Team 24: Magnetically Coupled Pump System for Cryogenic Propellant Tank Destratification

FAMU/FSU College of Engineering
Department of Mechanical Engineering

Final Report

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Due Date:
4/10/2015

Submitted to:
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Team Member Biography's

Matthew Boebinger (Team Leader): Matthew is a senior mechanical engineering student that is specializing in mechanics and materials engineering at Florida State University. After graduating in Spring 2015 with his Bachelors of Science in Mechanical Engineering, he plans on pursuing a Master's degree and then a Doctoral degree in materials engineering.

Kahasim Brown: Kahasim is a senior mechanical engineering student specializing in thermal fluid and aerospace sciences with a minor in Business Administration. After graduating he plans on receiving his professional engineering degree while sharpening his mechanical tools development and starting a business hosted in his hometown.

Anthony Ciciarelli: Anthony is a senior mechanical engineering student with a focus in thermal fluids at Florida State University. He will graduate in the spring 2015 with a Bachelor of Science in Mechanical Engineering. After graduation he plans on pursuing a full time job in the industry, obtaining his MBA, and obtaining a professional engineering license.

Janet Massengale: Janet is a senior mechanical engineering student specializing in thermal fluid sciences at Florida State University. This is her second year as the treasurer of ASME. She is also the webmaster for both the SWE and AIAA. Upon graduation she plans to work in the pulp and paper industry and obtain a professional engineering license.

Acknowledgement

The team would like to acknowledge faculty advisor Dr. Wei Guo, as well as Ram Dhuley, Jim Martin, and James Smith for their assistance and knowledge in the team's success. Additional acknowledgements to Dr. Gupta and Dr. Shih for their constructive feedback on the teams project throughout the semester. We would also like to thank the machine shop machinists, especially James Gillman and Jeremy Phillips for their suggestions and help in fabricating a functional prototype.

Abstract

Liquid cryogenic propellants such as liquid hydrogen and liquid oxygen are used as fuel and its oxidizer in rocket engines. These cryogens are stored for long periods of time before use. NASA Marshall Space Flight Center is in need of another way to mix these liquid propellants to reduce the pressure rise and heat addition within the system. Currently, the system in place is a motor-pump unit completely submerged inside a cryostat. In order to remove the waste heat from the motor entering the tank, the task is to design a pump system prototype that incorporates magnetic coupling technology allowing the motor to be removed from the tank while still destratifying the thermal layers. A completed prototype has been constructed and meets the design specifications set by the sponsor. Upon completion of the prototype, the pump system was tested in water creating a range of volumetric flow rates from 0 – 16 gpm at varying speeds. After the completion of testing the system in water, the system was tested in liquid nitrogen to see if it was practical for use in cryogens. Although the flow rate could not be tested, proof of concept was demonstrated by measuring the frequency of the pressure relief valve concluding the system successfully demonstrates destratification.

1. Introduction

NASA Marshall Space Flight Center is in need of another way to mix liquid propellants such as liquid hydrogen and liquid oxygen to reduce the pressure rise and heat addition within the system. These cryogenic propellants are liquefied gasses stored at low temperatures and are used to create thrust in rocket engines. Currently and previously, the mixing process consists of using AC single and 3-phase motor systems which are directly coupled to a pump and placed within the tank itself or mounted to a flange with the motor operating in a submerged condition. A block diagram of the current system can be seen in Figure 1. Using this method, the waste heat from the motor is being transferred into the tank causing a rapid pressure rise. Also the feedthroughs or connectors may create leak paths for potential failure of the system, and it is expensive to develop such motors to operate in these low temperature conditions. The purpose of this project is to reduce the heat added to the cryogenic system while effectively mixing the cryogenics to uniform temperature.

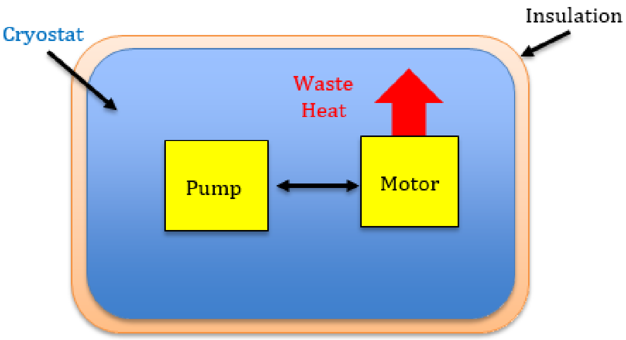


Figure 1: Block diagram of current system

4.1 Objective

NASA has given us the task to design, fabricate, and test an electric motor-pump unit that makes use of magnetic coupling technology. This will allow the position of the motor to be on the outside of a cryogenic tank, thus removing the waste heat created by the motor and still providing sufficient pumping pressure/flow in both water and liquid nitrogen. A simple block diagram of the system can be seen in Figure 2. As seen, the motor and power supply are placed outside of the cryostat. Each set of magnets are positioned inside and outside the cryostat coupled together by alternating poles. Once the motor is turned on by the power supply, the outside magnets will rotate, which will in turn rotate the inner magnets at the same speed. Attached to the inner coupler is a pump system that will pump the fluid in a cyclical motion creating destratification.

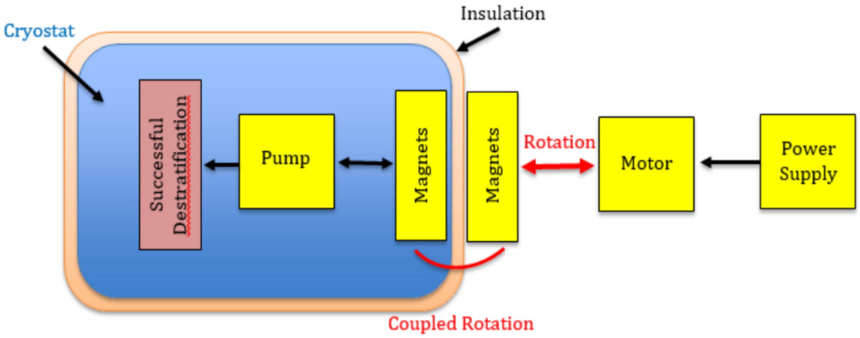
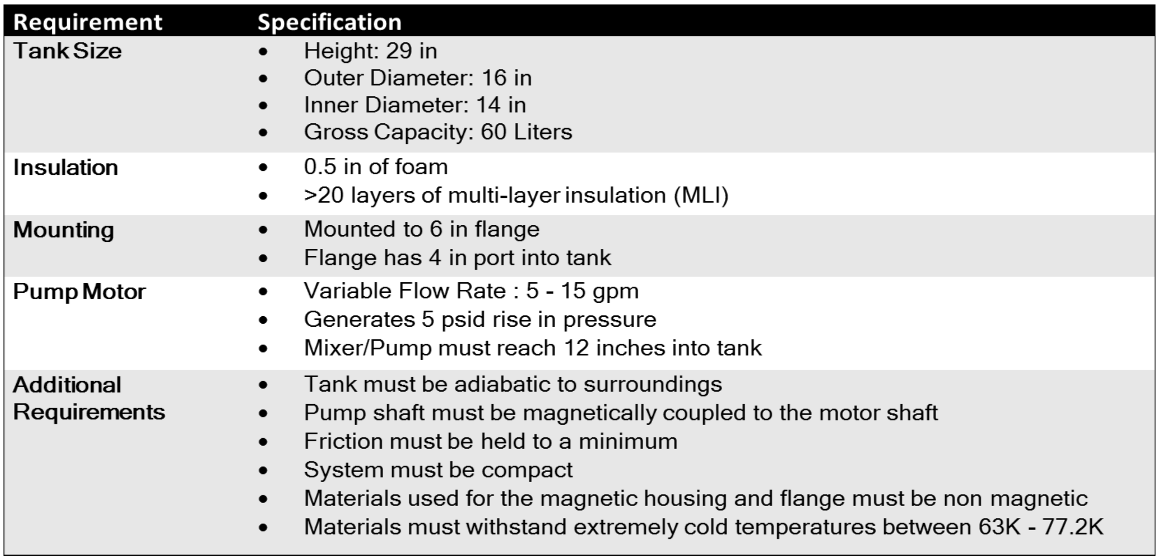


