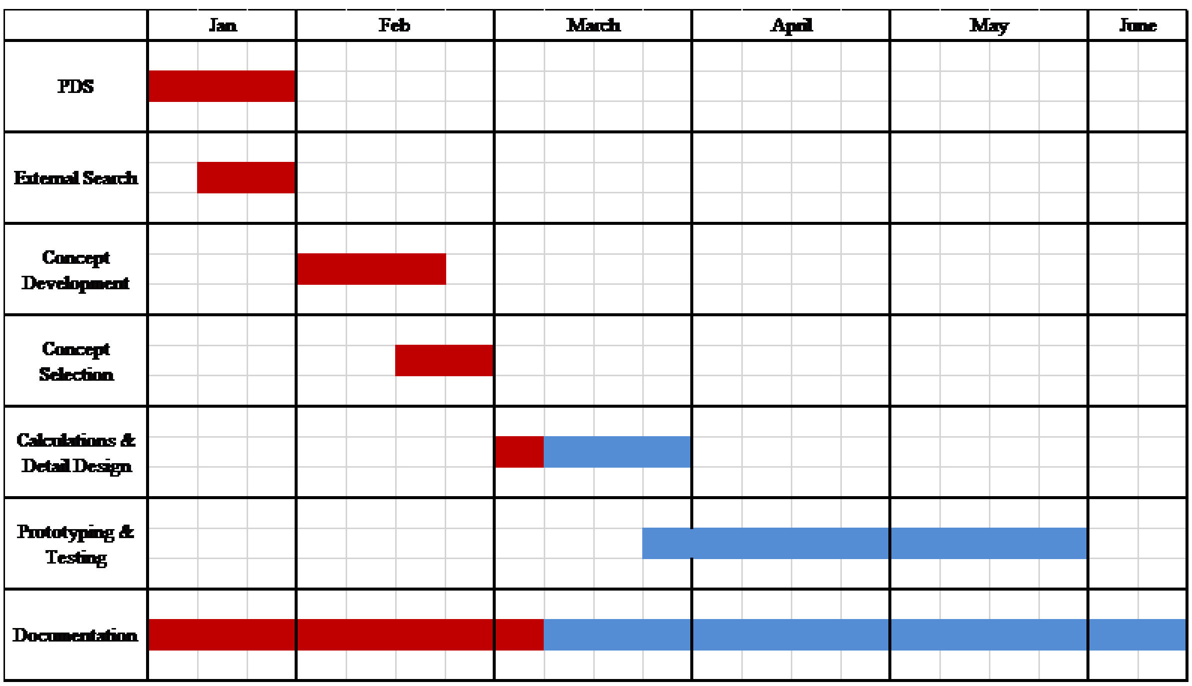


Figure 1: Project plan milesones - High priority Gantt chart. Red indicates time past and blue shows the remaning months of the project.

4 Product Design Specification Summary

The product design specification (PDS) is a document used to communicate customer requirements, risk management and specifications of design criteria. The 'high-priority' criteria from the PDS are tabulated in Fig. 2.

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
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

Figure 2: The high priority PDS criteria, including targets for categorized requirements.

Six categories of criteria are highlighted in the table below. Performance of the cooling channels and the overall combustion of the rocket and safe handling of the LOX are high priority as well as the environmental effects associated with use and disposal of the LOX. Cost and documentation are high priority for PSAS to ensure the rocket is cost effective and able to be replicated in future iterations. Finally, manufacturing, both traditional and additive, are important requirements set forth by PSAS. Within each subcategory, the target, target basis and verification of the tasks are available to allow PSAS and the capstone team to monitor and communicate about specific requirements throughout the project.

5 External Search

In recent years, liquid rocket engines are increasing being designed by amateur rocket builders. The design process of the project required extensive research from publications by the National Aeronautics and Space Administration (NASA) and other sources. Four main resources were utilized in the design process. Using Huzel and Huang's "Modern Engineering for Design of Liquid-Propellant Rocket Engines", 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.

Another resource, Rocket Lab's "How to Design, Build and Test Small Liquid Fuel Rocket Engines", was 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.

At the beginning of the year, 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.

Finally resources from NASA were utilized 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. Figure 3 shows an example of a pintle injector.

