MAE 2250 SP23 Water Pump Project Final Report

Lab 441 Group 1

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Design Process

Pump Choice & Rationale

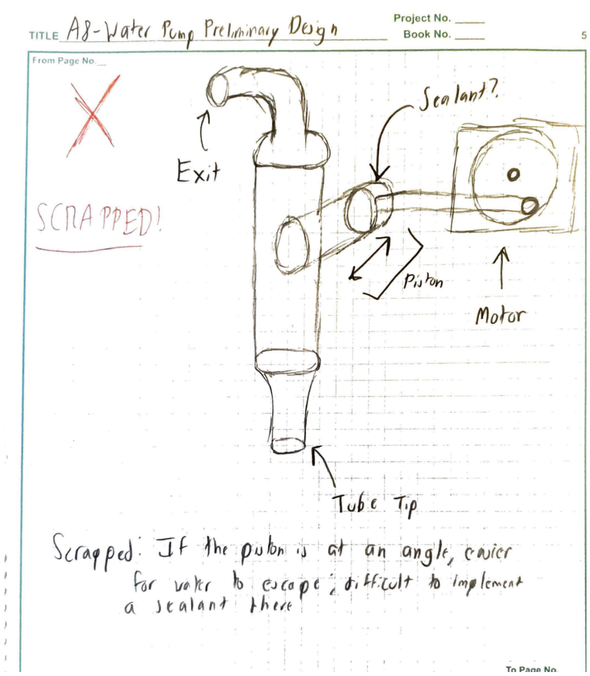
The pump design selection began with research about three pump designs: peristaltic, centrifugal, and piston. Each pump variation supported their own advantages and disadvantages, and the design that was ultimately chosen conformed to the design and manufacturing constraints. The water pump design that was selected was a cylindrical piston pump design. Piston pumps are advantageous because of their simplicity and versatility. Given the constraints for the project, the piston pump was deemed the most logical choice due to its ease of machinability and low material cost.

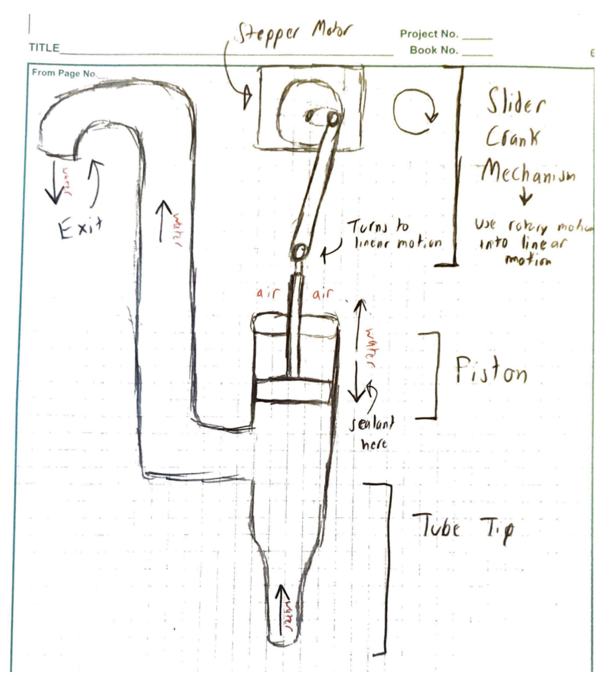
Additionally, there are multiple ways to convert rotational motion from the motor into linear motion necessary to move the piston to pump the water within the cylinder. The group considered a scotch yoke or a slider crank as means to transfer rotational motion to linear. In the end, it was determined that the slider crank was the ideal choice after considering Design for Manufacturing principles. The crankshaft and rotating shaft, pictured in the Fabrication Plan, were easier to assemble and machine.

Further advantages of piston pumps are their reliability and simple waterproofing. Piston pumps can be designed to handle a range of pressures and can be effective with both viscous and non-viscous fluids. Piston pumps can be waterproofed relatively easily using small variances between the piston and cylinder (~0.001in) and/or O-rings. Overall, the piston pump is advantageous because of the machinability of the components, simplicity of the design, affordability of the parts.

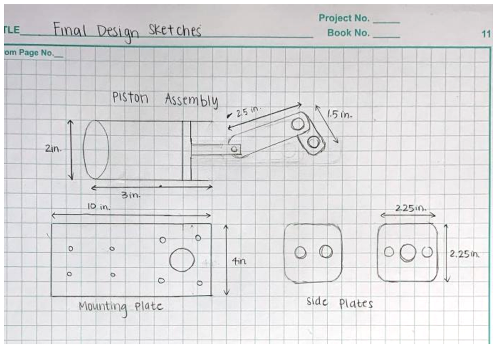
Sketches

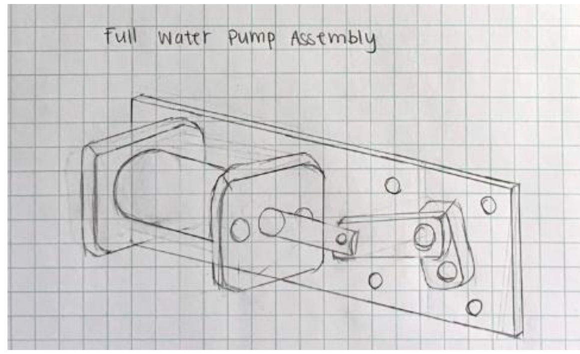
Below are the initial sketches of the pump. The test setup was not taken into account for this design.





Below are the final sketches of the pump that was made.



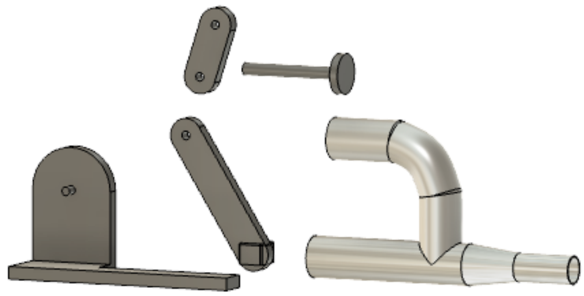


Paper Prototype

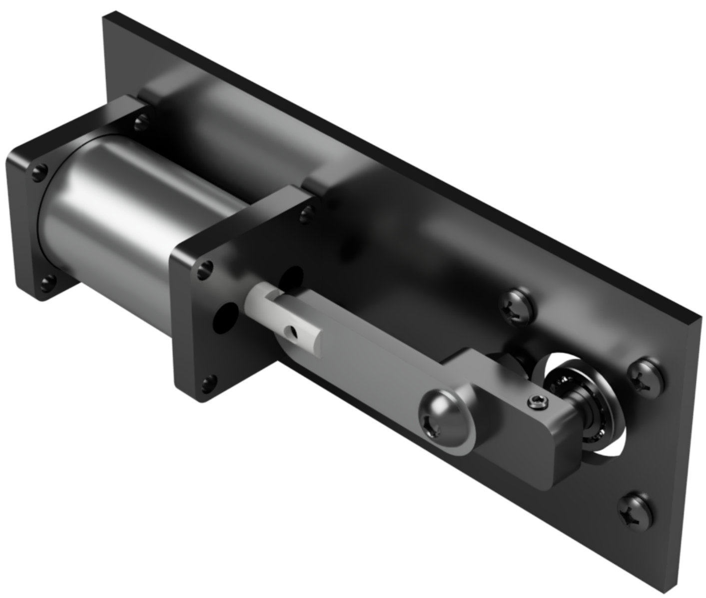
Below are pictures for the paper prototype of the piston pump.

