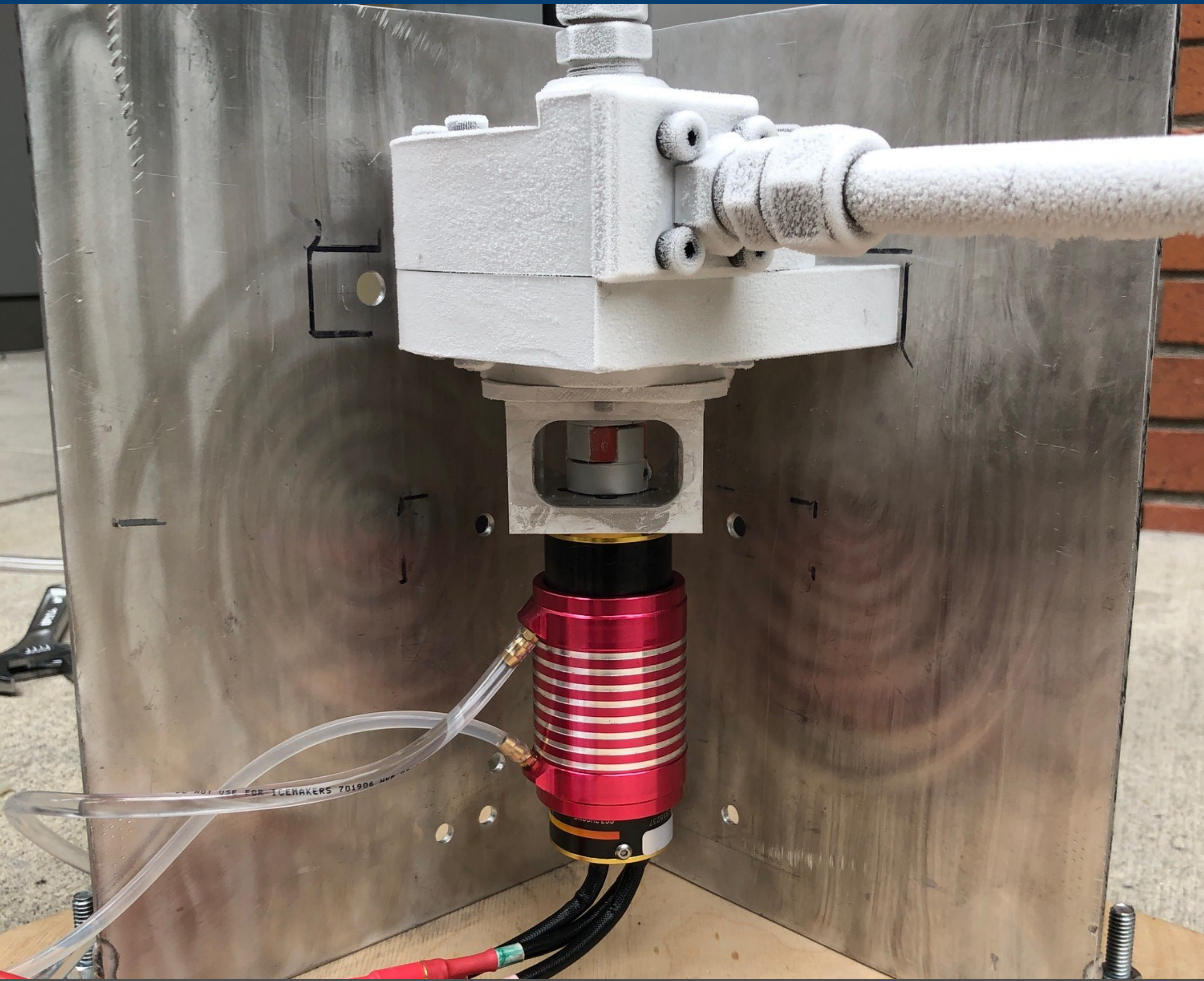
ME 493 | Spring 2019

Final Capstone Report



Flight-Ready Electric Feed System

Sponsored by Portland State Aerospace Society (PSAS)

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Executive Summary

Portland State Aerospace Society requires a Flight-Ready Electric Feed System for their upcoming Launch Vehicle 4. An Electric Feed System is an electronically controlled pump system used to provide the necessary pressure to deliver liquid propellant to the engine. The EFS must be cryogenic compatible to withstand the environment that the liquid oxygen (LOX) and isopropyl alcohol (IPA) propellants create. While this project has yet to provide a flight-ready system, significant headway was made on developing a cryogenic compatible system. Improvements were made upon the previous design, and recommendations on how to proceed are being drafted for future EFS design teams.

Figure 1: Cryogenic Testing of LOX Compatible Electric Feed System

Contents

1 Introduction

The goal of this project was to develop a cryogenic compatible, flight-ready electric feed system (EFS) for Portland State Aerospace Society (PSAS) for use in their upcoming Launch Vehicle 4 (LV4). This project has made significant advancements in the design and testing of a cryogenic compatible pump. However, more work must be completed before the EFS will be deemed flight-ready. Improvements were made upon previous EFS teams designs, resulting in a more compact, higher powered, and robust pump system. Crucially, the new design has been tested and confirmed to be cryogenic compatible. The final EFS design has successfully shown PSAS that the pump design is capable of pumping cryogenic fluids without seizing and is able to maintain single-phase fluid flow at the system outlet under specified conditions, as shown in Figure 1.

2 Mission Statement

The Electric Feed System Capstone aims to provide affordable, lightweight propulsion system technology, increasing the capabilities of amateur rocketry and student education.

3 Project Design Specification (PDS)

Portland State Aerospace Society has defined the requirements for the EFS capstone. Table 1: *Product Design Specifications* outlines and ranks the customer needs from highest to lowest priority items, with 5 being top priority, as of May 2019. Table 2: *Customer Requirements*, and Table 3: *Engineering Requirements* cover targets and metrics, along with our verification process for achieving these goals.