Figure 2: Block Diagram of system incorporating magnetic coupling technology

1.2 Design Specifications

The design specifications of the system are broken down as the tank specifications that must meet the requirements of the sponsor. The pump system must meet the constraints of the tank and its port and be portable to similar cryostats. The cryogenic tank that will be used in the project is the Cryofab CF 1424-F cryostat, and the design must be able to attach to a 6 inch ConFlat flange and must be able to fit inside a 3.75 inch port. With the size constraints, the design must also be compact, portable, and needs to attach to the top of the cryostat. Since the design will be used for multiple tanks, it needs to be compatible with current tanks. Also, the motor-pump unit must make use of magnetic coupling technology and the pump system must produce a volumetric flow rate of 5-15 gpm, and be tested in water and liquid nitrogen. Table 1 shows all design specifications for the project.

Table 1: Design Specifications



Requirement	Specification
Tank Size	• Height: 29 in • Outer Diameter: 16 in • Inner Diameter: 14 in • Gross Capacity: 60 Liters
Insulation	• 0.5 in of foam • >20 layers of multi-layer insulation (MLI)
Mounting	• Mounted to 6 in flange • Flange has 4 in port into tank
Pump Motor	• Variable Flow Rate : 5 - 15 gpm • Generates 5 psid rise in pressure • Mixer/Pump must reach 12 inches into tank
Additional Requirements	• Tank must be adiabatic to surroundings • Pump shaft must be magnetically coupled to the motor shaft • Friction must be held to a minimum • System must be compact • Materials used for the magnetic housing and flange must be non magnetic • Materials must withstand extremely cold temperatures between 63K - 77.2K

2. Background Research

Propellants are chemical mixtures that are burned to produce thrust in rockets and consist of the fuel and an oxidizer and are usually specified according to their state. Liquid propellants are classified into three groups: petroleum, cryogens, and hypergols, and are mostly used for longer flight durations and do not produce as much thrust as solid propellants [1]. Cryogenic propellants are liquefied gasses stored at very low temperatures and most frequently use liquid hydrogen (fuel) and liquid oxygen (oxidizer). In a liquid propellant rocket, the fuel and oxidizer are kept separately in two storage tanks and are fed through a piping system to the combustion chamber. Once in the combustion chamber these propellants are combined and burned to produce thrust. The combustion of these propellants happens in milli-seconds and can produce combustion instabilities at low, intermediate, and high frequency. One of the advantages to using liquid propellants rather than solids is that the flow of the propellant to the combustion chamber can be controlled.

Due to the low density of these propellants, they require large storage tanks and need to be stored for long periods of time before they are sent to the combustion chamber. The storage tanks for liquid cryogens require thermal insulation to decrease heat leak into the tank. Inside the tank, stratified layers build up in the tank causing the cryogens to boil, thus causing the pressure to rise and the tank to vent. When the rocket is in low gravity conditions, the position of the liquid and the vapor (ullage) is not known, so when the tank needs to vent out the pressure, there could be potential propellant loss.

To reduce the pressure rise due to the stratified layers that form inside the cryogenic tank, they can be mixed causing the destratification of these layers allowing for the temperature inside the tank to remain homogeneous. This allows for a lower rate of boiling and less venting.

To decrease heat leak from the surrounding environment, high performance insulation systems are incorporated into the design of the tank. Even with perfect vacuum, thermal radiation can still contribute significantly to the total heat leak [2]. Two types of common insulation are foam and multi-layer insulation (Fig 3). Multi-layer insulation (MLI) is a common radiation barrier used in cryogenic applications and generally contains multiple layers of reflective material that have low thermal conductivity (such as aluminum) and will typically contain about 60 layers per inch. The material spaced between each layer is either polyester, nylon, or mylar. MLI is designed to work under high order vacuum. If these layers were to come in contact with each other, a thermal short circuit is created thus increasing the heat transfer. For high volume vessels, “orbital wrapping” is the method used and requires special equipment to wrap the alternating layers. For liquid nitrogen storage tanks, about one inch in total thickness surrounds the tank. Foam insulation is usually not favored in cryogenic applications due to the likely hood of cracking from thermal cycling and environmental exposure.

Figure 3: Layers of insulation currently in place on cryogenic tank

Magnetic coupling was introduced that may allow the placement of the motor outside the cryogenic tank. Magnetic couplings are generally used to transmit torque from one system to another where the magnetic transmission is required to maintain a hermetic seal to prevent leakage and contamination [3]. Magnetic coupling would is used to transmit rotational motion from the motor across the tank wall to a pump located on the inside (Fig. 4). Another advantage to using magnetic coupling is that there is no surface contact, so there is no wear. The air gap between the magnets and the magnet strength determine the amount of torque that can be generated. For this application, the magnets are a mix of neodymium, boron, and iron and can operate in low temperature conditions; however, when submerged in liquid nitrogen (about 77 K), a 1 Tesla magnet’s strength will be reduced to 87%.

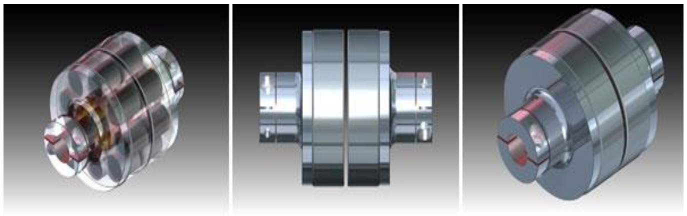


Figure 4: Example of magnetic coupling [3]

The pump system would be designed to operate in the cryogen receiving the magnetic rotational motion and imparting it to the fluid through impellers/etc. contained within a housing to produce flow up to 15gpm and pressure rise up to 5psid.

3. Concept Generation

In the following section, the process for design generation and the evolution of the proposed design is discussed. The design concept process for the project was unique. The first design consideration was the method for magnetic coupling. A pancake magnet coupler and concentric magnet cylinder design were considered. While the concentric cylinder magnet design would yield a very strong magnet coupling, it would require a large protrusion that attaches to the flange. After discussing with the sponsor, this was deemed unsuitable; therefore, the pancake coupler idea was pursued. The sponsors then sent a basic design for concept generation and can be seen in Figure 5. This proposed design consists of two pancake style magnet couplers and a Tesla pump.

