PUmped Liquid System for Amateur Rockets

Project PikaPump

Final Design Review

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Executive Summary

This report is a summary of the work completed by PULSAR to create project PikaPump. PikaPump is an electric fuel pump created for amateur rocketry. To create an efficient, safe, and cost-effective pump, the team began with analyzing existing commercial fuel pumps to understand their working principle and the design of each component. Having completed the market analysis and project overview the team began to integrate design components. The team used different softwares to model designs before moving into the final phase which includes testing and validation.

Having completed the initial modeling of the design within CAD, CFD and CFTurbo the team went onto manufacturing. The team reached out to multiple companies and specialists to communicate the project requirements and receive the best fit recommendations. The manufacturing process began for the housing, the magnetic coupler and the drive shaft assembly. Each component was further analyzed on the best way to create sealed intersections to avoid pressure loss. The team also built the test stand that would hold the water tank, motor, and pump as well as create protective housing for the electronics during the test.

The next step was iterative designing. After initial manufacturing, the team iteratively tested component alignment, and interaction with the housing. As more components were added the team ensured that there was the appropriate clearance between each part of the assembly and an effective locking system to ensure proper rotation. Additional integration of pressure and flow rate sensors allowed the team to collect data regarding the pump performance and pressure ranges when compared to the expected pump curves.

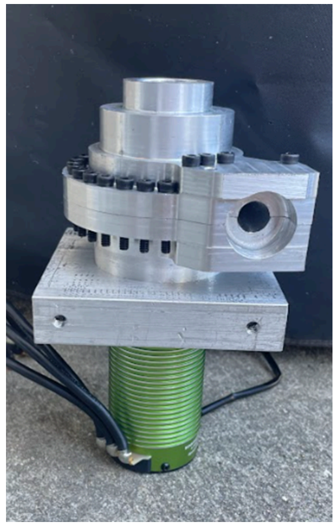


Figure 1: Final Pump System

Once the physical and electrical assembly were working, the team went on to integrate both components and begin the testing phase. The team assembled the drive shaft, tested the pump for water leaks and then went on to attach the pump to the water tank and the motor as well as the respective sensors and the e-stop. The team ran iterative tests, disassembling and reassembling the assembly as interferences were cleared and clearances adjusted. The data collected from the tests were then extrapolated to visualize where they interacted with the expected pump curves. These tests provided proof of concept while also verifying the reliability of the CFD analysis. When the expected pressure and flow rates at lower rpms were reflected by the test, this provides evidence for reasonable claim that under better operating conditions and perfected clearances the designed pump would work as expected at higher rpms.

In conclusion, the development done by PULSAR exemplifies a comprehensive approach to designing and testing a fuel pump for amateur rocketry. Through meticulous analysis, integration of design components, and utilization of advanced software, the team successfully achieved the project's objectives of enhancing efficiency, safety, and cost-effectiveness. The selection of the magnetic coupler design and the implementation of electronic systems further underscore the project's commitment to innovation. Ultimately, PULSAR represents a significant advancement in the field of amateur rocketry, offering a reliable solution for fuel pumping systems.

Main Body

Since humanity landed a man on the moon in 1969 we have been obsessed with launching people, and things, into space. Purdue is a perfect example of that, having the nickname "The Cradle of Astronauts" and housing the Purdue Space Program (PSP), one of the largest student rocketry teams in the United States. One of the most difficult aspects to design of those rockets is how they are propelled into space. It has been found recently by companies like Rocket Lab that electric pump-fed systems are very efficient at moving rocket fuel from the tank into the combustion chamber. These electric pump feed systems provide many benefits over traditional rocket fuel systems like less chance of failure, higher efficiency, and easier manufacturing. Despite these revolutionary new findings, very little progress has been made towards creating a similar system for amateur rockets.

PUmped Liquid System for Amateur Rockets (PULSAR) aims to bridge this gap between commercial rocketry and amateur rocketry spaces. Some of the members of the team were formerly on the PSP team and have experience developing amateur rockets. After seeing the potential that electric pump feed systems have in the amateur space, the team was disappointed to find that there have been very few attempts to create this fuel feed system for an amateur rocket. With this, the team saw an opportunity to create a large amount of value for amateur rocketry by using their expertise. The team decided on the goal of furthering the knowledge of liquid amateur rocketry by designing, analyzing, and then creating an electric pump feed system for rocket fuel on an amateur scale.

PULSAR's preliminary design phase saw the team create an initial project scope, analyze the market for existing products (Appendix E), create customer requirements based on the market (Appendix G), create concepts for those requirements, and finally select a final design idea for the critical design phase. The team was satisfied with where the project was headed after the preliminary design review. The structure of team management had worked well and those areas of the projects remained largely unchanged (Appendix 1). Figure 2 shows the initial concept sketch that the team planned to refine moving into the critical design phase. There were some additional considerations into what the team would deliver for the unique value proposition (Appendix F) along with some deliberation into which specific aspects of the project to focus the design more heavily on. The team did think the initial prototyping ideas were still valuable so the design began there while the overall project was being analyzed with an FMEA.

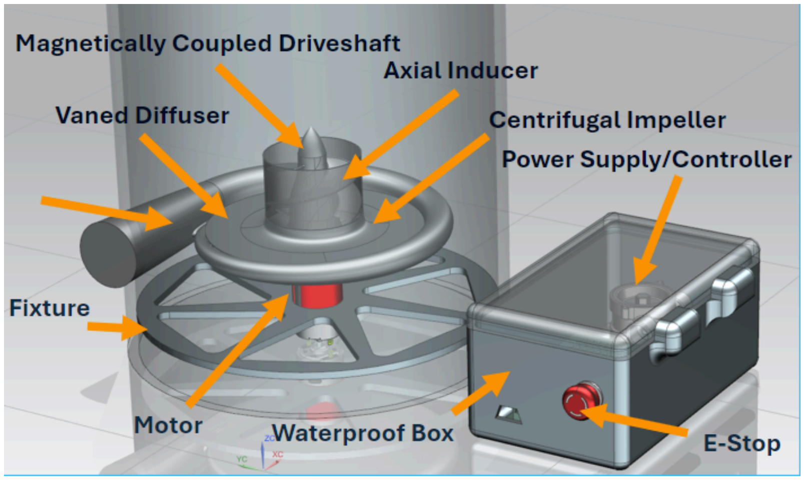
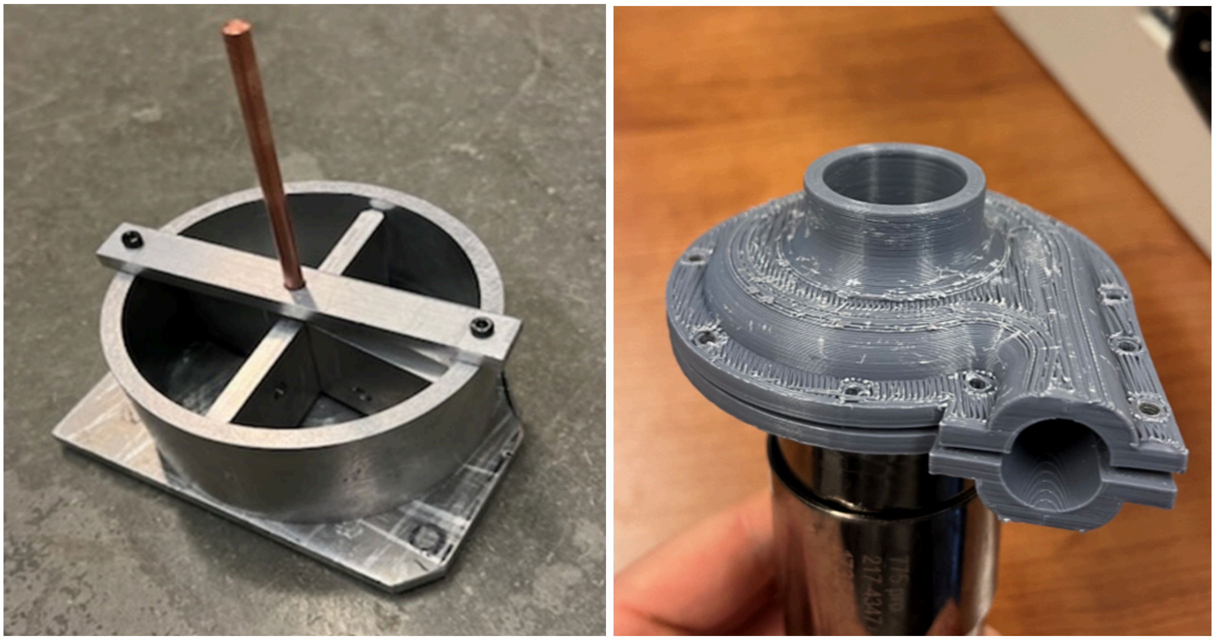


Figure 2: Concept sketch at the end of PDR

PULSAR's critical design phase began with the creation of a FMEA (Appendix J) to identify the greatest potential failure points of the pump, which were determined to be the pump impeller and materials and clearances of the housing. Following this, centrifugal pump design textbooks were referenced in order to calculate a design for the impeller that would reach the desired parameters of a 200 psi pressure increase and 1.19 lbm/s mass flow rate. These calculated design values were then provided to CFTurbo, which assisted in creating a preliminary model of the internal pump components. The remaining design values were left unchanged for simplicity and time constraints. A material analysis was also performed to decide a suitable material for the operating conditions. After the analysis it was decided that aluminum and stainless steel would be the best materials for the final product as they would provide both machinability and resistance to cryogenic corrosion.

After the initial design calculations the team decided to create two different prototypes in order to attain a better understanding of the final product. The two prototypes were a 3D printed impeller with very similar geometry to the actual final impeller that will be used and a roughly machined simple impeller to test material tolerances and rotation. Photos of the prototypes can be seen in figures 3 and 4.

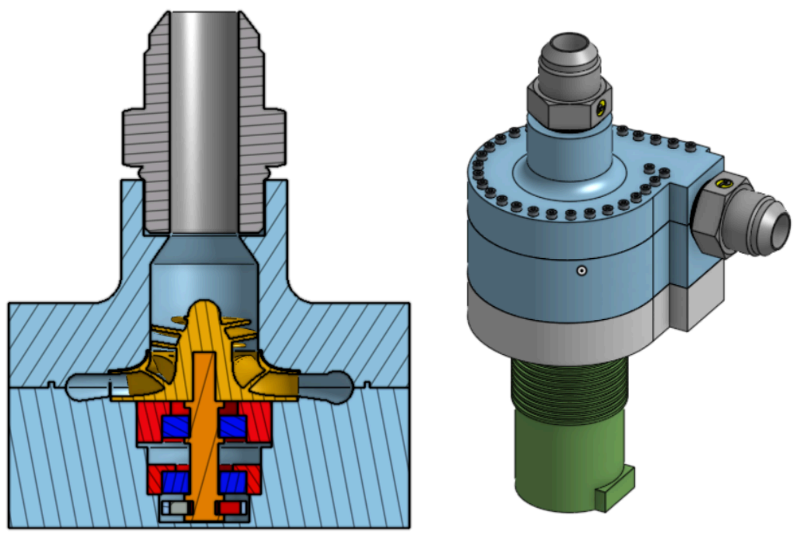


Figures 3 and 4: Material tolerancing prototype (left) and accurate impeller prototype (right)

These prototypes both performed as expected, providing valuable design insights for the team. The 3D printed impeller gave the team a better understanding of how the final project will look as well as provided info about 3D printing clearances and sealing on the housing. The machined fin served to verify material tolerance calculations and to confirm that the materials chosen would be able to rotate effectively under very cold temperatures.

While the initial prototypes were being created and analyzed some members of the team were also working on performing CAE analysis on the project. More specifically, CFD simulations of the pump using both cryogenic fuel and water were performed (Appendix I). These provided an insight into how the impeller would function in both the real and testing operating conditions. Using these simulations, a rough validation plan was created that would be refined more in FDR. The rough test plan involved creating a test stand to hold the pump while water would be pumped through. This would provide both quantitative and qualitative results to be analyzed.

After the initial prototypes, the team decided on final designs for many other components of the system. The team selected a motor with the necessary power and RPMs, a sealing method that would function under cryogenic conditions, a sufficient amount of fasteners, and a suitable shaft size. The team also designed a custom magnetic coupler to transfer rotation without the need for a costly dynamic seal. The final designs from CDR can be seen in figures 5 & 6. From all of these selections, a bill of materials and budget were created (Appendices C & K). Both of these were updated as the team moved into the final design phase and those changes are detailed in the appendices.



Figures 5 and 6: Section view of the pump and with the impeller and axial inducer highlighted in yellow, bearings in blue, bearing blocks in red, shaft in orange, fitting and magnets in gray, and housings in blue(left) and final CDR CAD design (right).

PULSAR went into a critical design phase with a final concept selected and a general idea of where to go with the analysis. The team performed a FMEA to further direct what functions the analysis should cover. Preliminary analysis of the pump and materials was performed. Upon completion of the initial analysis, simulations and prototypes were created to verify the results of those analyses. With the additional information from the prototypes and simulations the team finished the design of the rest of the necessary concepts and now has a final design for the PikaPump. The final CAD is shown in figure 7 below. Using that final test plan, PULSAR created a validation plan to confirm the function of the pump upon manufacturing. At that point, the team had attained all the knowledge necessary to move forward from critical design and into the manufacturing and test phase.

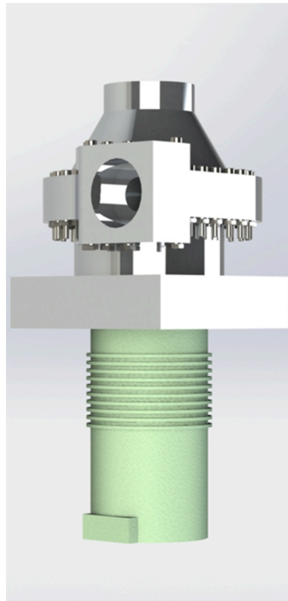


Figure 7: Side view of final CAD model.

To start the manufacturing and test phase, the team began with the primary internal pump components, the impeller and inducer. These parts needed to be made to a tight tolerance to ensure adequate operation of the pump. For these reasons, it was decided to outsource the manufacture of these parts to an external metal 3D print supplier, Craftcloud, which created the parts out of 316 stainless steel using the team's provided CAD models. Some minor design changes were made in order to comply with Craftcloud's printing requirements, namely the thickening and squaring of the impeller blade tips. A subsequent analysis showed this had a minimal impact on overall performance. After receiving the parts, a final sanding was performed to ensure smoothness for both tolerancing and ideal water flow throughout the system. The final parts are shown in figure 8 below.