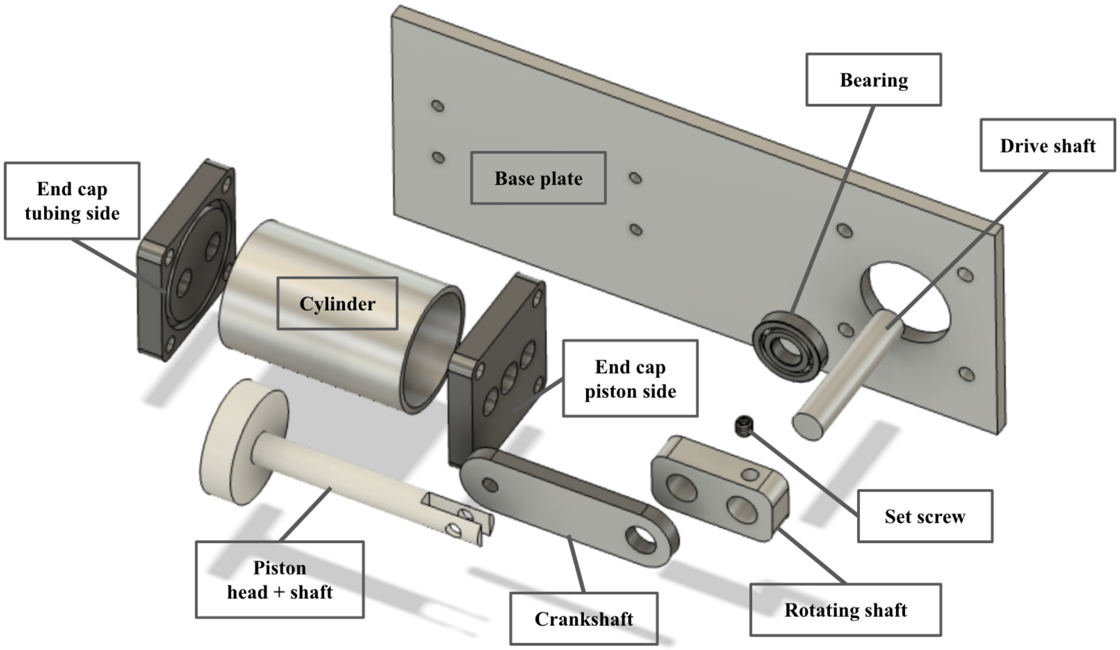
CAD Model

Below are the rendered and exploded views of the pump's initial design. The initial design was used to see how a slider-crank mechanism would work for a piston pump so did not take into account the test set up or rules for the project.



Below are the rendered and exploded views of the pump's final design.





Hardware included in the exploded view are the set screw that secures the drive shaft onto the rotating shaft, and the bearing that enables smooth rotation of the drive shaft that connects the pump to the sprocket. Hardware simply for mounting were not included in the view.

Challenges

The main challenges faced during the design phase was determining simple solutions to obstacles that were not reflected in the CAD model. At first, the team planned to have two inlets and two outlets on each side of the side plate, but during manufacturing, it found that the pipe fittings on one side would crash into the crankshaft. This reduced the overall pumping efficiency because the additional pipe fitting would have to be forfeited on that side. This mistake taught an important lesson to always have the full CAD to account for all parts of the geometry. Due to that change, the water pump was expected to lose around 50% efficiency. During the testing, the water pump achieved around 40 percent efficiency, so it was suspected that the other 10 percent was lost from water leaking out from the side plate. The teflon tape was placed on the pipe fitting to seal the threads and in the grooves of the side plate to minimize leakage. The sealing could be improved if there was more teflon tape in the groove or by exploring other methods.

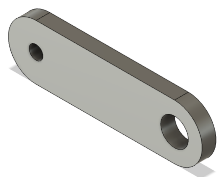
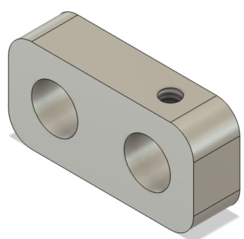
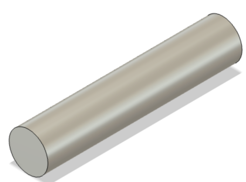
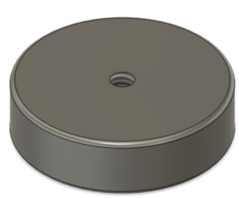
Other challenges include figuring out how things work in Fusion 360 such as putting in hardware and assembling parts. The design could have been enhanced by having smaller hardware when bigger ones are not necessary. During manufacturing, the wrong drill was used on a part which resulted in scrapping it. Overall, the challenges were overcome by collaborating with one another, allowing the team to be satisfied with the final product.

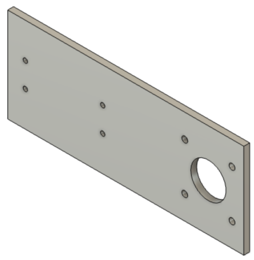
Fabrication Plan

Manufacturing

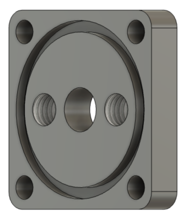
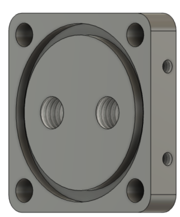
All parts of the pump were assigned to members of the group to be manually machined either on the mill or the lathe.

Below are the parts that were machined from stock:

Part name	Picture	Machinist	Brief description of machining process
Crankshaft (Aluminium)		Chen, Yoon	1. Face down stock 2. Drill through holes for bolts a. Step drill 0.5” hole 3. Round off edges with belt sander
Rotating shaft (Aluminium)		Yoon	1. Face down stock 2. Drill through holes for bolts 3. Drill & tap set screw hole (¼-20) 4. Round off edges with belt sander
Drive shaft (Steel)		Wisniewski, Yoon	1. Reduce length using drop saw 2. Round off edge with belt sander
Piston head (PVC)		Yoon	1. Reduce Radius 2. Drill & tap hole (¼-20) 3. Reduce length using cutoff tool 4. Round off edges with belt sander ● Low spindle speed to prevent PVC from melting
Piston shaft (Aluminium)		Chen	1. Reduce radius 2. Thread connection with head (¼-20) 3. Drill through holes for bolt 4. Make slot using end mill

Base Plate (Aluminium)		Moulia Arriola, Ho	1. Face down stock 2. Drill through holes for bolts

Below are the parts that were bought from Emerson lab that went through additional machining:

Part name	Picture	Machinist	Brief description of machining process
End cap piston side (Aluminium)		Wisniewski, Motto	1. Drill & tap ¼ NPT holes 2. Drill ½” hole for piston shaft 3. Drill and tap 3/16” holes for mounting
End cap fitting side (Aluminium)		Moulia Arriola, Ho	1. Tap pre drilled holes with ¼ NPT tap drill 2. Drill and tap 3/16” holes for mounting

There were a few problems that arose during machining. The initial idea was to machine the piston entirely in PVC, but once machined the end part with the hole and the slot was too flimsy. As a result, the piston head was machined in PVC and combined with an aluminum shaft to improve durability. Another problem was the piston getting jammed when the shafts rotate. The suction created by a tight fit between the piston head and the cylinder had to be compromised in order to fix this problem by sanding down the inside of the cylinder using a cylinder hone.

The method of mounting the end caps to the base plate also posed a challenge. The initial idea was to use long bolts that go through the end cap from the top, but this had two major problems. The clearance between bolts screwing the end caps onto the base plate and the bolts connecting the end caps on the cylinder would be too small, and machining such a small but long hole would be difficult. Eventually, the team decided to use ¾” ¼-20 bolts to screw the end caps onto the base plate from the bottom.

Refer to Appendix D. Project Management for more detail on the machining process.

Ordering Process

All orders from Emerson Lab and McMaster were processed through Teaching Assistants Adrien Antoinette and Jack St. Louis. All stock needed for machining/hardware needed for assembly were compiled onto a spreadsheet and sent to Antoinette and St. Louis. Parts were prepared to use by the next day.