Table 1: Product Design Specification

Product Design Specification (PDS)			
Customer Need	**Primary Customer**	**Priority**	**Time**
Must be tested with liquid Nitrogen (LN2) and isopropyl alcohol (IPA)	PSAS	5	*****
Must safely keep the propellants separated at all times	PSAS	5	*****
Should have embedded sensors for data acquisition	PSAS	4	*****
Should have emergency shut off procedure and battery cutoff	PSAS	4	*****
Should have embedded sensors for feedback, and control	PSAS	3	***
Must deliver propellants at 450 PSI with NPSH of 45-100 PSI.	PSAS	3	***
Must be able to operate for multiple engine test fires (≥ 10 firings) without system overhaul	PSAS	3	****
Must handle launch module vibration and 10g's acceleration for 20 seconds.	PSAS	3	***
Must be compatible with liquid oxygen (LOX)	PSAS	2	*****
Should minimize system plumbing losses (major and minor)	PSAS	2	*
Must be able to be used on the PSAS engine test stand	PSAS	1	****

Table 2: Product Design Specification

Customer Requirements							
	Requirements	Primary Customer	Metrics & Targets	Metric	Target	Target Basis	Verification
Performance	LN2 Compatibity	PSAS	Must be able to safely pump liquid nitrogen	N/A	No damage	Customer Defined	Cold flow testing
Performance	Fluid Separation	PSAS	Must restict fluid mixing even in the event of failure	N/A	No fluid mixing	Customer Defined	Prototyping
Installation	Manpower to test	PSAS	Manpower	# People	4 People	Customer Defined	Cold flow testing
Installation	Time to replace spare parts	PSAS	Time	Mins	2 Hours	Team Defined	Timed after prototype built
Safety	LOX Safety	PSAS	Design with all chemical safety requirements via B11 Training	N/A	No LOX hazards	Customer Defined	Cold flow testing
Safety	Electrical Safety	PSAS	Ensure all controls systems are safe from fluids, etc.	N/A	No electrical hazards	Customer Defined	Prototyping
Maintenance	Minimal upkeep between test fires	PSAS	No overhaul to be required between tests	Hours of Work Rqr'd	< 4 hours	Group Defined	Testing
Maintenance	Replaceable Parts	PSAS	Readily Available Parts for replacement bearings, rings etc.	N/A	Off the Shelf Parts	Group Decision	Budget
Cost	Minimal production cost	PSAS	Cost	Dollars	< $9,500.00	Customer Defined	Budget

Table 3: Product Design Specification

Engineering Requirements							
	Requirements	Primary Customer	Metrics & Targets	Metric	Target	Target Basis	Verification
Performance	EFS size	PSAS	Must be able to fit within LV4 rocket module	inches	11.3"	Customer Defined	Airframe simulation
Performance	Repeatability	PSAS	Reusable for 10 test fires	# Fires	10	Customer Defined	Failure testing
Performance	Pressure Gain	PSAS	Must achieve target pressure differential	psi	350	Customer Defined	Cold flow testing
Environment	Withstand Launch Environment	PSAS	Maintain operation during launch conditions	g	10	Customer Defined	Testing
Environment	Withstand vibration of Airframe	PSAS	Components must be designed to avoid harmonic frequency of rocket structure	Hz	TBD	Customer Defined	Simulation

4 Concept Design

The following sections provide the background to previous design ideas for the electric feed system pumps leading to the final manufactured design.

4.1 Single Drive Dual Pump Design

Initially, the EFS was conceptualized as a pumping system in which two centrifugal pumps were driven by a single power source. The goal of this design was to decrease the total space and weight used by the electric feed system by reducing the need for a second motor.

4.1.1 Axially Split Inline Pump

The first design concept for the EFS featured two pumps with axially split pump cases running inline with the same drive shaft. The center pump would have a pass-through shaft with bearing housings on either side of the pump to allow the shaft to continue out to drive the second pump, as shown in Figure 2a.

While the use of a single drive in this context would reduce the weight of the system by the removal of one motor, it was concluded that this design was not feasible after preliminary hydraulic calculations were made. Each fluid requires a different rotational speed to achieve the appropriate pump specific speed required for suction[1], so it was concluded that the two pumps could not share a drive directly.

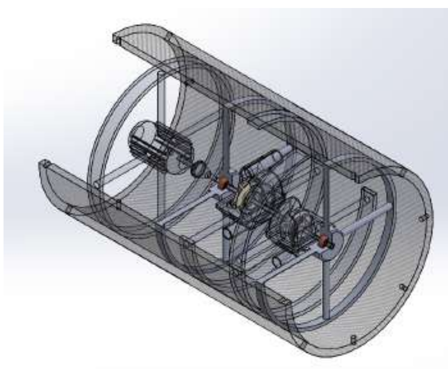
4.1.2 Gearbox Driven Pump

Given the issues with running a single drive inline, a design was generated that featured a single motor used to drive a bevel gearbox. Both pumps were then run orthogonally from the direction of the motor shaft, as shown in Figure 2b.

This design would allow for separate rotational speeds by utilizing gear ratio relationships to drive the two pumps at different rates. However, this would require a motor with very high power density, which was determined to be outside of the scope of the project budget. Additionally, the use of a gearbox would result in larger amounts of energy loss and overall system inefficiency, which would not be optimal for integration into the rocket. Moreover, the energy lost to the gearbox would result in a large amount of heat generation in close proximity to the flow region of the cryogenic fluid, resulting in two-phase flow and risk of cavitation in the LOX pump.

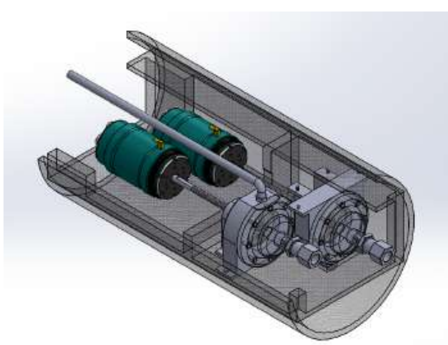
4.1.3 Dual Drive Parallel Pump Design

The optimal pump orientation was decided to be two pumps running parallel to each other on separate drive shafts, as shown in Figure 2c. While the second motor and mount add additional weight, the system is more reliable and more effective overall, as two motors with the required separate power densities can be procured for less than the cost of a larger single shaft drive system with comparable power density. Additionally, this design allowed for the fabrication and testing of initial prototypes for IPA while design and analysis continued to be performed for the LOX system.