Figure 8: Metal 3D printed inducer (top) and impeller (bottom).

All additional major pump components were created in-house by the team. The top and bottom pieces of the pump casing were cut from a block of 6061 aluminum using the MB-15 CNC mill in the ME Machine Shop. In order to create the complex geometry of the pump casing, a combination of flat endmills, ball endmills, and drills were used. A 1/16” endmill was also purchased specially for these parts. After CNC, a manual mill was used to thread the inlet and outlet and a dremel was used to deburr the inner geometry.

Figure 9: Bottom casing as machined by the CNC mill

The magnetic coupler is composed of two identical circular 6061 aluminum casings created using the lathe in the ME machine shop. These cases were made with walls as thin as feasible (.040”) to ensure close magnetic contact with each other. Five neodymium magnets were housed in each, held in place with an internal structure created using PLA 3D printing. One of the couplers is press-fit to the motor shaft through the 3D printed magnet holder to secure it, while the other coupler has a single-point-threaded lid that serves as an adaptor between the coupler and the pump drive shaft.

Figure 10: Upper magnetic coupler with the single-point-threaded lid attached.

The pump drive shaft was also created from 6061 aluminum. Left handed threads were added to one end of the shaft to allow it to be screwed directly to the coupler. This was done to prevent unscrewing during the operation of the pump. The drive shaft also contains an integral ring that secures its placement against the bearings it rides on. At the top of the driveshaft, it is slotted for a keyway and threaded so that the impeller and inducer can be fastened to it. Two cryogenic-rated Alpine bearings initially secured the shaft in place, but these were later replaced with traditional McMaster-Carr bearings for final testing. The cryogenic bearings will perform great for conditions of -190 degrees Celsius at 30000 RPM, but they have too much friction when used with water at room temperature and lower RPMs.

Figure 11: Pump driveshaft. The upper magnetic coupler attaches to the right side and the impeller attaches on the left.

Originally intended to be manufactured on the CNC mill, the coupling block was fabricated using a combination of the lathe with a four-jaw chuck and a manual mill. This block is the center of the design, for it is what the motor, pump housings, and test stand are all bolted to. The coupling block also holds the lower magnetic coupler inside of it.

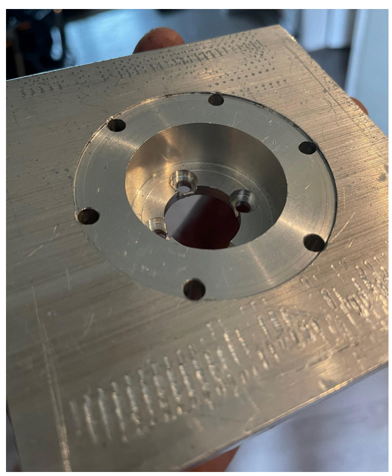


Figure 12: Coupling block with four holes to mount the motor on the inside and six holes to mount the pump casings on the outside. Lateral holes on the side of the block are used to attach it to the test stand.

With many moving components assembled together in a complex manner, design iteration was inevitable. The first and most obvious iterations made were those to do with assembly. The driveshaft and bearing assembly was found to be impossible to assemble, prompting the team to split the driveshaft into two parts that screw together. Another problem was that there was interference with the motor and the tooling required to fasten certain bolts in, so the team chose to use smaller bolts and move them farther away from the motor to provide enough clearance. Later on in testing, problems more inherent to motion were discovered, such as the impeller binding with the housing or the magnetic coupler skipping over itself. Below in Table 1 is a comprehensive list of all iterations complete with the problem encountered and the solution created by the team.

Table 1: Design Iteration Summary

Problem	Solution
Bolt assembly interferes with the motor	Shrink bolt size and adjust placement
Driveshaft cannot be assembled through bearings	Split the driveshaft into two parts that screw together around the bearings
Magnets inside coupler are not strong enough; stacking magnets doesn't increase strength	Purchase larger single-piece magnets
Magnetic coupler must be larger to accommodate new magnets	Bore out more material from the bottom casing and make larger bearing blocks
Magnets are pulled out of the bottom coupler and stick to the motor during assembly	Add a backing plate to the lower coupler
Impeller and inducer bind with the casing and will not spin with the motor	Grind down roughness from the 3D printed impeller and adjust clearances in the pump casing.
Bearing blocks cannot be removed after being press fit into the bottom casing	Mill out old blocks and create new ones with a transition fit for testing purposes
Cryogenic bearings do not spin well at room temperature and low RPMs	Use cheaper, similarly sized bearings for testing
Pipe threads in outlet cause casings to be pushed apart when tightened	Design flaw: use straight threads and a purchased bushing
Magnetic coupler skips and loses torque transmission at higher RPMs	Design flaw: need smoother finish on coupler faces, closer contact, and stronger magnets
Motor drive shaft strips its contact with the 3D printed magnet holder	Design flaw: need a stronger material to support motor loading.

After all components for the pump were manufactured, work began on creating a test system. The test system was divided into two major sections. These comprised the physical pump support and water delivery structure, and the electronics and software system for control and data collection. The main support structure was built around a square wooden frame, with a water storage tank secured to the top and a welded steel H-bracket supporting the pump. Pipes connected the tank to the pump inflow and directed the pump outflow away from the structure. Two ball valves allowed for the regulation of water flow at both points. Control and data collection was primarily driven by an Arduino UNO linked to a laptop, which provided for direct control of the pump motor speed, as well as measurement of water pressure at the pump outflow via a pressure transducer. A flow meter was also utilized to measure the water flow rate at the pump outflow. An E-stop button was connected to the system to allow for a complete shutdown in the event of an emergency, with extension wires to allow it to be operated from a safe distance.

Following final assembly of the test system, the setup was moved outside to conduct the tests. All physical and electronic components connections were checked to ensure they were adequate. To start, the electronics system was powered off and both the inflow and outflow ball valves were placed in the closed position. Initially, the Arduino and electronics system were powered on to verify correct operation of the pressure transducer and flow meter without any water present. The E-stop was also tested to ensure it would cut all power to the system if need be. Following this, approximately 5 gallons of water were added to the water storage tank at the top of the system. The inflow ball valve was then opened, followed shortly after by the outflow ball valve, allowing a small but steady stream of water to flow through the entire system. At this point, the team cleared the immediate area and retreated to a safe distance away from the setup.

In order to have analytical data to compare the test setup to, additional CFD simulations were run at various different RPM values to create new pump curves. The team also created performance curves based on the test system attached to the pump. Where these two curves intersect will be the operating point of the pump. This gave the team an idea of how the pump should function when running.

The motor was then activated, initially at 10% of its rated power, but this was found to be inadequate for testing due to it not being sufficient to break the stall torque. Subsequent successful tests began at 15% power, at which point the water outflow was noticeably impacted by the operation of the pump. At this operating point the motor was spinning at ~5000 RPMs, generating a flow rate of 0.17 lbm/s, and a pressure rise of 10 psi. Tests continued, increasing the power in increments of 5% up to a maximum of 20% power. This yielded an RPM value of

7000 and led to a measured pressure increase of 15 psi with a flow rate. These operating points matched with the values expected from the simulations so the team was satisfied with the performance (Appendix L).

Upon trying to increase the power to the system the team found that the impeller was unable to function properly due to the skipping of the magnetic coupler. Unfortunately, as designed, the magnetic coupler was not strong enough to support any more powerful operating points. The team was disappointed the pump could not reach higher RPM values. However, there were still many valuable takeaways from the validation tests. The team found that nearly all the project requirements created during the preliminary design phase were met. The only requirements not met were related to the flow rate and pressure rise, but the team believes the design would hit these requirements during a cryogenic liquid test. The simulations were proven accurate by the validation tests and the simulations showed the design would work so the team deemed this satisfactory.

The iteration and the lessons learned from it are arguably the most important part of the project. After all, the goal is to provide instructions and blueprints to others looking to create a similar design. While the pump does not fully function as the team intended and no cryogenic testing was actually done, the team has learned plenty about magnetic coupling, sealing, and cryogenic design such that a far better pump could be made if the team had more time to do it. The following is a list of every design change that would be beneficial to a redesigned pump. Making these changes would drastically improve pump performance and durability.

List 1: Pump Design Changes

- **Switch to an even number of magnets in the coupler.** As of now, only one orientation is “correct”, making it easy for the magnets to skip.
- **Polish the magnetic coupler faces and all surfaces in between.** This will allow the faces to be closer together and generate less friction in the event of contact.
- **Use stronger magnets.** The team tried to purchase stronger magnets, but they still need to be stronger to achieve the 30000 RPMs that the rest of the system is designed to operate at.

- **Secure the lower coupler to the motor shaft using a set screw or bolted connection.** The 3D printed interface stripped twice, necessitating a stronger material choice.
- **Make all driveshaft components left-threaded.** Left-threading was an afterthought, therefore only one of three driveshaft connections was left-threaded, causing problems for assembly and defeating the purpose of left-threading in the first place.
- **Post-process the impeller and inducer to smooth the rough 3D printed finish.** Roughness on the bottom of the 3D print caused problems with binding several times.
- **Use straight threads at the pump outlet or use the single-piece housing design.** Due to the nature of pipe threads being tapered, trying to tighten a pipe thread into a hole split across two casings will pry the casings apart, creating an unsealable joint.
- **Increase clearance where allowable in the drivetrain and machine to tighter tolerances for critical parts.** Many clearances in the design were tight simply because of the team's original stock size choice. A new design would ensure these clearances cause no problems and provide a more stable driveshaft with less play.
- **Secure the bearing blocks to the lower housing using set screws rather than press fit or transition fit.** A press fit is impossible to iterate with, but a solid base for the bearings is required for stability.
- **Use an ADC with more bits and acquire more reliable sensors.** While not a part of the pump design itself, these changes would allow much more accurate and credible data measurement.

After deciding upon design improvements, the team moved forward with creating an open source repository for all the team's work. The value proposition goal for this project was to create a guide on creating an electric rocket pump for any rocketry team attempting to do so (Appendix G). The team has created a Github and uploaded all relevant files. PULSAR hopes that these reports and materials can provide valuable information about what work the team did for this project. The team has provided a guide for how to navigate this resource as well as the contact information for all team members so any future user will be able to contact the team for assistance.

PULSAR set out to bridge the gap between commercial and amateur rocketry by developing an electric pump feed system tailored for amateur rockets. The project progressed through thorough preliminary and critical design phases, including market analysis, concept development, and prototyping. Despite experiencing challenges during testing, especially with magnetic coupling and system power, these hurdles provided valuable insights for future improvements. Ultimately, the team established an open-source repository aimed at guiding other rocketry teams in building similar electric pump systems, demonstrating a commitment to advancing technology in amateur rocketry. This initiative reflects its dedication to sharing knowledge and fostering innovation within the amateur rocketry community, driving progress in rocket propulsion technology.

Appendix 1 - Project Management

A. Charter

One of the first documents created was the team charter. Here, the vision statement is outlined, along with a problem definition, scope of work, assumptions and risks, key milestones, stakeholders, public benefit, resources required, and member roles (listed below in Table 2). This document guides the direction that the team will follow throughout the semester and serves as a reference that can be used to keep the design on track. The full team charter can be found attached to this report as an excel file, but the key takeaway can be summarized with the team's vision statement: "*To further the research and development of liquid feed systems primarily for the amateur rocketry space*". The Charter has remained unchanged throughout the second and third phase of this project. The team deemed the original goal attainable and achieved the plans set out at the start of the project by this document.

Table 2: Team Members and Primary Project Roles

James Beeman	Manufacturing Manager
Lamya Bhat	Power Systems Lead
John Clark	Purchasing Manager and CFD Lead
Max Cohen	Project Manager and CAD Lead
Fred Gouronc	Chief Engineer
Tom Neidlein	Testing Procedures Lead

B. Schedule

The schedule that was created previously with Microsoft Project continued to be utilized to guide the team toward accomplishing the set out goals. A few minor changes were made to the overall plan to account for deadline changes, as well as an adjustment to the safety review timeline. At this point, all phases of the project have been completed, save for the Malott demonstration and final peer review. These are expected to be finished on April 25th and April 26th, respectively. Excerpts of both the CDR and modified FDR phases are shown in Table 3 and

Table 4. below, with a new copy of the full updated schedule available in the attached Microsoft Project file.