Final Cost Analysis & Parts List

Below is the final Bill of Materials for the group's water pump bought from McMaster-Carr:

	A	B	C	D	E	F
11	**MCMASTER-CARR PARTS**					
12	**Description**	**McMaster Code**	**Quantity**	**# Extra**	**Unit of measurement**	**Total Cost**
13	Ball Bearing Open, Trade Number R8, 1/	6383K45	1		ea	$ 6.75
14	18-1 Stainless Steel hex Head Screws (p	92240A561	1		ea	$ 6.64
15	Mil. Spec. Alloy Steel Cup-Point Set Scre	98637A410	1		ea	$ 4.42
16						
17	TOTAL					$ 17.81

Below is the final Bill of Materials for the group's water pump bought from Emerson Lab:

	A	B	C	D	E	F
28	**EMERSON LAB PARTS**					
29	**Description**		**Quantity**		**Unit of measurement**	**Total Cost**
30	1 7/8" Diameter Plastic Rod (Piston)		3		in	$ 2.58
31	3/4" Diameter x 6" Aluminum Rod		1		ea	$ 2.50
32	1/4" x 1" Aluminium Bar (for crankshaft)		4		in	$ 0.56
33	1/2" x 2 1/4" Aluminium Bar (for rotating shaft)		3		in	$ 2.19
34	1/2" Diameter steel rod (for driveshaft)		6		in	$ 1.38
35	Machined End Caps (Two Holes)		2		ea	$ 2.00
36	Machined End Caps (Blank)		1		ea	$ 1.00
37	Bored Cylinder, 3"		1		ea	$ 1.00
38	1/2" x 4" Aluminium Bar (for Base Plate)		10		in	$ 11.80
39	Nylon pipe fittings (3/8" barbed x 1/4" NPT)		4		ea	$ 2.20
40	1/4-20 hex nuts		20		ea	$ 1.20
41	1/4" flat washers		5		ea	$ 0.10
42	1/4-20 x 1" cap screws SHCS		10		ea	$ 1.70
43	1/4-20 x 3/4" cap screw SHCS		4		ea	$ 0.60
44						
45						
46	TOTAL					$ 30.81

The completed product was well under the budget provided, which was \$30 for McMaster-Carr parts and \$45 for Emerson parts. Unused stock was returned to the shop and therefore not included in final expenses.

Timeline

Given the three weeks for the project, it seemed most reasonable to spend the first week finalizing the design and ordering parts/stock, the next week machining, and the final week assembling and completing additional machining if needed. After the design was finalized, all parts needed were compiled onto a sheet and ordered for machining to happen promptly. Machining and assembling happened simultaneously - parts were put together as they were machined to find parts that needed to be re-machined or altered.

Refer to the Appendix D. Project Management for the Gantt chart and manufacturing sheet used.

Power Calculations

Before starting the manufacturing process, calculations were done to verify that the dimensions were enough to satisfy the 1 liter per minute requirement:

$$Q = s \times A \times \omega_{out},$$

where

$$\begin{aligned} Q &= \text{flow rate } (\mathrm{m^3 s^{-1}}) \\ s &= \text{stroke length of piston head (m)} \\ A &= \text{cross sectional area } (\mathrm{m^2}) \\ \omega_{out} &= \text{output angular velocity } (\mathrm{rads^{-1}}). \end{aligned}$$

The cross sectional area and the stroke length can be calculated using the dimensions of the design, and the output angular velocity ω_{out} can be calculated using the motor input rpm (900) and the sprocket ratio (9/70) provided.

$$\begin{aligned} s &= 2.5 \text{ in} \\ &= 0.064 \text{ m} \\ A &= \pi \times (1.75 \text{ in})^2 \\ &= 2.41 \text{ in}^2 \\ &= 0.00155 \text{ m}^2 \\ \omega_{out} &= (\text{motor input rpm} \times \text{sprocket ratio})/60 \\ &= \frac{900 \times (\frac{9}{70})}{60} \\ &= 1.93 \text{ rads}^{-1} \end{aligned}$$

Using these numbers,

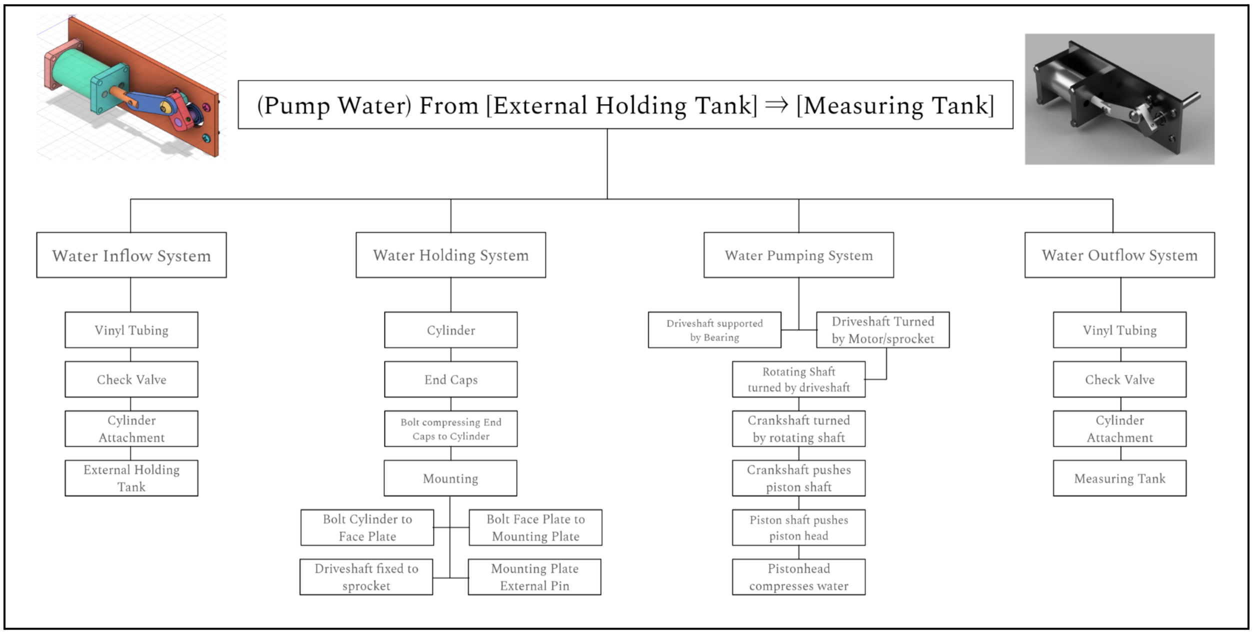
$$\begin{aligned} Q &= 0.064 \times 0.00155 \times 1.93 \\ &= 0.000190 \text{ m}^3\text{s}^{-1} \\ &= 11.4 \text{ Lmin}^{-1}, \end{aligned}$$

and it can be concluded that the pump should meet the requirement. However, a much lesser flow rate is expected in reality because of leaking due to tolerance stack up during machining.

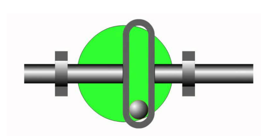
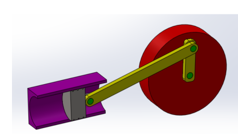
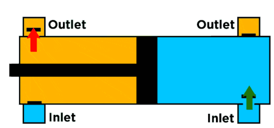
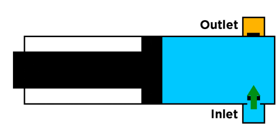
While the output rpm calculated with the given specs was about 115.7, the actual output rpm of the motor during testing was about 65, meaning the expected flow rate was **6.4 Lmin^{-1}**.