(a) Inline Drive System Concept with Shared Power Source

(b) Gearbox Driven Drive System Concept with Shared Power Source

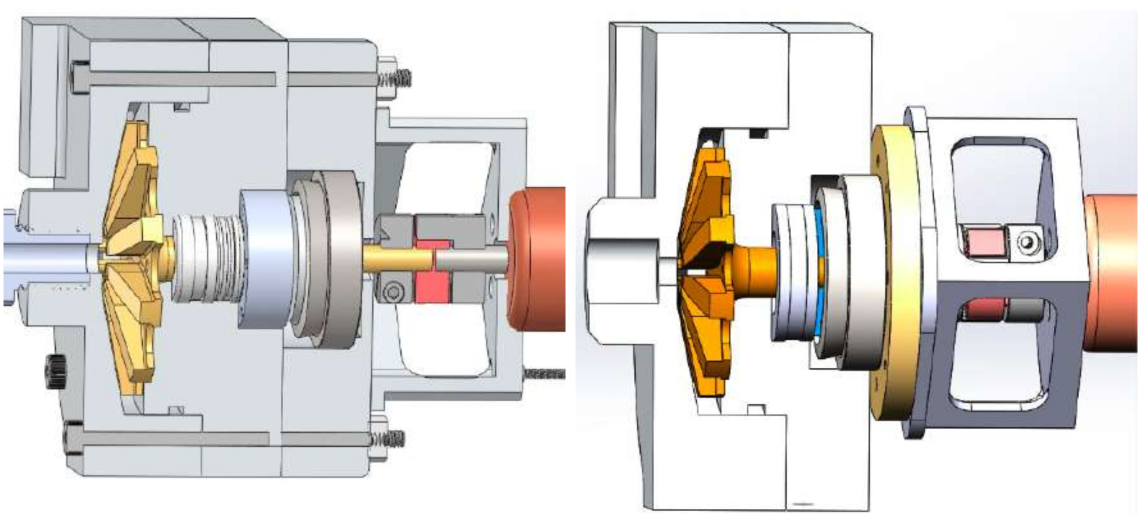


(c) Parallel Drive System Concept

Figure 2: Iterative Electric Feed System Design Concepts

5 Final Design Selection

The dual drive option was selected as the optimal power system configuration, as it allows for the greatest level of independence for rotation speeds between the two fluid pumps while remaining reliable and cost-effective. The final design consists of a three-piece pump housing that is assembled sectionally along the shaft axis, as shown in Figures 3a and 3b. The two assembled housings are mounted into the corners of the module mount, fastened in an orthogonal pattern to handle shock and vibration symmetrically in the XY plane. The final design's motor is mounted to the pump housing itself rather than the module mount, as this ensures optimal alignment from the drive shaft to the impeller, as shown in Figure 4. Flow is plumbed downward into the impeller eye opposite to the rocket's acceleration direction in order to achieve the flow rate calculated based on the rocket's ideal thrust. The outlet plumbing exits the side of the pump and is fed down to the engine. Manufacturability of all components was taken into consideration during the design phase. The cryogenic compatible pump used an experimentally derived tolerancing function to account for thermal deformation. This process is shown in Appendix C. The full manufactured assembly is shown in Figure 5.



(a) Final Isopropyl Alcohol Pump Design (b) Final Liquid Oxygen Pump Design

Figure 3: Cross-Section Views of Electric Feed System Pump Designs

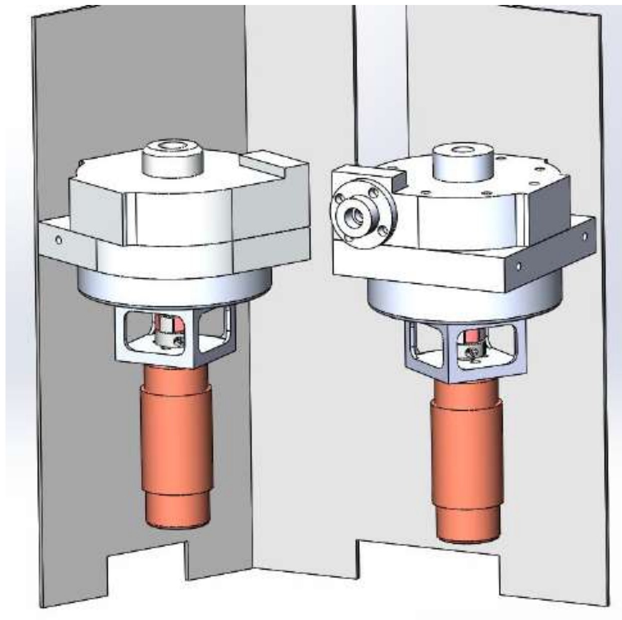


Figure 4: Electric Feed System Mounting Configuration

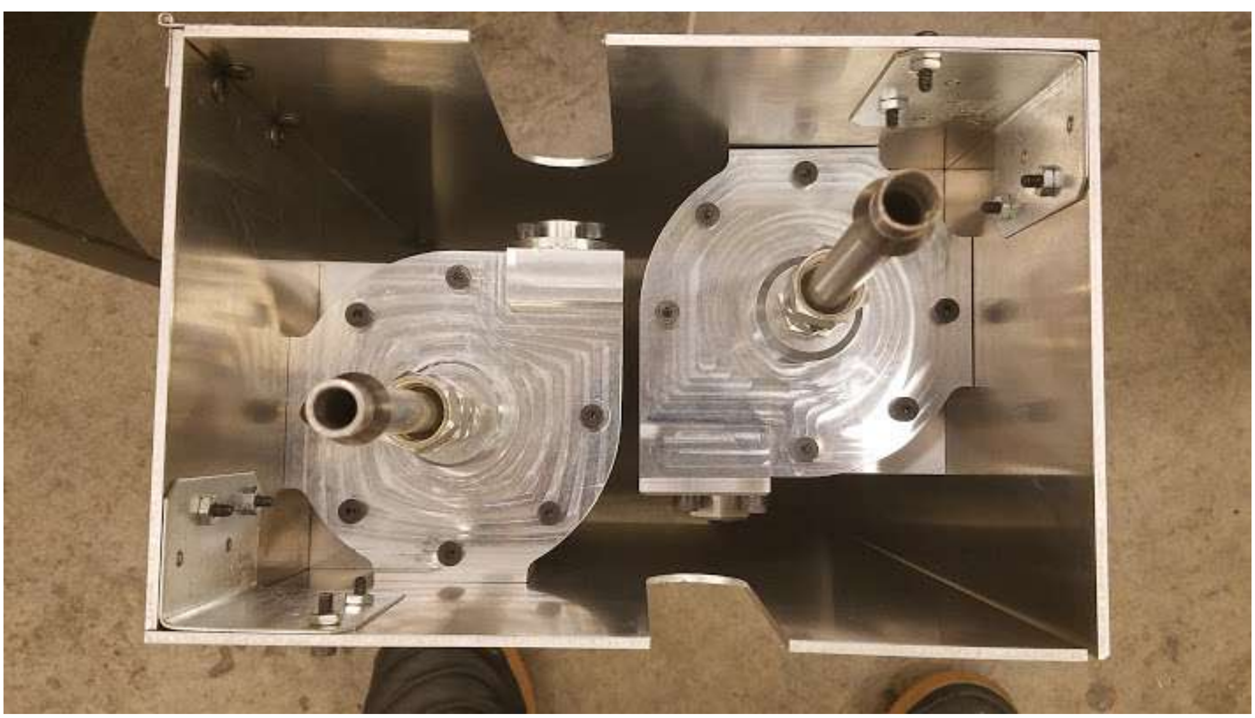


Figure 5: Full Assembly of IPA and LOX Pumps Mounted in Flight Orientation

5.1 Impeller Design

For the EFS, development of a specialized impeller was required to provide high-pressure gains while maintaining a low flow rate. Taking into consideration the previous team's research as well as industry literature on liquid propellant rockets, it was determined that a Barkse style impeller design would be the most fitting for this application. Barske impellers are intentionally designed to inefficiently move fluid through the pump. This inefficiency allows for large pressure gains while maintaining low flow rates. The previous team also tested a variety of impeller designs with a varying number of vanes. It was found that 10 vanes were the most efficient number of vanes for the pump.