Table 3: CDR Phase of Project Schedule

Critical Design Review (CDR)	25 days	Fri 2/9/24	Fri 3/8/24
Pump Initial Design Calculations	3 days	Fri 2/9/24	Mon 2/12/24
Motor Initial Design	3 days	Fri 2/9/24	Mon 2/12/24
Initial Material Analysis	3 days	Fri 2/9/24	Mon 2/12/24
Simulation Setup	3 days	Tue 2/13/24	Thu 2/15/24
CAD Design of Casing	3 days	Tue 2/13/24	Thu 2/15/24
CFD Simulations of Pump Impeller	4 days	Fri 2/16/24	Tue 2/20/24
Final CAD Models	4 days	Fri 2/16/24	Tue 2/20/24
Finalize CFD Simulations	4 days	Wed 2/21/24	Sun 2/25/24
DFM Analysis	3 days	Wed 2/21/24	Fri 2/23/24
Create Test Plan	3 days	Tue 2/27/24	Thu 2/29/24
Preliminary Mfg. Drawings	4 days	Mon 3/4/24	Thu 3/7/24
BOM and Budget	5 days	Sat 2/24/24	Thu 2/29/24
Prototype Creation	4 days	Fri 2/16/24	Tue 2/20/24
Create Written CDR Report	4 days	Fri 3/1/24	Tue 3/5/24
Create Oral CDR Report	4 days	Fri 3/1/24	Tue 3/5/24
Create Safety Report #2	3 days	Fri 3/1/24	Mon 3/4/24
Finalize Mfg. Drawings	2 days	Fri 3/8/24	Sun 3/10/24
Preliminary Prototype	0 days	Tue 2/20/24	Tue 2/20/24
Safety Review #2	0 days	Mon 3/4/24	Mon 3/4/24
Oral CDR	0 days	Tue 3/5/24	Tue 3/5/24
Written CDR	0 days	Tue 3/5/24	Tue 3/5/24
Mfg. Drawings & Operation Sheets	0 days	Sun 3/10/24	Sun 3/10/24
Peer Evaluation #1	0 days	Tue 3/5/24	Tue 3/5/24

Table 4: FDR Phase of Project Schedule

Final Design Review (FDR)	43 days?	Fri 3/8/24	Fri 4/26/24
Review Final Design	3 days	Fri 3/8/24	Mon 3/11/24
Purchase Materials	10 days	Fri 3/8/24	Tue 3/19/24
Manufacturing of Housing	7 days	Tue 3/12/24	Thu 3/21/24
Manufacture of Internal Parts	5 days	Wed 3/20/24	Mon 3/25/24
Electronics Assembly	5 days	Wed 3/20/24	Mon 3/25/24
Assemble Motor With Housing	4 days	Mon 3/18/24	Thu 3/21/24
Seal Housing Around Pump	1 day	Sat 3/23/24	Sun 3/24/24
Electronics Testing	3 days	Fri 3/29/24	Mon 4/1/24
Finalize Prototype	2 days	Sat 4/6/24	Mon 4/8/24
Initial Final Protoype Demo	0 days	Thu 4/4/24	Thu 4/4/24
Refine Pump Prototype	5 days	Sat 4/6/24	Thu 4/11/24
Refine Electronics System	5 days	Fri 4/12/24	Wed 4/17/24
Create Mallot Project Description	1 day	Sat 4/6/24	Sun 4/7/24
Create Mallot Poster	3 days	Wed 4/10/24	Fri 4/12/24
Create Written Report	5 days	Thu 4/18/24	Tue 4/23/24
Create Oral Report	5 days	Thu 4/18/24	Tue 4/23/24
Mallot Project Description	2 days	Tue 4/9/24	Thu 4/11/24
Mallot Poster	2 days	Wed 4/17/24	Fri 4/19/24
Safety Analysis on Final Design	5 days	Fri 4/12/24	Wed 4/17/24
Write Final Safety Report	5 days	Thu 4/18/24	Tue 4/23/24
Saftey Review #3	0 days	Wed 4/17/24	Wed 4/17/24
Initial Water Testing	2 days	Wed 4/17/24	Thu 4/18/24
Final Prototype Demonstration	0 days	Thu 4/18/24	Mon 6/10/24
Final Water Testing	2 days	Fri 4/26/24	Sun 4/28/24
Oral FDR	0 days	Tue 4/23/24	Tue 4/23/24
Written FDR	0 days	Tue 4/23/24	Tue 4/23/24
Peer Evaluation #2	0 days	Thu 4/25/24	Thu 4/25/24

C. Final Budget

Using the final bill of materials (BOM) a final budget was created for the project. It can be seen that the majority of the budget went to the motor, the pump impeller, and the power supply. Table 5 shows a detailed breakdown of all individual components to be purchased. The biggest additions Were the battery charger, connectors for wires and pipe flow, and the flow meter. All costs were updated to reflect their actual amounts after the orders were completed.

Table 5: Final budget for the PikaPump project.

COMPLETED ORDERS					
Item Description	**How will the item be used for the project?**	**Vendor**	**Item Cost**	**Shipping Cost**	**Purchase date**
Motor	Motor used to drive pump impeller and inducer	Castle Creations	$ 389.95	$ 12.30	9-Mar-2024
Stock Aluminum	It will be machined for the housing of the pump	Metals Depot	$ 68.43	$ 16.52	9-Mar-2024
Cheap bearings	inital testing of pump system	Amazon	$ 22.40	$ -	9-Mar-2024
Ball Valves	Used in test setup (2)	Amazon	$ 20.00	$ -	9-Mar-2024
Battery	Power the motor	Rotor Riot	$ 44.00	$ 14.00	9-Mar-2024
Ceramic Roller Bearings	Stabilize rotating componenets in pump	Alpine Bearing	$ 180.00	$ 15.00	9-Mar-2024
Pump Impeller	It will be metal 3d printed as the pump impeller	CraftCloud	$ 36.38	$ 19.50	26-Mar-2024
Battery Charger	Charge the 8s lipo battery	amazon	$ 59.90	$ -	26-Mar-2024
Bullet Conncetors	Connector the motor to the battery	Amazon	$ 46.42	$ -	29-Mar-2024
T reducing connectors	Connect the pressure sensors to the inlet and outlet pipe	Mcmaster	$ 9.95	$ 2.29	29-Mar-2024
Flow Meter	measure the outlet flow of the pump	Amazon	$ 41.68	$ -	1-Apr-2024
		TOTAL	**$ 919.11**	**$ 79.61**	**$ 998.72**

The budget ended up coming in under the $1,000 mark so the team was satisfied. Some objects had to be added later as the team could not foresee at the point of the critical design review. The overall budget still came in under the allotted budget.

D. Risk Register

In order to analyze and plan ahead for the risks on the project, a risk register was created. This document records the source of the risk, the cause, effect, and risk score for many sources of risk on the project. Table 6 shows the risk registers identification section. Twelve sources of risk were identified for the preliminary analysis and three more sources were added during the manufacturing and testing phase. The most urgent risk is the ability of the motor to operate effectively, the pump cavitation, and the test causing harm to a member of the team. The risks discovered after CDR relate to the magnetic coupler, which was found to lose function at higher speeds.

Table 6: Identification section of the PikaPump risk register.

	1. IDENTIFICATION					2. CURRENT ASSESSMENT			
I D	RAISED BY	DATE RAISED	CAUSE (IF...)	EFFECT (THEN...)	RISK OWNER	P	I	PI	Current Risk Score
	The originator of the risk	*When the risk was first identified*	*If uncertain event occurs due to (or because of) specified root cause(s). Tip: ask "why, why, why..." to drill down to root cause*	*then the ultimate impact to our objectives are. Tip: ask "so what, so what, ..."*	*Single named owner*	*Probability of the event*	*'Worst' impact*	*DO NOT MODIF*	*Calculated risk score*
1	Seals on pump	25-Jan-24	Liquid in pump wears down chamber sealing mechanism and it breaks	Pump chamber will no longer be sealed and seals are likely destroyed	Max	M	M	MM	10
2	Motor Power Supply	25-Jan-24	Power supply short circuits causing the motor to lose all power	Motor will shut off and pump will stop running, the power supply is potentially damaged	Lamya	M	L	ML	5
3	Motor internal components	25-Jan-24	Drive shaft and/or motor components overheat due to excessive power input	Motor will cease to funciton correclty and motor components are potentially damaged	Lamya	M	M	MM	10
4	Materials of Pump chamber	25-Jan-24	Materials in pump system fail due to cyrogenic fluid incompatibility	Pump chamber is compromised and pump ceases to function properly	James	L	H	LH	11
5	3D printing Manufacturer	25-Jan-24	Team is unable to 3D print critical components of pump geometry due to cost or lead time	Team will be required to find an alternate method of manufacturing	James	M	H	MH	15
6	Pump Volute outlet	25-Jan-24	Fluid is ejected in an undesirable direction	Potential damage to testing equipment or harm to indiviudal of the team.	Fred	M	H	MH	15
7	Pump Impeller	25-Jan-24	Pump impeller cavitates due to insufficient net positive suction head	Pump impeller is damaged and ceases to operate as designed	Tom	M	H	MH	15
8	Flow and Pressure Sensors	25-Jan-24	Team is unable to test the flow rate and pressure of ejected fluid	Accurate results about the operational efficieny of the pump are not able to be measured	John	M	L	ML	5
9	Pump Impeller	5-Feb-24	Pump impeller binds with pump housing	Motor may get damaged and pump will need to be remanufactured	James	M	M	MM	10
10	System Insulation	5-Feb-24	System is not properly insulated and the cryogenic fluid changes to gas	Pressure may spike and raise safety concerns, and fuel output will not be efficient	James	L	H	LH	11
11	Motor and Batteries	5-Feb-24	Motor/battery requirements necessitate a weight far higher than pressure-fed systems	The product will not outperform its benchmarks and will not be suitable for customers	Lamya	L	M	LM	6
12	Top-Level Design	5-Feb-24	Product cost vastly exceeds customer requirements	The product will fail to appeal to the target marget	John	L	H	LH	11
13	Magnetic Coupler	23-Apr-24	Motor shaft strips its fitting with the 3D printed magnet holder	The motor will not be able to supply power to the system	Tom	H	L	HL	9
14	Magnetic Coupler	23-Apr-24	The magnets inside the coupler are not strong enough to transmit the required torque	The system will not be strong enough to reach the desired pressure and flow rate	Tom	M	H	MH	15
15	Pump Housing	23-Apr-24	CNC mill cannot fully create the needed geometry of the pump housing	Manual post processing will be required	James	H	L	HL	9

For each identified risk the team decided to either accept or mitigate that risk. Based on that decision a treatment strategy was created for each risk that will be implemented by the responsible team member. The risks were then reanalyzed for their residual risk score after the treatment. The treatment section of the risk register can be seen in Table 7.

Table 7: Treatment section of the PikaPump risk register.

TIFI	3. TREATMENT		4. RESIDUAL ASSESSMENT			
I D	STRATEGY	TREATMENT DESCRIPTION	P	I	PI	Residual Risk Score
	Select overall approach to treatment (Mitigate or Accept)	*Summary of the treatment responses (actions, controls, fallbacks) that treat the risk.*	*Probability of the event*	*'Worst' impact*	*DO NOT MODIF*	*Calculated risk score*
1	Mitigate	Chose seals that will be cyrogenic proof and purchase extra seals in case they do break	L	M	LM	6
2	Mitigate	Ensure that the power supply functions properly by testing before full utilization	L	L	LL	1
3	Mitigate	Understand motor limitations and implement controls to ensure they are not exceeded	L	M	LM	6
4	Mitigate	Chose materials that will withstand corrosion from cryogenics and only use those materials	L	M	LM	6
5	Accept	Look for other method of purchasing parts or machine the pump parts ourselves	L	H	LH	11
6	Mitigate	Create an emergency shutoff and confirm the pump works as designed with water tests	L	M	LM	6
7	Mitigate	CFD analysis performed on pump before manufacturing to ensure proper design parameters	L	H	LH	11
8	Accept	Look for cheap sensors and/or find a test facility with the necessary sensors for the tests	M	L	ML	5
9	Mitigate	Adequately tolerance impeller/housing, account for shrinkage, match coefficeints of thermal expansion	L	M	LM	6
10	Mitigate	Create a pressure release valve and/or ensure the system is not closed. Also increase insulation	L	M	LM	6
11	Mitigate	Reduce weight in tubing/insulation/etc. and choose lightweight motors/batteries	L	L	LL	1
12	Accept	Look for the highest quality components while trying to remain within budget.	L	H	LH	11
13	Accept	3D print backup parts to use in case of failure	H	L	HL	9
14	Mitigate	Choose the largest neodymium magnets that can fit into the coupler	M	H	MH	15
15	Accept	Do as many operations as possible on the CNC and add time in the schedule for post processing	H	L	HL	9

The actions taken during this stage of the project were to review some of the risks and analyze how well the fixes have worked. Table 8 shows the review control and communicate section of the risk register. Currently there have only been some risks directly addressed as most of the risks will begin to arise in the testing portion of the project.

Table 8: Review, Control, Communicate section of the PikaPump risk register.

TIFI	5. REVIEW, CONTROL, COMMUNICATE	
I	Commentary	Last Updated
	Any additional notes, comments or actions	*Enter the last review or update date for the risk*
1		
2	Motor has been chosen to have more than required power for the system, risk goes to low low rating	27-Feb-24
3	Motor being purchased has control system on it, this will prevent over utilization and makes risk probability low	27-Feb-24
4		
5	Vendor online has been found, risk probability is still low	27-Feb-24
6		
7		
8		
9	The impeller did bind during testing, but no damage was done to the housing. Minor rework was required	
10		
11	Based on CFD and motor selection this risk is extremely unlikely to happen	27-Feb-24
12		
13		
14	The team used 5 neodymium magnets, since that achieved the greatest neodymium density. In hindsight, and even number of magnets would have performed better	
15		

This document proved quite accurate at the CDR stage, as only three new risks were identified while testing and manufacturing. The most common failure, which was impeller binding to the housing, had already been predicted. New risks were added and the risk register is now an accurate documentation of the problems faced in the final stages of this project.

Appendix 2 - Business/Marketing

E. Market Analysis

A market analysis was conducted to study the feasibility of meeting the goals outlined by the team. Major factors included both identifying target customers for the design and their specific needs, as well as finding potential competitors or patents that might preclude further development of the design. Data from existing non-electric rocket pump designs was also used as both a reference and point of comparison, due to the limited amount of resources available in this market due to it being a relatively niche product.

Patent research was conducted primarily through the online Patent Public Search database of the United States Patent and Trademark Office (USPTO), to identify any patents that may cover the proposed electric pump fed system design. This revealed that several such designs do exist, with a majority being held by the U.S. aerospace company Rocket Lab. These primarily deal with the design, control systems and integrated propulsion of the Rutherford engine, an electric turbopump-driven rocket engine, used on Rocket Lab's Electron launch vehicle. A picture of the Rutherford engine is shown in Figure 13, and a simplified diagram of its turbopump is shown in Figure 14. Despite this, the pumps used on the Rutherford engine differ from the proposed design in two key areas. They are much larger being intended for commercial use, and are turbopumps, meaning that they rely on the combustion gasses produced by the engine for power. Being that the proposed design is intended for amateur use and relies solely on electric power to drive the pump, we believe that it falls outside the scope covered by these patents.