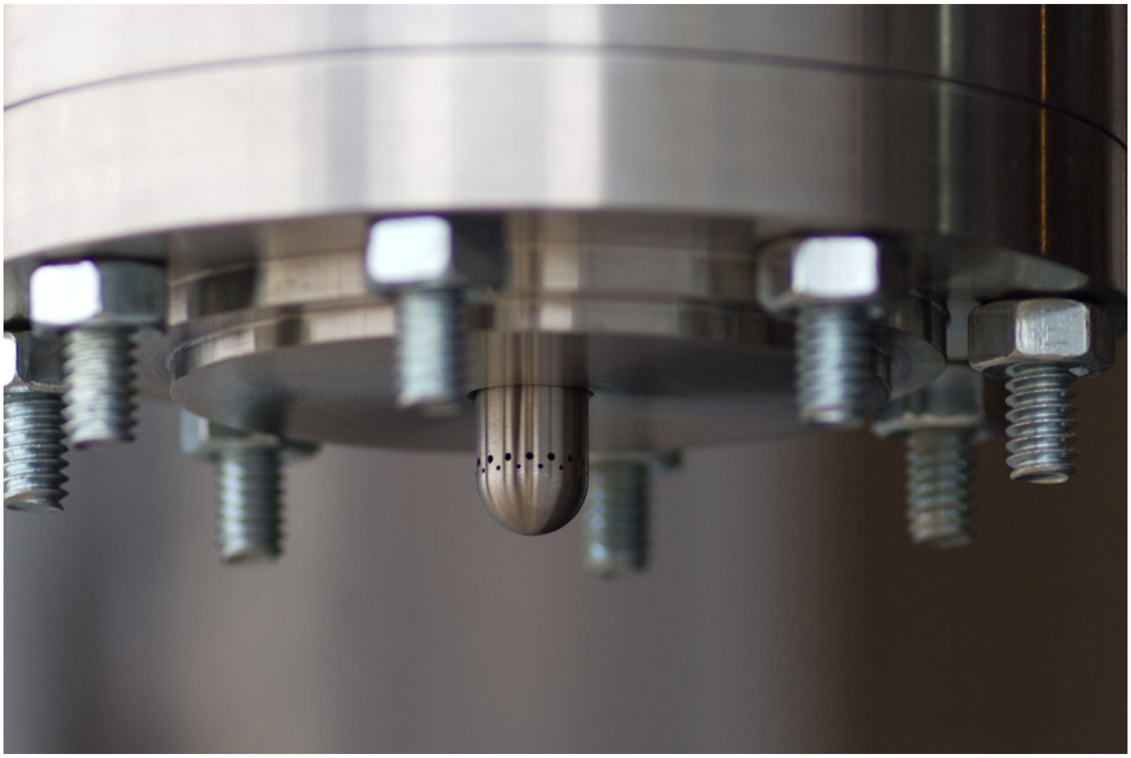


Figure 3: Typical pintle injector design.

6 Internal Search

Propulsion Class

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 bipropellant engine will be uploaded to GitHub for ease in the design of future iterations.

Jupyter iPython Notbook

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. Figure 4 shows the pintle iPython Notebook, for all notebooks currently available refer to the liquid engine repository at https://github.com/psas/liquid-engine-capstone-2015.

7 Top-Level Design Evaluation

The bipropellant engine has been broken down into a two part design, one of which is the design of the nozzle geometries. Included in this criteria is the selection of the nozzle material to allow for optimal stress and heat transfer quantities from iterative analysis as well as the method of cooling the combustion chamber and nozzle. The second part of the design includes the type of injector and the method of attachment to the combustion chamber. Numerous types of injectors are available with advantages documented well for large scale rockets. For a smaller, 250 lbf engine, documentation is not as readily available and further research was performed. The flanged connection from the combustion chamber to the injector plate is still being researched. The flanged connection design will be evaluated further after a final design of the injector is completed.