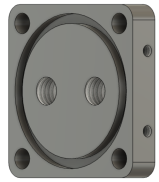
Functional Decomposition and Morphological Chart

Functional decomposition



Morphological Chart

Reciprocating Motion	 Scotch Yoke	 Slider Crank
Piston Stroke	 Dual Action	 Single Action

Mounting System	 End caps & drill + tap mounting holes	 Mounting bracket
Piston Head/Shaft Material	PVC	Aluminum

Reflection

Performance Analysis

The pump was successful as it pumped 2.8 liters in one minute, completing the task of pumping 1 liter per minute. The success of the project was due to a variety of reasons: one being that the tolerances were acknowledged in the design. When manufacturing parts, especially parts that integrate or are moving parts, the thousandths of an inch can make a large difference in the assembly and testing of the part. With this in mind, the parts would need to be methodically and slowly produced so that there would not be integration issues, which could result in the part needing to be revised, replaced, or failing in the testing process. By also calculating the flow rate in advance, while also acknowledging the tolerances, it could be predicted how well the water pump would function; essentially, giving room for error when the real product was made. If the calculations predicted a flow rate close to 1 liter per minute, the design would need to be further improved because it would not allow any room for error. Having the calculations be around 6.4 liters per minute gave ample room for error in the production process, continuing with the current design and measurements.

Another reason for success was testing the integration of the product together as it was being manufactured. Whenever there were integration issues, there was ample time to revise them as the other parts were being manufactured. If the parts were not integrated until the testing day, there would have been multiple issues, and ultimately not have been able to test the product.

Learnings

By sticking to the deadlines, attending the weekly meetings, and communicating with one another about the challenges faced or milestones completed, the team was successful in the project. By utilizing the group chat, the team communicated what times would be best to meet in person in Duffield to discuss the aspects of the project. When a member was sick, the utilization of Zoom allowed team members to communicate in real-time about the issues/topics that were being discussed. Even when facing unexpected obstacles in people's schedules, the team still made sure to find different ways to stay on track with the schedule made. In terms of time management, following the Gantt chart and Manufacturing sheet, the team was able to stay on track with the parts being manufactured or ordered, allowing ample time to test the integration of parts well before testing day. On days that a part would need more time to be manufactured, the team scheduled the next available work shift so the part could still be completed on time. The allowed time in the schedule made sure that there was ample time to manufacture the parts, especially if the parts were to take multiple days. The only complication that the time management gave was that the schedule did not have ample time to test fit the entire system onto the test setup before testing day. This resulted in the shaft of the pump running into the mount behind the sprocket. However, since this was a fairly simple issue, the shaft was cut into an improved size, fitting into the mechanism perfectly. By testing the integration of the other parts together well in advance, there were no other issues. If other issues were to be found with the water pump on testing day, there would not have been time to correct them and test the water pump on the same day. Staying on track with the schedule was essential to the success of the water pump being manufactured and tested properly.

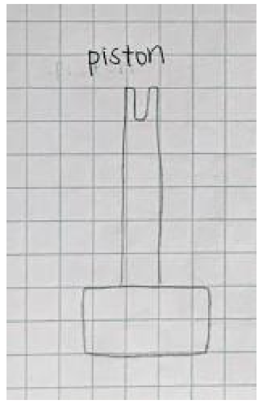
Ultimately, this project demonstrated the importance of time management and delegating tasks. When working on a team, it is necessary to create and adhere to a robust and well thought out timeline, but it is equally as important to adapt to the ever changing circumstances and allow for flexibility. As mentioned prior, a large contributor to the success of the project stemmed from adhering to deadlines while skillfully adjusting to unforeseen setbacks. Additionally, it is best to be conservative with deadlines when planning out a schedule as it is possible that the team runs into obstacles that take longer than expected to resolve.

An additional learning from this project was the importance of focusing on the process rather than the results. Although the team was overjoyed that the water pump was successful during the testing phase, it is important to acknowledge that the goal of this project was to focus on the actual process rather than the final results. All team members acquired or honed in on their technical skills regarding the design, manufacturing, and assembly processes, and additionally gained newfound insight on working and communicating effectively on a team. Thus, the project was a success regardless of the final outcome, as all members grew from this learning experience.