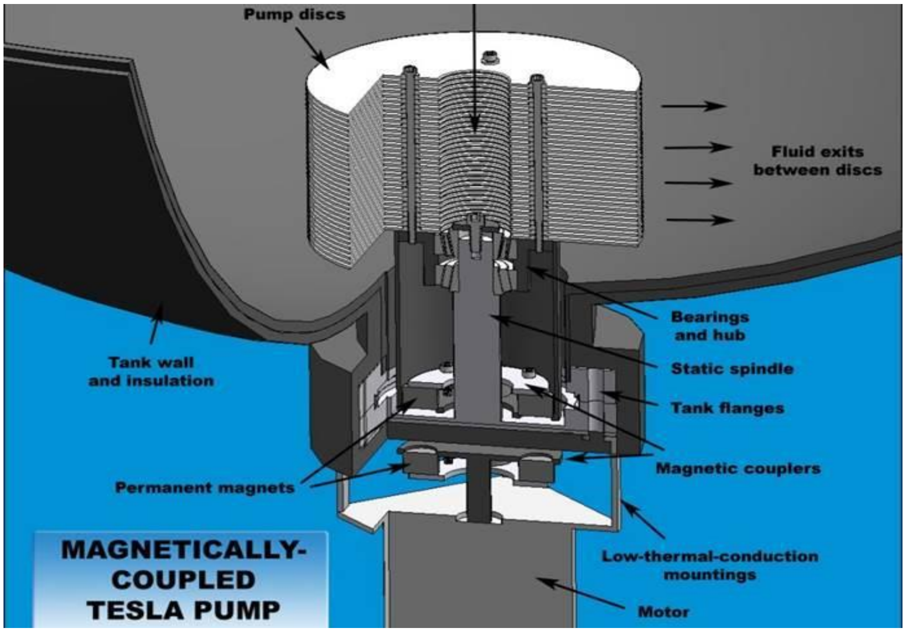


Figure 5: Design for magnetically couple Tesla pump provided by the sponsor

After deciding to use the pancake magnet coupler setup, the design went through two phases before fabrication. The first rendition of the design can be seen in Figure 6. This design makes use of two pancake couplers, a static spindle/shaft, and low-thermal conduction motor mount, similar to supplied design, but several changes were implemented to meet the project specifications. A major difference was replacing the Tesla pump with an inducer pump that uses an impeller supplied to us by our sponsor. This decision was made based on the amount of power it would be able to deliver to the system given the size constraint. A decision matrix was used to select the axial pump over the Tesla pump, and other types of pump systems that will be discussed in the next subsection 3.1. The first rendition is also designed for use through the top of a tank as per our sponsor’s request. The pump itself was extended twelve inches into the tank allowing its location to be in the center of the tank. This new design also can be easily installed by attaching it to a flange allowing easy installation through the top of the cryostat.

The second rendition, as seen in Figure 6, consists of several changes that were made to individual components. An improved and smaller motor was selected and therefore resulting in a redesign of the motor mount. The outer coupler required a through hole with a keyway to ensure that the coupler was attached to the motor shaft. The bearing system was a source of large redesign and the inner coupler had a lip to ensure that the bearings stay in place. A bushing was then placed in between the two bearings on the static shaft where a washer and locking nut were then placed on the end locking it in place. To hold the inner coupler in place and guarantee that there is space between it and the flange, an inner coupler pump attachment was created providing the distance between the flange and the inner coupler. This addition to the pump system has an extending cylinder that braces itself against the second bearing thus ensuring the spacing. Another key change in the design was the material of the pump shaft. It was found that using the aluminum shaft, it would bend during use. A stainless steel shaft was fabricated and implemented to remove the bending of the rotating shaft. Also, since the shaft was only secured at one end of the pump, there was a substantial amount of wobble. To reduce this, a bearing plate was constructed and welded to the top of the pump housing with a bearing that secured the end of the pump shaft. Incorporating these two points of contact, it significantly reduced the wobble in the system.

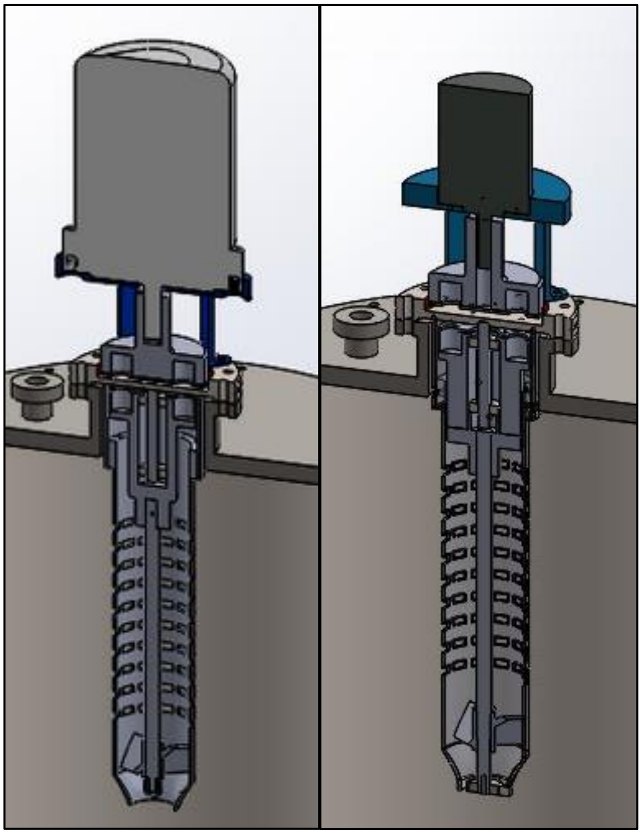


Figure 6: Design proposed by the group utilizing the provided inducer. On the left is the first rendition and on the right is the final design used.

3.1.Evaluation of Pump Types

At the beginning of the project, the decision on what type of pump to be used was selected. Each type of pump has performance advantages and disadvantages. To determine the best type of pump for the application, a decision matrix was constructed and can be seen in Table 2. The ratings for each pump where determined based on criteria of the project specifications ensuring power, efficiency, cost, and simplicity in fabrication.

The Tesla pump would seem to be the best option for this design due to the ease of manufacturing the pump. However, the efficiency of the tesla pump has be questioned with past research and the pump produces a low rotor torque [4]. In addition the size constraint of the 3.75” access port limits the size of the tesla pump disks which severely limits the pumping capacity.

The centrifugal pump has its own advantages and disadvantages. These pumps are generally small in size and require little maintenance. However the flow supplied by these is not viscous and these pumps can suffer from cavitation. But overall this type of pump was eliminated based on the cost and the complexity required to make a reliable centrifugal pump.

The standard axial pump is used for high flow rates and low pressures making it suitable for the system. However this type of system was not selected due to its inability to provide suction lift [5].

A three toothed inducer was supplied by NASA. The inducer usually acts as impeller for a centrifugal pump. However in the design accepted by the group, we have combined elements of the axial pump with the use of an inducer as the impeller to provide more suction, but with a greater ease of fabrication. This hybrid of pumps we called the inducer pump.

The decision matrix below compares the previously mentioned four pumps. The scale for the decision matrix is 1-10 with 10 being the best and 1 being the worst. The highest number yields the best option for the pump. Since the budget for the project is $600, the weighing factor for the cost of the pump was one of the more important weighing factors. The power efficiency is also heavily weighted since the efficiency from the motor will already be depleted through the magnet coupling. The fabrication ease is also weighted slightly higher than the other considerations due to the limited time available for fabrication. From this decision matrix the optimum choice was the pump that made use of the three tooth inducer that was supplied in the axial pump system. This final design was designed around this inducer pump system.

