PSAS Electric Feed System

ME493 Final Design Report

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June 9th, 2017

Table of contents:

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Executive Summary:

Project Objective Statement

The Portland State Aerospace Society (PSAS) aims to design, build, and test an electric feed system (EFS) prototype using commercial off-the-shelf (COTS) parts and in-house manufacturing for the existing 2.2kN liquid fueled bi-propellant rocket engine by June 6, 2017.

Final status of Design Project

The EFS design was largely dictated by the engine vehicle requirements given to the EFS team by PSAS. This dictated working within the requirements of the engine vehicle which required the EFS to satisfy a low flow, ~10-12 GPM, high head, ~300-400 Psi, regime. A semi open Barske impeller geometry coupled with a concentrically bored bowl design with a single emission throat was chosen to satisfy the flow conditions. A complete list of client requirements is shown in Table 1.

The EFS is primarily comprised of five subsystems, the hydraulic, mechanical, power, flow loop, and measurement subsystems. At the time of this writing, a first prototype of the EFS pump design has been manufactured, and pump performance testing and analysis are in progress. System characterization was achieved using a mix of off the shelf and custom designed live sensor readings.

Key Performance Metrics

Table 1 shows key performance metrics laid out by PSAS. Please see the "Client Requirement" section for a discussion on the success measurements of the EFS project.

Table 1: *Key customer requirements and deliverables.*

Customer Requirements	Target	Achieved	Witnessed
Design, build, and test EFS for under $8000	< $7900	$3,117.00	N/A
Pressure delivery	300 < P > 400 Psi	284 Psi	> 400 Psi
Flow Capacity	10 < Q > 12 GPM	10.5 GPM	> 14 GPM
Off-the-shelf components	YES/NO	YES	N/A
Transferability	YES/NO	YES	N/A

Client Requirements:

Our project had two layers of requirements. The initial requirements defined a project that called for the creation of propellant pumps that met explicit quantitative and qualitative measures, such as pressures and flow rates, but in the course of the year, the implicit definition of the project shifted away from the delivery of a final product capable of achieving a specific level of performance and towards the establishment of a technology development platform that could inform the design of a future end product. To be specific, we discovered that the first step in the EFS project needed to be the design and characterization of a test pump which would later be scaled to meet PSAS' LV4 rocket requirements.

The need for an experimental phase preceding the design of an end product is the consequence of the atypical pump requirements of the PSAS LV4 rocket. We discovered that a pump providing 400 psi pressure at 12 gpm is an unusually high head - low flow pump. If we required less head than 400 psi, we might have been able to use something like a typical Francis style impeller pump. If we needed less flow than 12 gpm, we might have been able to use a positive displacement pump like those found in pressure washers. In either of these cases, the scope of the EFS project might have been able to use an off the shelf pump, or to scale and adapt a common pump design, and the capstone project might have been to jump directly to the design and creation cryogenic LOX and IPA compatible pumps as we initially expected.

Before we dove into the literature, we assumed that we would simply be absorbing the canon of pump design literature and crafting and testing pumps based on that knowledge. Because our initial review led us outside the head-flow regimes of common pump designs, the intent of the EFS project shifted. It was immediately clear that the scope of the project had expanded, shifted away from production of an end product, and shifted backwards towards the investigation of pump design fundamentals. The real intention of the project became the investigation of a relatively unexplored regime of pump performance.

The pump that this investigation produced was not necessarily intended to hit the performance requirements that the project began with. We could have successfully have met PSAS' real needs if we produced a pump that achieved performance significantly below the original 300-400 psi & 10-12 gpm targets, so long as the design of the experiment was sufficiently rigorous that it could produce pump characterizations that could decisively inform later designs. That we created a pump that appears capable of actually hitting these numbers is remarkable and scientifically convenient, and shortens the path from investigation to final design, but was not necessary for the project to meet PSAS' real needs.

The original client requirements represented in the R-M matrices, and in earlier requirement lists, remain valuable as they provided the target that our technology development platform pursued. For example, the original pressure-flow requirement is that the EFS pump can deliver ~400 psi at ~11 gpm. Translated from an end product requirement to a technology development platform requirement, this means that our goal is not to deliver a pump capable of this performance, but to *try* to design such a pump, and design it in such a way that future PSAS efforts can immediately adapt the next design iterations.

We did hit high pressures, and we did high flows, but we did not pursue hitting pressures as high as 400 psi at flows as high as 12 gpm. Pump sizing is a process of scaling, using affinity laws, and the first step in characterizing a pump does not require pushing the pump to its designed operating point. In our case, we performed our initial battery of tests and characterized the pump at a ~16,500 rpm, a lower speed than our pump was designed for. This approach allowed us to begin testing by extracting the needed characterization and system curves from the pump at a speed that did not risk damaging the pump's rotating assembly, motor, battery, or speed controller. Did we hit 400 psi at 12 gpm? No. Did we characterize the pump such that we know that this design should hit 400 psi at 12 gpm at a higher rpm? Yes.

Delivering this characterization was the critical achievement that the project needed to be a success, and the immediate next steps for the project can be to pursue the ~400 psi at ~12 gpm LV4 performance requirements. This will mean more thorough investigation of the variables we currently control, such as blade number, diffuser angle, and most importantly, RPM. The capstone timeline allowed us to conduct a cursory exploration of the effect of blade number, diffuser angle, and RPM; several test replicates of the critical combinations were conducted, but certainly not a full DOE regimen. The next step will be to fully optimize these low hanging variables. For example, we started with 8, 10, and 12 degree diffusers. If 12 was the best of this lot, might 14 be better still? These easily established critical points need to be found first. Following that, we can calculate a target RPM from our characterization and attempt to actually hit the LV4 requirements of ~400 psi at ~11 gpm by incrementally testing the pump at higher speeds until we meet the requirements, or suffer component failure. From initial testing, we know that our seal design begins to fail around ~24,000 rpm, and this may be the limiting factor for this physical design in the pursuit of LV4 requirements. Though some system redesign and fabrication may be required to hit our original requirements, we expect that the most critical element - the hydrodynamic design of impeller, housing, and diffuser - are capable of achieving these numbers.

While our key requirements involve pump performance numbers and hydrodynamic design, a significant amount of effort went into the creation of the *platform* in a technology development platform. This did not translate directly to any of the key requirements used to define the project, but is an inherent requirement when considering PSAS' actual needs. A pump design that theoretically meets the needs of the LV4 rocket is valuable, the development of that pump and future iterations required an experimental platform that allows for consistent, predictable testing. In one light, the meeting of the key requirements required effort in three categories: hydrodynamic design, transferrable documentation, and creation of the platform required to test that design and produce that documentation. This platform can be seen as including the flow loop, water tank, instrumentation, data acquisition, the motor, power supply, and controls. After the initial decision making about the impeller and pump housing, the vast majority of the project's effort went into the creation of the platform to support the testing of this design, and it can be seen as one of the key deliverables to PSAS, as it allows for the ongoing testing of this pump and future EFS pump iterations.

The yes/no requirement of using off the shelf components became somewhat unimportant as the project matured. Because of the high cost, in hours, of custom fabrication, we were incentivized to avoid it wherever possible. For example, we weren't going to build a custom electric motor unless absolutely necessary, and an off-the-shelf item would suffice. A significant investment in fabrication became inevitable, however, when we discovered that our performance needs fell out of normal pump sizing regimes. No off the shelf pumps, housings, or impellers were likely to achieve this particular combination of pressure and flow. Viewed through the lens of financial investment, raw materials for fabrication only accounted for 6% of our budget (see appendix section F), and thus we might say that our project was nearly entirely created from off the shelf components. Through another lens, it's possible that the majority of hours spent on the project might have been on custom fabrication, and that is only hidden in the budget because we are students. Were we to have outsourced the fabrication, it would have dominated our expenses.

Behind the claim of meeting the transferability requirement is significant effort that is not reflected by performance numbers. Transferability, for our project, implies that future PSAS efforts can leverage the assets we provide to directly jump to future designs and iterations. Considering the stages of the project, we have left behind a framework that should allow for the replication and refinement of our work. We have documented the literature that provided the theory bedrock for our pump sizing stage. Our solid modeling was parametrically done using a single equation sheet that allows future workers to simply change key parameters to produce designs that align with the theory we used (see appendix figures C3, C4, and section E). Most importantly, our test procedures and subsequent data analysis used ANSI test and analysis standards that allow for interpretation and scaling for future pump designs. All files were documented in PSAS' open source Github.

Conceptual Design Summary:

The EFS project was provided to the team with many conceptual design decisions already completed per LV4 engine/vehicle requirements. Most design challenges of the EFS centered around meeting a unique set of fluid dynamic requirements. Key features addressing these challenges included the impeller design and pump casing.

Concept selection process: Impeller type

In typical pump design, the choice of impeller type would be a straightforward result of a pump sizing process and would not represent a major concept selection. The nature of the EFS project required a deeper investigation into impeller style. As a consequence this selection affects nearly all other subsystems. Pump sizing calculations typically use a set of requirements to produce a specific speed value, and impeller geometry is dictated by this value. For example, a particular specific speed value may dictate a Francis vane impeller is more ideal than a normal radial vane impeller see Figure 1. The specific speed requirement for the EFS system is calculated using Equation (1),

$$(n_s)_{EFS} = \frac{n(Q)^{0.5}}{(H)^{0.75}} = 479 \tag{1}$$

where n is rotational speed, Q is flowrate, and H is head. The EFS project's unusually high head and low flow rate requirements lead to a specific speed requirement that falls outside of the ranges of common impeller types (fig ref).