The material selection design evaluation matrix is shown in Fig. 5. Inconel, titanium,

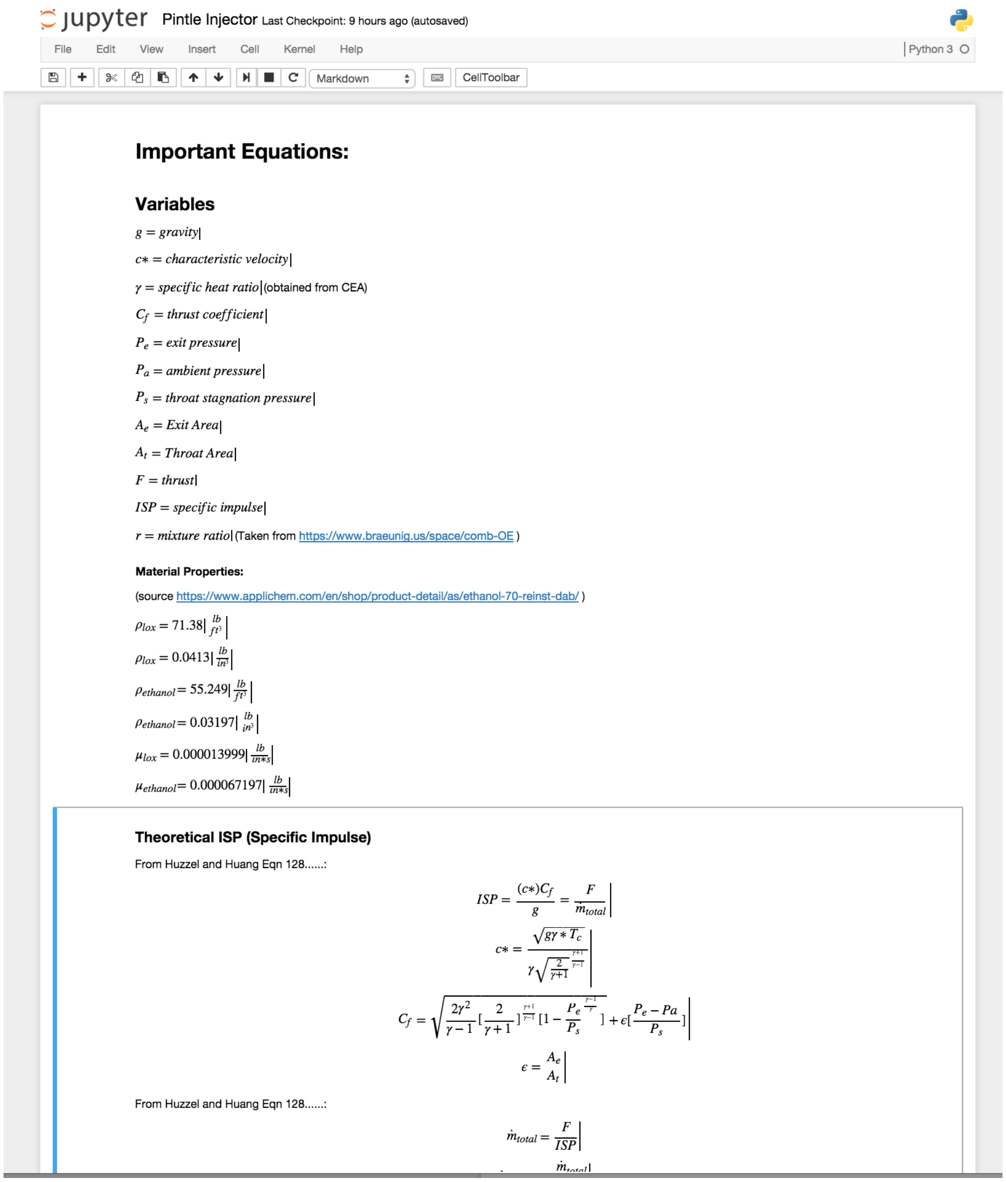


Figure 4: Exerpt from an iPython Notebook of the pintle injector design that demonstrates the use of iPython as an organizational tool as well as an accelerated form of analysis for future iterations. For a more comprehensive sample of the notebook, see Appendix B.

aluminum and stainless steel are the four metals chosen for comparison as they are the most accessible for local additive manufacturing. The ratings range from 0-10, with 10 being the highest rating for the corresponding characteristic.