Figure 13: Rocket Labs Rutherford Electric Turbopump-Driven Engine

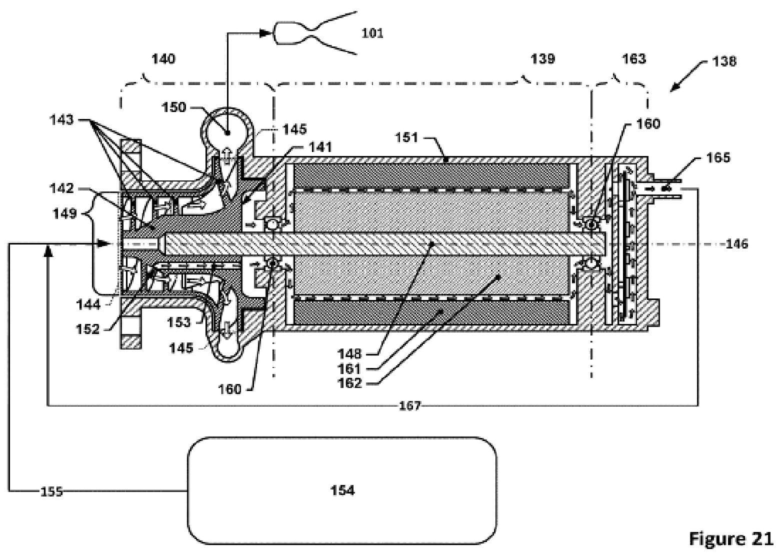


Figure 14: Simplified Diagram of Rocket Labs Electrically-Driven Turbopump

After extensive market research, it was found that there are no existing designs currently available for sale in the amateaur and hobbyist market for electric pump fed systems. However, several different groups and organizations have produced their own unique electric pump fed designs. The Portland State Aerospace society, based at Portland State University, created a dual electric pump system for use in their own bi-propellent rocket. A picture of this completed pump is shown in Figure 15. However, this design suffered from a lack of engineering analysis, and no qualitative data was collected from the testing. This would make it difficult to verify the performance of this design, limiting the ease of replication or potential use as a base template for other designs. Another group at San Diego State University created a similar design, and conducted significantly more fluid engineering analysis in the design creation. A picture of this completed pump is shown in Figure 16. Despite this, there were still notable flaws, as the design was not intended to work with cryogenic fuel, and suffered notable leakage during testing, a major potential safety hazard. As a result of this leakage, the system also failed to meet projected performance targets. While both pump projects offered valuable insight into the design of electric pump feed systems, ultimately neither were sufficient in producing a viable design that could be further marketed or sold.

Figure 15: Portland State Aerospace Society Electric Pump Feed System

Figure 16: San Diego State Electric Centrifugal Pump

Due to the aforementioned shortcomings of existing resources, and to provide further insight into design requirements, Purdue Space Program (PSP) was contacted and provided data from their existing pressure-fed rocket propulsion system. This allowed the team to have a set of verifiable benchmark performance metrics to use as a baseline target when designing the electrically-driven pump.

The market analysis has remained unchanged as no additional information was uncovered during the critical and final design phase. The team believes that the continued application of the proposed design will be providing new and beneficial value not yet captured by any product currently on the market.

F. Value Proposition

This project appeals to a very niche market of around 75 liquid rocket teams, totalling less than a thousand people in the United States. This market would not support an engineering company focused solely on electric pumps. Additionally, the average hobbyist and student rocketeer is someone who relishes the opportunity to solve their own problems, build their own custom hardware, and is driven to innovate. Therefore, PULSAR aims to provide these individuals not with a pre-built solution, but with a roadmap that assists them as they traverse through the complex design space that is an electrically pumped feed system. This roadmap would be provided for free to individuals, and consist of a repository of all the work done by the team and a handbook of recommendations for individual's projects. Despite a lack of a conventional business case, this project would still provide societal value.

As stated previously, industry launch vehicles utilize primarily pumped liquid systems, and by assisting amateur and student teams, individuals can develop their skills and train themselves to more easily pursue a career working in the space industry. Assuming that 100 professionals graduate each year from one of these organizations, each utilizing knowledge attained from PULSAR's roadmap, they would have an economic impact of tens of millions of dollars simply due to their salaries and their impact on the 3.5 billion dollar space launch market.

In order to fulfill this value proposition the team has created a github to showcase the design materials created during this project: https://github.com/twneidlein/PULSAR/. The team put all relevant design files and reports on this github for anyone to access. The contact information of all team members will also be included so if someone accessing the materials has questions and wants further explanation the team will be available to assist. The team believes this is the best way for the value to be created with this project. PULSAR hopes the design considerations uncovered will aid in furthering the design of future liquid rocket fuel pumps.

Appendix 3 - Design Process

G. Engineering Requirements and Constraints

To establish a benchmark of success the team then worked on creating engineering requirements and constraints. The goal here was to cross-reference the requirements against the specifications to check which need to be met to fulfill a customer's need being met. The team then worked to compare and understand the current competition. The team created benchmarks based on how current products meet the team's customer requirements. These allowed the team to adapt using current ideas and improve them to better fit all customers. The team finally worked on creating numeric goals and targets to achieve that combined the market research, customer requirements, and engineering specifications. These goals and design targets give the team direction on where to start, what to improve, and how to identify an improvement.

Table 9: Engineering Specifications and Constraints

	HOW(Engineering Specs)								
	Cost	Mass Flowrate	Outlet Pressure	Temperature	Weight	Lifecycles	Number of Sensors	Outter Diameter	Lengths
	$	lbm/s	psi	deg(K)	lbs	Num	Num	in	in
	↓	↑	↑	↓	↓	↑	↑	↓	↓
Amateur builder	40	13	13	5	5	8	6	5	5
Student Club	30	13	13	8	10	10	6	5	5
Hobbyists	50	10	10	5	5	5	5	5	5
PSP Pressure fed systems	1,500	2.92	240	125	10	1	1	6.6	31.9
PSAS electric feed pump	9,736	N/A	N/A	125	N/A	10	0	11.3	N/A
SDSU Electric feed pump	3,000	2.7	530	125	N/A	5	2	5	8
Target	1000	1.19	240	125	20	10	3	6.6	31.9
Threshold	1500	1	200	200	30	2	0	7	40
Average	1250	1.095	220	125	25	6	1.5	6.8	35.95

Having completed the House of Quality, the team evaluated that competitors mostly met goals on weight, material reliability, and cryogenic capabilities. The team aims to maintain these standards set by competitors but improve on mass flow rate, meeting required pressures as well as being cost-efficient. These goals and targets are specifically selected to fulfill the requirements of the target demographic which are college students and hobbyists that need an efficient, reliable fuel pump that fits within their price range. There have been no updates to the engineering requirements throughout the critical and final design phase.

H. CAD

Mechanical CAD

The overall mechanical CAD includes the core pump, magnetic coupler, and motor components. The CAD of the internal pump components including both the impeller and volute were initially created using CFTurbo, and exported to OnShape. They were then modified to improve printability and enable mounting on the driveshaft. A two-piece pump housing was then created around the impeller using OnShape. The magnetic coupler, which allows for a contact-free connection between the pump and motor shaft using a series of strong magnets, was manufactured in house, due to both inadequate market availability and cost constraints. A 3D printed insert was used to hold neodymium magnets on both sides of the coupler, which were threaded onto the metal driveshaft. The motor which drives the system was also purchased from an external supplier.

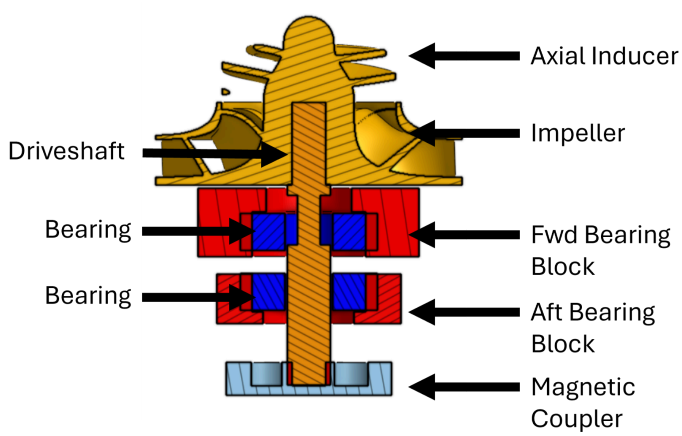


Figure 17: CAD Model of Internal Pump Components

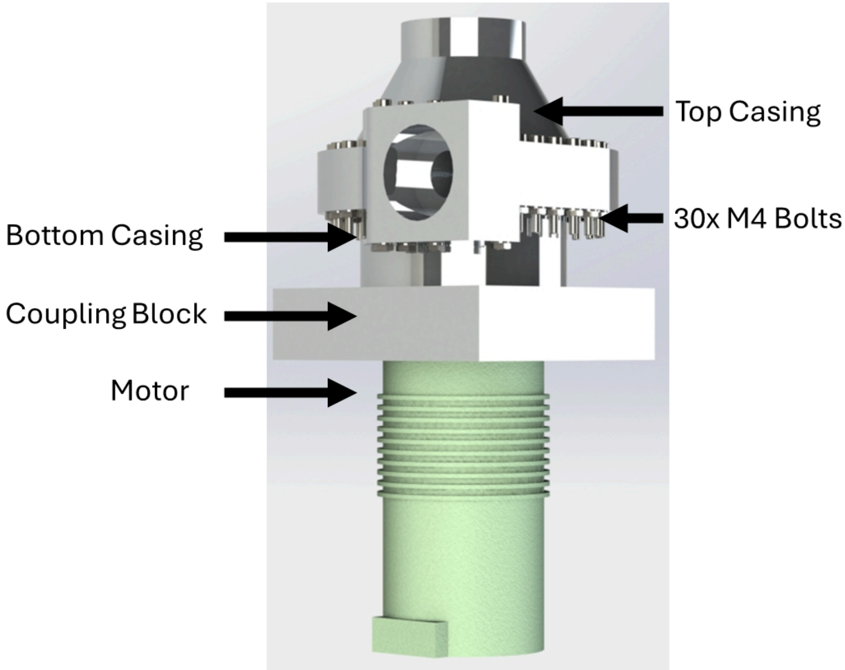


Figure 18: Final CAD Model of Pump

Electrical CAD

For the final prototype, electrical circuits were designed to fulfill three main functions: control and power the brushless motor, get measurements from the different sensors, and allow automatic emergency shutoff. All components for the circuit were bought or loaned from the E-Shop. A schematic of the electrical CAD is shown in Figure 19

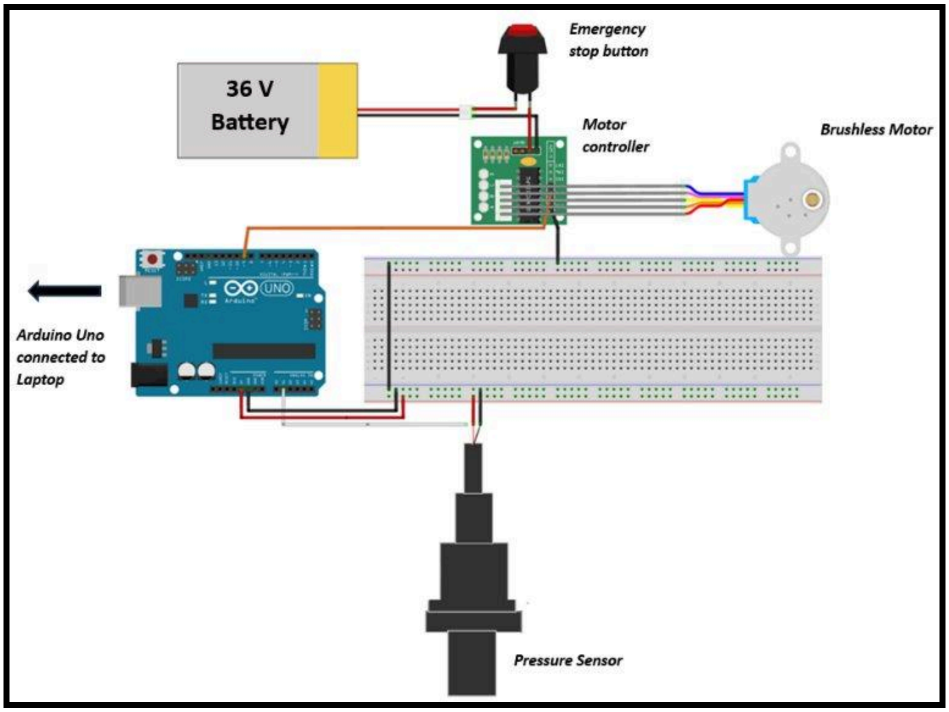


Figure 19: Schematics of the electrical CAD

The electric motor used by the team is a brushless motor that uses its own controller (MAMBA MONSTER X 8S, 33.6V ESC). The motor and the controller are powered by a 32V DC battery. A battery was favored over a power supply for testing since the motor requires a high DC voltage and can go up to 3000W, values that batteries can reach for relatively cheap. Power supplies that can fulfill these requirements are very expensive and such power supplies require special outlets.

There are three different types of sensors in the circuit: tachometer, pressure sensor and flowmeter. The tachometer is built inside the motor, so the RPMs can be found after a test was run by connecting the motor and the controller to a laptop using software (castle link) provided by the manufacturer. An Arduino connected to a computer is used to obtain data from the pressure sensor located at the outlet of the pump. The arduino is used as an ADC to get analog inputs from the pressure sensor and then convert the information into pressures. The pressure sensor is powered by a direct 5V voltage that the Arduino can supply. The flow meter is independent from the Arduino and works on its own and is used to get the fluid flow at the outlet of the pump. The sensor displays the flow in real-time on a small built-in screen. The arduino and the code, connected to the motor controller output can control the throttle of the motor using PWM (Pulse Width Modulation). An emergency stop switch is located between the battery and the controller to open or close the circuit as desired and is used to disconnect the battery to the motor in case of an emergency. The piping and instrumentation diagram with all the sensors is shown below in Figure 20.