Another critical decision involved in the impeller design was the impeller and shaft connection interface. The impeller needed to be able to withstand high torque values and be machinable within the campus machine shop. The final design evaluation for the impeller resulted in the selection of a single-piece shaft. It was determined that this design could be made in-house at Portland State University from 3" diameter, $3\frac{3}{4}$ long raw stock 6061-T6 aluminum. This design scored the highest against the matrix design criteria and was selected to move forward with to begin prototyping. The final manufactured design is shown below in Figure 6b. Hydraulic design calculations for determining impeller geometries can be found in Appendix C.

(a) Machined Impeller Vanes

(b) Balanced Impeller

Figure 6: Impeller Machining Processes

5.2 Material Selection

Research in material properties and compatibility led to the selection of Aluminum 6061 for the fabrication of both the isopropyl alcohol and liquid oxygen pumping systems. The primary factor impacting this decision was material compatibility with LOX. Because of the volatile properties of liquid oxygen, material selection for this fluid required the consideration of a number of safety and reliability factors, including oxidation, corrosion, and cavitation. It was decided that an aluminum alloy would be the safest selection based on the research performed in these areas.

6061 was selected as the ideal alloy for this project's application, as it is relatively low-cost and is more machinable than stainless steels, which were also considered for use. This allowed for more practical in-house fabrication, lowering the cost of production and lead times.

The material behavior of this alloy was also determined to be the most desirable for cryogenic applications. While most stainless steels may have higher strengths and lower tendencies to oxidize, it was found that aluminum 6061 is more ductile at cryogenic temperatures than any of the stainless steels researched. Loss of ductility would generate risk of ductile-to-brittle transition for the stainless steels considered, which increased the risk of catastrophic failure at the pressure magnitudes required for the EFS.

Table 4: Material Selection Matrix

Material	Mechanical Properties	Machinability	Cost	Extreme Temperature Performance	LOX Compatability	Score
Aluminum 6061	3	5	5	3	2	18
Aluminum 7075	3	5	2	3	3	16
SS 304	5	1	2	1	5	14
SS 316	5	1	2	1	5	14

5.3 Power Components

The requirements for shaft power led us to select the TP Power 4070CM as the BLDC motors for both the IPA pump and Cryogenic pump. A Swordfish 200A electronic speed controller (ESC) was used for each motor. The full power system is shown in Figure 7. Including the batteries and other accessories, this combination was within budget, at approximately $1000, and well exceeded the requirements for both systems. Purchasing an overpowered motor for the IPA pump increased our design efficiency by replicating the components to the cryogenic pump. The use of identical motor systems for both pumps saved time and freed up to focus for other components.

Safe operation is a strong requirement for the system to be considered successful. This project is to focus on designing for the flight which entails autonomous operation for the EFS. When selecting the ESC, batteries, and connectors, safe autonomous operation during the flight was prioritized by PSAS for the team. Gold plated, 8mm bullet connectors are found along with the entire wire harness because they offer a safety factor of 1.75 against high current load damage. This minimizes the risk of meltdown and electrical fires. The batteries powering the motors have a 350A capable discharge rate which provides a 1.88 safety factor, once again, against fires due to meltdown or damage from high current demand from the motor. Lastly, the Swordfish 200A ESC provides a built-in water cooled case for heat dissipation and a safety factor of 1.34 against damage due to high current.

Figure 7: Power System Components for IPA and LOX Pumps

5.4 Internal Pump Components

5.4.1 Dynamic Seal Selection

The IPA pump design utilized a Flowserve bellows-style Type 15 PacSeal to contain fluid in the impeller chamber. Additionally, to run cryogenic tests in time to meet the customer deadline, a seal was designed in-housing using a PTFE collar press-fitted onto the pump shaft to allow cryogenic tests to be run. The IPA and LOX seals can be seen in Appendix D, Figures 10a and 10b, respectively.

5.4.2 Bearing Selection

The IPA pump was designed to run with a Timken Stainless Steel Axial Thrust Roller Bearing, shown in Appendix D, Figure 10c. Further research and testing led to the addition of a Boca ceramic thrust bearing to operate in series with the Timken roller bearing. A cross section of the placement of these bearings can be seen in Figure 3b.

6 Results and Evaluations

The final EFS designs for IPA and LOX outlined in Section 5 were manufactured and tested three times in total; two tests were performed for the IPA pump using water, and one test was ran on the LOX pump. For the cryogenic test, liquid nitrogen (LN_2) was used instead of LOX due to campus safety policies. This allowed the team to accurately observe the performance of the pump under cryogenic conditions. Because LN_2 and LOX have similar physical properties, it was determined that testing with LN_2 would still provide accurate results regarding the behavior and performance of LOX.

Initially, the highest primary customer need presented for the EFS capstone was to test both IPA and LN_2 in each fluids respective pumping system. However, initial water testing for the IPA pump indicated several imperfections in the system design. When power was supplied to the pump, the rotating element seized in the pump housing and was not able to rotate. This caused the motor to pull more power than the system was designed for due to increased torque, which resulted in the control systems electronic speed control (ESC) to overload and short circuit from a rapid increase in current.

Failure analyses concluded that the seal and bearing within the pump were not aligned properly, resulting in the shaft locking in position. Rather than redesigning the IPA pump and testing again based on these considerations, the customer requested that this information be applied to the development of the cryogenic pump. At the customers request, the requirements were changed to prioritize the fabrication and testing of the cryogenic pump rather than moving forward with the IPA design.

These considerations led to the final cryogenic design shown in Figure 3b. To improve shaft alignment and rotating element concentricity throughout the pump, a new motor mounting system was designed in which the motor was attached directly to the rear end of the pump, rather than bolted to the support mount. After this pump was manufactured and assembled, tests were ran with the front face of the pump open to confirm proper alignment. A final full test was performed on the redesigned cryogenic pump with LN_2. This test resulted in a successful run of the EFS pump, pressurizing the fluid to maintain a fluid state at the outlet of the pump. This fluid jet can be seen in Figure