The design evaluation matrix for determining the type of injector is shown in Fig. 6, four injectors, commonly used in liquid rocket engines, are compared.

Material				
	Inconel	Titanium	Aluminum	Stainless Steel
Cost	7	6	10	5
Performance-Thermal	10	8	4	9
Performance-Strength	10	7	2	7
3D Print Tolerance	8	9	6	9

Figure 5: Design matrix used to evaluate material selection

Type of Injectors				
	pintle	Like-Doublet	Unlike-Doublet	Unlike-Triple
Cost	9	4	4	3
Machinability	9	5	5	4
Dependability	8	9	9	9
Combustion Instability	9	8	7	7
Throttleability	10	0	0	0
Atomization	8	9	9	9

Figure 6: Design matrix used for comparison of different types of injectors.

8 Progress on Detailed Design

Nozzle Material

From the four materials selected in the design matrix, inconel was chosen due to the material properties outweighing the cost of the material. Compared with the other metals, it ranked highest in thermal performance and material strength. With the material selected, the preliminary design of the nozzle and combustion chamber with regenerative cooling channels is complete. Currently a finite element analysis (FEA) is being completed in Abaqus to evaluate the stress analysis calculations pertaining to the wall thicknesses and cooling channel geometries. The preliminary design has been created in Solidworks and correspondence has been initiated with two local additive manufacturing companies for budgetary quotes. After the completion of FEA, the next step is to obtain a plastic 3D printed model to assess the flow rates, pressure differentials, and loss coefficients utilizing cold testing. Figure 7 shows the preliminary design of the combustion chamber and nozzle with cooling channels.

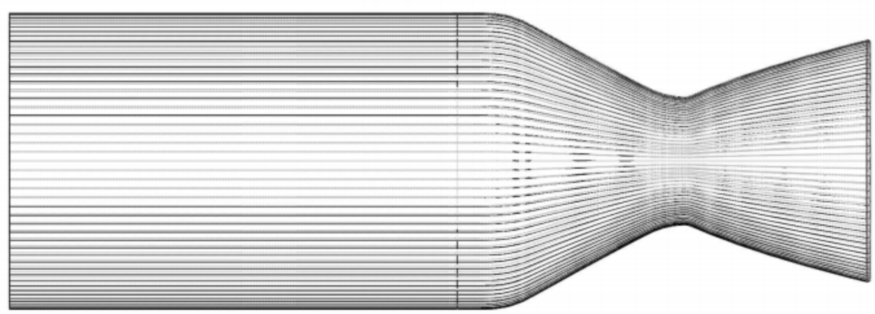


Figure 7: Combustion chamber and nozzle preliminary design.