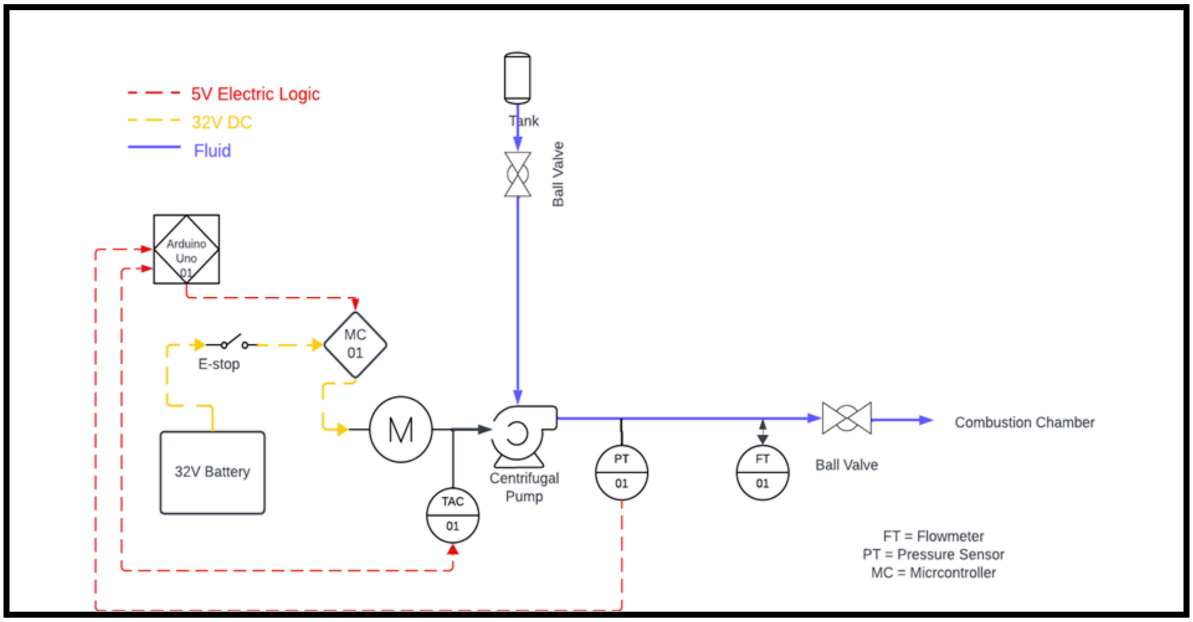


Figure 20: Piping and Instrumentation Diagram

I. Analysis

Pump Selection Calculations:

To create an initial understanding of the model the team chose to reference reliable sources such as past NASA textbooks as well as similar projects taken on by senior design teams over the past couple years. The team researched the complicated models of different pump designs and the principals based on which they ran. Based on goals and priorities the team set early on when analyzing the target market the team used textbooks to understand different pumps and the benefits of different designs. The team settles on a centrifugal pump design due to its reliable design when compared to a positive displacement pump as they contain fewer moving parts, with no check valves and lower pressure pulsations. Centrifugal pumps are also known for their capabilities to handle high pressures efficiently as well as economically in terms of weight and size.

The team further chose to use an axial inducer to the eye of the impeller. This addition helps raise pressure and addresses the risk of cavitation at the blades. Having completed this research the team then completed hand calculations to find the expected efficiency, specific speed, net positive suction head available(NPSHa), i.e. how much power the pump can output and net positive suction head required(NPSHR) i.e. how much power is required by the system. These calculations helped the team set expectations for pump performance but also set up the model in CF Turbo and CFD.

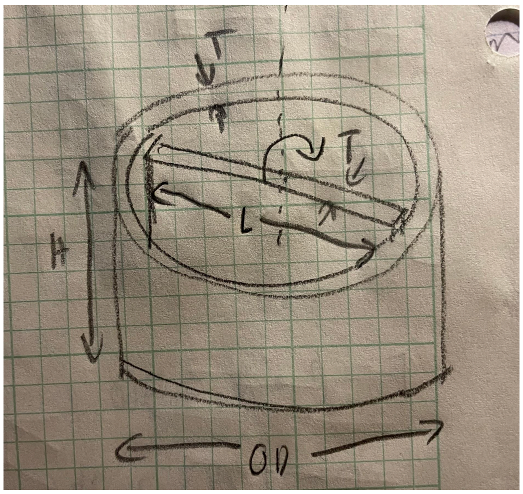
Table 10 - Pump Specifications

Criteria	Value	Units	Resource
Fluid Type:	Liquid Methane	-	PSP CMS
Fluid Density	25	lb/ft^3	CFturbo
Mass Flowrate	1.19	lb/s	PSP CMS
Inlet Pressure	40	psia	PSP CMS
Outlet Pressure	240	psia	PSP CMS
▲ Pressure	200	psi	Calculated
Efficiency	75%	%	Worthington Graph
Volumetric Flowrate	21.376	GPM	CFturbo
Power	3.325709841	HP	Calculated
Power	2479.981828	Watts	Calculated
Head	1152	ft	CFturbo
Revolutions	18000	RPM	San Diego Report

Impeller-Housing Cryogenic Tolerancing Calculation:

Problem: Need to verify that the pump housing will not shrink more than the impeller and bind when exposed to cryogenic temperatures.

Assumptions: cryogenic temperature is constant, lumped capacitance analysis is valid, fluid exposure is instantaneous, surrounding convection is negligent, radiation is negligent.



Known Quantities	Value
Aluminum COTE (α)	23*10^(-6) m/mC
Aluminum Thermal Conductivity (k)	237 W/mK
Aluminum Density (ρ)	2710 kg/m3
Aluminum Specific Heat Capacity (Cp)	903 J/kgK
Time (t)	10 s
Housing Outer Diameter (OD)	100.603 mm
Impeller Length (L)	88.595 mm
Wall Thickness (T)	5.75 mm
Height (H)	40 mm
Coefficient of Thermal Heat Transfer (h)	800 W/m2K
Fluid Temperature (Tf)	100K
Initial Impeller Temperature (Tii)	300K
Initial Housing Temperature (Thi)	300K

Calculated Quantities	Formula	Value
Impeller Surface Area (Asi)	L*H*2	.00708 m2
Impeller Volume (Vi)	L*H*T	.0000204 m3
Housing Surface Area (Ash)	π*(OD-2T)*H	.0112 m2
Housing Volume (Vh)	$\pi * \frac{H}{4} * (OD^2 - (OD - 2T)^2)$	.00006854 m3

$$\textit{Biot Numbers:}\ \ Bi = \frac{h^*L_c}{k} = \frac{h^*V/A_s}{k}$$

$$Bi_{impeller} = \frac{800^*V_i/A_{si}}{237} = .0097 \qquad Bi_{housing} = \frac{800^*V_h/A_{sh}}{237} = .0206$$

-Lumped Capacitance analysis is valid, Bi < .1

$$\frac{T - Tf}{T_i - Tf} = e^{-\frac{thA_s}{\rho V C_p}}$$

$$\text{Housing:}\quad \frac{T - 100K}{300K - 100K} = e^{-\frac{10^*800^*A_s}{2710^*V^*903}} = .5861$$

T = 217.22K

Impeller: $\frac{T-100K}{300K-100K} = e^{-\frac{10*800*A_s}{2710*V*903}} = .32155$

T = 164.31K

Thermal Strain: $\varepsilon = \alpha * \Delta T$

Housing: $\varepsilon = (c_f - c_o)/c_o$ $c_f = 2\pi r_f$ $c_o = 2\pi r_o = .2799\text{m}$

$$\Delta T = 217.22 - 300K = -82.78K$$

$$\varepsilon = (2\pi r_f - .2799)/.2799 = 23 * 10^{-6} * -82.78$$

$r_f = 44.466$ mm $ID_f =$ **88.933 mm**

Impeller: $\varepsilon = (L_f - L_o)/L_o$ $L_o = .088595m$

$$\Delta T = 164.31 - 300K = -135.69K$$

$$\varepsilon = (L_f - .088595)/.088595 = 23 * 10^{-6} * -135.69$$

$L_f =$ **88.318 mm**

RESULTS (converted to inches)	
Initial Housing ID	3.508"
Final Housing ID	3.501"
Initial Impeller L	3.488"
Final Impeller L	3.477"
Initial Clearance	.01"
Final Clearance	.012"

Clearance levels will remain the same or increase so long as the impeller is designed to be as thick as or thinner than the casing. A thinner impeller means that the temperature will drop more, causing even more shrinkage and increasing the clearance. This reduces the likelihood of binding, but also decreases pump efficiency. The impeller should therefore be a similar thickness to the housing.

Minimum Shaft Size Calculation:

Problem: With a high power motor acting on an aluminum drive shaft, the minimum shaft size must be determined to avoid failure.

Assumptions: motor torque on shaft is .8185 Nm and other forces (inertia, turbulence, etc.) are negligible, max shear stress occurs at the outer surface of the shaft, aluminum properties remain the same or stronger in the cold temperatures.

Known Quantities	Value
Aluminum Max Shear Strength	207 Mpa
Input Torque	.8185 Nm

$$\tau = \frac{T*r}{I_p} \qquad I_{p(circle)} = \frac{\pi}{32}D^4$$

$$\tau \geq \frac{T*D/2}{\frac{\pi}{32}D^4}$$

$$207 * 10^6 Pa \geq \frac{.8185\ Nm*16}{\pi*D^3}$$

$$D^3 \geq .00000002$$

$$D \geq .0027m \qquad D \geq .107"$$

With a factor of safety of 1.8, the shaft diameter should always exceed .193".

Bolt Number Calculation:

Problem: Pressure inside the pump will be as high as 360 psi. The number of bolts used to hold the casing together must be calculated such that the bolts elongate no more than .0001", to prevent leakage.

Assumptions: Pressure is a uniform 360 psi throughout the pump, bolts are sufficiently insulated to neglect cold-temperature effects, 18-8 stainless steel M2.5 bolts are used, radial pressure loads are equal around the pump walls and cancel out.

Known Quantities	Value
Stainless Steel Yield Strength (Ys)	29.73 ksi
Stainess Steel Young's Modulus (E)	28,000 ksi
Effective Bolt Length (Lb)	.25"
Pressure (P)	360 psi
Pump Diameter (D)	2.483"

Variable	Meaning
δ	Elongation (inches)
σ	Axial Stress (psi)
ρ	Threads/Inch
At	Tensile Stress Area
OD	Bolt Diamter (inches)
N	Number of bolts

Bolt elongation formula: $\delta = \sigma * L_b/E$

Bolt tensile stress area: $A_t = .7854 * (OD - (.9743/\rho))^2$

For a M2.5 bolt, pitch is .45mm/thread. $\frac{.45mm}{thread} * \frac{1inch}{25.4mm} \Rightarrow 56.44\ threads/inch$

$$A_t = .7854 * (.0984 - (.9743/56.44))^2 = .0052\ inch^2$$

$$F = P * \pi D^2/4$$

$$F = 360psi * \pi * 2.483^2/4$$

F = 1743 lbf

$$\sigma = F/A \qquad A = A_t * N$$

$$\sigma = \frac{1743}{.0052*N} \qquad \sigma = 335192/N$$

$$\delta = .0001" = \frac{\sigma*.25"}{28*10^6}$$

$\sigma = 11200\ psi$ 11200 psi < Yield strength (27000 psi),

11200 = 335192/N **N ≃ 30 bolts**

The elongation requirement already imparts a factor of safety of 2.4, so no extras are needed. 30 bolts will be sufficient to contain the pump and prevent leakage. This calculation was crucial, as our original design only used 10 bolts.

Fluid Dynamics Simulations:

In combination with the pump calculations and CFTurbo, a CFD simulation was created and ran to verify the calculations done. The workflow created in Ansys workbench can be seen in figure 21.

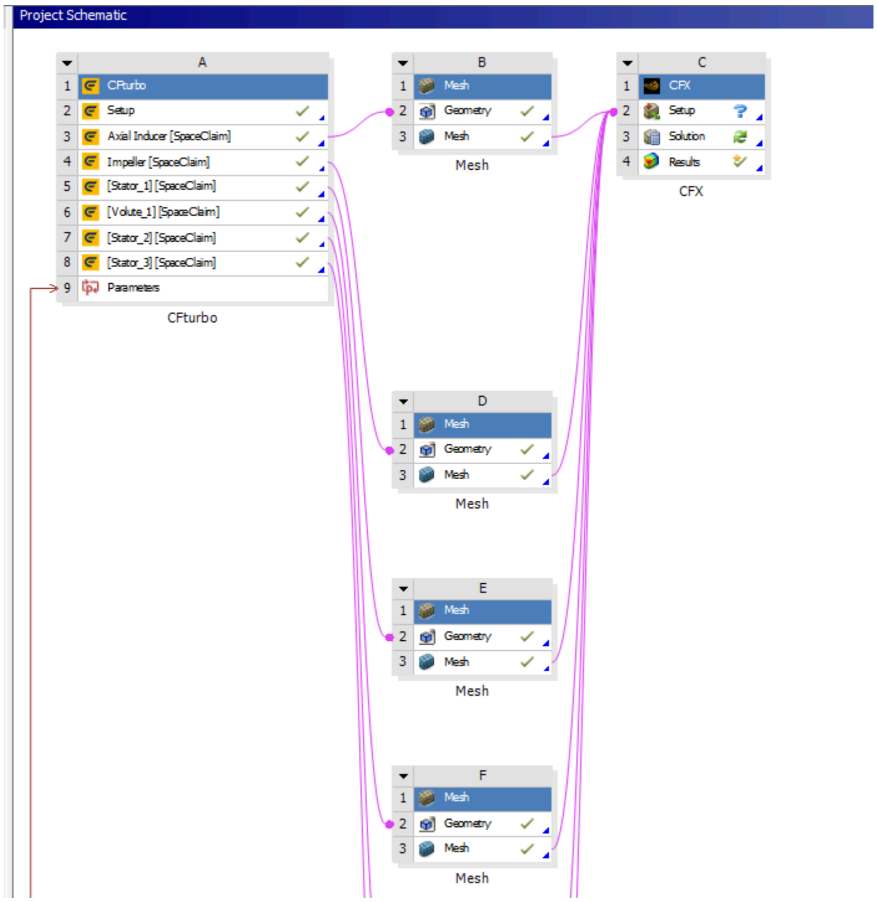


Figure 21: Ansys workbench simulation workflow

The first step in the workflow was to import the geometry from CFTurbo using space claim. This allows for a separate fluid domain to be created for each part of the pump. From there each part was separately meshed using Ansys meshing. A minimum mesh size was chosen based on the size of the overall geometry. The total simulation domain has a volume of around a 1 in^3 so a maximum element size of 1*10^-4 in^3 was chosen to allow for the elements to be small enough for the solution to converge properly. A basic mesh spacing was used on inlet and outlet domains, but for the other domains and inflation mesh was used. The inflation mesh adds a boundary layer to the mesh which is important for capturing the boundary layer which will form in the flow. This inflation mesh also adds more mesh elements at the fine corners and edges of the domain which will need the smaller elements for proper convergence. Figure 22 shows the mesh for the axial impeller. It demonstrates the meshing methods mentioned above.