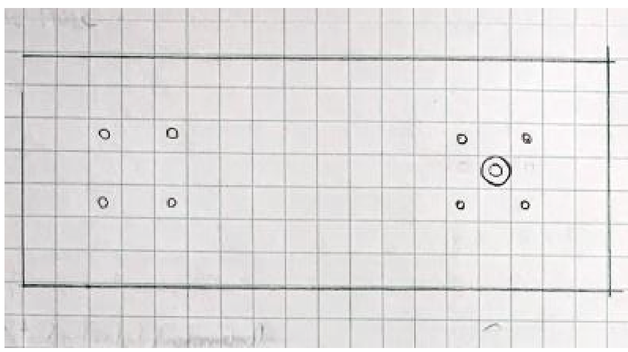
Appendix

A. Sketches

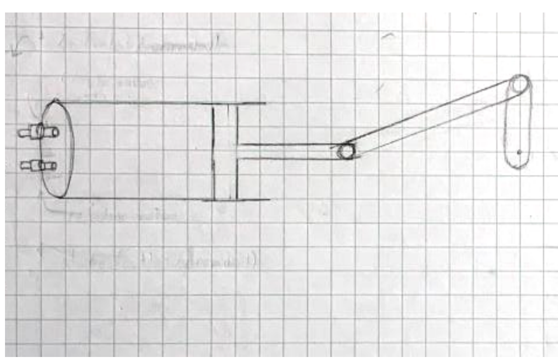
A.1 Piston



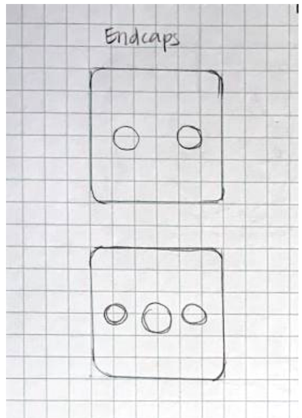
A.2 Mounting Plate



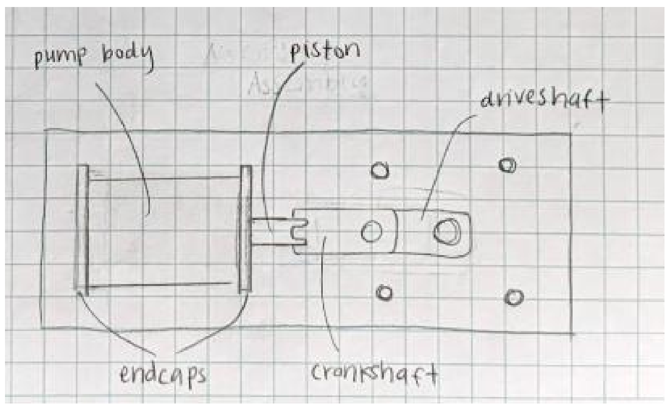
A.3 Piston Assembly



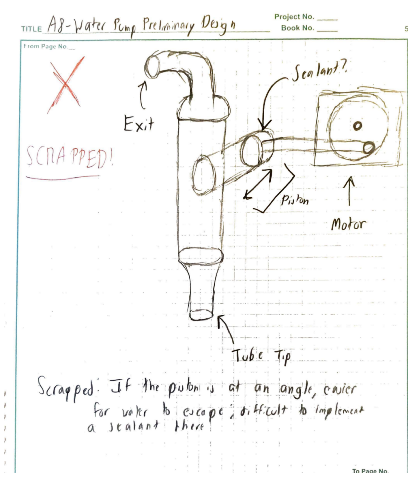
A.4 End Caps



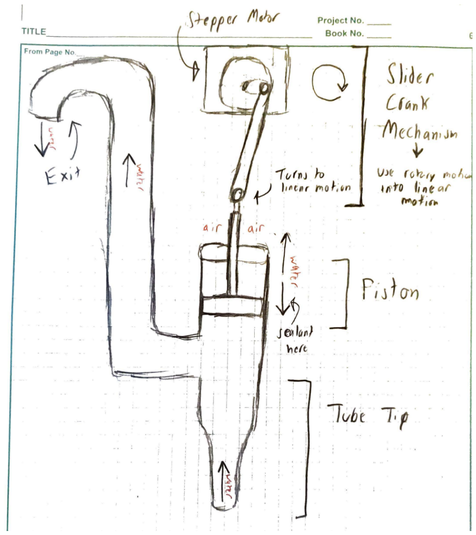
A.5 Full Assembly



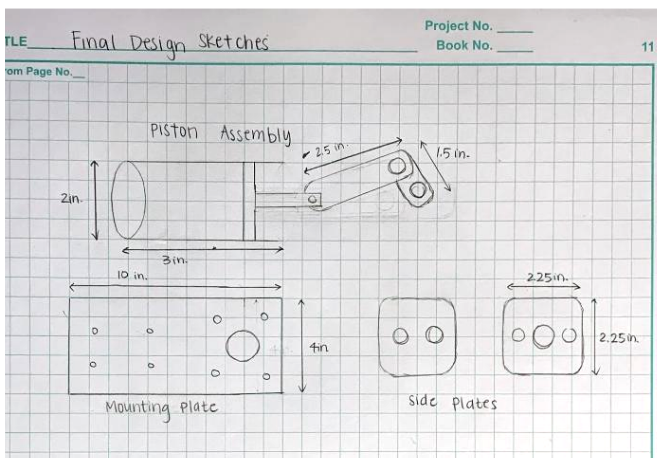
A.6 Preliminary Sketches 1



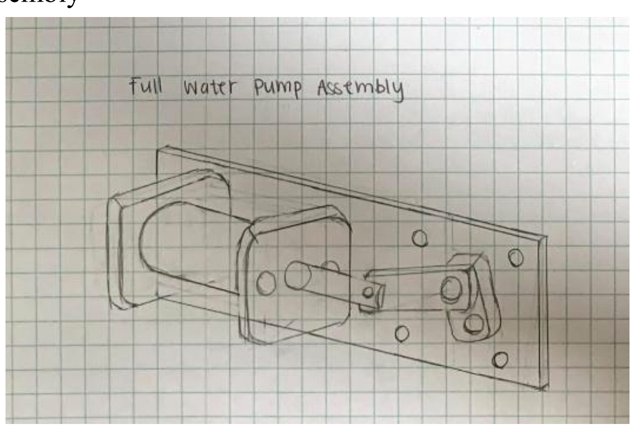
A.7 Preliminary Sketches 2



A.8 Final Design Sketches