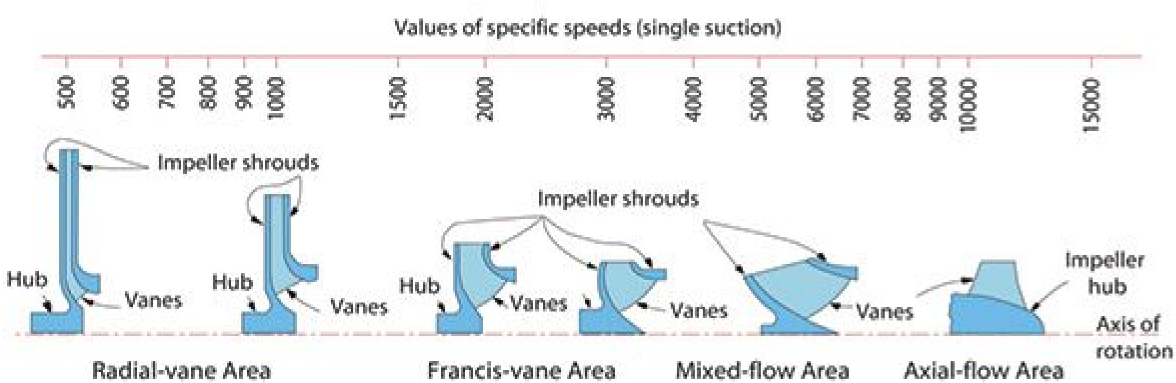


Figure 1: *Typical flow classification of pump impellers as per specific speed*

This forced the design process to take a radical departure from the typical options found in pump design documentation. Literature review outside of the normal canon of rocket pump design led to the suggestion of a Barske design impeller figure 2: an unorthodox, straight vane radial impeller design suitable for low flow, high head, and low specific speed requirements.

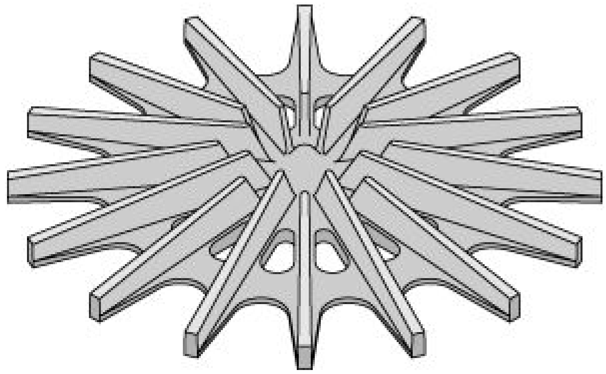


Figure 2: *Barske impeller design*

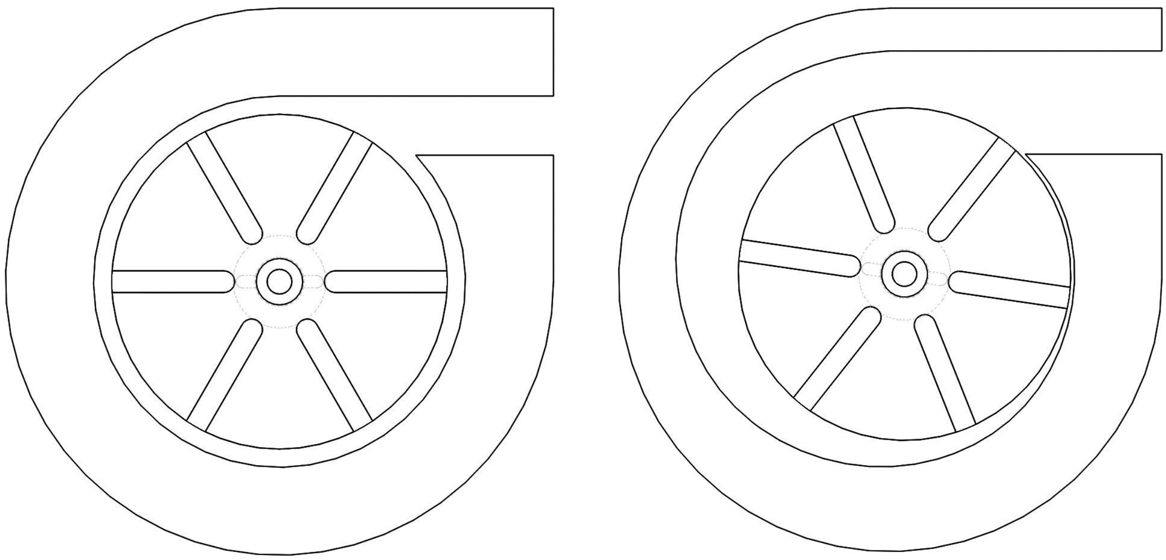
The decision was made to proceed with designing the EFS system around a Barske impeller for two reasons: a Barske design is suitable for the pump's specific speed range and it is easy to manufacture do to its geometric simplicity. The disadvantage of the Barske design is that it is not represented well in the usual pump sizing documentation, and thus required more experimental testing and one-off design to characterize its performance. This was an acceptable trade off because the performance of the EFS largely falls outside of the regimes covered by common pump sizing documentation already, and thorough experimentation would be required for any approach. The unknown character of Barske impellers was an acceptable risk, as the EFS' requirements put it outside of common pump characteristics. A subsystem performance matrix interpreting this decision is included in appendix A.E. See appendix C for more detailed development of the Barske impeller design.

	Specific speed range (design value = 479)	Manufacturability	Documentation availability
Common designs (radial, Francis, mixed flow, axial)	500-8000 (our value is on the limit of ideal range)	Very complex: investment casting or 5 axis milling of impeller and housing.	Designs are included in pump sizing literature, though our performance requirements fall outside of common regimes.
Barske design	400-1000 (our value falls into ideal range)	Very simple: impeller and housing can be made with 3 axis mill.	Not included in common literature and experimentation required for basic characterization.

Figure 3: *Screening matrix for impeller style selection*

Concept selection process: Housing type

Another major decision was the housing type to be used for the initial prototype and water testing. A simple option for an impeller housing is a concentric design, which is the easiest to manufacture but may reduce efficiency. Higher performance housing options could include an expanding volute or the addition of a cutwater to the concentric design see figure 4 below.



Concentric volute housing *Expanding volute housing*

Figure 4: *Comparison of a concentric volute to an expanding volute*

In the interest of developing a prototype to validate theory (before hitting performance targets), a concentric volute housing was chosen to simplify manufacturing. The first prototype test is intended to prioritize isolating the influence of factors represented in the pump sizing theory used for fundamental design calculations. For example, impeller diameter, height, blade number, inlet size, and outlet size are critical dependant variables. Fortunately, many of these variables are connected, and a test regimen does not need to independently manipulate each variable. Introducing housing design as a dependant variable at this stage, however, dramatically complicates the testing required without providing clear validation of the theory used in the design.

	Testing influence	Performance	Costs
Housing with expanding volute, cutwater, or other modifications	- May need to be designed and tested for second prototype anyway. - Introduces a unique variable to testing not represented in our pump sizing calculations.	- May bring us closer to target values.	- Significant design process. - Cannot be manufactured on lathe.
Concentric housing	- Simplifies analysis of test data.	- May cause low performance that complicates test data analysis	- Simple to design. - Can be manufactured on lathe or 3 axis mill.

Figure 5: *Screening matrix for housing style selection*

Subsystem Highlights:

As seen in Fig. 6, the electric feed system subsystems consists of the following: The hydraulic subsystem, the mechanical subsystem, the power subsystem, the flow loop subsystem, and the measurement subsystem. Each subsystem was designed to work in tandem to support the unorthodox fluid characteristics of the EFS, and to provide reliable results during testing. These systems can be seen in Figure 8, taken during a testing run.

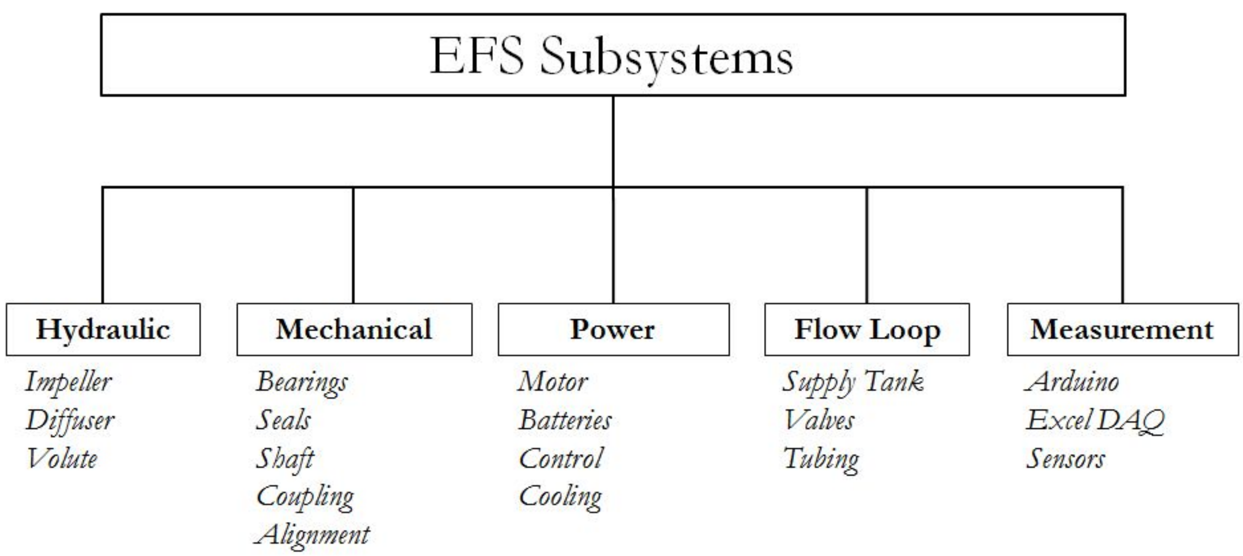


Figure 6: *The subsystem decomposition of the Electric Feed System.*

The hydraulic subsystem shown in Figure 8. consists of the components housed in the pump casing designed to convert an inlet fluid to a specified outlet pressure and flowrate. This includes the impeller, volute, and diffuser. The hydraulic subsystem is designed for modularity and has the ability to test various impellers and diffusers to experimentally determine the performance effects on the pump.