Type of Injector

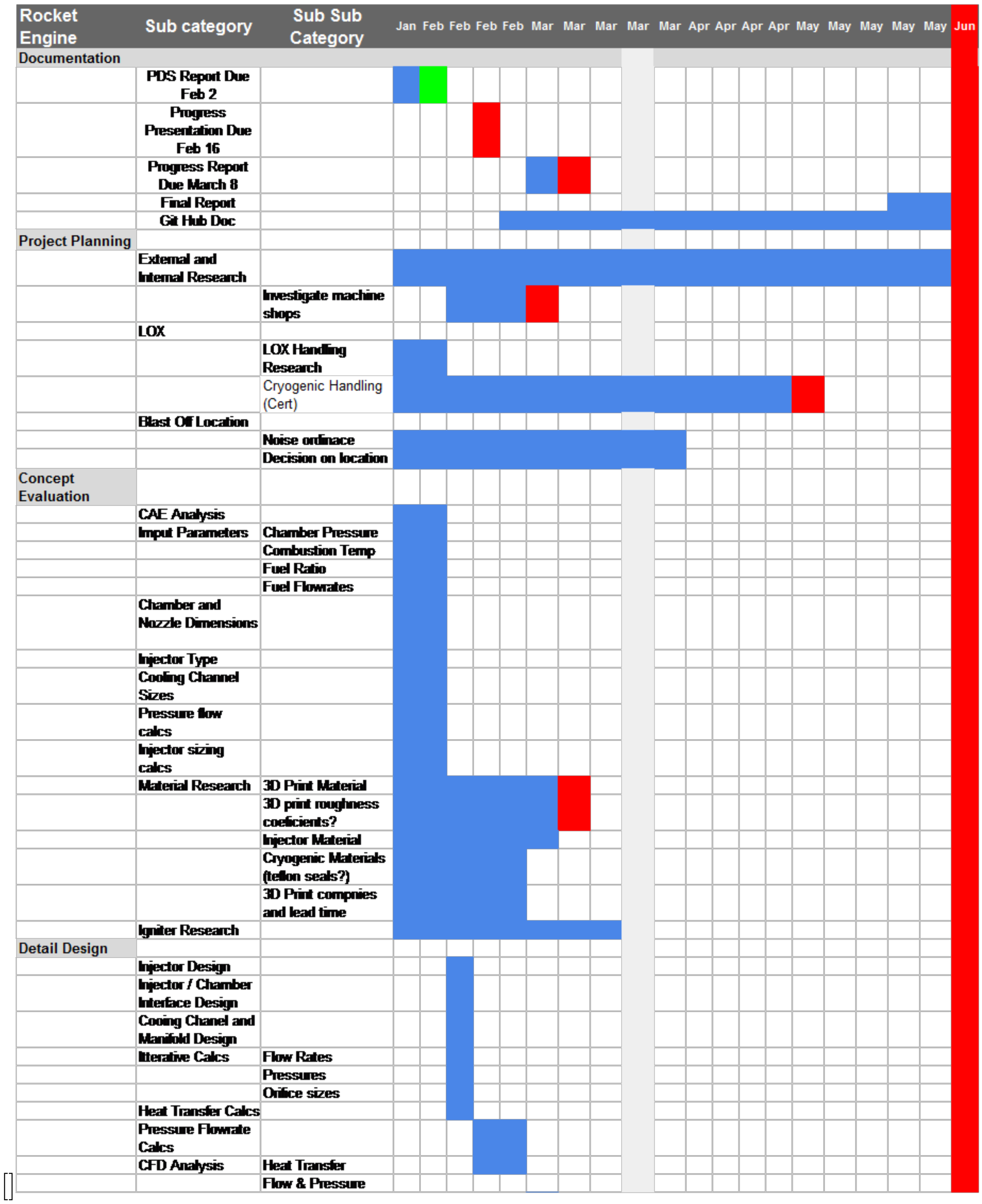
Most injectors are stable and atomize well in a liquid engine with 250 lbf thrust capabilities, therefore, among the four types of injectors shown in the design matrix, the pintle injector was chosen due to its machinability and cost. It also has the capability of throttleability for future iterations. The pintle injector has been thoroughly researched and a preliminary design has been started along with a Solidworks 3D model. As the research, calculations and decisions are concluded, the information is successively being upload to GitHub via iPython.

9 Conclusion

The design stage of the project is nearing completion. With the first iteration of heat transfer and stress analysis completed, a change in material or surface roughness is easy to implement and the Solidworks model will be modified to reflect the final design. The manufacturability of the nozzle is currently halting the design process. The first design has been sent out to additive manufacturing companies for budgetary quotes, feedback on complexity of the print, tolerances of the print and surface roughness. This will lead to printing a plastic prototype for testing and the current design will be assessed and be determined if further calculations will be performed. The design of the injector plate is the next task that needs to be completed. With the known geometries of the pintle injector, the connection to the nozzle will be designed and both will be manufactured at Portland State, if tolerances allow it. This research will serve as the foundation for future rocket development at Portland State University. PSAS is currently flying on the largest solid rocket motor available and the von Karman line is not achievable without a liquid fuel engine.

10 Appendix A

A detailed Gantt chart of major deadlines and estimations of time commitments for categorized requirements. This chart is currently updated as the project progresses.