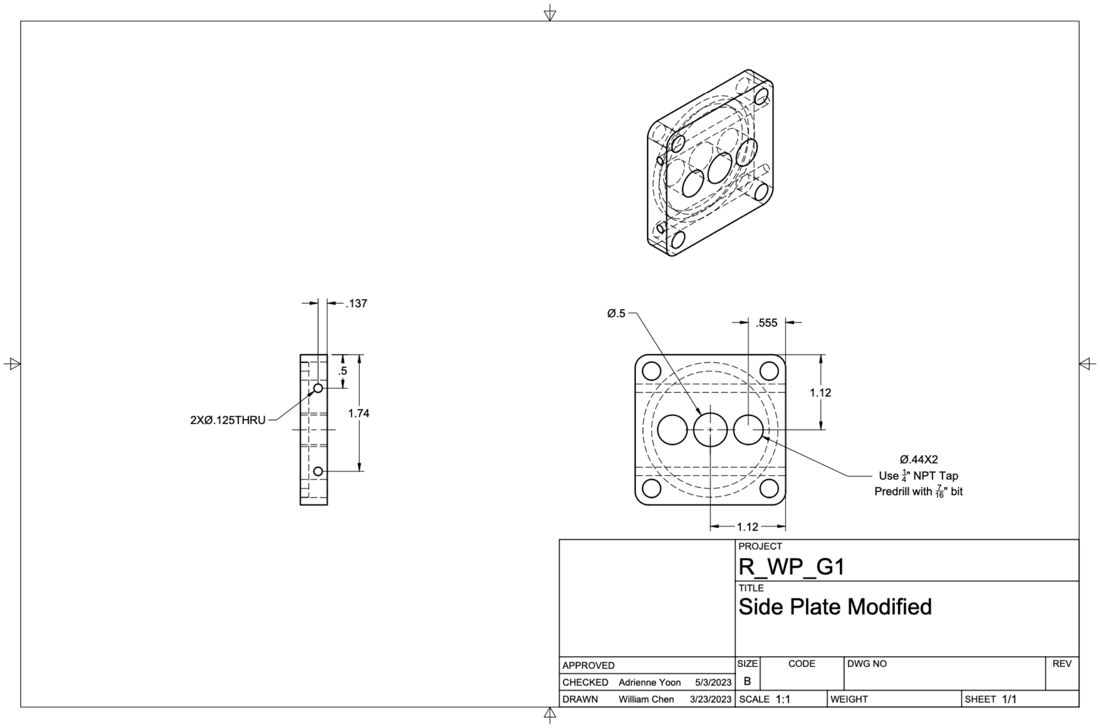


A.9 Final Water Pump Assembly

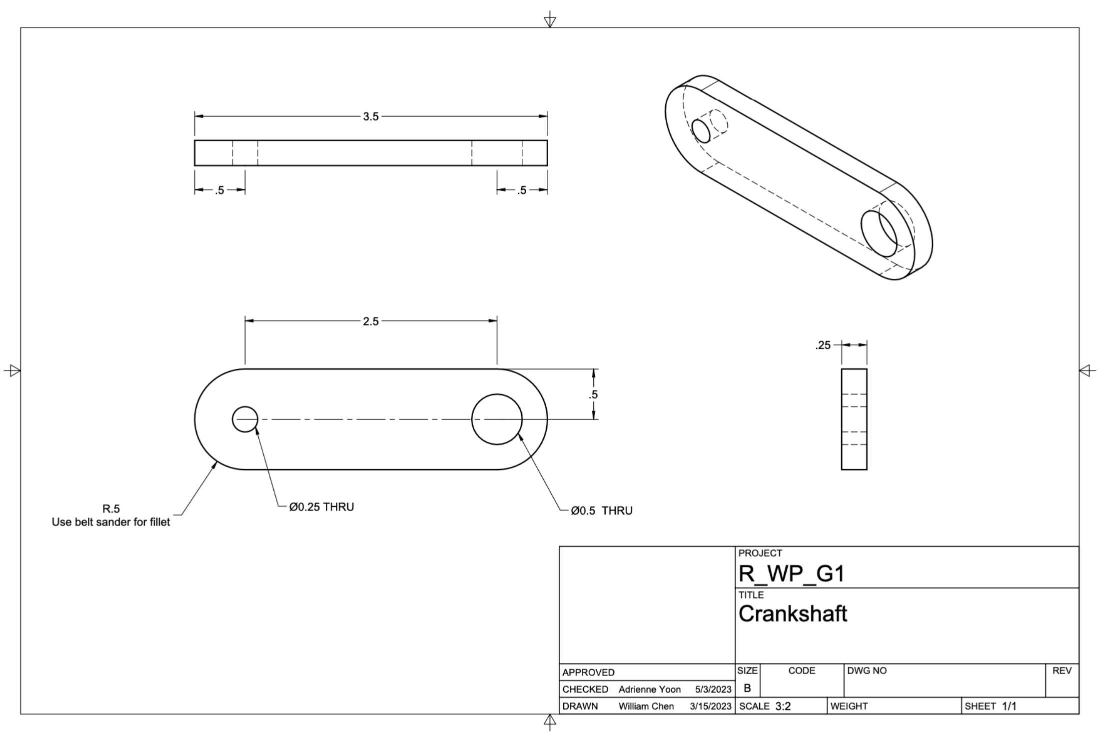


B. Part Drawings

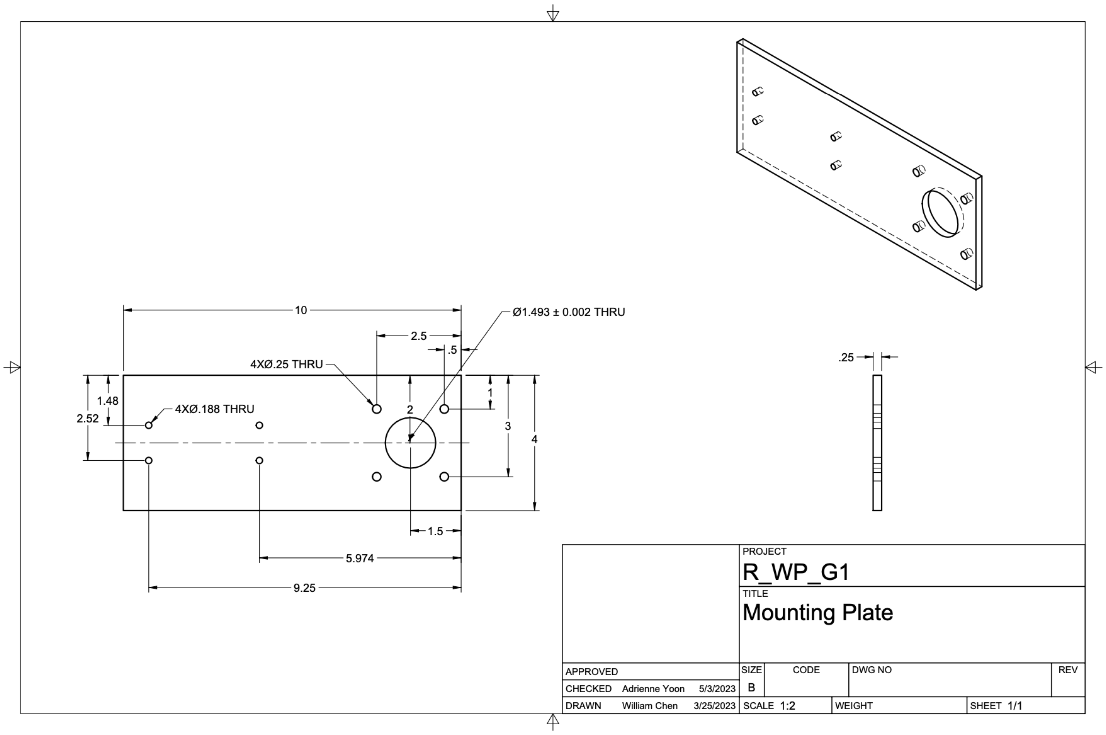
B.1 Side Plate Modified Drawing



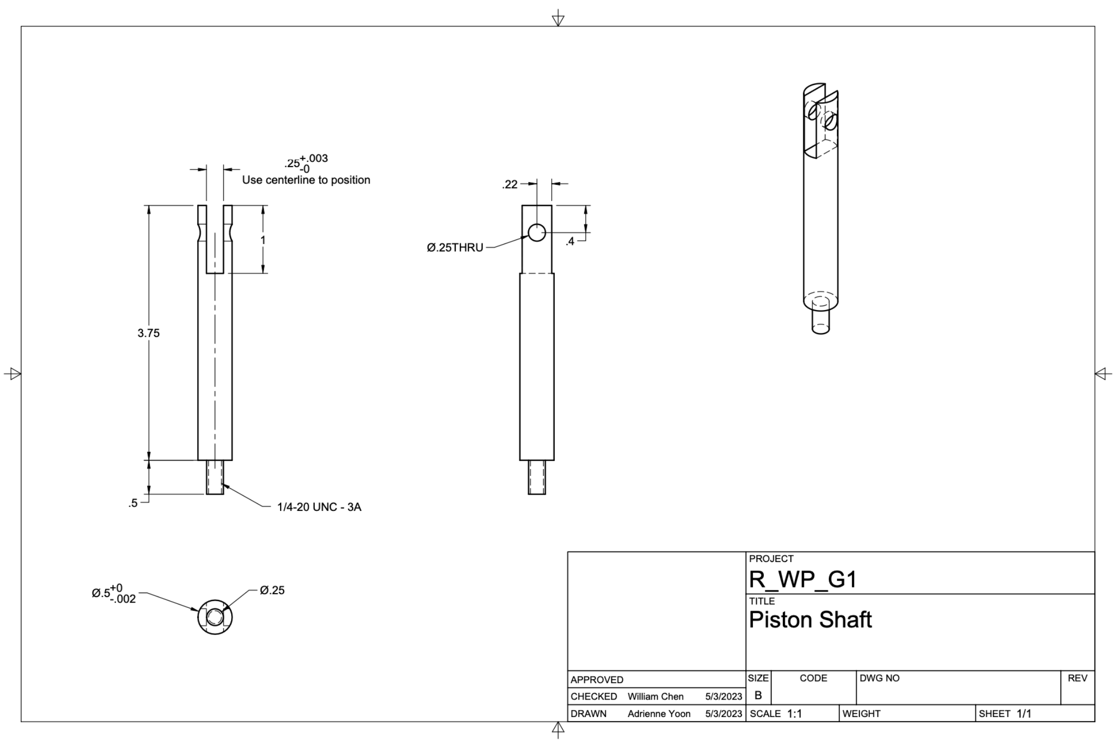
B.2 Crankshaft Drawing



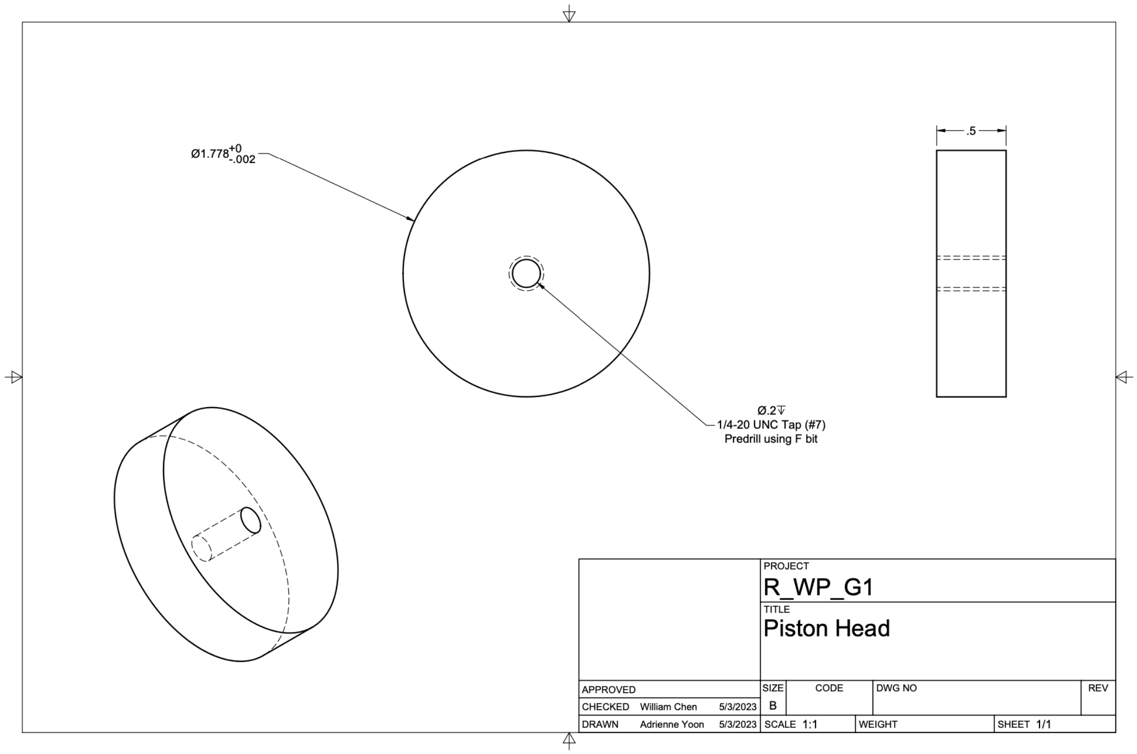
B.3 Mounting Plate Drawing



B.4 Piston Shaft Drawing



B.5 Piston Head Drawing



C. Team Charter

Team Charter Group 1

FROM: Nevin Motto, William Chen, Eileen Ho, Adrienne Yoon, Tyler Wisniewski, Katlyn Moulia