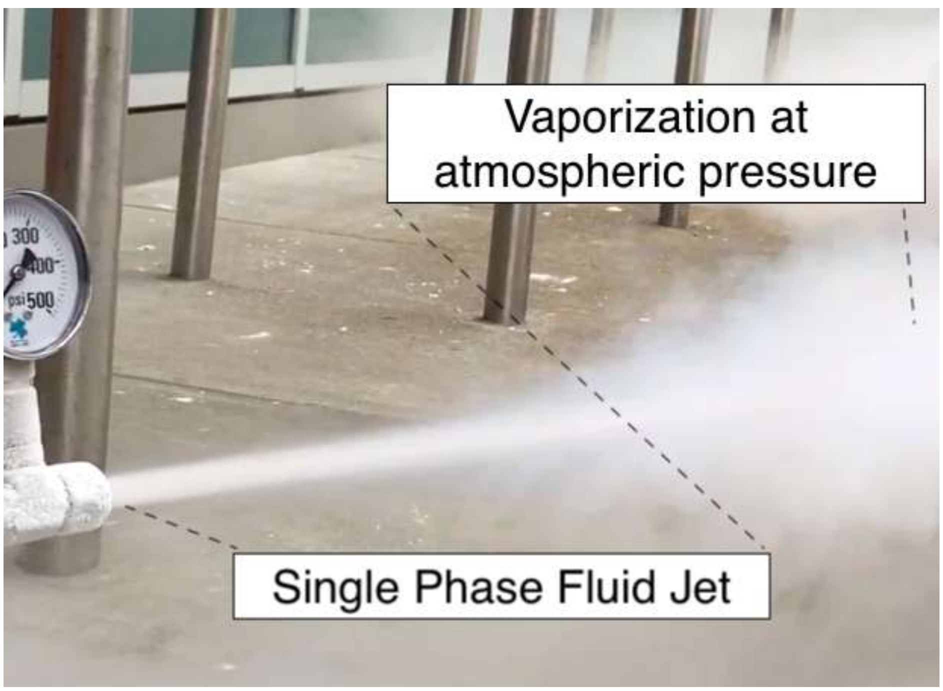


Figure 8: Single Phase Liquid Nitrogen Jet Exiting EFS Pump

Apart from the testing requirements described above, the EFS design was required to adhere to designated safety standards. First, it was stated that the system must maintain complete fluid separation throughout all points in the system. The selected design in which both pumps are powered by separate drives ultimately satisfies this customer request.

However, during cryogenic testing, it was observed that some gas leakage was experienced from the sealing chamber, as shown in Figure . In order to conclude that the propellants are perfectly separated, the sealing mechanism for the cryogenic pump will be improved on the ensure no interactions can occur between the two fluids. Additionally, the design was required to have an emergency shut off and battery cutoff. This was achieved by integrating a killswitch into the control system, allowing the operator to shut down all power to the system if necessary.

7 Conclusion

Ultimately, it is apparent that there is sufficient work to be done before the electric feed system will be deemed flight-ready. However, verification that the system is capable of pumping cryogenic fluids without seizing up marks a major milestone in the overall EFS design process. The design modifications in the LOX pump that led to a successful run can be replicated in the IPA pump; namely the use of dual thrust bearings. Doing so should allow the IPA pump to run without interference within the rotating elements, allowing for data collection to begin. Additionally, our research has identified the use of spring energized c-ring seals as a potential alternative to the bellows-style seal that we believe may be better suited for the EFS technical requirements, in addition to increasing reliability.

Our team has identified areas for improvement and are currently drafting an onboarding document for PSAS to guide future EFS design teams. This document will detail our recommendations for the next steps necessary to continue development of the pump systems. These suggestions cover a variety of topics, including cryogenic seals, custom motor shafts, further weight reduction, and bearing usage. Once fully functional pumps are completed, and pressure gain targets have been achieved, focus should shift towards sensor integration for both pumps. Assuming research and development of the EFS design project continues in the 2019 - 2020 academic year, a flight-ready EFS system should be attainable in time for LV4s anticipated launch.

Appendices

A Tables

Table 5: Theoretical & Measured Geometries of Cryogenically Cooled EFS Components

Component		Measurement	Unit	Initial Length	Length @Cryogenic Temperatures		
					Theoretical	Measured	% Difference
SHAFT	Shaft Seal Diameter	B	[in]	0.5001	0.4976	0.4984	0.1617
	Shaft Length	D	[in]	3.2470	3.2296	3.2400	0.3199
COLLAR	Bearing Diameter	A	[in]	0.9950	0.9900	0.9920	0.1969
CASE 1	Impeller Seat Diameter	A	[in]	3.4500	3.4328	3.4400	0.2081
	Impeller Shaft Bore Diameter	B	[in]	0.9310	0.9261	0.9287	0.2761
CASE 2	Housing Internal Diameter	A	[in]	3.4500	3.4328	3.4408	0.2313
	Housing Depth	B	[in]	1.1670	1.1612	1.1590	0.1898
S.R. Ring	Seal Seat Diameter	A	[in]	0.9940	0.9893	0.9919	0.2570
BRG. PLATE	Bearing Outer Diameter	A	[in]	1.9690	1.9594	1.9632	0.1920
						Average % Difference:	0.2259

Table 6: Gantt Chart

Legend	
Low Priority	
Medium Priority	
High Priority	
Completed Task	

Task	People	Priority	Start Date	End Date	Days Left	Status
Concept Design IPA Pump	All	High	1/1/2019	2/1/2019	-126	Completed
Purchase DAQs and Pressure Transducers	Tim, Julio	Low	2/1/19	2/7/19	-120	Completed
Purchase Tachometer and Temperature Sensor	Julio	Low	2/1/19	2/7/19	-120	Completed
Purchase Flow Meter	Julio	Medium	2/1/19	2/7/19	-120	Completed
Finalize Shaft & Impeller CAD	Phil	Low	2/1/19	2/8/19	-119	Completed
IPA Pump Prototyping	Jonas, Nick	Medium	1/26/2019	2/15/2019	-112	Completed
Finish machining impeller / shaft for open tank testing	Nick, Jonas, Shayli	High	1/21/19	2/25/19	-102	Completed
Run open tank test	All	Medium	2/1/19	2/28/19	-99	Completed
Motor Selection	Phil, Julio	Medium	2/16/19	3/1/19	-98	Completed
IPA Shaft & Impeller Material Selection	Henry, Nick	Medium	2/16/19	3/1/19	-98	Completed
Finalize CAD designs based on open tank test results	Phil	Medium	2/28/19	3/22/19	-77	Completed
Finish Progress Report - Winter Term	All	Low	2/1/19	3/15/19	-84	Completed
Begin FEA Analysis for LOX Pump	Nick, Julio	Medium	2/16/19	4/12/19	-56	Completed
Concept Design LOX Pump	All	High	1/1/2019	4/12/2019	-56	Completed
Control System Design	Julio, Nick	Medium	1/1/2019	4/19/2019	-49	Completed
Manufacturing IPA Pump	Jonas, Nick, Shayli	High	2/15/19	4/19/19	-49	Completed
Control System Testing	All	High	3/7/19	4/19/19	-49	Completed
Testing IPA Pump	All	Medium	3/7	4/23/19	-45	Completed
Testing LOX Pump	All	Medium	4/21/19	5/7/19	-31	Completed
Full System Test	All	High	5/7/19	5/21/19	-17	Completed
Creating Github Repo for PSAS	Phil	Medium	04/01/19	06/01/19	-6	Completed
Final Write Up	All	Low	4/1/19	6/15/19	8	Completed
System Demonstration	All	Low	6/7/19	6/15/19	8	Incomplete
IPA Test #2	All	High	5/9/19	5/16/19	-22	Completed
Manufacturing LOX Pump	Jonas, Nick, Shayli	High	05/06/19	05/20/19	-18	Completed
Mounting Case Manufacturing	Jonas, Shayli, Nick	Medium	5/6/19	5/20/19	-18	Completed
Capstone Poster Design	Shayli	Medium	5/6/19	5/25/19	-13	Completed