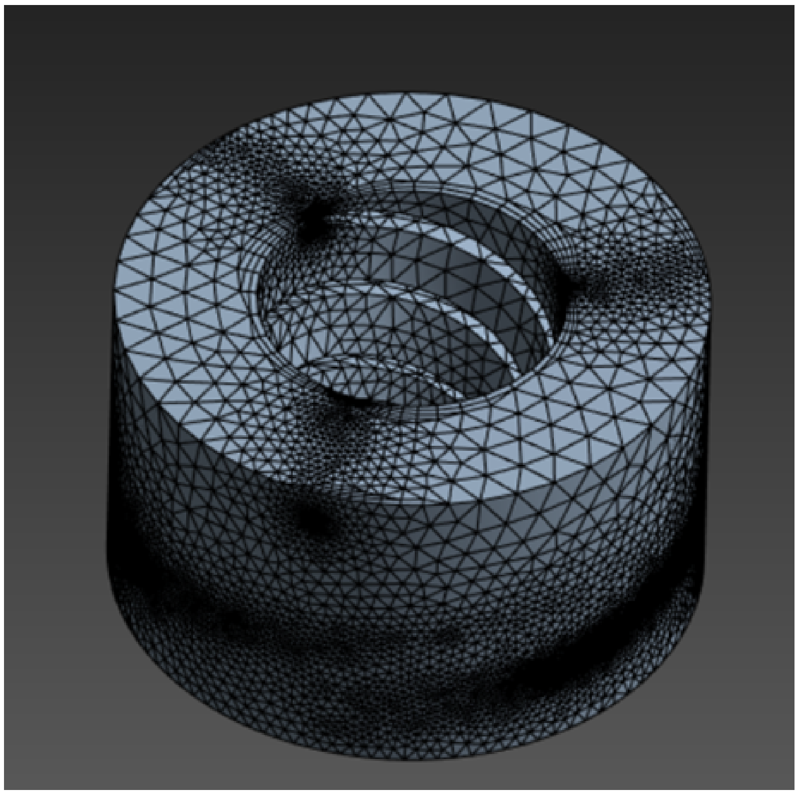


Figure 22: Mesh for the axial impeller in Ansys Mesh

The bigger elements where not much of interest is happening in the flow are limited by the maximum mesh size. There is a small boundary layer visible around the center opening. The mesh is refined on both the top and edges where the blades hit the edge of the domain and is visible where the dark spots of the mesh are. All domains in the simulation were meshed in a similar fashion to this one.

After the mesh for each element was created they were imported into CFX for simulation. Due to how the geometry is imported the domains import into their correct respective locations already. First inlet and outlet conditions are specified. It can be seen that extensions have been attached to the outlet and inlet, this is to help with the convergence of the solution as this is likely how the pump will be functioning in reality. The inlet is a pressure inlet at 40 psi as specified by PSP's pressure inlet for the pressure driven flow method. The outlet is a mass flow outlet at 1.19 lbm/s as that is the target mass flow rate for the pump. The boundary conditions for the rest of the domains are then specified. The stationary walls are set as stationary and the rotating domains, mainly the impeller and axial inducer, are set to rotate at 35000 rpm. Between the domains interfaces are set up. For the interfaces between stationary domains it is just a simple interface connection. For the domains where one is rotating and one is stationary a frozen rotor method is used. This method allows for the rotation to still have the correct impact on the fluid in the domain that is rotating without affecting the domain that is stationary. Figure 23 shows this final setup of the simulation.

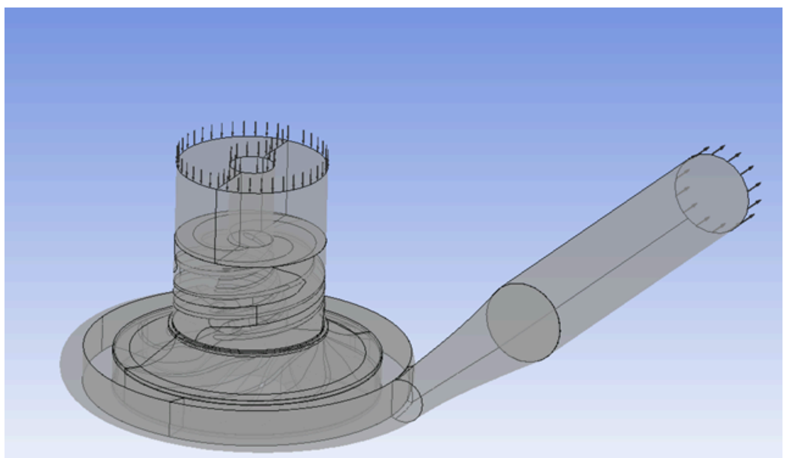


Figure 23: Flow domain setup in CFX-Pre

After the boundary conditions are set the solver controls are specified. The residuals are aimed to converge to 1e-04 and the max iterations is set to 1000 as if it gets to that point without convergence it will likely never converge. Figure 24 shows the residuals converging for the simulation.

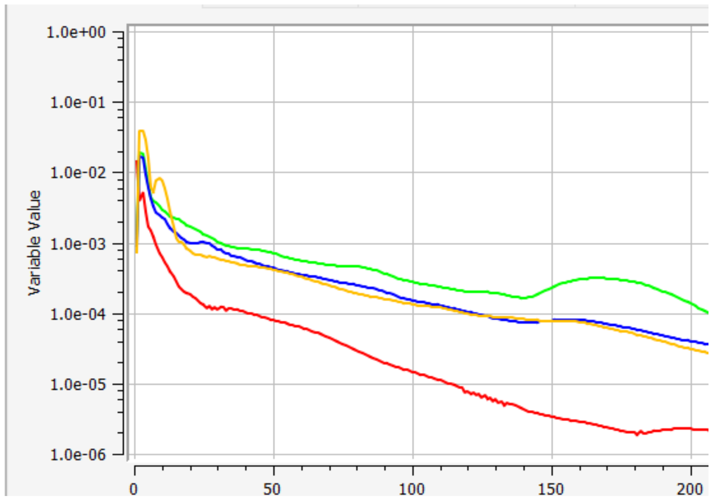


Figure 24: Residuals vs. iteration for the simulation

The simulation converged after around 1 hour and 225 iterations. After the initial simulation it was realized the pump was not performing well enough and the team decided to add a back flow region into the impeller. Figure 25 shows that backflow region.

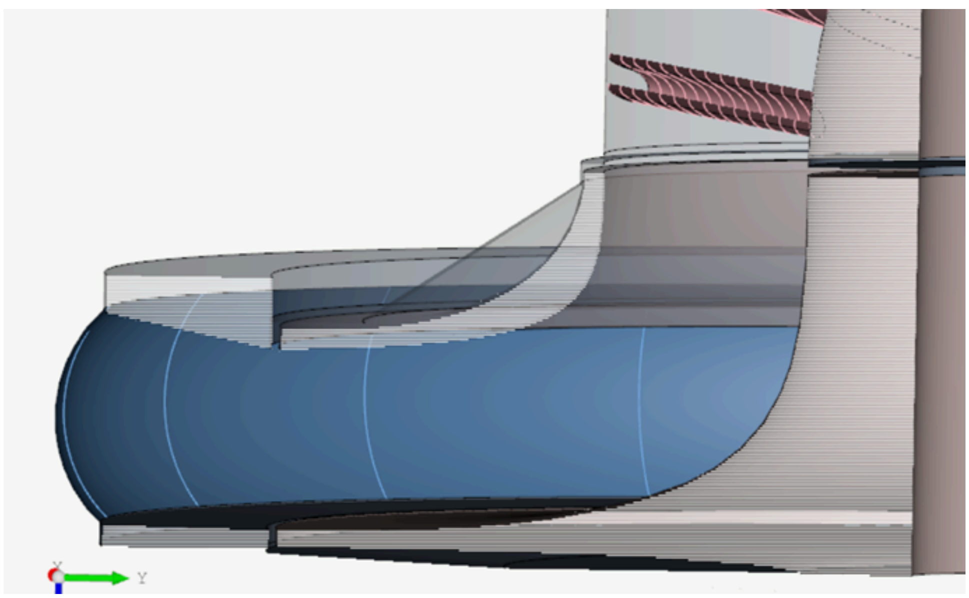


Figure 25: CFTurbo 3D model with backflow region

The backflow region is the linear gray portion above the shroud of the impeller. After adding the backflow region and repeating all the steps again as specified a final simulation was performed. Figure 26 shows the results of that final simulation.

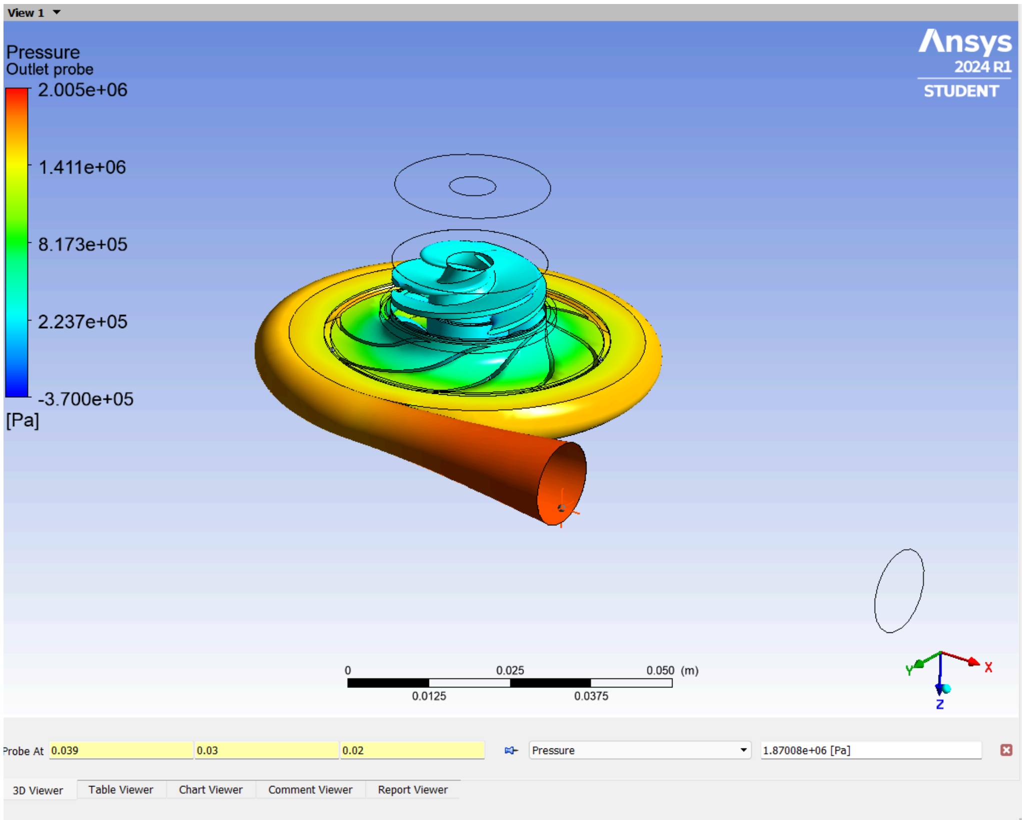


Figure 26: CFX post results of final simulation

It can be seen that the final pressure is around 1.87e6 Pa or 275 psi. This is above the design requirement of 240 psi so the team was satisfied with the results of the simulation. It can also be seen that in the impeller region the pressure does not drop below the vapor pressure of methane at -235 F. This means that the pump will not cavitate under the operating conditions which is satisfactory to fulfill that requirement.

To assist in understanding the validation a CFD simulation with water instead of methane was performed. The pressure, rotational speed, and outlet conditions were kept the same as the cryogenic simulation as that will be the conditions of the test. However, the temperature and fluid properties were changed to make the simulation more accurate to the test conditions. The simulation took much longer to converge, but in the end still was able to attain good results. Figure 27 shows the results of this simulation.

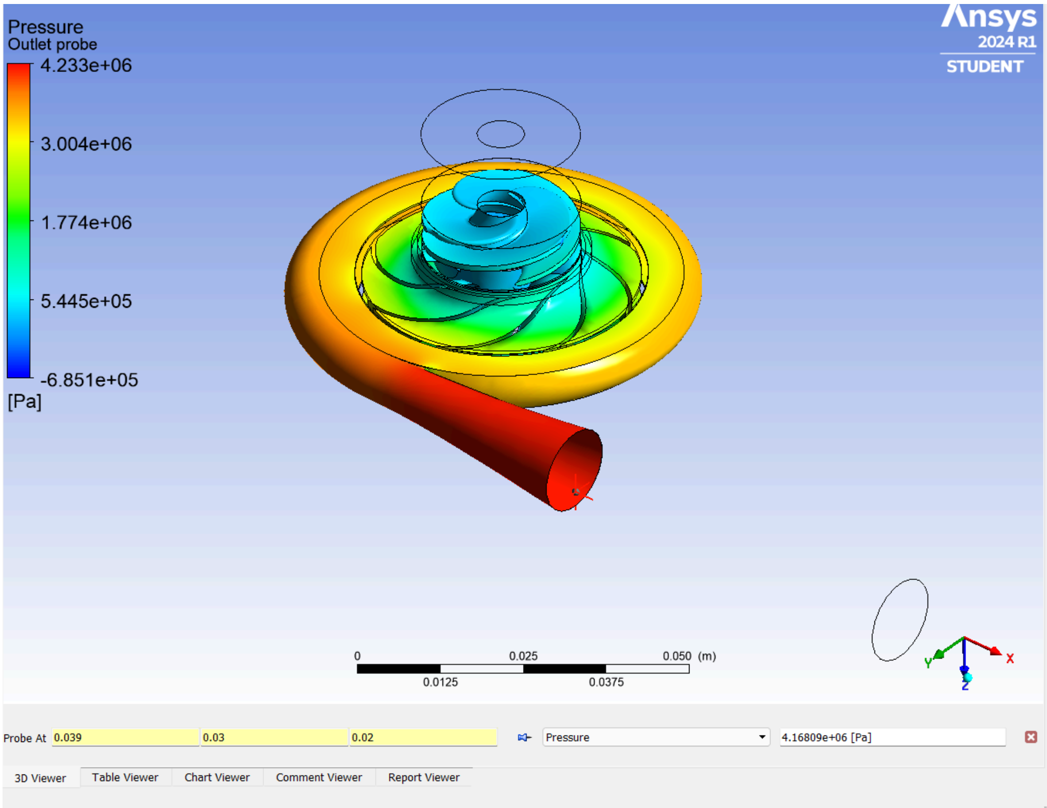


Figure 27: CFX-Post of simulation with Water

It can be seen that the pressure resulting is much higher than with the cryogenic fluid which is expected due to the properties of water. The outlet pressure is expected at around 4.168e06 Pa or 605 psi. Due to this high pressure, the team has decided when testing to start running it at a lower rpm value to ensure all the functions, primarily the seals and fittings function properly. From there the team will step up the rpm until reaching operating conditions.