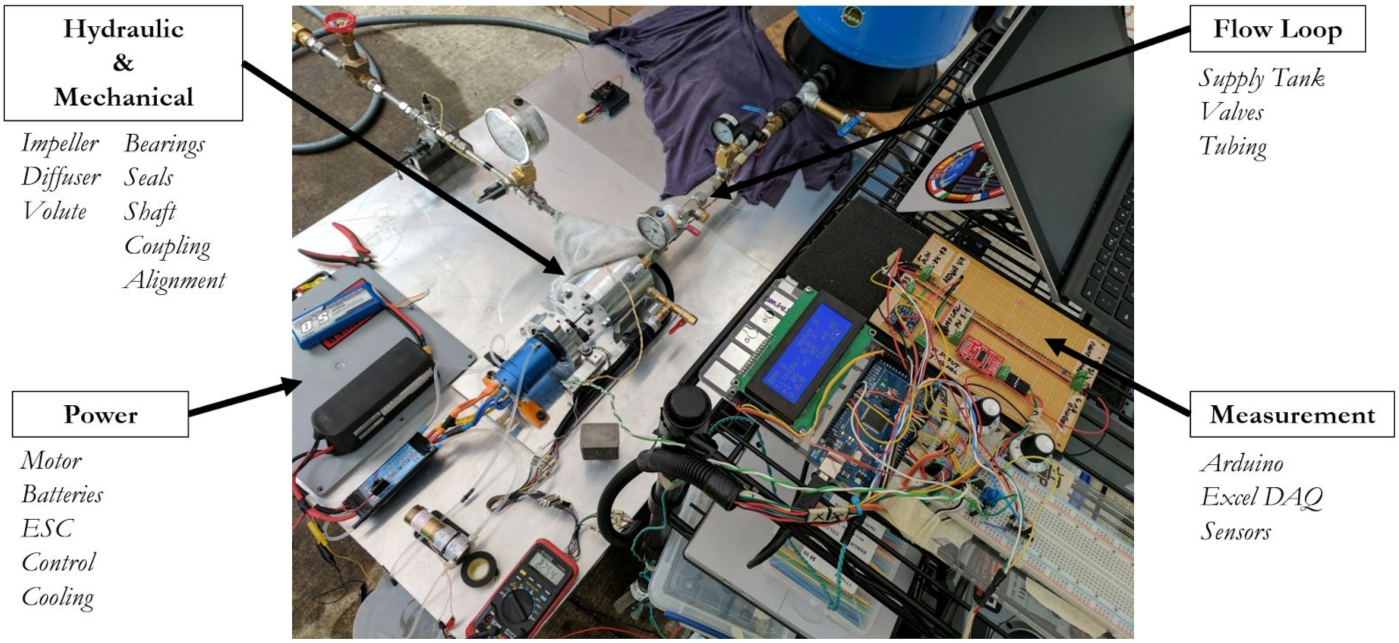


Figure 7: *Photograph of the electric feed system taken during the testing, highlighting the different subsystems*

The mechanical subsystem, also housed in the pump casing, can be seen in Fig. 7, but also in further detail in Fig. 8 . The mechanical subsystem consisted of the bearing assembly, seals, shaft, coupling, and structure of the pump. This system transmits rotational and power requirements to the hydraulic assembly, prevents leakage of water during operation, and eliminates any unfavorable dynamic effects during operation that could result in excessive vibrations and rubbing which could cause the pump to fail. The structure of the casing is also included in this subsystem, supporting the critical alignment of the mechanical components, from the drive to the impeller.

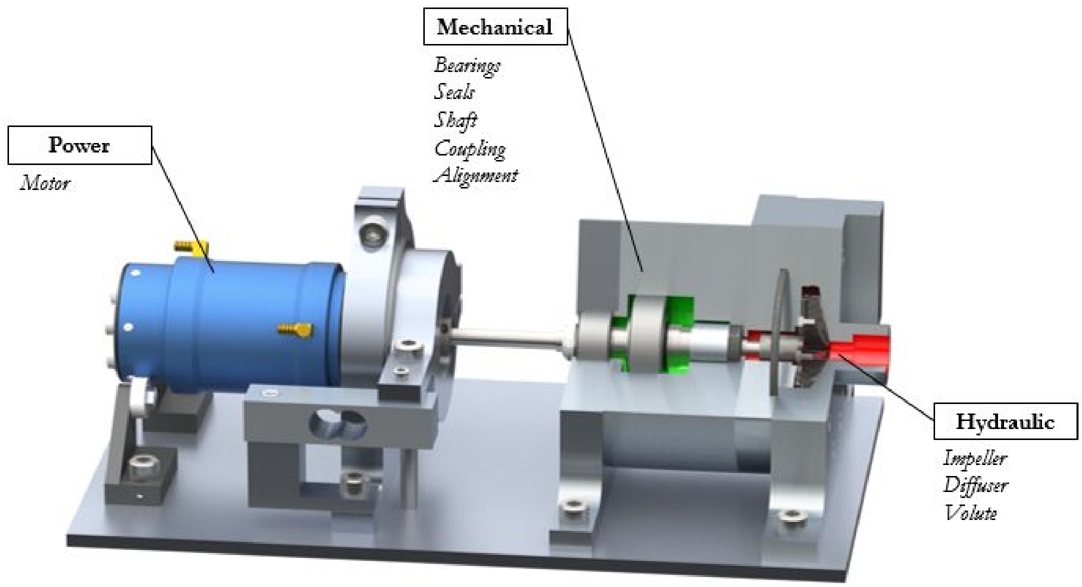


Figure 8: *Detailed view of power, mechanical, and hydraulic subsystems*

The power subsystem, composed of the components used to drive the impeller, can be seen in Fig. 8. This subsystem consists of the DC brushless motor, the batteries that supply electrical power, the motor, and, Electric Speed Controller (ESC), the cooling system, and the remote controller. The batteries and motor components of the power subsystem were chosen to test for feasibility as potential candidates for a flight-ready system.

The measurement subsystem, seen in Fig. 7, measures and logs experimental data taken during testing. This included the various sensors to measure pressure, flow rate, RPM, and torque. Due to the unique requirements of the EFS, custom sensors were designed and implemented, such as the in house dynamometer to measure torque and a tachometer using an optical sensor to achieve accurate RPM measurements at high rotational speeds. An Arduino Mega was used as a data acquisition system, which outputs the values digitally to an MS Excel sheet.

The flow loop subsystem was comprised of the valves, fittings, tubing, and supply tank, seen in Fig. 7. The flow loop provides fluid to the pump for performance testing. The components were selected and designed to deliver the inlet water at a specified pressure, and carry the discharge outlet from the pump. A throttling valve at the pump outlet provides variable flow capacity for characterization of pump performance.