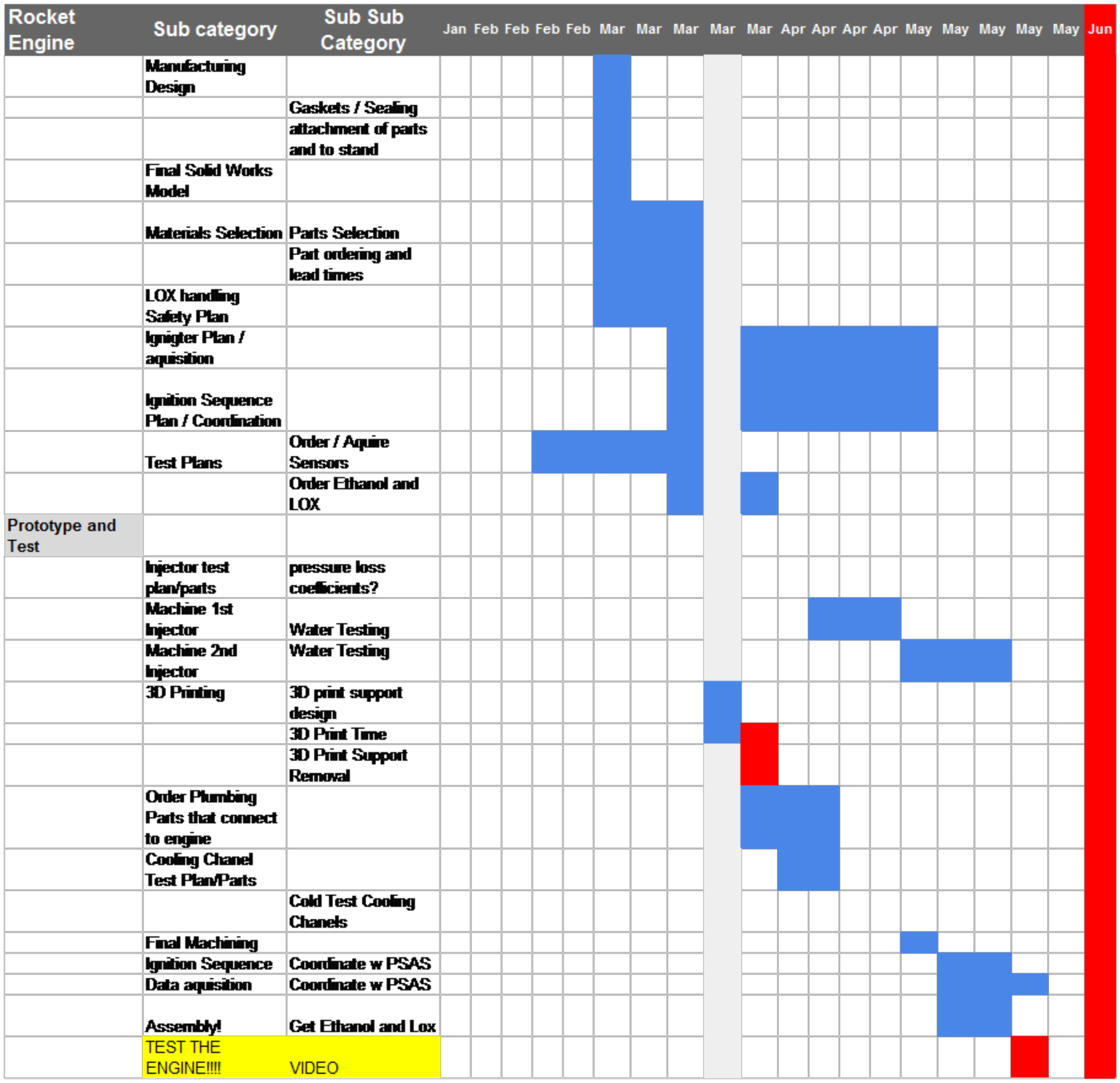


Figure 8: Detailed Gantt chart

11 Appendix B

An iPython Notebook except from the initial pintle injector design calculations. Notebooks made in iPython are crucial to documentation during the project, they serve as an organizational and calculations tool for the capstone team.

jupyter LFRE (autosaved)

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Initial Design Considerations

Parameters must be selected. The generation of force is the desire of a rocket engine. the force equation is:

$$F = \frac{\dot{w}}{g} V_e + A_e(P_e - P_a)$$

This is important when designing engines for flight, but when testing engines P_e is optimally expanded and assumed to be atmospheric pressure (14.7 psia) and the equation becomes:

$$F = \frac{\dot{w}}{g} V_e$$

For engines in flight the effective exhaust velocity, c, can be used, and equation X can be expressed as:

$$F = c\frac{\dot{W}}{g}$$

Where c is defined as

$$c = V_e + A_e(P_e - P_a)\frac{g}{\dot{W}}$$

which changes with altitude.