J. FMEA

In order to identify the critical components of the project that needed to have some analysis performed on them, a failure modes and effects analysis (FMEA) was created. The FMEA was created to serve as a guide for the team on what aspects of the design needed engineering analysis performed on them and which design aspects specifically were most critical for the project's design. To begin all the potential failure modes were identified through a team brainstorming session. The failure mode identification can be seen in table 11.

Table 11: Failure mode identification section of the FMEA

Line No.	Item / Function	Potential Failure Mode	Potential Effect(s) of Failure
1	Seals	Seals breaking	Liquid spills out of pump
2	Motor	Short Circuit	Motor loses power, could cause power supply to be damaged
3	Motor	Overheating	Internal Motor components are damage
4	Housing	Corrosion	Housing material is corroded causing geometry damage
5	Housing	Fluid ejection	Damage to test equipment or team members
6	Impeller	Cavitation	Impeller is damaged due to cavitation
7	Impeller	Binding	Impeller and housing are bound together causing the pump to cease functionality
8	Housing	Fluid evaporation	Minor damage to impeller
9	Motor Coupling	Coupling Disconnection	Coupler disconnects, the impeller will no longer spin
10	Motor Coupling	3D Print Failure	3D printed magnet holder is stripped by motor shaft, prohibiting power transfer

Once the failure modes were identified they were all ranked based on three different criteria. These criteria are severity, occurrence, and detectability. Severity describes the damage done to the project with 1 being no effect and 10 being complete destruction of a critical component the pump. Occurrence ranks how frequently this risk is to occur with 1 being never and 10 being every time the pump runs. Detectability ranks how easy the failure will be to detect with 1 being the design will reliably detect the failure every time and 10 being no possibility to detect the failure until it is too late. Table 12 shows the rankings for each corresponding failure mode.

Table 12: Failure mode ranking section of FMEA

Line No.	SEV	Potential Cause(s) / Mechanism(s) of Failure	OCC	Current Controls	DET	RPN
1	4	Seals on the housing burst due to excess pressure	4	Pump and seals are being designed to prevent this scenario from happening	1	16
2	6	Motor supply short circuit due to operating conditions	3	A control system is being put in place to monitor the motor conditions	4	72
3	8	Motor is given excessive power or is run outside of operating conditions	3	The motor control system and E-stop will prevent this from happening	4	96
4	9	Cyrogenic fluid corrodes the material in the housing	2	Materials will be chosen that are corrosion proof to prevent this	5	90
5	7	Fluid is ejected in an undesirable location	5	The E-stop will allow for operation to cease immediately if this does begin to happen	2	70
6	10	Pump cavitates due to operating conditions	3	The pump will be designed and simluation to ensure it will not cavitate under the conditions	7	210
7	4	Tolerancing and vibration allow the impeller to make contact with the housing and create friction	8	The impeller will initallly be run at a lower rpm to make the housing ready for operating conditions	4	128
8	5	Improper insulation causes the cyrogenic fluid to evaporate	5	The pump will be insulated by the materials and test fixture to prevent this from happening.	3	75
9	1	Magnetic force is not strong enough to support force	6	The necessary coupler force will be calculated beforehand and tested without the impeller to ensure it functions before being sealed	2	12
10	6	Too much force is applied between interfaces and the magnet holder breaks	6	An interference fit will strengthen the bond to the 3D print	4	144

The team used these rankings to determine where to spend more time in the critical design phase. The failure modes with a higher risk priority number (RPN) were addressed first. The highest being the potential cavitation of the impeller, the binding of the impeller with the housing, and the magnet holder getting stripped. As a result these aspects of design were where the team spent most of their time. CFD was performed on the pump geometry and other hand calculations were performed on the motor and materials in order to ensure these failure modes do not occur.

After performing the engineering analysis the failure modes were reassessed with the necessary mitigation actions reported in the FMEA. The team has decided after this reassessment that all of the failure modes have been satisfactorily addressed and the project will be able to move into the manufacturing and testing phase without any critical failures. The reassessment can be seen in table 13.

Table 13: Mitigation section of the FMEA

Line No.	RPN	Mitigation Action (s)	by Who	by When	New SEV	New OCC	New DET	New RPN
1	16	Seals chosen to withstand required pressure	Tom	2/25/2024	4	3	1	12
2	72	Control system design to limit motor	Fred	3/1/2024	5	3	3	45
3	96	Estop implemented into control system	Fred	3/2/2024	7	3	3	63
4	90	Material chosen to prevent corrosion	James	2/25/2024	8	1	5	40
5	70	Test setup design with this failure mode in consideration	Max	2/28/2024	5	3	1	15
6	210	CFD performed on pump to create geometry where this will not happen	John	3/3/2024	10	2	7	140
7	128	Housing designed with correct clearances and adjusted as needed during testing	James	3/3/2024	4	5	4	80
8	75	Housing will be precooled before testing	Max	4/15/2024	5	3	3	45
9	12	Magnetic coupling calculations performed to ensure strong enough force.	Tom	2/28/2024	1	5	1	5
10	144	Print extra 3D prints for the magnet holder	Tom	4/18/2024	3	6	4	72

After testing and iteration, some risks proved to be more prominent than others and their scores have been adjusted from the CDR FMEA to more accurately reflect their consequences. Additionally, another failure mode was discovered during testing that was not predicted by the FMEA. This failure lies within the magnetic coupler where the motor shaft fits with a 3D printed slot. Too much force was applied and the slot was stripped. Due to time constraints, redesign was not feasible, so the team's only option was to print more backup parts. A change in design is needed to further mitigate this failure risk rather than simply treat it.

Impeller binding is also far more prominent than the team expected. To combat this, clearances had to be increased by a less-than-desirable margin. The root cause, the team has determined, lies within the large amount of play inherent to a magnetic coupler. The drivetrain assembly (including the driveshaft, bearings, and couplers) needs to be given more clearance where allowable and machined with greater precision at the coupler face interactions.

K. BOM and Sourcing Plan

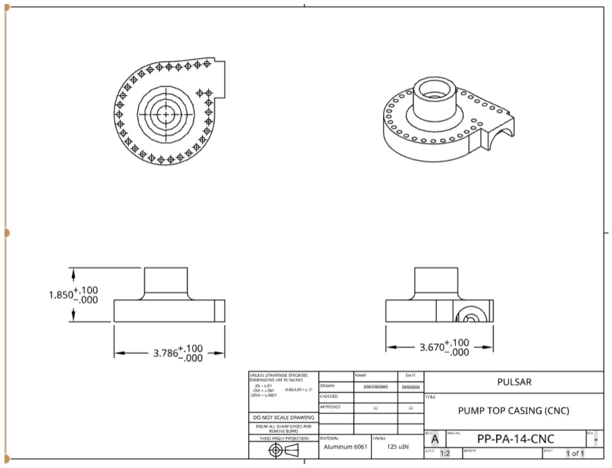
The Bill of Materials below reflects all changes made since CDR and represents the prototype as of the final demonstration. Items in red were not used for the final design, items in green were added since CDR, and items in yellow have been changed. The prices in yellow have just been changed to update the accurate price after the part was purchased. The source of each of the components has been attached as well as if the team had to "make" or buy the part. The sources are fairly diverse since the project requires parts such as seals, bearings, electronics, motors or some parts to be machined or 3D printed in stainless steel. Some parts are listed as "Pre-owned", meaning that the team already possessed these parts and no sourcing plan is needed for them. Conventional machining was completed in the ME Student Project Machine Shop and the CNC work was done in the same location with the help of John Wheeler. Stock aluminum was purchased online via Metals Depot and sourced from the stock room across from the ME Machine Shop. Any items added to the BOM after CDR were mostly sourced from Amazon, as timely delivery was essential at that stage.

Notable changes since CDR are the BOM additions in green. The addition of parts 13 and 14 are for new parts that the team discovered it needed during the manufacturing process. Items 23-29 represent the additional items needed for testing and data acquisition that the team was not completely sure of at the CDR stage. Cheaper bearings were also required, since the cryogenic bearings did not perform well at the temperature used for testing.

Table 14: Bill Of Materials

Part No.	Part Name	Units	Quantity	Material Description	Source/Machine Tools	Catalog No.	Make(Get Free) / Buy	Unit Cost ($)	Total Price
1	Roller Bearings	pcs	2	Ceramic Ball Bearings	Alpine Bearing	HYSV607P4D15	Buy	$97.50	$195.00
2	6061 Aluminium	ft	1	Material needed to machine pump housing and fittings	Metals Depot	F41123	Buy	$84.95	$84.95
3	Axpeller	pcs	1	Rotational impeller to be installed inside the pump	Cloud Craft	-	Buy	$55.88	$55.88
4	Static Seals	pcs	4	Seals for statics parts between the pump and the pipes	McMaster	-	Make	$0.00	$0.00
5	Magnet Holder	pcs	2	Forms the base of the magnetic coupler, holds magnets in place	3D printed ~~Machined~~	-	Make	$0.00	$0.00
6	Electric Motor	pcs	1	33.6V Brushless DC motor	Castle Creations	010-0165-02	Buy	$402.25	$402.25
7	Battery	pcs	1	8S Lipo Battery	Rotor Riot	414230	Buy	$58.00	$58.00
8	Arduino	pcs	1	Microcontroler used to control the motor	Persanix	Arduino Uno	Make	$0.00	$0.00
9	M4 Bolts	50 pack	1	Stainless Steel Fasteners	McMaster	91292A806	Make	$0.00	$0.00
10	Top Pump Casing	pcs	1	Top housing component of the pump	Machined (CNC)	-	Make	$0.00	$0.00
11	Bottom Pump Casing	pcs	1	Bottom housing component of the pump, also houses magnetic	Machined (CNC)	-	Make	$0.00	$0.00
12	Magnetic Coupler	pcs	2	Assemblies built to transmit torque between one another	Machined (lathe)	-	Make	$0.00	$0.00
13	Coupling Block	pcs	1	A block to connect the motor to the pump, as well as house the	Machined (lathe, mill)	-	Make	$0.00	$0.00
14	Coupler Adaptor	pcs	1	A part of the driveshaft that must be made as a separate part	Machined (lathe)	-	Make	$0.00	$0.00
15	Neodymium Magnets	pcs	48	Magnets to be used inside the magnetic coupler	Pre-owned	-	Make (free)	$0.00	$0.00
16	Bearing support	pcs	2	Plates for bearings to be press-fit into, inserted into	Machined (CNC, lathe)	-	Make	$0.00	$0.00
17	Drive Shaft	pcs	2	Transmits power from motor to axpeller	Machined (lathe)	-	Make	$0.00	$0.00
18	Pump Inlet Line	pcs	1	Transfers liquid from upper reservoir to pump	Pre-owned	-	Make	$0.00	$0.00
19	Volute Outlet	pcs	1	Transfers liquid from pump to lower reservoir	Pre-owned	-	Make	$0.00	$0.00
20	Upper Reservoir	pcs	1	Container to hold liquid before moving through pump	Pre-owned	-	Make (free)	$0.00	$0.00
21	Lower Reservoir	pcs	1	Container to eject pump output into	Pre-owned	-	Make (free)	$0.00	$0.00
22	Ball Valve	pcs	2	Valve to isolate pump from upper reservoir	McMaster	47865K24	Buy	$10.00	$20.00
23	AN Fittings	pcs	4	Fitting for fluid inlet and outlet	anhosefittings	-8AN O-Ring	Buy	$3.90	$15.60
23	Bearings	pack	1	Cheaper bearings for testing	Amazon	B09CZDXNRQ	Buy	$22.00	$22.00
24	Battery Charger	pcs	1	Device to recharge batteries	Amazon	B0823DGJXS	Buy	$59.90	$59.90
25	Bullet Connectors	pack	1	Connectors from battery to motor	Amazon	B001ASFWL8	Buy	$12.24	$12.24
26	T reducers	pcs	2	T reducers for pressure sensors to connect to pipes	McMaster	4464K944	Buy	$23.21	$46.42
27	Flow Meter	pcs	1	Flow meter to measure flow rate	Amazon	B0CF1YTYQC	Buy	$41.68	$41.68
28	Test stand	pcs	1	Wood and Stel for test stand	Pre-owned	-	Make	$0.00	$0.00
29	Pressure Sensor	pcs	1	Pressure sensor to measure outlet pressure	Pre-owned	-	Make	$0.00	$0.00
Total Project cost									$998.72

Manufacturing Drawings for "Make" Parts:



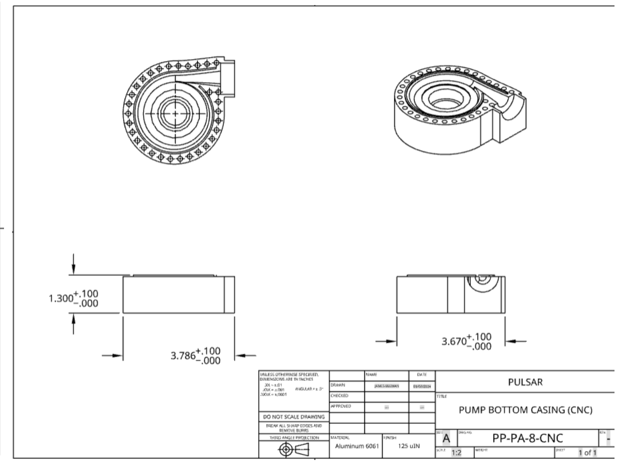
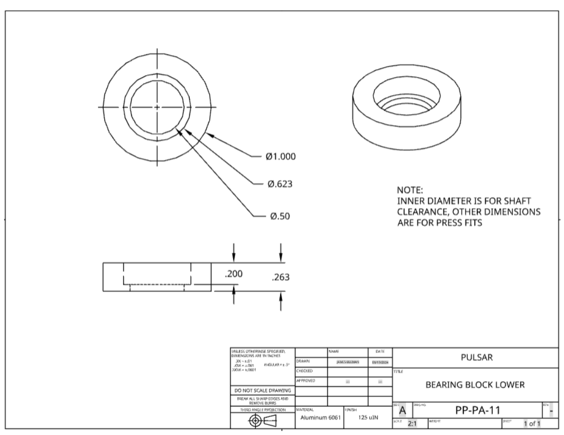
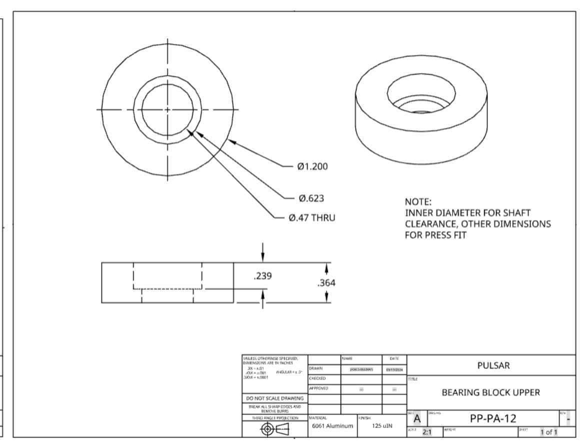
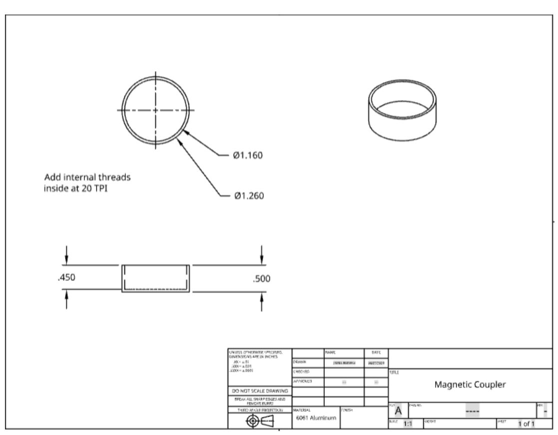
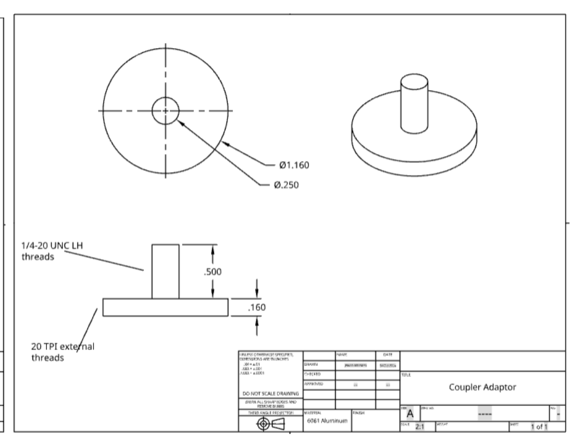


Figure 28: Drawings for manufacturing stock prior to CNC









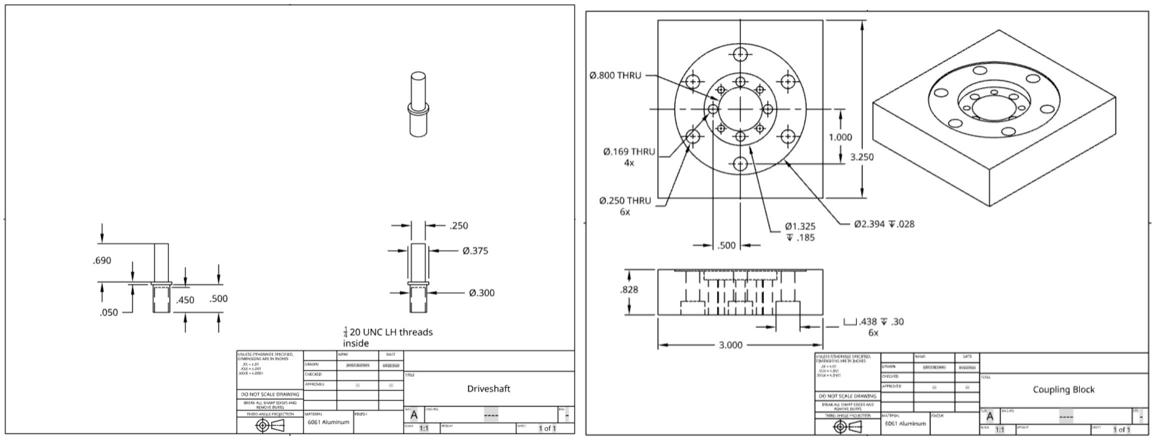


Figure 29: Manufacturing drawings for all parts that were manually machined on the mill and the lathe.

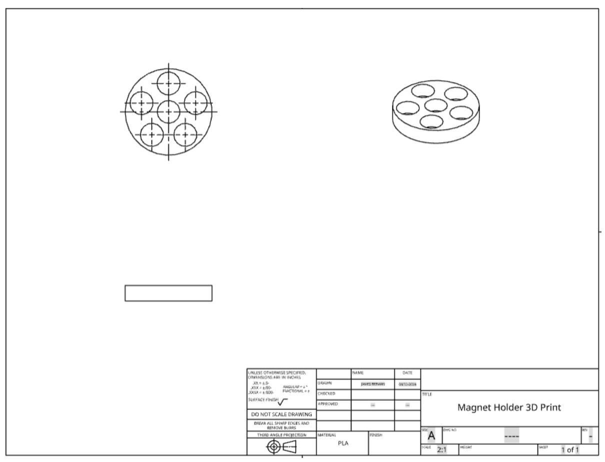


Figure 30: A drawing showing the magnet holder that was 3D printed

L. Validation Plan

The primary goal of the project is to design, build, and test an electric pump that could feed cryogenic liquid propellants at sufficient pressures and mass flow rates into a combustion chamber. Due to timing and Zucrow test stand availability, it is unlikely that the team will be able to do a full cryogenic test of the system, therefore, following industry standards, PULSAR will be testing the PikaPump using liquid water.

In order to test the pump and get results in terms of pressure flow rate and RPMs, a test setup was built. The test setup includes a test stand and the data acquisition system. The test stand is composed of a 5 gallon tank, a pipe feeding water to the pump, a pipe at the outlet of the pump, the E-stop button and the structure. The data acquisition system is composed of a tachometer, a pressure sensor, a flowmeter, an Arduino and two water proof boxes.

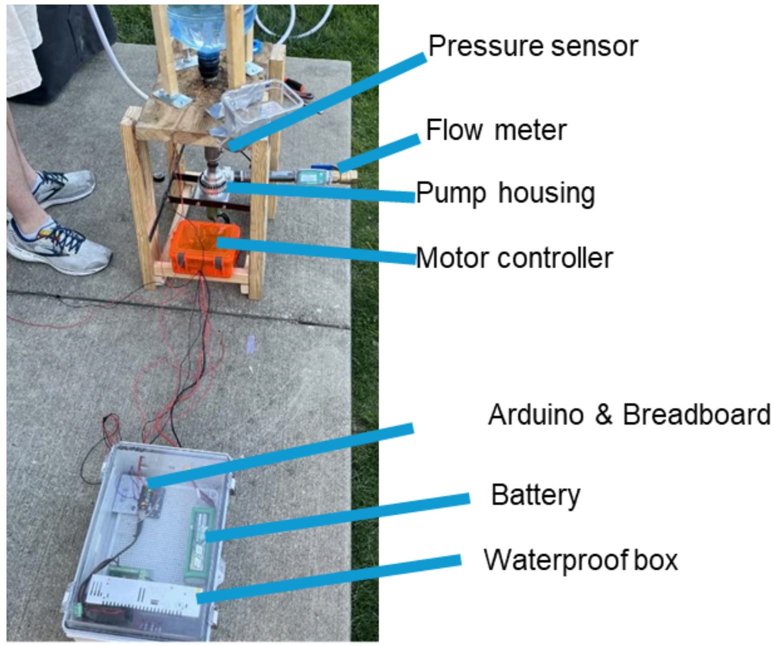


Figure 31: Test Setup and Data acquisition system

The functions of the pump that were tested during tests were : characterize and confirm system, enable emergency shutoff, create pressure differential, be water tight, rotate an impeller. The test procedure consisted of loading the code with given throttles with a fifteen seconds timer, opening the valve at the inlet of the pump, get data during the ten seconds of the test and press the E-stop button in case something was wrong. The tests happened in an outdoor flat field with a lot of space for the water to flow. At all times, the electric components such as the battery, the arduino and the motor controller were kept in water proof boxes at a safe distance apart from the pump. To validate each function, data of the flow rates, pressures at the outlet and rpms were recorded during different tests at different throttles.

In order for the results of the simulations to be deemed accurate they need to be compared to a real life experiment and found that the values are the same. Since the team knew that lower rpms would be utilized, simulations were run at those lower rpms. Pump curves were created for three different rpm values and can be seen in Figure 32. There are also performance curves in that figure. Those are calculated based on the head rise required to push the liquid through the system. Since the height of the pipe will not be changing and the velocity is expected to be constant throughout the system the only factor contributing to losses from the system will be head rise. Using equation 01 below the major and minor losses were calculated, where h is the loss, f and K are the loss coefficients, V is the fluid velocity, L is the pipe length, D is the pipe diameter, and g is gravity. The significantly largest component of the losses come from the valve so that will be the most critical part of the test setup.

$$h = f\frac{L}{D}\frac{V^2}{2g} + K\frac{V^2}{2g} \quad \textbf{Eq. 1}$$

Three performance curves were created for different possible valve closed positions. The pump will operate at the points where the pump and performance curves intersect. So to validate the simulations the team will select an rpm value and close the valve a certain amount which should result in a specific operating point.

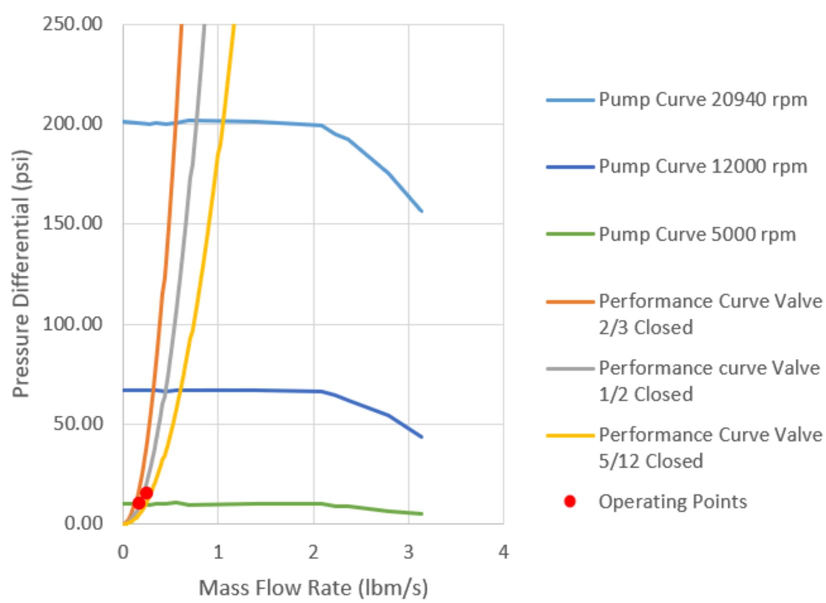


Figure 32: Pump and performance curve results from CFD. Operating points from the experiment are shown in red

After running the tests as specified above the team was able to obtain results for two specific operating conditions at both 5000 and 7000 rpms. At 5000 rpms a pressure rise of 10 psi was recorded along with a flow rate of 0.17 lbm/s. At 7000 rpms a pressure rise of 15 psi and a flow rate of 0.22 lbm/s was recorded. Both of these points matched nearly exactly with what was predicted in the simulations of the pump operation. The team was satisfied with this and from this believes the simulations were accurate in predicting how the pump would function. From this the team can say the pump will most likely function properly for cryogenic liquids as designed.

The team would have liked to attain more design points at higher rpms. However, it was found that the magnetic coupler was not strong enough to support any faster rotation than 7000 rpms. When any more power was inputted to the motor to increase the speed the magnetic coupler would begin to skip and no longer function. The team was disappointed with this result, but overall with the data obtained believes that if stronger magnets were attained the data would continue to match the simulations. Further confirming the results from the CFD.

Ultimately, when comparing the results with the initial requirements set by the team in the preliminary design phase, shown below in Table 15, eight of the ten were met. The two requirements that were not met, the liquid methane pressure output and liquid methane flow rate, were due to a lack of full cryogenic testing of the system, rather than any inherent flaw in the design or testing procedures. Overall, the team was able to meet or exceed many of the requirements.

Table 15: Final Requirements Assessment

Requirement	**Description**	**Rqmt Met?**	**Reasoning**
Pressure	Liquid methane pressure output of 240 psia	No	No cryo test
Flow	Liquid methane flow rate of 1.19 lbm/s	No	No cryo test
Weight	Total system weight below 12.5 lbs	Yes	~4 lbs
Sizing	6.6” Max diameter, 16” Maximum height	Yes	4" Dia., 10" Tall
Temperature	Can withstand temperatures of -190 °C	Yes*	Full compliance
Corrosion	Resistant to corrosive cryogenic fuels	Yes*	Full compliance
Reusability	Will be able to operate for at least 2 flights	Yes	Multiple tests
Measurement	Able to record outputs using sensors	Yes	Data acquired
Safety	Automatic and manual emergency shutoff	Yes	E-stop works
Test Ready	System is cryogenic test ready	Yes*	Full compliance

*No tests performed with cryogenics, but all components are designed for cryogenic use

As far as qualitative results the team found that nearly all aspects of the pump functioned as designed and was very satisfied with the performance. The sealing method was able to prevent any leaks out of the casing. The pressure sensors were able to provide live measurements of the pressure. The casing was able to withstand a pressure rise without issues. The magnetic coupler was able to transfer rotation effectively up to a point, again the main issue being strength of the magnets not being able to transfer higher amounts of torque. Overall the team determined the validation tests a success and learned lots about the functioning of all components of the pump. Though not everything functioned exactly as designed, these validation plans verified the results of the simulations while providing great insights into performance of all individual aspects of the pump.

M. List of Standards Applied

Due to the niche nature of the project, there are no applicable standards that could be utilized in the evaluation or design of our pump. There were a number of textbooks and research papers that informed our work, which can be seen in the works cited in appendix 4.

Appendix 4 - Works Cited

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