Table 2: Pump Type Decision Matrix

	Cost	Fabrication Ease	Power Efficiency	Cavitation	Pressure Conditions	Total
Weight	0.3	0.2	0.3	0.1	0.1	10
Axial	9	6	9	4	8	7.8
Centrifugal	6	7	7	2	4	5.9
Tesla	5	8	5	9	8	6.3
Inducer	10	10	8	6	6	8.6

4. Final Design

The final design can be seen in the Figure 7. This design makes use of the magnet coupling system with the bearing system around a static shaft as well as the pump system that has two points of contact. The cross-section shows the magnet coupling area.

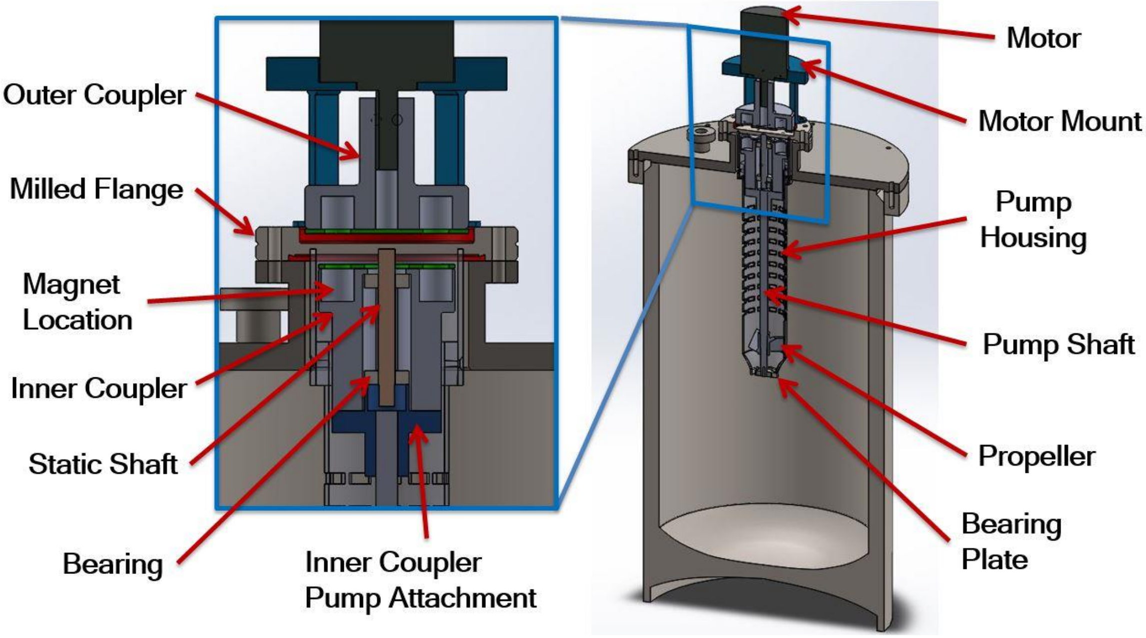


Figure 7: Labeled Cross –section of the prototype system

4.1. Component Analysis

The final design of the system has many individual components necessary for optimal use. In this next section each one of these parts is discussed in detail.

4.1.1 Motor Mount

The motor mount is constructed to hold the outer coupler at the very center of the flange. To do this the coupler has a form fitting cut out section of 3.125” in diameter to hold the motor along with four clearance holes for the 8-32 motor securing screws. A guide piece was then constructed to ensure that the four motor mount legs are attached in the proper places. Also to ensure proper placement the legs are attached to the flange and kept in place while the epoxy sets. Along with ensuring that the outer magnet coupler is centered, the motor mount material has to have a low thermal conductivity. Therefore PVC was selected due to its very low thermal conductivity coefficient of 0.2 W/(m·K). The motor mount can be seen in Figure 8.

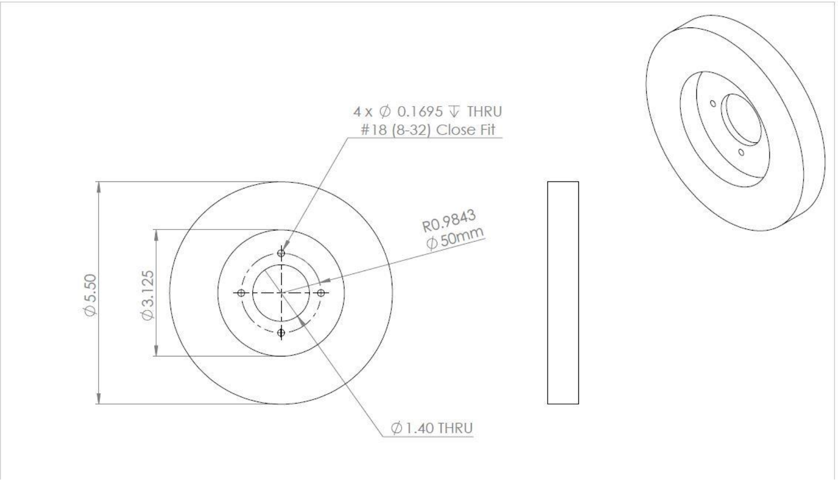


Figure 8: Motor Mount Engineering Drawing

4.1.2 Outer Coupler and Faceplate

The outer magnet coupler is the one of the two essential components of the total design of the system (Fig 9). This coupler is directly attached to the motor used in our project and holds the four 1 T magnets used for the magnet coupling in place. The essential dimensions of the outer magnet coupler are the large diameter must be 3.75” diameter and coupler itself must be 3.0” tall. Dimensions crucial to the function of the system are the diameter of the magnet circle and the female hole for the motor shaft. The magnets must be on a 2.25 inch diameter circle with alternating poles to ensure coupling. The female hole for the motor shaft is 0.5” in diameter with a 1/8”keyway. The outer coupler is attached to the motor shaft using a set screw with an offset of 3/16” from the motor to ensure that the coupler does not scrap against the flange. The faceplate fits into the matching screw holes to secure the magnets in their locations.

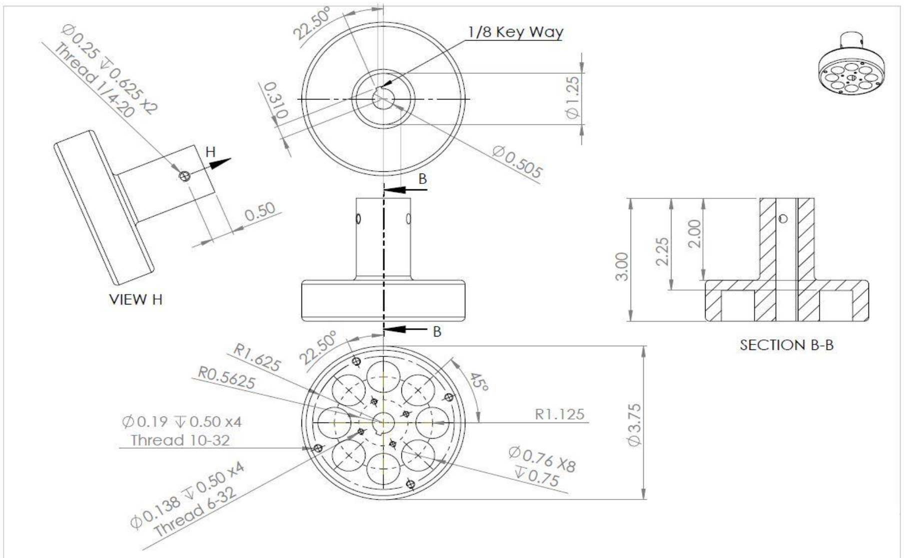


Figure 9: Outer Magnet Coupler Engineering Drawing

4.1.3 Flange

The flange used in this project was provided to us by our sponsor. It is a 6” ConFlat flange with a knife edge for sealing with a copper gasket and sixteen 13mm bolts for sealing. The only machining done to the flange is adding guide slits for the static shaft and pump housing anchor, and milling the flange down to reduce the distance between the couplers to have a greater degree of coupling. After milling the flange the thickness should be 0.125”. The flange can be seen in Figure 10.