TO: Professor Shepherd, Akane Shirota , Jack St. Louis , Emilie Baker, Matt Menis, Adrien Antoinette

RE: Team Charter

DATE: 3/9/2023

Team ID/Names

Name	Preferred Email	Phone Number
William Chen	yc876@cornell.edu	346-303-6976
Nevin Motto	nam96@cornell.edu	609-216-1600
Eileen Ho	ech225@cornell.edu	408-425-3654
Adrienne Yoon	yay8@cornell.edu	253-553-7445
Katlyn Moulia Arriola	kgm49@cornell.edu	561-707-8486
Tyler Wisniewski	ttw24@cornell.edu	732-444-7432

Team Logistics and Coordination

The team will distribute documents using Google Drive. All documents and relevant files should be placed in the folder for team members to reference. A shared Autodesk Fusion 360 folder named R_WP_G1 has also been created for members to share CAD designs and files. Team members are expected to review updates to the team folder when notified that new files have been added.

A texting group chat has been created for communication purposes. On days that in-person meetings have not been scheduled, members should notify the progress of each aspect of the project via the chat. Team members will be expected to check the group chat regularly during non-class times (after 3:00 pm) and provide updates leading up to and following meetings. In-person meeting times will be decided based on the results of a When2Meet.

Outside research sources will be stored in the shared document labeled "Research Material". The member that adds a source is responsible for writing a short annotation describing the relevance. The website "EasyBib" will be used to create citations.
Meetings will be held in Duffield Hall from 8 - 10 pm on Sunday, Monday, and Tuesday. Members that cannot physically attend the set meeting times should be expected to connect online via Zoom.

Teamwork and Collaboration

Specialized Skills by Member:

Name	Skills
William Chen	CNC machining, Solidworks, manufacturing in composites, power tools, welding
Nevin Motto	Solidworks, Fusion 360, designing packaging
Eileen Ho	Fusion 360, ordering parts, design sketching
Adrienne Yoon	Fusion 360, Autodesk Inventor CAD, machining
Katlyn Moulia Arriola	Solidworks, Fusion 360, ordering parts, ordering 3D printed parts, machining, composites manufacturing, leadership skills
Tyler Wisniewski	Fusion 360, Autodesk inventor, composites manufacturing, cardboard supplier

Leader
The leader, Moulia Arriola, will set the goals for each week of what must be done. The leader will also set the responsibilities for the members and keep track of if the members are making progress. They are the initial contact of problems that arise and responsible for making sure those problems are solved. The leader will be the one to assign which people to machine and remind members of important deadlines and tasks.

Design Integrator
The design integrator, Chen, will be the one to keep track of the parts that are ordered and received. They are the direct contact for ordering parts. They are responsible for making sure that the parts are the correct size and making sure everything fits together. They are also responsible for checking the tolerance of the machined parts. They must keep track of the parts that are being printed and keep in contact with the Rapid Prototyping Lab (RPL).

Other Responsibilities
Other responsibilities would be designing and manufacturing the actual parts. The design will be divided into three main parts: designing the piston, the test setup, the slider crank mechanism, the primary seal on the head of the piston and secondary on the shaft. Everyone in the group should participate in the design phase. After the design is completed, Yoon will make drawings for machined parts after Motto has made

revisions in the CAD. All non-leader members, (Wisniewski, Ho, Motto, and Yoon) are required to machine parts. Another important aspect is budgeting which Yoon will be in charge of - it is Yoon's responsibility to make sure the team does not go over budget. Moulia Arriola will be responsible for testing the pump once it has been completed.

Team Consequences

The first time a team member fails to meet team expectations, the individual will be required to bring snacks for members to share during the next in-person meeting. Failing to meet expectations includes arriving late to an in person meeting without notice, failing to complete an assigned aspect of the project by our internally set deadlines, or communicating poorly regarding the status of an aspect of the project. If the problem progresses, the other members will give the team member failing to meet expectations opportunities to make it up to the group by asking the member to improve their habits. If it continues to be a frequent issue, the other team members will reach out to the lab TAs Shirota or St. Louis to help resolve the issue.

For grade-impact consequences, such as a member missing hard deadlines that require submission of documents, evidence of the member's missed responsibilities, through the form of screenshots and other online files, will be sent by email to Professor Hoffman. The lab TAs, Shirota and St. Louis, along with the remaining members of the team, will be CC'd in this email. The team leader and design integrator, Moulia Arriola and Chen, will be responsible for facilitating this communication.

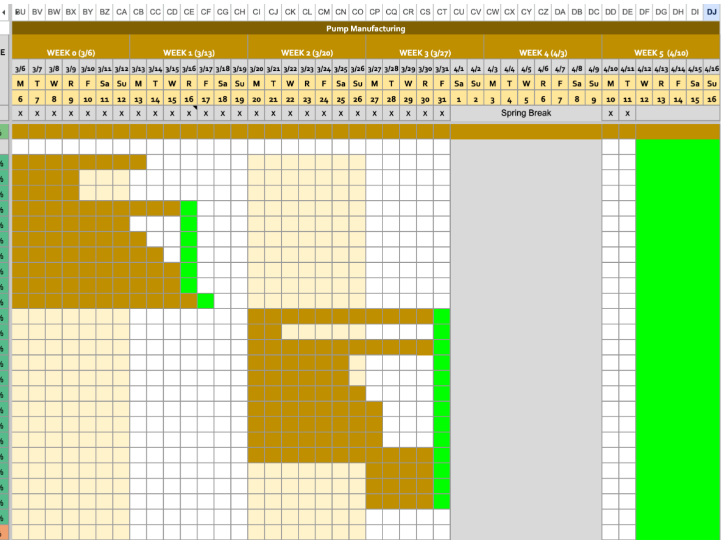
Expected Outcomes

The team has held a discussion on the desired outcomes of the project. Each member has expressed the grade they wish to receive for this water pump project. These expectations have been understood by all team members.

D. Project Management

D.1 Gantt Chart

	B	C D E	F	G	H	I	J	K
1	5/5/2023							
2	#	TASK TITLE	TASK OWNER	START DATE	DUE DATE	DAYS LEFT	STATUS	% DONE
7	P1	Water Pump Design Project		1/4/23	5/16/23	11	IN PROGRESS	89%
9								
10	P1.1	Preliminary Design	All	3/5/23	3/13/23	--	DONE	100%
11	P1.1.1	R&D	All	3/5/23	3/9/23	--	DONE	100%
12	P1.1.2	Slides	All	3/5/23	3/9/23	--	DONE	100%
13	P1.2	A9 - Water Pump Final Design Review	All	3/5/23	3/15/23	--	DONE	100%
14	P1.2.1	Finalize design	All	3/5/23	3/12/23	--	DONE	100%
15	P1.2.2	CAD Model	Will, Adrienne	3/5/23	3/13/23	--	DONE	100%
16	P1.2.3	Paper Model	Nevin, Tyler	3/5/23	3/14/23	--	DONE	100%
17	P1.2.4	Slides	All	3/5/23	3/15/23	--	DONE	100%
18	P1.2.5	Misc	All	3/5/23	3/15/23	--	DONE	100%
19	P1.3	A10 - Team Charter	All	3/5/23	3/16/23	--	DONE	100%
20	P1.4	Manufacturing	All	3/20/23	3/30/23	--	DONE	100%
21	P1.4.1	Purchasing	Adrienne	3/20/23	3/21/23	--	DONE	100%
22	P1.4.1	Machining	All	3/20/23	3/30/23	--	DONE	100%
23	P1.4.2.1	Crankshaft	Will, Adrienne	3/20/23	3/25/23	--	DONE	100%
24	P1.4.2.2	Rotating Shaft	Will, Adrienne	3/20/23	3/25/23	--	DONE	100%
25	P1.4.2.3	Piston	Will, Adrienne	3/20/23	3/26/23	--	DONE	100%
26	P1.4.2.4	Side Plate	Katlyn, Eileen	3/20/23	3/27/23	--	DONE	100%
27	P1.4.2.5	Side Plate for Piston	Nevin, Tyler	3/20/23	3/27/23	--	DONE	100%
28	P1.4.2.6	Base Plate	Katlyn, Eileen	3/20/23	3/27/23	--	DONE	100%
29	P1.4.2.7	Drive Shaft	Will, Adrienne	3/20/23	3/30/23	--	DONE	100%
30	P1.5	Assembly	Will	3/27/23	3/30/23	--	DONE	100%
31	P1.5.1	Slider Crank Assembly	Will	3/27/23	3/30/23	--	DONE	100%
32	P1.5.2	Piston Assembly	Will	3/27/23	3/30/23	--	DONE	100%
33	P1.6	Testing	All	5/4/23	5/4/23	--	DONE	100%
34	P1.7	A11 - Final report	All	5/5/23	5/16/23	11	IN PROGRESS	20%