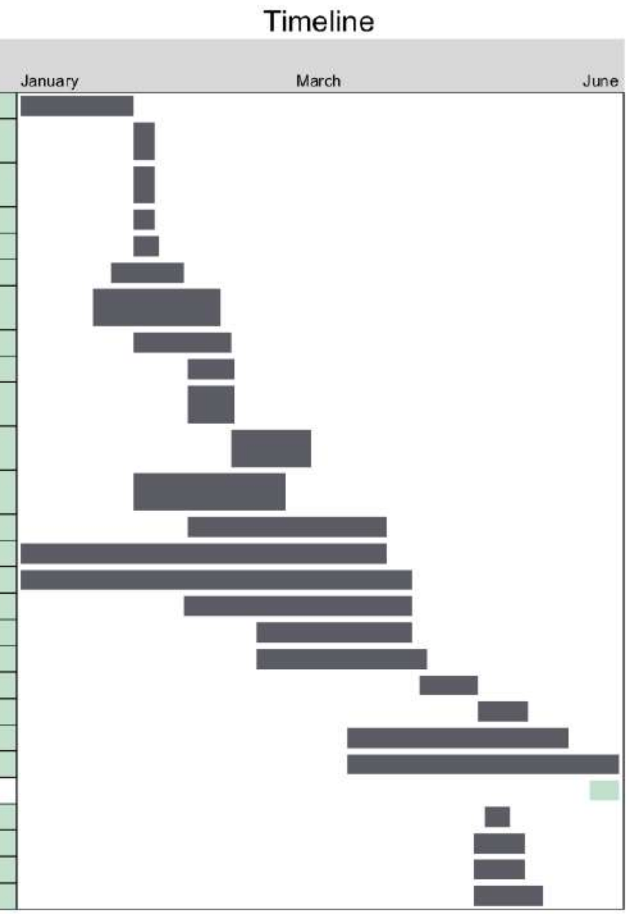


Table 7: Bill Of Materials

Item	Description	Vendor	Award Amount	1.5:1 Cost Share
Cost Share				
In-Kind AY effort	Dr. Mark Weislogel donating his time working as PI on Project	Portland State University		$6,556
Award Budget				
304 SS Steel	Raw material used to machine pump housing	McMaster-Carr	$800	
Tooling	Pump House machine tooling	Western Precision Products Inc	$1,400	
6061 Aluminum	Raw Material to create EFS Airframe Structure	McMaster-Carr	$200	
304 SS Steel	¼" x 24" TGP Precision Shaft	Metals Depot	$10	
Impeller	Rotational Impellers for propellants	Shapeways	$200	
ISO Plumbing	Various plumbing fittings for alcohol	Home Depot	$100	
LOX Plumbing	Various LOX compatible fittings	AcmeCryo	$300	
Aluminum Piping	½" Aluminum piping for plumbing	Metals Depot	$100	
Seals	Metal C-Ring Internal Pressure Face Seals	Parker	$30	
Liquid Oxygen	40 Gallons of LOX for testing	Airgas	$200	
Liquid Nitrogen	40 Gallons of LN for cryo testing	Airgas	$200	
Electric Motor	Brushless Motor for shaft drive	Hobbyking	$150	
Heat Sink	Heat Sink for Brushless motor	Amazon	$25	
Arduino	Arduino to Controlling pump	Amazon	$50	
Sensing Equipment	Pressure Transducers and flow meters for fluid monitoring	Omega	$500	
Total Direct Costs			$4,265	$6,556
Total Indirect Costs		48.50%	$2,069	$3,180
Total Project Costs			**$6,334**	**$9,736**

B Testing Procedures and Outcomes

Test 1: IPA Pump

Test one of the full IPA pump assembly was performed after all machined components were completed. Initial setup of the system proved difficult discovering there was not an accurate method for positioning the components along the shaft. Our design called for a clearance 0.008 inches between parts and there was no way of measuring the internal component positioning. The greatest risk associated with the unknown positioning was the impeller contacting the inside of the pump housing. To monitor this possibility, the inside of the pump housing was painted so disturbances could be observed after testing was completed.

To begin testing, we slowly turned the potentiometer on so that the motor would start at a lower speed. Immediately upon startup, rubbing and churning noises came from the system. With no obvious sign of what was making the noise, we cut the test immediately. After inspection of all external components and still no sign of interference, we tried them again. The same noises ensued, however, this time we decided to keep the system running a few moments longer to see if things would pick up and engage. During the second attempt, a loud pop came from the ESC and the system came to a halt. The ESC had. We suspected this was either from an overload in current or water entering the ESC housing.

The system was disassembled and inspected for the further prognosis of the unknown noise. Scratches were found in the paint on the inside of the pump housing which verified contact of the impeller. We did not believe this was the cause of the noise. Discussion among group members revealed the difficulty that existed in turning the impeller by hand. Questions arose around whether there were inaccuracies within the concentricity and alignment of the components. The noises were thought to have come from two or more internal components rubbing on each other. Other possibilities left open for investigation were the possibility of bearing wobble, sticking seals, and too much tension in the seals.

Further time would need to be invested into the cause of the short-circuited ESC and failed test. A replacement ESC was ordered and all internal components were evaluated after testing.

Test 2: IPA Pump

After the first test, we were able to diagnose some of the issues and made some modifications to the pump case. In order to release the tension that been put on the seal, the lower pump case was been re-machined. This time we increased the inside diameter of the lower casing. By doing that, we let the dynamic seal made contact directly with the lower face of the impeller. The result showed us that the tension on the seal was released. The reason we did that is to decrease the pressure that been put on the impeller and to make it spin freely with no contact with either of the faces. After the new ESC had arrived, we came up with the countermeasure for it. We used the hot glue and sealed the open areas in order to isolate the circuit board from the outside atmosphere to prevent the water been leaked in.

The second test was implemented after all of the problems have been fixed. The test procedure was strictly followed by the first test. After the power been turned on, there was no problem in the control circuit, as we turn up the speed of the motor, the noise started to get loud, after a few seconds, there was a electric spark appeared around the ESC. We immediately aborted the test, because we were afraid that the new ESC would be destroyed. The similar problem has appeared at the second test. We disassembled the entire system and tried to find the problem.