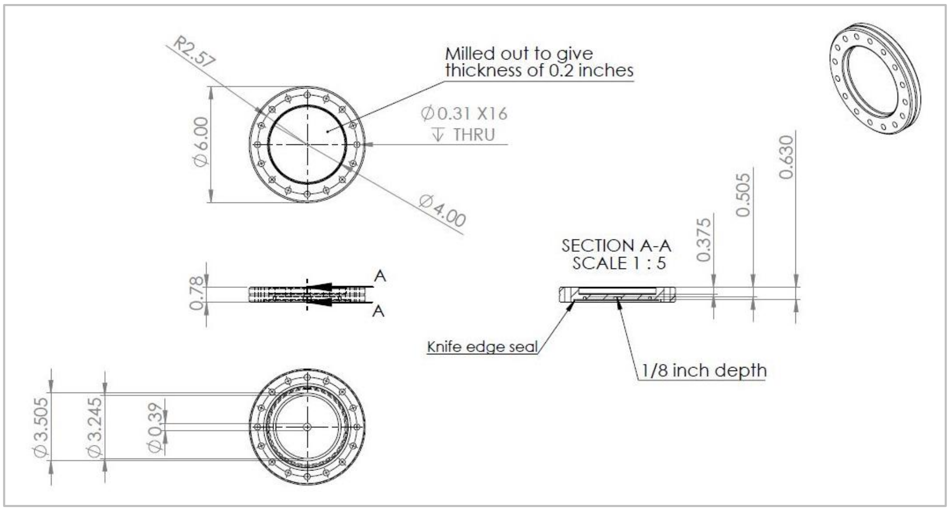


Figure 10: Milled ConFlat Flange Engineering Drawing

4.1.4 Static Shaft

The static shaft is made out of stainless steel due to its strength and stiffness. The shaft height is 3.60”, which has to be very precise to ensure that the inner coupler is the appropriate distance from the flange. The diameter of the shaft must also be 10 mm to fit the bearings. The end of the shaft is threaded with a 10-32 so a locking nut and washer can be put in place to hold the bearing system.

4.1.5 Inner Coupler and Faceplate

The inner coupler is the complimentary part to the outer coupler and will couple with it through the four opposite 1 T magnets on the same diameter (Fig 11). The large diameter is 3.125” and the secondary diameter is 2.50”. The system also has a height of 3.25” and a central hole that is 28mm in diameter with a lip that has a diameter of 22.5mm on the magnet face. This coupler will rotate around a static shaft that is 3.5” long using a bearing system that consists of two bearings with an outer diameter of 28 mm and inner diameter of 10mm.

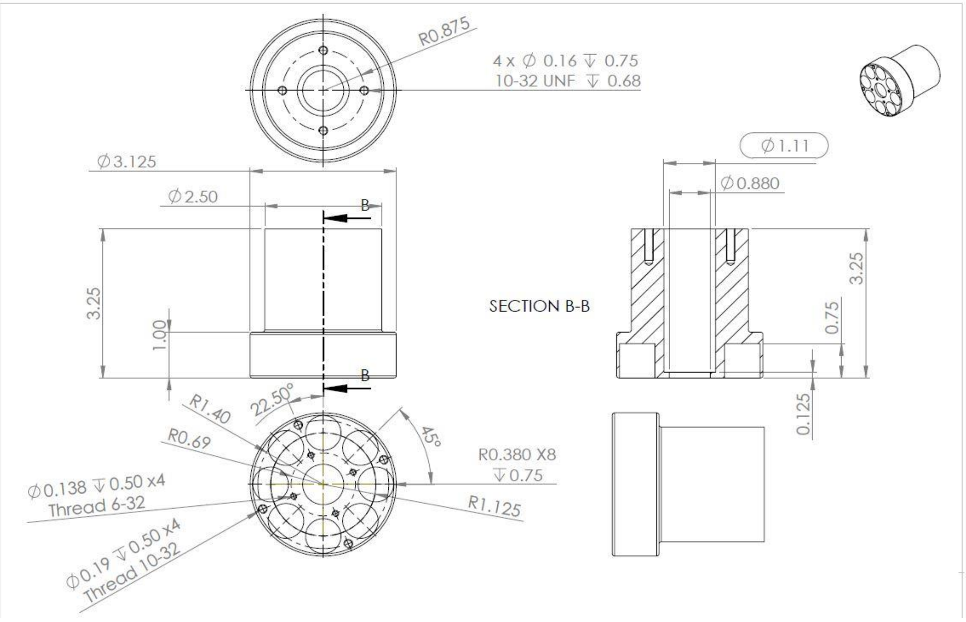


Figure 11: Inner Magnet Coupler Engineering Drawing

4.1.6 Inner Coupler Pump Attachment

The bearings system is then suspended by attaching the inner coupler pump attachment. This part has an extended cylinder that goes into the central hole and braces against the second bearing, thereby suspending the system with about a 1/10" separation from the flange. The inner coupler pump attachment also has the female hole for the new steel pump shaft that is 0.5" in diameter and will hold the shaft in place through a press fit.

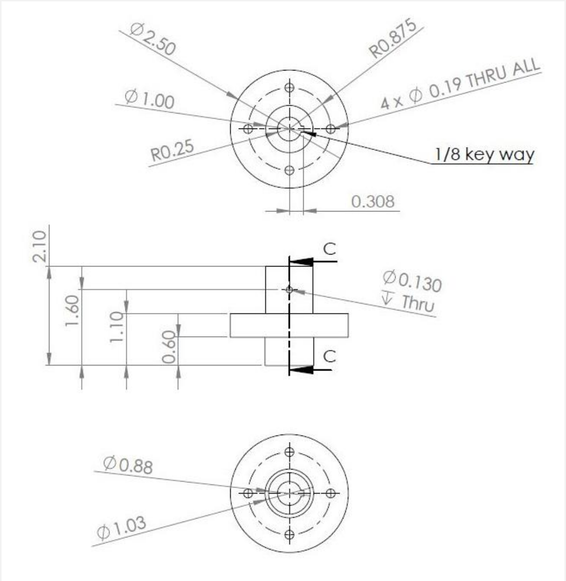


Figure 12: Inner Magnet Coupler Pump Attachment Engineering Drawing

4.1.7 Bearing System

The bearing system as previously discussed is composed of the static shaft, the inner magnet coupler and inner coupler pump attachment. As seen in Figure 13 the bearings on the static shaft are held in place by the lip on the inner magnet coupler, the bushing, and the extrusion from the inner coupler pump attachment. This system holds the system 1/10 of an inch from the flange. To ensure that the system does not fall off the shaft, however unlikely, a 10-32 locking nut and washer are attached to the end of the static shaft.