Performance Summary:

Performance testing of the EFS prototype as a complete system is an involved and ongoing process. Pump tests are based on standardized testing procedures[1] relating to the characterization of centrifugal pumps. This requires the production of several standardized plots to determine the characteristics and operating performance of a particular pump. In order to produce these plot a testing platform and series of designed experiments were developed. These plots include flow rate (Q) vs. head (H), Q vs. net pressure suction head (NPSH), Q vs. efficiency, and a system curve describing the friction losses of the particular system. Preliminary test results show that the pump outperforms expected results in several key performance measures. Shown below in Fig. 9. are the standard performance curves for the 10 blade impeller at 16500 RPM

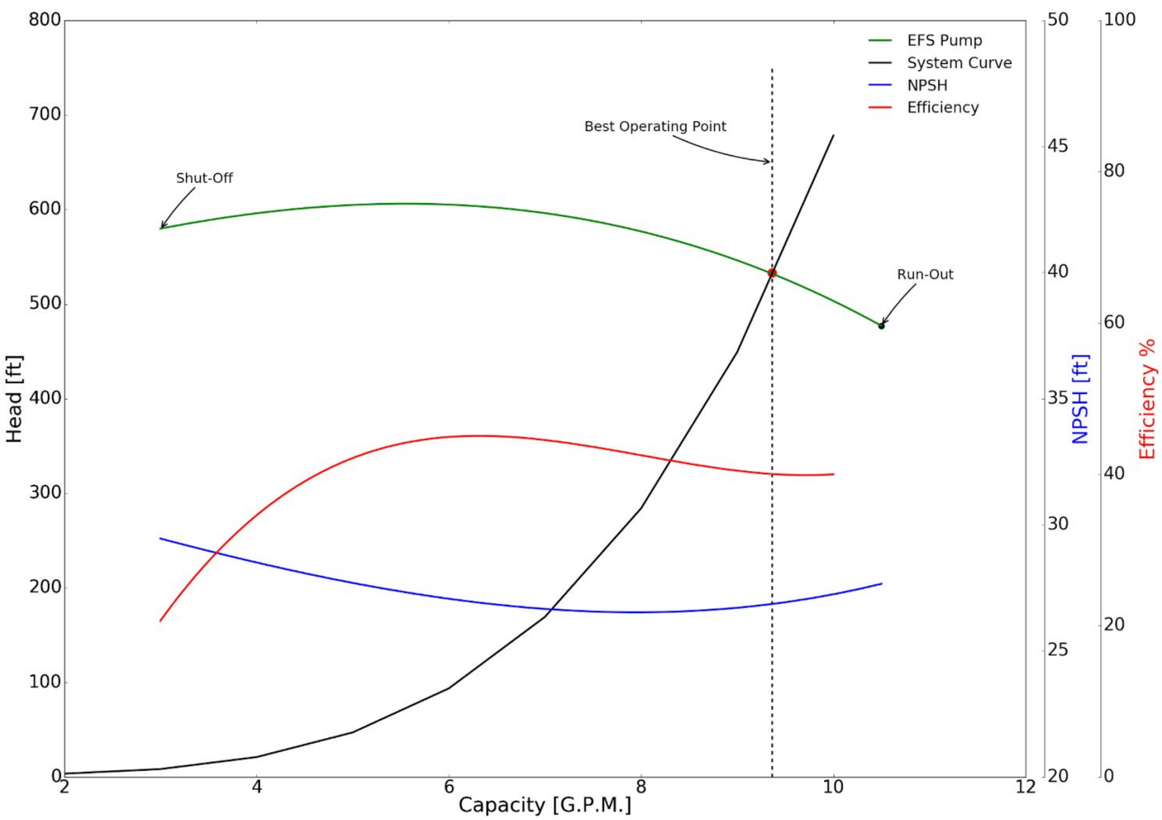


Figure 9: *Graph of performance characteristics for 10 blade impeller & 8 degree diffuser at 16500 RPM.*

[1] Hydraulic Institute Test Standard (ANSI/HI 14.6)

From early pump performance runs, the EFS is on track to meet key performance targets. Although data analysis is in progress for higher RPM testing, discharge pressure and flow rates exceeding requirements have been witnessed in preliminary testing as shown in table X. Current data analysis shows maximum outlet pressure of 284 psi for a 10 blade impeller at 16500 RPM. The optimal rotational speed for the conceptual design was predicted at 22000 RPM. Challenges with battery performance inhibited full testing at these speeds. Future iterations of this project with revised power supply are expected to exceed design requirements for outlet pressure delivery.

Table 2: *performance summary of preliminary pump performance testing*

Customer Requirements	Target	Achieved	Witnessed
Design, build, and test EFS for under $8000	< $8000	$3,086.78	
Pressure delivery	300 ≤ Pd ≥ 400 psi	284	> 400
Flow capacity	10 ≤ Q ≥ 12 gpm	10.5	> 14
Off-the-shelf components	YES/NO	YES	
Transferability	YES/NO	YES	

In addition, performance of individual subsystems were evaluated prior to pump performance testing. Due to extremely tight tolerances and clearances, large pressure differentials, and high rotational speeds, the verification of component dimensions and clearances was done extensively before the final assembly of the pump to lower the risk of catastrophic system failure.

For example, manufacturing difficulty involved in producing sufficient surface finish for diffusers led to a decision to 3D print the diffusers on a high precision SLA resin printer. Due to the lack of information available about the proprietary material used, there was some concern about the durability and strength of the printed parts. To verify the SLA resin diffusers, a test rig was built , shown below in Fig. 10. This experimental set up tested various diffuser geometries at static pressures of up to 500 psi without leakage or failure. In addition, diffusers were flow tested prior to pump testing at 100 psi without damage.

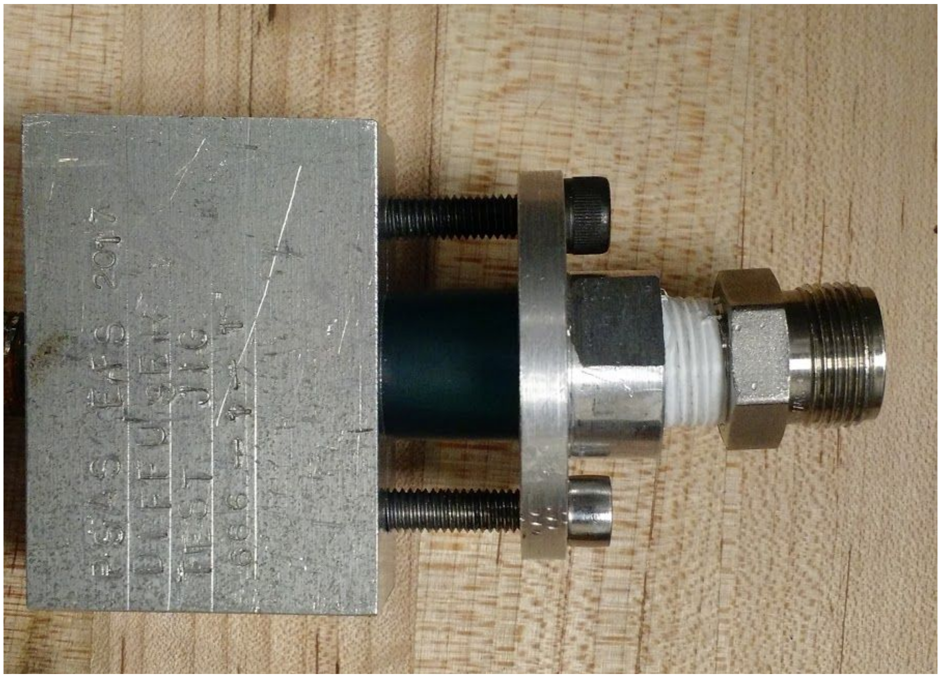


Figure 10: *Test apparatus for diffuser pressure verification.*

Overall, the mechanical subsystem performed well in preliminary testing. The selected off the shelf seals within the pump housing were able to withstand high rotational speeds and pressures without failure or leakage. Off the shelf bearings were able to handle the large forces and torques present in the system and did not show visible wear after preliminary testing. The in-house manufactured shaft and coupling maintained concentricity at high RPMs without unwanted vibrations or rubbing.

The flow loop and measurement subsystems of the test stand also performed well. The tank and fittings provided controllable and measurable inlet pressure to the pump without leakage. Off the shelf pressure transducers were successfully wired and calibrated to interface with the Arduino mega. Due to the unique features of the EFS, some sensors were designed and manufactured by the team to provide accurate performance characterization. For example, a custom dynamometer shown in Fig. 11 was designed and manufactured to measure torque. The motor drives a torque arm into a small load cell calibrated to measure force. By collecting data from the load cell, the measured force and known arm length are used to calculate torque. This torque measurement was critical in creating the system performance curves.

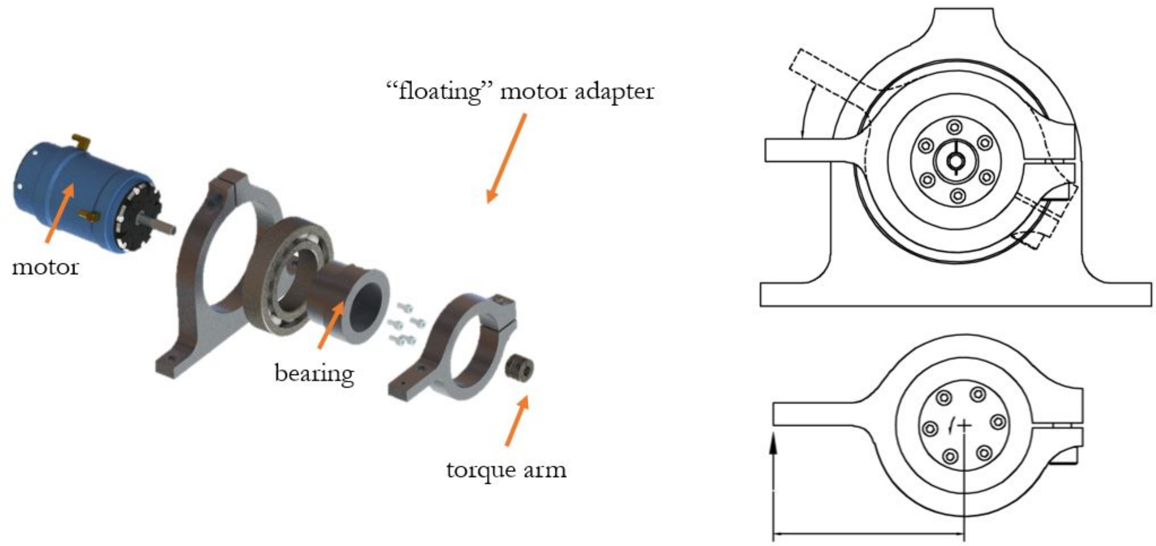


Figure 11: *Design of custom built dynamometer for live torque measurements.*

The power subsystem was able to provide smooth rotational speeds of up to 16500 RPM. This was the maximum speed available using 1 - 6S cell 22.2V Li-Po battery. Adding a second battery in series allowed the system to reach rotational speeds over 22000 RPM. However, the addition of the second battery created an unstable power supply. It became difficult to keep a constant speed over the course of a full test, and batteries drained within several minutes. Future modifications of this pump should reevaluate power requirements and power supply options.