After the pump takes down from the test stand, we were found that the motor was still hard to turn with the impeller shaft. After the pump casing was separated, we found that there was a scratch on the inside of the upper casing, the cause of that was due to the impeller been contacted with the face of the case. When we separated the bearing case with the lower case, there was water leaked into the gap between those two faces. We were assuming that making the seal in contact with the impeller has made the seal lost efficacy. As the seal not only lost the function as a dynamic seal but obstructed impeller moving freely. Because there was such a big force was put on the motor, it was also increased the resistance on the circuit board which caused the power surge that fried the component of the circuit.

We were trying to see if the ESC was able to work again without everything being put on the motor. The result showed that the component that communicates with the motor was damaged, so the ESC was not working properly, and a replacement has to be ordered. As we examined every component been put on without the upper case, we also found that there was an alignment issue. As we tied up the coupler, the impeller shaft and motor shaft were not aligned, which would also cause the one side of the impeller been touched with the upper case. Based on all of the problems, the proper measures were been used to the new cryogenic pump design.

Test 3: Cryogenic Pump

Taking all the procedure practice from the IPA pump led to developing a cryogenic test protocol for the finished cryo pump. The goal of experimenting was to satisfy the most critical customer requirement which is to prove cryogenic compatibility. Furthermore it would help create data set to identify the pump cooling time necessary to operate at cryogenic conditions. To begin testing, the propellant tank needed added insulation to reduce boil off while containing the liquid nitrogen. This insulation also provided an extra safety measure against cold temperature contact burns from exposed metal. The test stand stand successfully provided propellent to the pump throughout the entire test duration without leaks and damage. The pump was cooled using a small flow of liquid nitrogen from the propellant tank. Temperature of the pump was estimated by visually inspecting the amount of liquid nitrogen exiting the outlet. Once vaporization was minimal, the liquid nitrogen flow was cut off and 40 PSI was added to the propellent tank using compressed air. This inlet pressure was equivalent to the necessary minimum inlet pressure for the pump design. After opening the propellent valve, the pump was turned on and began applying energy the moving fluid. Single phase flow from was observed leaving the exit, however no numerical data was gathered due to instrumentation failure caused by the low temperatures. During operation, the internal seal began leaking gaseous nitrogen during rotation meaning there was an internal pressure loss. The exit propellant flow showed signs of cavitation after a few seconds by intermittently ejecting large streams of the gaseous nitrogen. This is common behavior at the inlet of the pump when the propellent running low causing a very quick pressure loss along inlet resulting in the phase change. Once only gaseous nitrogen was expelled from the exit, the pump was shut off and inspected for damage and final condition. All components apart from the seal remained intact and without damage. The pump was left to warm up under ambient conditions as the entire system was cooled to extremely low temperature, including the power components.

C Design Processes

Cryogenic Tolerancing

The process outlined below was used to accurately oversize the critical dynamic components of the cryogenic electric feed system to account for thermal deformation.

Thermal expansion can be theoretically found as[1]:

$$\Delta L = L_m \alpha \Delta T$$

Here, ΔL is the dimensional change, L_m is the machined (initial) dimension, α is the coefficient of thermal expansion, and ΔT is the change in temperature. Note that $\Delta T = T_C - T_\infty$, where T_C is the cooled temperature and T_∞ is the ambient temperature of the room. Then the theoretical cooled length, L_C, can be calculated as:

$$L_C = L_m + \Delta L$$

Individual components were submerged in a container of LN_2 at $T_C \approx -196°C$. 12 distances were measured on the shaft, pump housing components, and bearing collar. Measurements were taken 3 to 5 times using micrometers or bore gauges, then averaged to increase accuracy. Each measurement was made initially at an ambient temperature of $T_m \approx 20°C$, then repeated after the component was submerged for two minutes in the cryogenic fluid.

The experiment showed an average reduction in component size of 0.226%. The measured reductions in size did not match the theoretical values calculated. However, they displayed a direct linear correlation to the theoretical results, which can be seen in the plot below. The relationship between room temperature, theoretical cooled, and measured cooled dimensions are shown in Table 5.

The trendline polynomial shown in the plot can be substituted into the above equations and used to solve for the target machined dimension to achieve optimal cryogenic performance geometry:

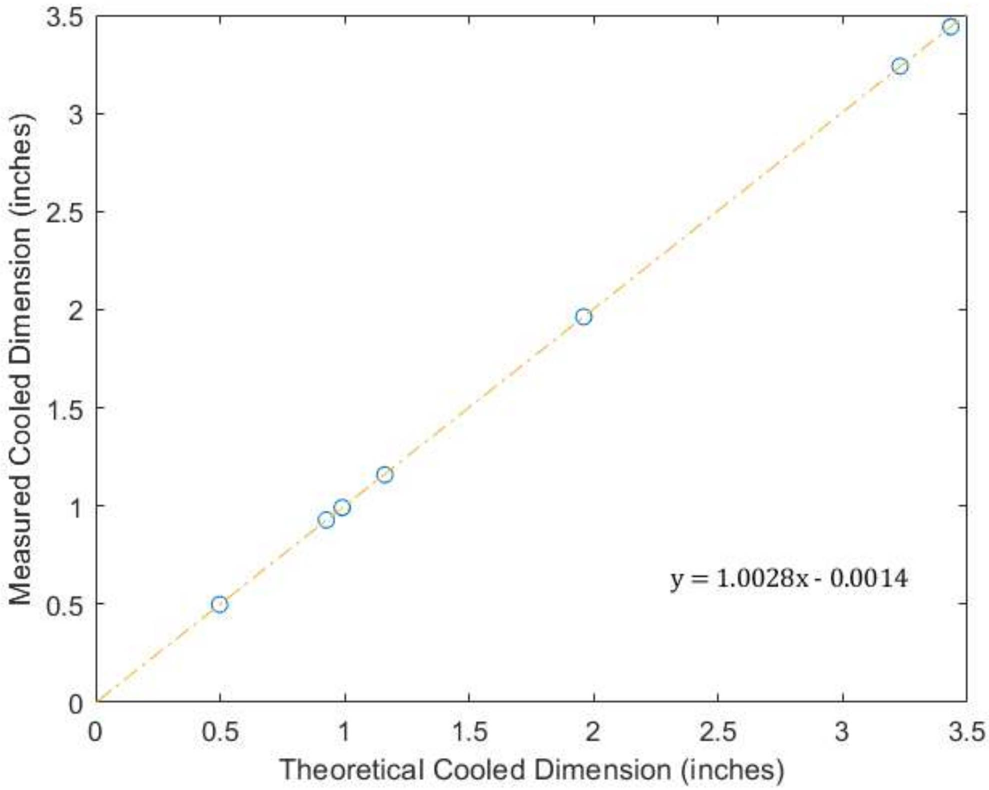


Figure 9: Measured Versus Theoretical Cooled Component Geometries

$$\begin{aligned} L_c &= L_o + \Delta L \\ \Delta L_{actual} &= m \cdot \Delta L_{theoretical} + b \\ &= (1.0028)(L_o \alpha \Delta T) + (-0.0014) \\ \Rightarrow L_c + (0.0014) &= L_o(1 + [(1.0028)(\alpha(T_c - T_\infty))]) \end{aligned}$$

$$\boxed{L_o = \frac{(L_c + 0.0014)}{(1 + [(1.0028)(\alpha(T_c - T_\infty))])}}$$

Pump Design

The following calculations were performed to determine the optimized impeller dimensions for the Electric Feed System pumps. The process for liquid oxygen is shown.