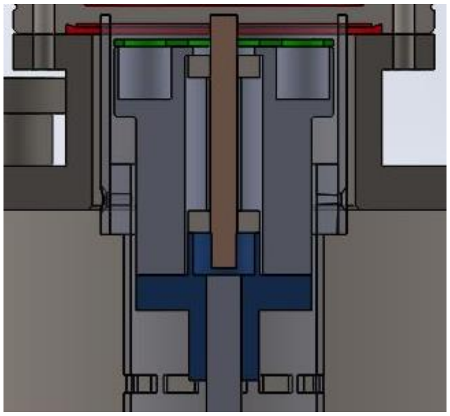


Figure 13: Bearing System Cross-section

4.1.8 Pump Shaft

The pump shaft part caused problems originally. The shaft was originally made of aluminum to save weight, however this shaft was not strong enough and bent under normal use. Therefore a new shaft was designed and manufactured made of stainless steel and this shaft is shown in Figure 14. The shaft is 0.5” in diameter made to be 12.25” in length. 2.725” down the shaft the diameter is 0.483 to be a close fit with the impeller. The next section is threaded with 7/16 thread to secure the impeller with a lock nut. The last bit of the shaft is 10 mm in diameter to have the bearing force fitted to the end of the shaft.

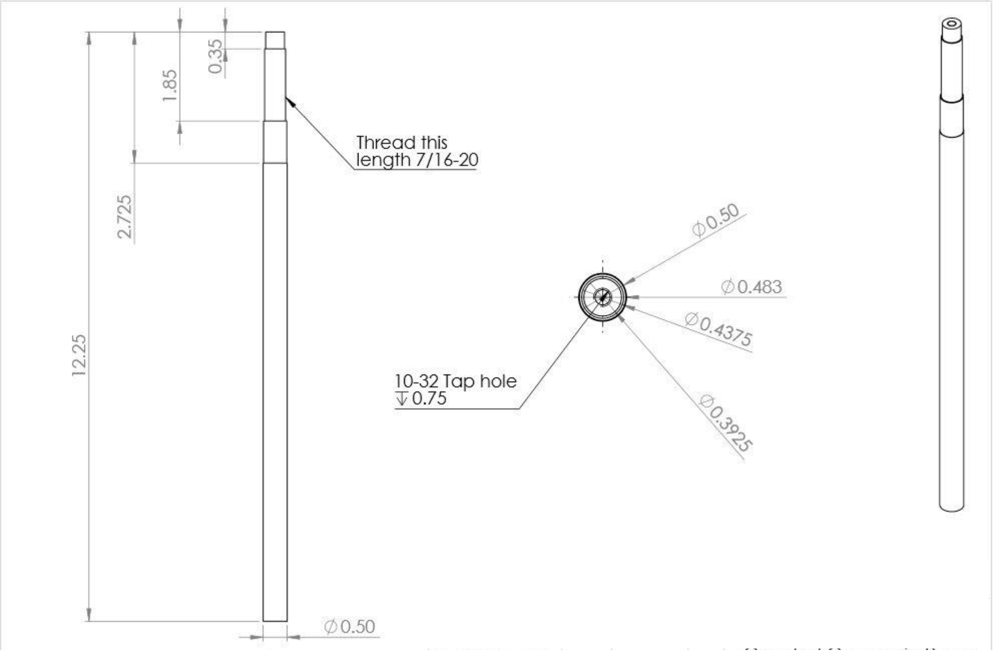


Figure 14: Steel Pump Shaft Engineering Drawing

4.1.9 Impeller

The impeller is the three toothed inducer provided to us by our sponsor, NASA Marshall Space Flight Center. It can be seen in Figure 15. The inner diameter is 0.483” and the outer diameter is about 2.65” in diameter.

Figure 15: NASA Marshall Space Flight Center provided Impeller

4.1.10 Pump Housing Anchor

The pump housing anchor is a simple part that is necessary to the design. It is a cylinder with an outer diameter of 3.50” and an inner diameter of 3.25”. It is 3.125” long and 0.5” from the end of the cylinder six #10 countersink holes.

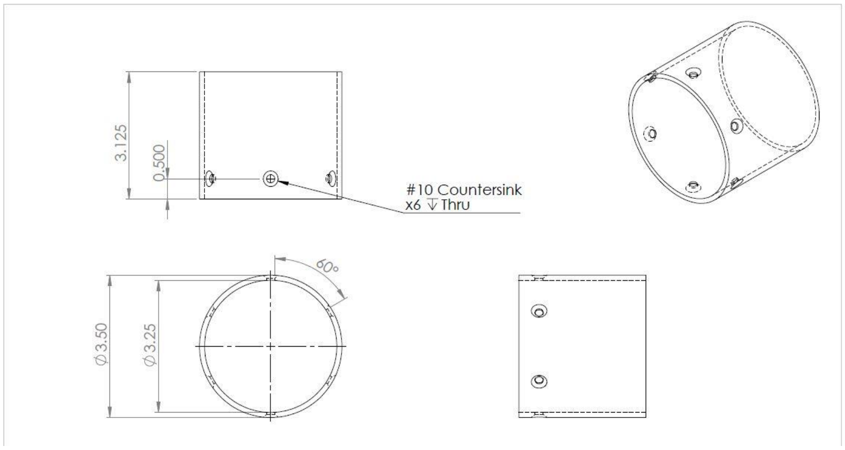


Figure 16: Pump Housing Anchor Engineering Drawing

4.1.11 Pump Housing

A key component in the pump design is the pump housing and it can be seen in Figure 17. The pump housing was made to be able to go over the impeller provided and be able to attach to the pump housing anchor. The impeller is shown with an outer diameter of a little less than 2.65”. Therefore the inner diameter of the pump housing was made to be 2.65” to ensure the pumping of fluid through the housing. The pump housing was made to be 13.5” long making it the largest part of the prototype design. The pump housing has an outlet of 1.55” in diameter as was designed for in earlier calculations and inlets throughout the length of the pump housing to allow fluid flow.