For a desired force, there must then be selected an exit velocity to find the necessary flow rate, $\dot{w}$. The theoretical exit velocity is defined as:

$$V_e = \sqrt{\frac{2g\gamma}{\gamma - 1} R T_i \left[1 - \left(\frac{P_e}{P_i}\right)\right]^{\frac{\gamma-1}{\gamma}} + v_i^2}$$

Because the inlet velocity is very small, it is assumed to be zero, this gives the following:

$$V_e = \sqrt{\frac{2g\gamma}{\gamma - 1} R (T_c)_{ns} \left[1 - \left(\frac{P_e}{(P_c)_{ns}}\right)\right]^{\frac{\gamma-1}{\gamma}}}$$

which is dependent on the propellants and chamber pressure which should be chosen for the design, P_i.

Flame temperature and gamma can be obtained for a given propellant combination by using NASA's CEArun tool. link to portion in document which describes how to use cearun

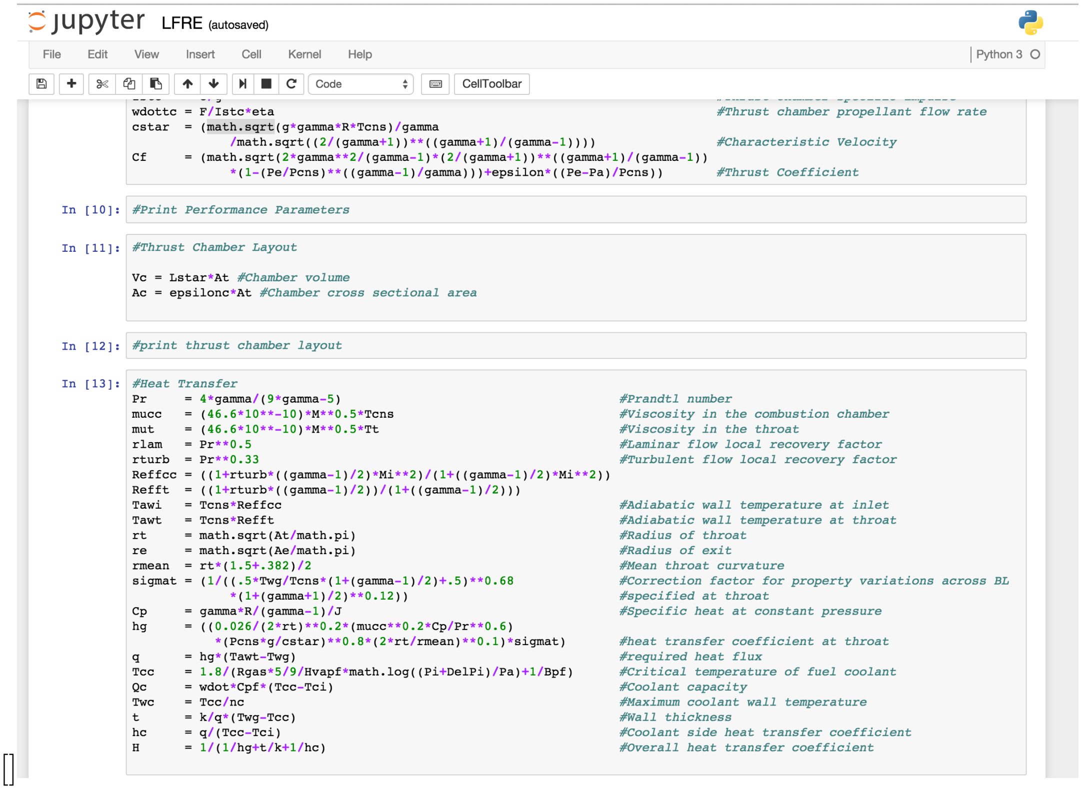

Figure 9: Detailed Jupyter iPython Notebook

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.