Final Status:

The EFS team successfully designed and built a test water pump to meet the needs of PSAS's 2.2 kN rocket engine, shown in fig. 12. Key conceptual design developments included the design of an unorthodox barske style impeller, diffuser, and pump volute of the hydraulic subsystem to meet the hydrodynamic requirements necessary to deliver fluid at the specified flowrate and pressure of ~12 gpm and ~300-400 psi, respectively. A flow loop subsystem was designed and manufactured to meet the flow and pressure requirements of the pump in performance testing. A mechanical subsystem was designed and manufactured to include involved a high speed shaft, shaft coupling, and bearing and seal system required for the pump to operate at its design rotational speed of 20000 rpm. The power subsystem was sized to provide a motor and battery pair that can successfully to meet the pump's power requirements. Finally, a measurement subsystem was successfully implemented for continual data acquisition of sensors, which measure flow rate, inlet and outlet pressures of the pump, and rotational speed of the pump.

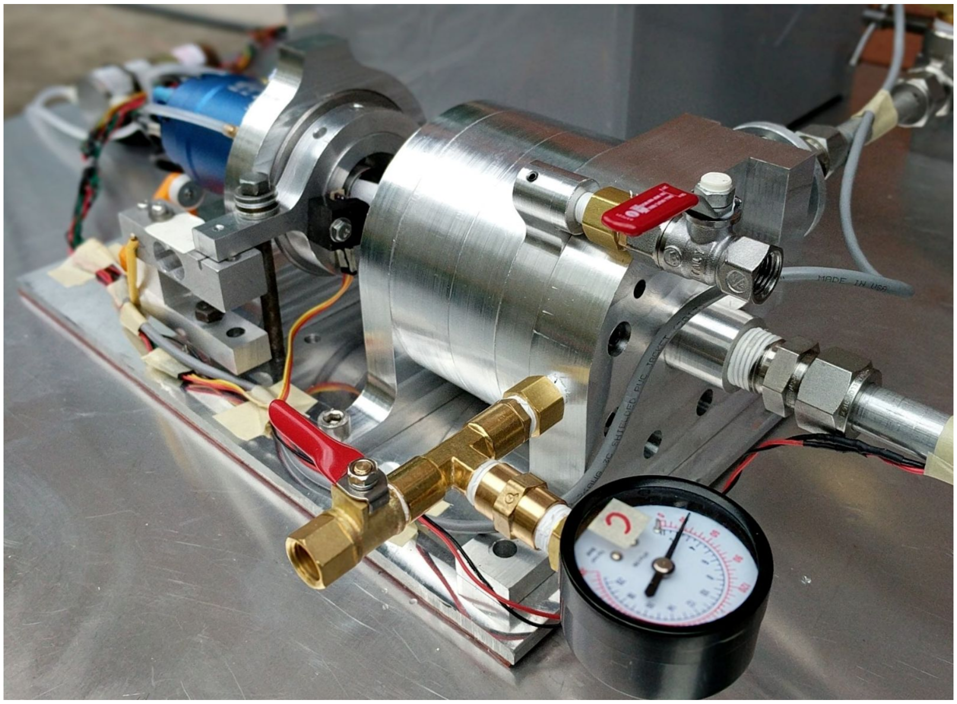


Figure 12: *Image of the completed EFS system.*

Notable achievements of the EFS system include:

- Successful manufacturing and testing of EFS system
- Meeting of the pressure and flow requirements of 400 PSI and 12 GPM
- Pump efficiency of 42.8% (Exceeding expected efficiency of 30%)
- Fully documented and transferrable open-sourced pump design. Documents available on the PSAS Electric Feed System github page[2].
- Pump design and build for $3,117.00, significantly under the allotted $7900 PSAS budget.
- Pump built using only 8% custom parts, meeting PSAS's off-the-shelf-component requirement. See bill of materials in Appendix F and component pie chart in Appendix F.1.

Next steps for the EFS project include full testing and characterization of the pump at design conditions. Further testing is required to achieve a complete characterization of the system, including experiments where impeller blade number and diffuser angle combinations are investigated. Future iterations of this design should include modifications of the mechanical

[2] https://github.com/psas/electric-feed-system

system to meet the rigors of cryogenic temperatures. Modifications include selection of cryogenic seals, selection of liquid oxygen compatible materials for pump housing, and manufacturing considerations for single piece volute and diffuser design. The power supply to the motor should also be re-evaluated for more robust testing. Considerations for safety of the people testing the pump also need to be taken into consideration. These include increased separation between pump operator/DAQ stand. Separation should exceed 10 meters. Along with increased separation, blast protection from the cryogenic ready pump needs to be investigated and implemented due to the possibility of ejection of failing components at high speed.

Appendices:

A. Supplemental Images:

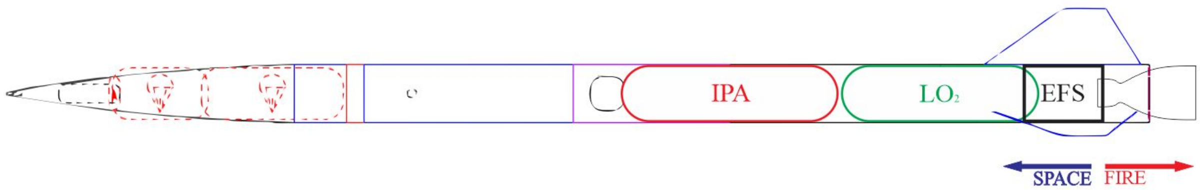


Figure A.1: *Schematic of the PSAS LV4 rocket showing IPA and LOX fuel tanks, the EFS, and the rocket engine.*

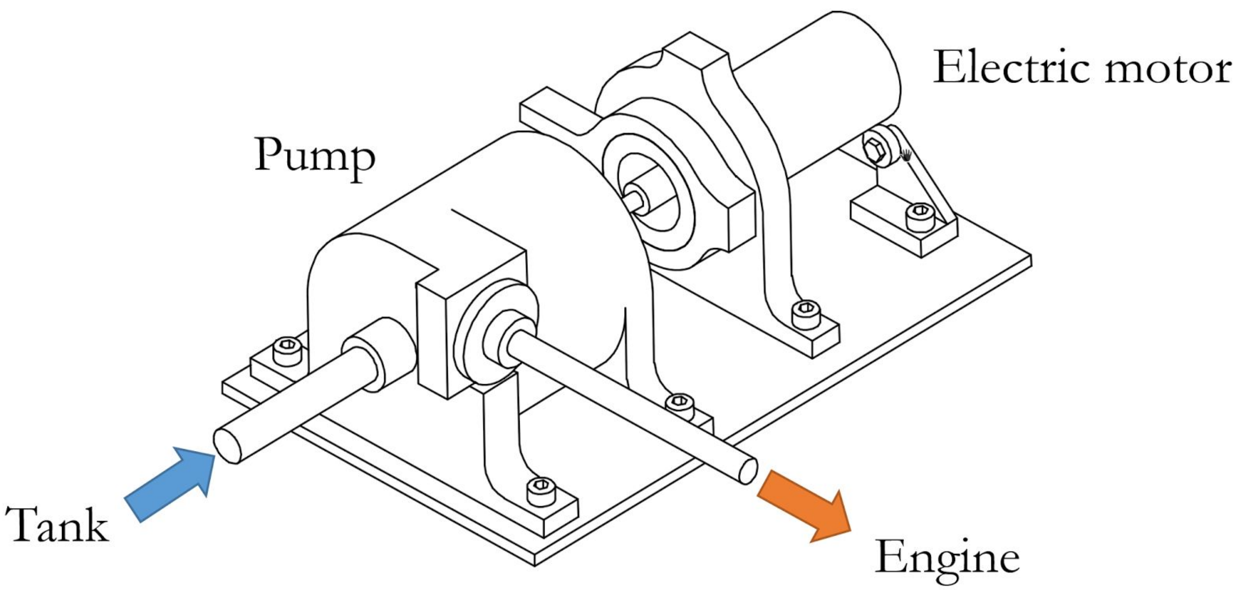


Figure A.2: *Final conceptual sketch of the EFS system.*

Table A.1: *Table of measurements and devices needed to measure them.*

Measured variable	Monitoring device		What do we gain?
Pump Inlet/Outlet Pressure	Pressure Transducers/Gauges	 	Pump Flow/Head Characteristics
Pump Flow Rate	Liquid Turbine Flow Meter		
Impeller Cavity/Seal Cavity Pressures	Pressure Transducers/Gauges		Loading on Pump Seals and Bushings
Pump Rotational Speed	Optical sensor		Pump Power and Efficiency
Pump Torque	Load Cell		
Required Electric Power	Indirect Measure	Sensing simultaneously motor current and voltage	