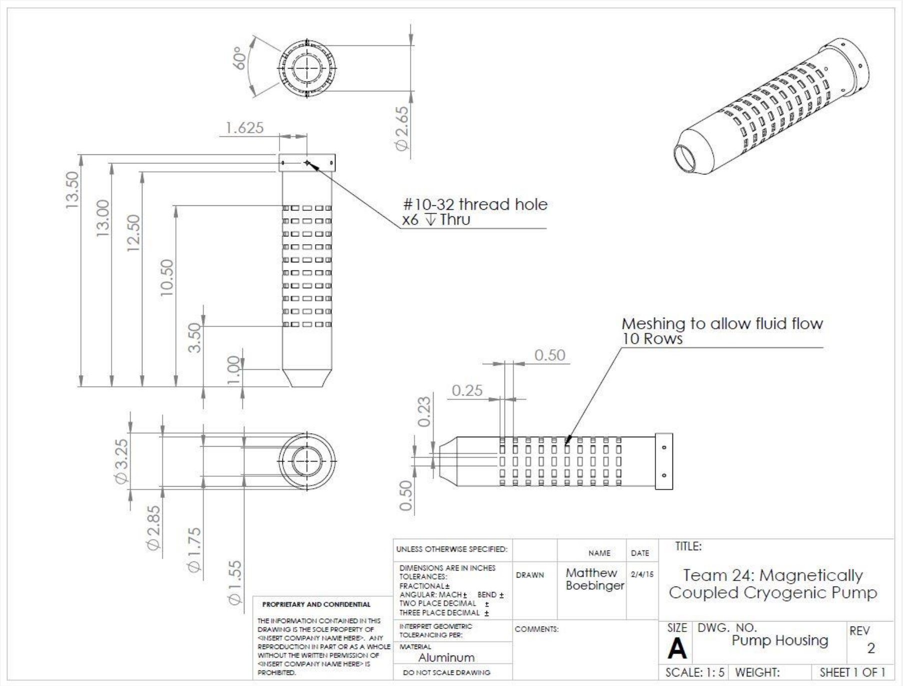


Figure 17: Pump Housing Engineering Drawing

4.1.12 Bearing Plate

The bearing plate component is made of aluminum and is welded to the end of the pump housing. It has a central hole that allows for press fitting the bearing at the end of the pump shaft, along with three slots cut into it to allow fluid flow. However with the addition of this part not enough fluid flows through the end of the pump housing even through the slots. To solve tis more slots were cut into the pump housing tip to allow fluid flow.

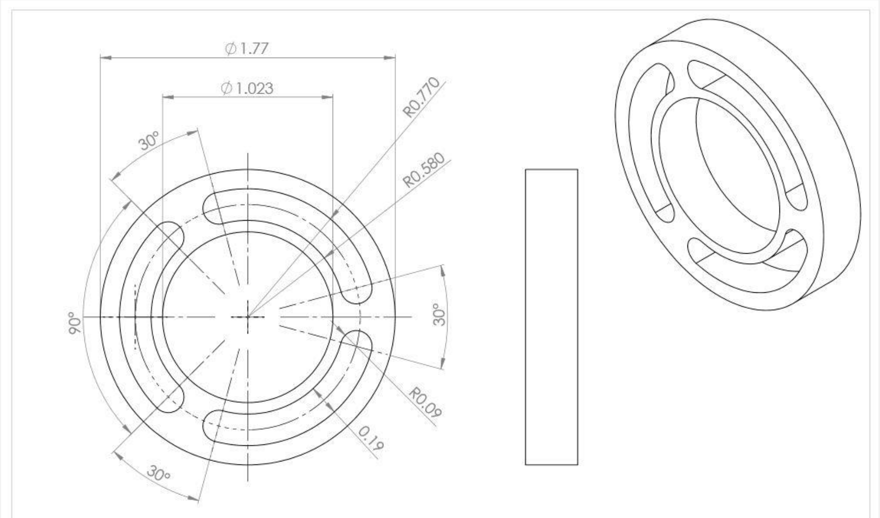


Figure 18: Bearing Plate Engineering Drawing

4.1.Design Analysis

This project required extensive computational analysis in order to properly select various components for the design. The major calculations that are required for this project are the required power of a motor to produce the specified flow rate and pressure rise, the angular velocity of the pumps propeller to produce the indicated flow rate, the type of bearings needed to support the design, and in the later experimental section the strength of magnets is discussed and plotted. All of these calculations are important to ensure the device works properly.

4.2.Motor and Pump Calculations

Calculations had to be done in order to select a motor that would be able to sufficiently supply the power needed to work the pump. Using the lowest requirement of 5 gpm and the inducer inlet cross-sectional area the meridional flow velocity can be found using the following equation 1,

$$C_m = \frac{\dot{V}}{A_{inlet}} = 0.265\,\frac{ft}{sec} \tag{1}$$

In order to calculate the flow coefficient the tip speed is then needed. Picking an RPM of 1500 as suggested by our liaison engineer at NASA, the tip speed was found to be 18 ft/sec. Therefore using equation 2 the flow coefficient can be found,

$$\phi = \frac{C_m}{U_{tip}} = 0.015 \tag{2}$$

Using the flow coefficient, ϕ, the head coefficient, ψ, is extrapolated from the following plot in Figure 19 provided to the group by our liaison engineer. It is found to be about 0.3.

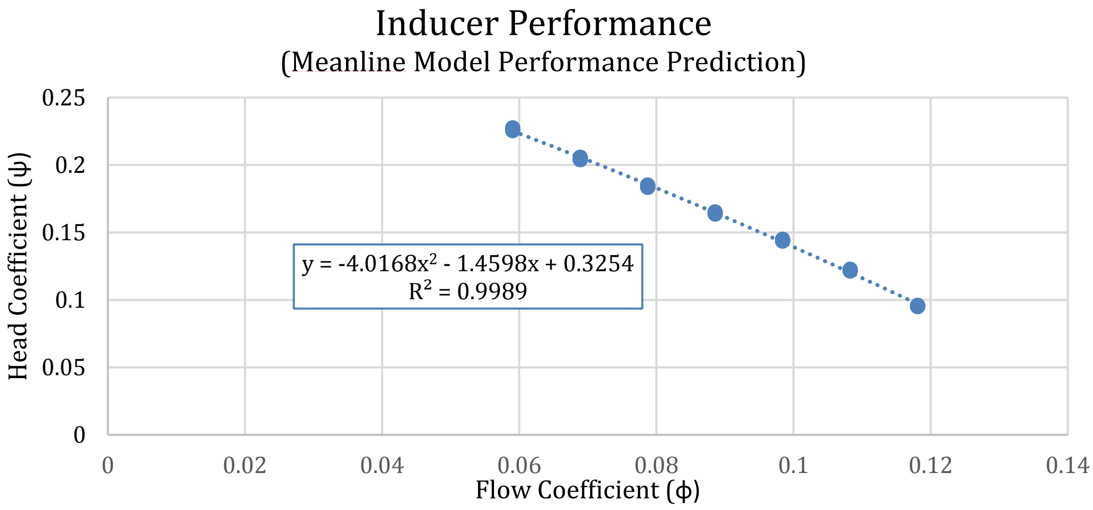


Figure 19: Inducer meanline performance plot relating the head and flow coefficients.

The head of the pump is then found using the following equation 3,

$$Head = \frac{\psi \times U_{tip}^2}{g} = 3\ ft \tag{3}$$

Using the head of the pump mass flow rate of the fluid across the pump, which can easily be found using the density of the fluid and the required volumetric flow rate, the power requirement of the pump can be found using equation 4. We assume that the overall efficiency with losses is 20%.

$$Power = \frac{(\dot{m} \times Head)}{(\eta \times 550)} = 0.02\ hp \tag{4}$$

Finally a motor with at least 5 to 10 times this calculated power is selected in order to be safe and allow for more functional flexibility. Using the calculations shown in Appendix C-2, a motor that runs at >1500 RPM and supplies ≥0.5hp must be selected for this design. To confirm these values an inducer map was constructed showing various constant speed and constant flow lines. Generally for more power a greater degree of RPM and a lower flow coefficient are desired. The inducer map can be seen in Figure 20. In the map shown the red lines show the minimum RPM and flow coefficient needed, and the green lines show the RPM (at peak torque output) and flow coefficient of our selected motor.