Given:

$$m_{mix} = 1.8 \qquad \Delta P = 343\ psi$$
$$f = 2200\ N \qquad U_{ss} = 7000$$
$$I_{sp} = 242.4\ s \qquad \eta = 60\%$$
$$P_i = 40\ psi \qquad L = 0.3$$
$$P_L = 53\ psi$$

Find:

Impeller dimensions and motor requirements for liquid oxygen pump.

Solution:

A mixture ratio of $m_{mix} = 1.8$ was provided by the customer. This value is the ratio of liquid oxygen to isopropyl alcohol. Additionally, a thrust of $f = 2200\ N$ and specific impulse of $I_{sp} = 242.4\ s$ were provided. The mass flow rates are then found as:

$$\begin{aligned}
\dot{m}_{tot} &= \frac{f}{g \cdot I_{sp}} \\
&= \frac{2200\ N}{(9.81/m/s)(242.4\ s)} \\
&= 0.93\ kg/s
\end{aligned}$$

$$\begin{aligned}
\dot{m}_{LOX} &= \frac{\dot{m}_{tot}}{1 + (1/m_{mix})} \\
&= \frac{0.93\ kg/s}{1 = 1/1.8} \\
&= 0.59\ kg/s \\
&= 1.31\ lbm/s
\end{aligned}$$

The required head rise, H_p, inlet head, H_i, and vapor pressure head, H_v, are found as [1]:

$$
\begin{aligned}
H_p &= 144 \times \frac{\Delta P}{\rho_{LOX}} \\
&= (144)\frac{343\ psi}{71.230\ lb/ft^3} \\
&= 693.41\ ft
\end{aligned}
$$

$$
\begin{aligned}
H_i &= \frac{P_i}{(\frac{\rho_{LOX}}{\rho_{H_2O}}) \cdot 0.433} \cdot \frac{1}{2} \\
&= \frac{40\ psi}{(\frac{71.230\ lb/ft^3}{62.428\ lb/ft^3}) \cdot 0.433} \cdot \frac{1}{2} \\
&= 40.48\ ft
\end{aligned}
$$

$$
\begin{aligned}
H_v &= \frac{(0.000145038)(144)P_{v,LOX}}{\rho_{LOX}} \\
&= \frac{(0.000145038)(144)(2.346\ psi)}{71.230\ lb/ft^3} \\
&= 2.35\ ft
\end{aligned}
$$

The impeller tip speed, u_t, is found by [1]:

$$
\begin{aligned}
&= \sqrt{2gH_p} \\
&= \sqrt{(2)(32.2\ ft^2/s)(693.41)} \\
&= 211.32\ ft/s
\end{aligned}
$$

The available NPSH and rotational NPSH for the pump are found as [1]:

$$
\begin{aligned}
NPSH_a &= H_i - H_v \\
&= (40.48 - 2.35)\ ft = 38.14\ ft \\
NPSH_r &= \frac{NPSH_a}{\tau} \\
&= \frac{38.14\ ft}{2}
\end{aligned}
$$

Here, τ is the Thoma Parameter. The rotational speed and pump specific speed are [1]:

$$\begin{aligned} n &= \frac{U_{ss} NPSH_r^{0.75}}{21.2\sqrt{Q}} \\ &= \frac{(7000)(19.07)^{0.75}}{(21.2)\sqrt{\frac{1.31\ lbm/s}{71.230\ lb/ft^3}}} \\ &= 22206.87\ rpm \end{aligned}$$

$$\begin{aligned} n_s &= \frac{(21.2)n\sqrt{Q}}{H_p^{0.75}} \\ &= \frac{(21.2)(22206.87\ rpm)\sqrt{\frac{1.31\ lbm/s}{71.230\ lb/ft^3}}}{(693.41\ ft)^{0.75}} \\ &= 4513.91\ rpm \end{aligned}$$

Now the impeller and motor values can be found. The impeller diameter, D_o, eye diameter, D_i, and impeller housing diameter, D_p, are [1]:

$$\begin{aligned} D_o &= (12)\frac{u_t}{2n_s} \\ &\boxed{= 2.682\ in} \end{aligned}$$

$$\begin{aligned} D_i &= (12)\left(\frac{4Q}{\pi\phi n_{rad}(1-L^2)}\right)^{1/3} \\ &\boxed{= 0.267\ in} \end{aligned}$$

$$\begin{aligned} D_p &= (1.152)D_o \\ &\boxed{= 3.091\ in} \end{aligned}$$

Where ϕ is the inducer inlet flow coefficient. Because an inducer is not being used, $\phi = 1$. Note that the rotational speed used to calculate D_i is in radians. The power and torque requirements of the motor can now be identified [1]:

$$
\begin{aligned}
P &= \frac{\dot{m}H_p}{(0.738)\eta} \cdot \frac{1}{1000} \\
&= \frac{(1.31\ lbm/s)(693.41\ ft)}{(0.738)(0.60)} \cdot \frac{1}{1000} \\
&\boxed{= 2.053\ kW}
\end{aligned}
$$

$$
\begin{aligned}
T &= \frac{(9.5488)P}{n} \cdot 1000 \\
&= \frac{(9.5488)(2.053\ W}{2220687rpm} \cdot 1000 \\
&\boxed{0.88\ N \cdot m}
\end{aligned}
$$

D Additional Figures

(a) Flowserve Type 15 PacSeal for IPA Pump

(b) In-House Designed PTFE Contact Seal for LOX Pump

(c) Timken Axial Thrust Roller Bearing

E References

[1] I. Karassik, 2007,“Pump Handbook” ($4^{th} Ed$)

[2] E. Oberg, 2012,“Machinery’s Handbook” ($29^{th} Ed$)

[3] E. Logan, R. Roy, 2003,“Handbook of Turbomachinery” ($2^{nd} Ed$)

[4] K. Huzel, D. Huan, 1971, “Design of Liquid Propellent Rocket Engines” ($2^{nd} Ed$)