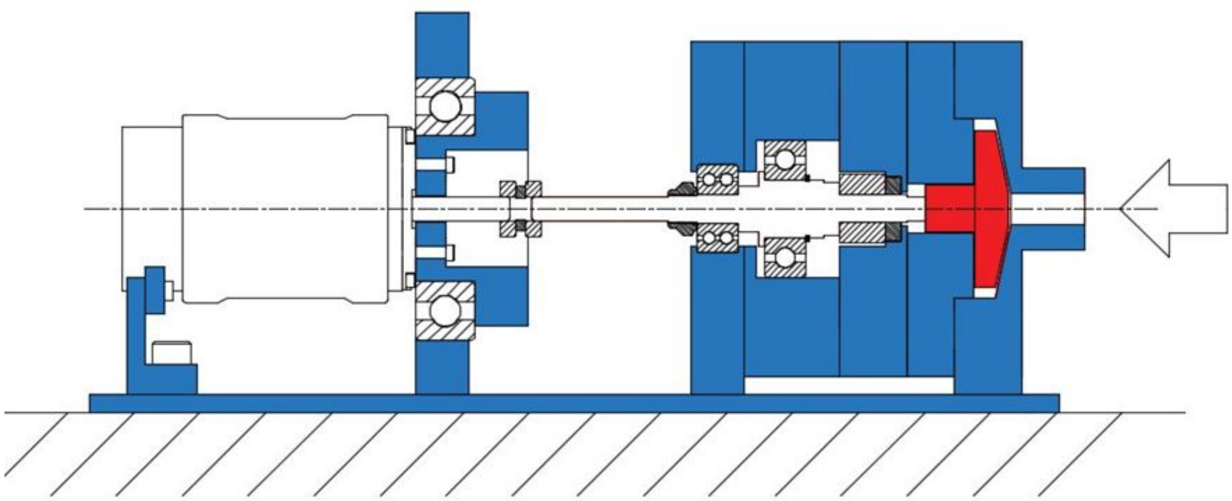


Figure A.3: *Section schematic, in-house fabricated components shown in blue (shaft also fabricated in-house), 3D printed impeller shown in red. Other components purchased of the shelf not feasible for in-house production.*

B. Catalog of Design Artifacts

1. 2.2 kN folder
    a. CAD folder
        i. Includes all CAD models and revisions of all the custom pump components, including impellers, shaft, impeller housing, etc.
        ii. Includes drawings of the EFS components and assembly.
    b. Analysis folder
        i. Includes electric pump notebook, which includes pump sizing calculations for the PSAS 2.2 kN rocket engine along with equations and parameters used in sizing the pump.
2. 8.0 kN folder
    a. Includes electric pump notebook, which includes pump sizing calculations for the PSAS 8.0 kN rocket engine along with equations and parameters used in sizing the pump.
3. Docs folder
    a. Papers folder
        i. Includes copies of EFS papers submitted for AIAA, capstone, and OSGC.
    b. Presentations folder
        i. Includes copies of the final EFS poster.
        ii. Includes final EFS presentation slides and images used in making those slides.
    c. System Materials folder
        i. Includes spec sheets for electric motor and ESC, various fittings, solenoids, valves, drill sizes, and flowmeter.
    d. Templates folder
        i. Includes various EFS document templates.
4. Performance folder
    a. Data Analysis folder
        i. Includes performance plots from tests of the EFS system.
        ii. Includes raw data from the EFS experiments.
    b. Operating Code folder
        i. Includes arduino codes used in calibrating the flow meter, load cell, thermocouples, and pressure transducers.
        ii. Includes arduino codes used in the data acquisition from flow meter, load cell, thermocouples, pressure transducers, and RPM sensor.
5. Publicity folder
    a. Photo folder
        i. Include an archive of images taken during the EFS project

b. Presentation Parts folder
    i. CAD models of various concept pieces that would be used at the EFS table to hold impellers and diffusers.
c. Video folder
    i. Includes a video of the EFS running.

6. Purchasing folder
    a. Includes Bill of Materials, receipts, and invoices for the EFS.

C. Concept analysis

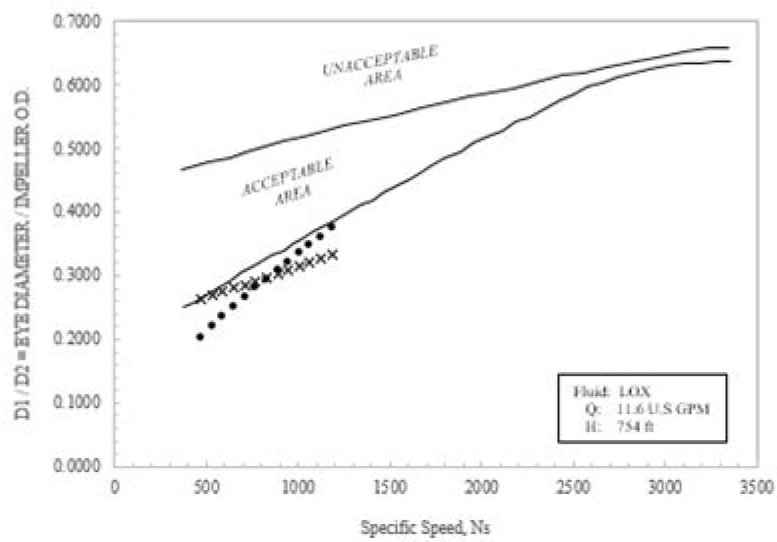


Fig C.1: *Plots of theoretical impeller specific speeds for different impeller diameters.*

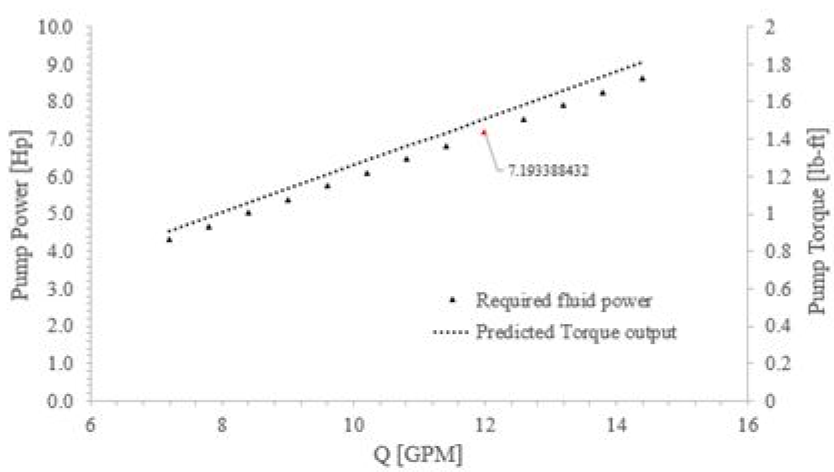


Fig C.2: *Theoretical pump power for various flow rates.*

LOX	
RPM	20000
Specific Speed	472.594
Fluid Power [kW]	1.87631
Required Motor Power [kW]	4.69077
Specific Diameter [in]	0.184903
Impeller Diameter [in]	2.13375
Throat Diameter [in]	0.177869
Eye Diameter [in]	0.425981
Impeller Eye Area [in^2]	0.570073
Inlet blade tip height [in]	0.0625
Blade Number	6

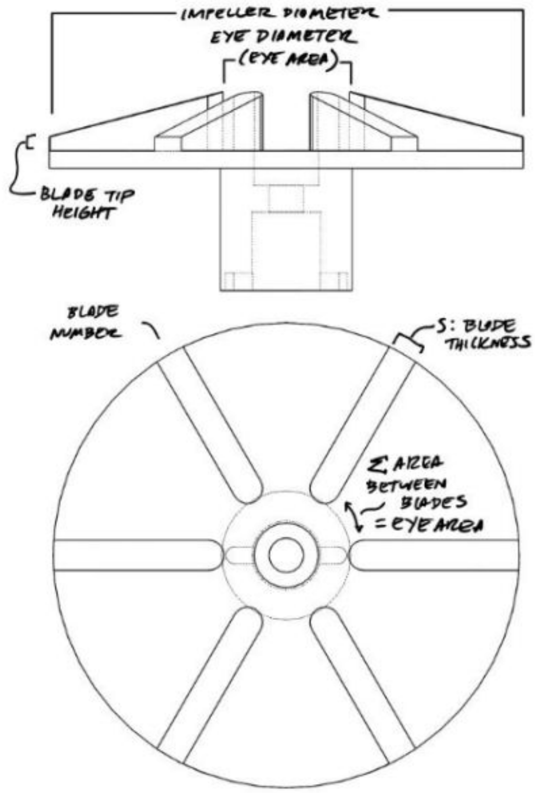


Figure C.3: *Preliminary design sketches and calculations for barske impeller design.*