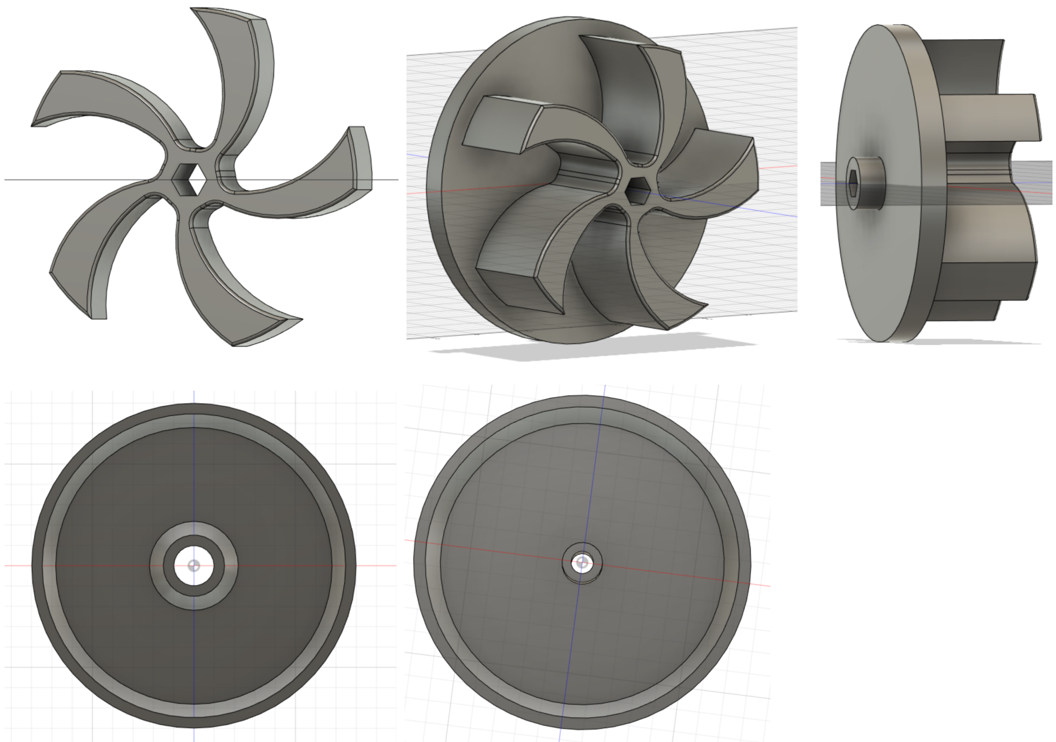


D.2 Manufacturing Sheet

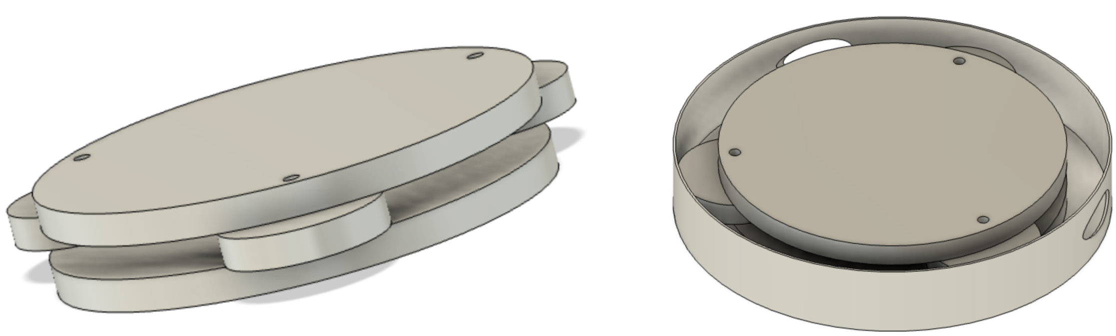
	A	B	C	D	E	F	G	H
3	Part Name	QTY	Machine (Mill, Lathe, CNC)	Difficulty	Machinist	Target Completion Date	Status	Notes
4	Base Plate	1	Mill	1 - Red Apron	Eileen, Katlyn	3/27/2023	Completed	Just a few thru holes
5	Crankshaft	1	Mill	1 - Red Apron	Will, Adrienne	3/25/2023	Completed	Step drill (1/4" > 7/16" > 1/2") Slow down RPM if drill makes noise Be gentle when peck drilling, the bit might get stuck in the hole
6	Rotating shaft	1	Mill	1 - Red Apron	Will, Adrienne	3/25/2023	Completed	Set screw hole: 1/4-20 tap, use number 7 bit for pre-drill 0.5 inches from side, 0.25 inches from bottom Don't forget accounting for 0.1 in of edge finder when zeroing and using center drill before actually drilling
7	Piston head	1	Lathe	1 - Red Apron	Will, Adrienne	3/30/2023	Completed	1/4-20 tap
8	Piston shaft	1	Mill+Lathe	1 - Red Apron	Will, Adrienne	3/30/2023	Completed	1/4-20 thread
9	End cap piston side	1	Mill	1 - Red Apron	Nevin, Tyler	3/27/2023	Completed	Tap 2 holes with 1/4 NPT tap, step drill 1/2" hole
10	End cap pipe side	1	Mill	1 - Red Apron	Eileen, Katlyn	3/27/2023	Completed	Tap 2 holes with 1/4 NPT tap

E. Other Preliminary Designs (A8 & A9)

E.1 Centrifugal Pump



E.2 Peristaltic Pump



Both pumps were not chosen due to the complexity of the design: both have parts that would have had to be manufactured either using a CNC machine, which is costly, or 3d printing, which is unreliable for a fast spinning motor.

F. References

1. Agarwal, Tarun. “Piston Pump: Working, Types, Advantages and Disadvantages.” *ElProCus*, 18 June 2019, https://www.elprocus.com/piston-pump-working-and-different-types/.
2. “All about Axial Piston Pumps - What They Are and How They Work.” *Thomasnet® - Product Sourcing and Supplier Discovery Platform - Find North American Manufacturers, Suppliers and Industrial Companies*, https://www.thomasnet.com/articles/pumps-valves-accessories/all-about-axial-piston-pumps/.
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4. Sales , Lubetec. “Advantages and Disadvantages of a Piston Pump.” *Lubetec UK*, 21 Jan. 2021, https://lubetec.co.uk/blogs/news/advantages-and-disadvantages-of-a-piston-pump#:~:text=As%20well%20as%20the%20above,a%20machine%2C%20regardless%20of%20viscosity.
5. Team, Linquip. “4 Main & Practical Types of Piston Pumps.” *Linquip*, 5 Sept. 2022, https://www.linquip.com/blog/types-of-piston-pumps/.