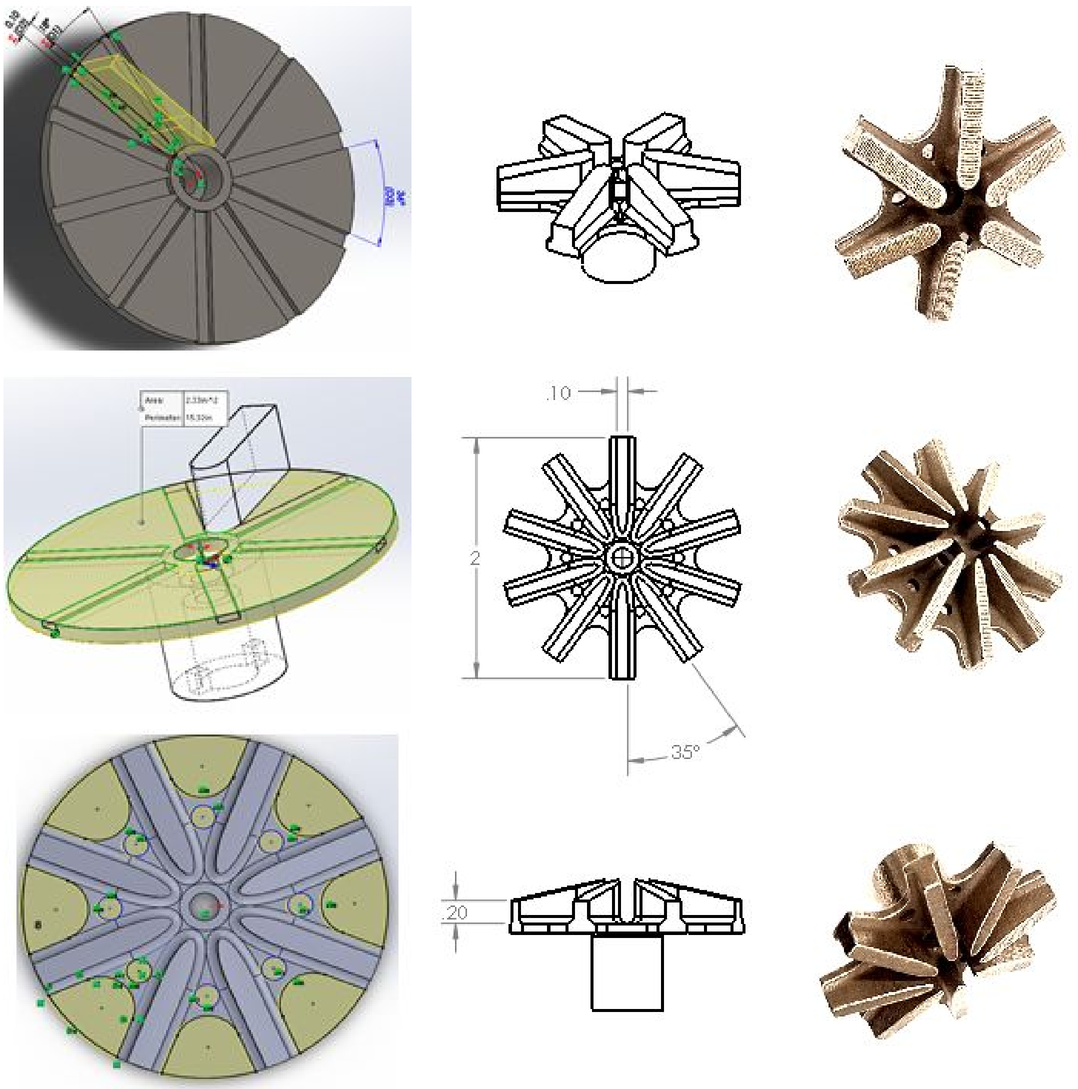


Fig C.4: *Parametric design process for barske impellers of different vein numbers*

D. System-level RM Matrix

System RM matrix attached as a separate file in D2l.

E. Subsystems

Hydraulic Subsystem:

Subsystem: Hydraulic

Subsystem performance measures		*Pressure | PSI*	*Flow | GPM*	*Interchangable Impellers | Yes / No*	*Interchangable diffusers | yes / no*
Target design requirements	< Imp	1	2	3	4
Hydraulic preformance	3	•	•		
Modular Design	2			•	•
	Imp ->	3	3	2	2
	Lower Acceptable	260	9	-	-
	Ideal	350	12	Yes	Yes
	Upper Acceptable	440	-	-	-

Figure E.1: *Requirements - Measurements matrix for the Hydraulic subsystem.*

Design analysis: The hydraulic subsystem was comprised of the impeller, volute, and diffuser. These three components worked together to convert the incoming fluid to a higher pressure. A heavy literature review was done to design and develop these components. Multiple diffusers and impellers were designed, therefore requiring a modular design of the subsystem in order to be able to interchange the components. Figure E.2 shows the different components of the hydraulic subsystem in detail. See 2.2 kN folder in design artifacts USB for design and analysis details.

Performance: The hydraulic subsystem performed well, hitting pump the performance requirements, seen in Table 2. It is also important to note that the modularity of the design did not hinder the overall performance and reliability of the subsystem.

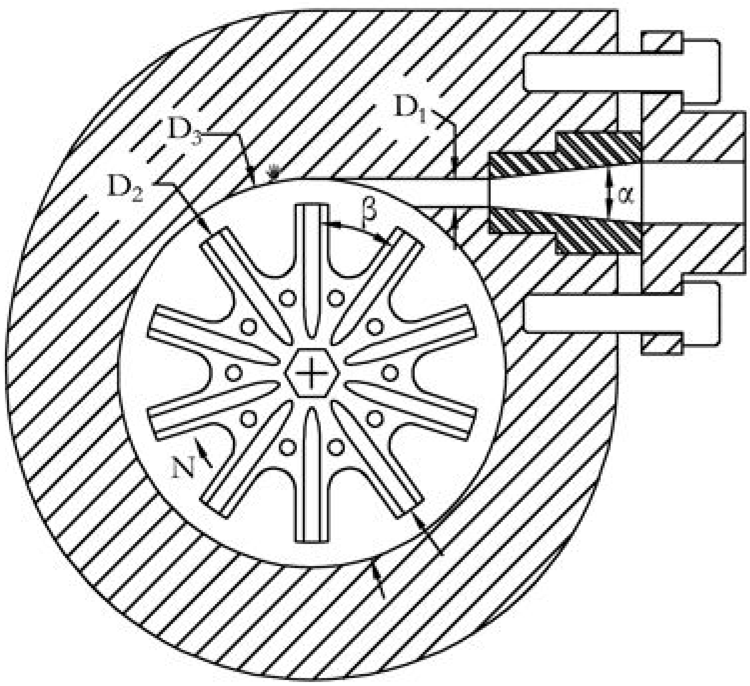


Figure E.2. *Section view of the hydraulic assembly.*

Mechanical Subsystem

Subsystem: Mechanical

Target design requirements	< Imp	1	2	3	4	5	6	7
Subsystem performance measures | Units		*Shaft Rotation | RPM*	*Shaft Power Transmission | kW*	*Impeller / Volute Condition | NA*	*Vibrations | NA*	*Offset Alignment | .001" inch*	*Angular Alignment | Degrees*	*Leakage of testing fluid | NA*
delivers operation speed and power	3	•	•					
Negating unfavorable shaft dynamics	3			•	•	•	•	
Leakage	1							•
	Imp ->	3	3	3	3	2	2	1
	Lower Acceptable	-	-	-	-	-	-	-
	Ideal	25000	3Kw	No Damage	No noise	0	0	0
	Upper Acceptable	29000	5kW	Marginal Damage to volute and impeller. No effect to preformance	Minimal noise during testing. No effe to testing	11	0.8	During testing, leakage that can be wiped with a rag once, hourly

Figure E.3. *Requirements -measurements matrix of the mechanical subsystem.*

Design Analysis: The mechanical subsystem was comprised of the bearing assembly, the seals, the coupling, the shaft, and the casing. These components functioned together to transmit rotational power to the impeller while reducing any unfavorable shaft dynamics during operation. The mechanical subsystem also prevented leakage of water during testing, and supported the alignment of the rotating assembly. Without precise execution and implementation of the mechanical subsystem, unreliable and even dangerous operation of the pump is risked during testing. To determine the effectiveness of the mechanical system, extreme precaution and precision development was taken during the selection, design, and manufacturing of the various components. Before operation, the shaft alignment was verified with a dial indicator, checking for offset and angular misalignment that could not be handled by the shaft coupling of the bearing system. CNC machining practices were implemented during the manufacturing of precision components to achieve the high quality and repeatable fabrication of components made in-house. The precision of the components were then verified using dial indicators, micrometers, telescoping gages, and digital calipers. See 2.2 kN folder in design artifacts USB for design and analysis details.

Performance: The mechanical system performed above the requirements defined by the scope of the project. The EFS team was able to hit the specified tolerances of the design through diligent design and fabrication, resulting in reliable, consistent operation of the pump during testing at lower RPM. It should be noted that during initial operation of the pump, the system experienced vibrations, but were immediately minimized with the adjustment of mounting bolts on the pump casing. At higher RPMs, above 18,000, the system started to experience seal failure, with small leakage of water draining from the casing. The amount of leakage was able to be cleaned with a single rag, but the seal was replaced. This was expected, the seals were not designed for the RPMs and pressure the electric feed system would produce during operation. Impeller rubbing also occurred at higher RPMs, resulting in minor damage to the pump volute. It should be noted, that this could have been due to a slight dimensional defect of the 3D printed impeller, as wear was indicated in a single point of the impeller. This damage was not catastrophic, as operation of the pump continued at a lower RPM with a different impeller.

Power Subsystem

Subsystem: Power	Subsystem performance measures	Rotations per minute | RPM	Power | KW	Throttling range | 0-RPM	Throttling Accuracy | RPM	Battery discharge | Tests	Emergency Stop
Target design requirements	< Imp	1	2	3	4	5	6
Can achieve pump testing requirements	3	•	•	•	•	•	
Safe Start up / Shut down	3						•
	Imp ->	3	3	2	1	3	3
	Lower Acceptable	0	NA	25000	NA	1	no
	Ideal	25,000	3 kW	29000	50	3	Yes
	Upper Acceptable	29,000	5 KW	>29000	100	NA	NA

Figure E.4. *Requirements - measurements matrix of the power subsystem.*

Design analysis: The power subsystem was comprised of the motor, batteries, remote control, and the cooling system. The motor and batteries were chosen as potential flight-ready components to validate the concept of an electric propellant feed system, and not chosen to optimize pump testing. See 2.2 kN folder in design artifacts USB for design and analysis details.

Performance: The power subsystem yielded the most challenges during the testing phase of the project. Failure of the team to consistently monitor the voltage of the batteries during testing resulted in running the batteries below the minimum voltage level, resulting in permanent damage to the batteries. Damage to the battery resulted in the ability to only complete a handful of experimental replicates before having to switch batteries or stop altogether. During testing, the motor repeatedly shut down due to reaching the low voltage cutoff of the motor. This was initially diagnosed as motor control problems, not as low battery voltage problems. Future work should seek to replace the batteries with a power supply for testing purposes.

Measurement:

Subsystem: Measurement

Target design requirements	< Imp	Pressure Accuracy / PSI	Flow / GPM	Shaft Rotation / RPM	Power Applied to fluid /in-lbs	Data was recorded / NA	Data was provided live / NA
Subsystem performance measures		1	2	3	4	5	6
Accurate Pressure Measurement	3	•				•	•
Accurate Flow Measurement	3		•			•	•
Accurate Shaft Rotation Measurement	3			•		•	•
Accurate Power Applied to Fluid Measurement	3				•	•	•
	Imp ->	3	3	3	3	2	2
	Lower Acceptable	20	0.2	100	0.1	hand recorded	gauge readings
	Ideal	0	0	0	0	digital recorded / stored 10hz	Digital and gauge readings
	Upper Acceptable	-	-	-	-	-	-

Figure E.4. *Requirements - measurements matrix of the measurement subsystem.*

Design Analysis:

The measurements subsystem was a relatively straightforward array of sensors managed by an Arduino Mega. Data was transmitted over USB from the Arduino to Excel during test runs by using an Excel spreadsheet and the PLX-DAQ Excel add-in.

The general measurement approach was to use sensors that could integrate with the Arduino based DAQ in tandem with (and calibrated against) analog reference gauges.

Pressure measurement was accomplished using three pressure transducers and two analog Bourdon tube gauges used across four locations: Suction pressure (transducer), volute pressure (transducer), seal pressure (gauge), and discharge pressure (transducer and gauge). All transducers were calibrated against the pair of Bourdon tube gauges.

Flow measurement was conducted with a turbine flow meter in series with a Hedland in-line flow meter.

Shaft rotational speed (RPM) was measured with an IR sender/receiver pair and checked against a handheld IR digital tachometer.

Power applied to the fluid was determined by combining the RPM value with a measurement of the torque applied to the shaft. Measuring shaft torque was a significant design challenge. This was accomplished by mounting the motor in a rotationally floating motor mount that did not allow for axial or radial translation but allowed the motor to rotate about the shaft's axis with minimal friction. The motor rested inside of a large bearing and would be free to spin were its rotational motion not restrained by a "torque arm". This arm, in turn, rested on a strain gauge based load cell. As the motor applied torque to the shaft in order to apply power to the fluid, it attempted to rotate in the opposite direction but could not due to the load cell. The load cell was calibrated with known weights in situ so that any friction effects due to the motor mount bearing or resistance to motor rotation due to the motor's cables or coolant lines were accommodated for in the load cell calibration.

The DAQ frequency was set relatively low (5 Hz) to avoid errors with the PLX-DAQ Excel daq. Higher frequency data would be desireable but 5 readings per second was acceptable as we sought measurements at steady state conditions and were not interested in transient effects. See Performance folder in design artifacts USB for design and analysis details.

Performance:

Good performance of the measurement system was a hard fought victory. In the final testing runs, the load cell was physically damaged and shaft power measurements were not used, though these values were obtained for the early testing period. All other measurement devices worked as intended.

Flow Loop

Subsystem: Flow Loop

Target design requirements	< Imp	*Inlet Pressure | PSI*	*System Leakage | NA*	*Set up | minutes*	*Uninterrupted number of runs | NA*
		1	2	3	3
Inlet water delivery requirements	3	•			
Minimized Flow loop leakage	1		•	•	
Rapid replicate turnover rate	2		•	•	•
	Imp ->	3	1	1	1
	Lower Acceptable	20	-	-	3
	Ideal	45	no leakage	5	5
	Upper Acceptable	50	manageable with single ra	20	-

Figure E.5. *Requirements - measurements matrix of the flow loop subsystem.*

Design analysis: The flow loop is designed to deliver the required fluid capacity to the pump to prevent dry running and to route discharged fluid away from critical electrical components. This system consists of a pressurized water tank and the system of plumbing that makes up the suction and discharge lines connected to the pump. It is critical that these components function as designed to prevent the pump from running dry and potentially damaging seals which require contact with the operating fluid to function properly. See Docs folder in design artifacts USB for design and analysis details.

Performance: The flow loop functioned sufficiently well for a significant portion of testing and did not leak. Notable minor failure point was: most significantly the fact that the water tank needed to be overpressurized significantly in order to remain pressurized during operation of the pump this was due to the fact that the flow rate of pressurant delivered by the shop air supply was insufficient to match the flowrate of the fluid leaving the tank resulting in decreased suction pressure shortly after the beginning of a test run. During later tests the tank was modified to allow for a higher flow rate of pressurant into the tank however this was still insufficient to maintain correct suction pressure during testing, but sufficient enough to retrieve meaningful results from testing. Future iterations of the flow loop will likely use regulated high flow compressed nitrogen as a pressurant to avoid this problem.

F. Bill of Materials

Bill of materials attached as a separate document, see submitted Excel Sheet in D2l.

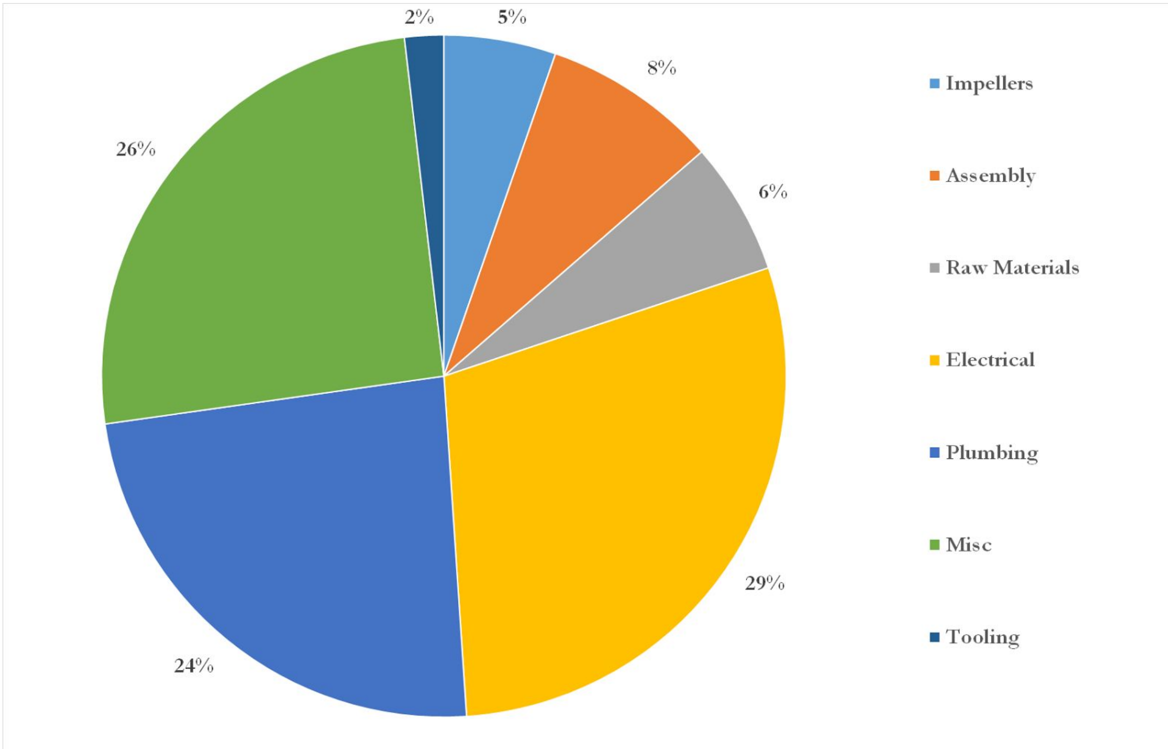


Figure F.1. *Pie chart of the distribution of components used in the EFS system. Raw materials accounts, which are used to make custom components, account for 6% of the total number of items that went into building the EFS. This 6% figure gives the EFS team confidence that it met the COTS component requirement from PSAS.*