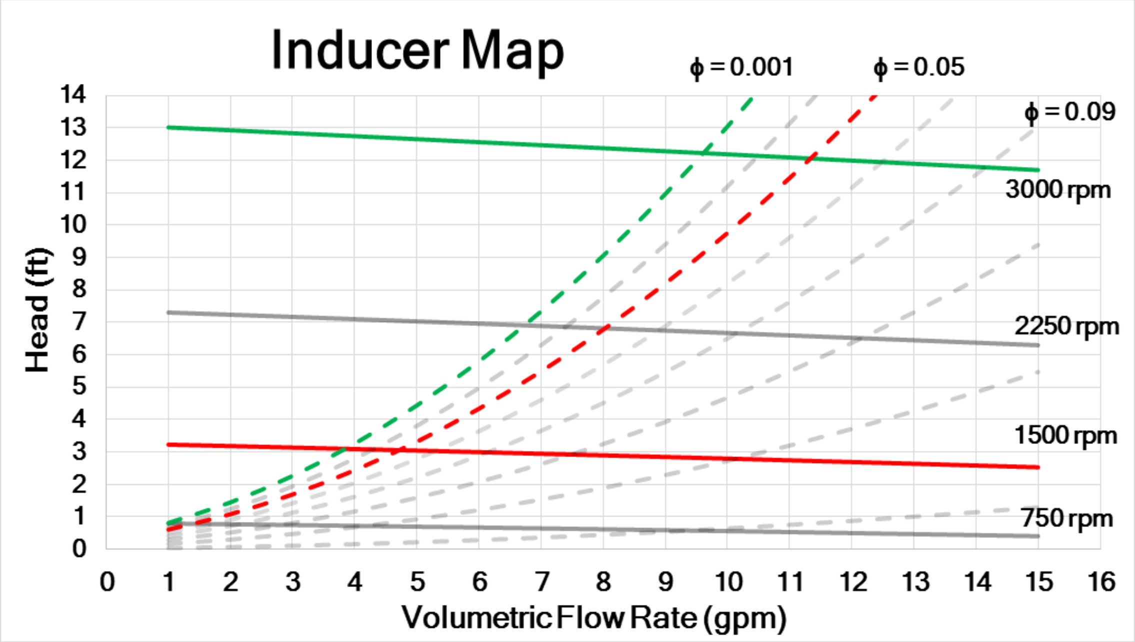


Figure 20: Inducer map used for provided inducer. Solid lines indicate constant speed lines and dashed represent constant flow coefficient lines.

Based on these calculations a 24V DC motor, and a motor controller were selected. The system is design to be used for an extended period of time so a large 24V 20 Ah battery will be used to test the prototype. The battery is then wired to the RioRand RRCCM9NSPC DC motor controller which consists of two PWM frequency switches and a potentiometer knob. The PWM frequency switches can be adjusted to reduce noise for motors. Since our motor will be running at relatively low speeds both switches should be flipped to the on position. The potentiometer can be used to change the speed of the motor to ensure the best pumping conditions. The motor that is being used in our prototype is the AmpFlow E30-150. It is a 24 V DC motor that has a peak HP of 1.0 and a maximum RPM of 5600. More specifications of the selected motor can be seen in Table 3. The geometry of the motor consists of a diameter of 3.1”, a length of 4.0” and a shaft diameter of 0.5” and shaft length of 2.0”, and a more detailed look at the dimensions of the motor can be seen in the Appendix A. The motor controller and motor can be seen in Figure 21.

Table 3: E30-150 Motor Specifications

Diameter (inches)	3.1	**Shaft Dia. (inches)**	0.5
Length (inches)	4.0	**Shaft Length (inches)**	2.0
Peak HP	1.0	**Keyway (inches)**	0.125
Stall Torque (oz.-in)	710	**Capacitors**	No
Efficiency	76%	**No Load Amps**	2.1
Voltage	24 V	**Resistance (Ohms)**	0.190
RPM @ 24V	5600	**Kt (oz.-in/Amp)**	5.70
Weight (pounds)	3.6	**Kv (RPM/Volt)**	237

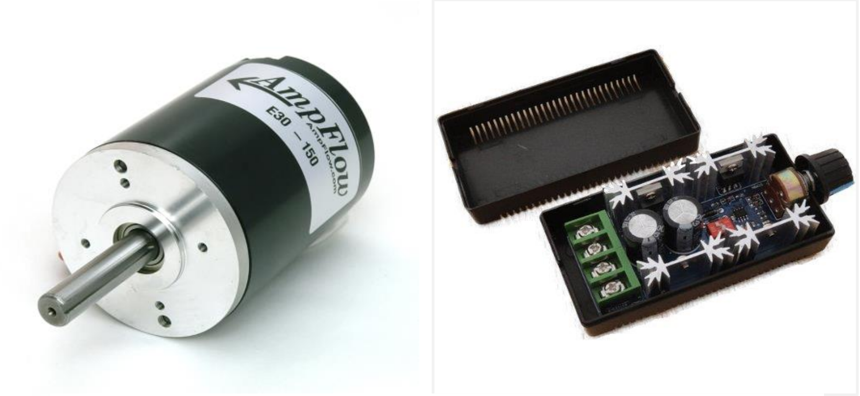


Figure 21: Electrical Components that consist of the AmpFlow 24 V DC motor and the RioRand motor controller

4.2.2 Bearing Calculations

Once the necessary rpm, and power were calculated bearing computations were performed. The first step to in bearing calculations is to first find the life of the bearings in millions of revolutions. Using factory defaults for bearing life in hours the bearing life in millions of revolutions was found using equation 5.

$$L_{10} = L_h * \omega * 60 \times 10^{-6} \tag{5}$$

In equation 5, L_h is the life in hours ω is the angular velocity of the system in rpm and $60X10^{-6}$ is a conversion factor. The life L_{10} was found to be 720Mrev. Once the life L_{10} was found the dynamic load of the bearing was calculated using equation 6.

$$C = F_e L_{10}^{\frac{1}{3}} \tag{6}$$

In equation 6, F_e is the equivalent force applied to the bearing which is a combination of radial force and thrust. The equivalent force F_e was first estimated using a RMS method shown in equation 7.

$$F_e = \sqrt{F_a^2 + F_r^2} \tag{7}$$

In the above equation F_a is the axial force or thrust and F_r is the radial force. These forces were doubled in order to guarantee a factor of safety of 2. Using the equivalent force F_e the dynamic load was found to be 108.45lbf. Next the static load C_0 was found using the SKF bearing catalog for stainless steel bearings. Once the static load was found equation 8 was used to find a ratio between the static load and axial force.

$$\frac{F_a}{C_0} \tag{8}$$

After finding this ratio linear interpolation was performed to find a factor e using Figure 11-24 in the "Machine Design an Integrated Approach" [6]. This factor e was then compared to another ratio shown in equation 9.

$$\frac{F_a}{VF_r} \tag{9}$$

Where V is a rotation factor that is based on whether the inner or outer ring of the bearing is rotating. For a bearing with a rotating outer ring V is determined to be 1.2. Using this ratio the radial factor X and thrust factor Y were determined by performing linear interpolation in Figure 11-24 in the "Machine Design an Integrated Approach"[6]. A new equivalent force F_e was found using equation 10

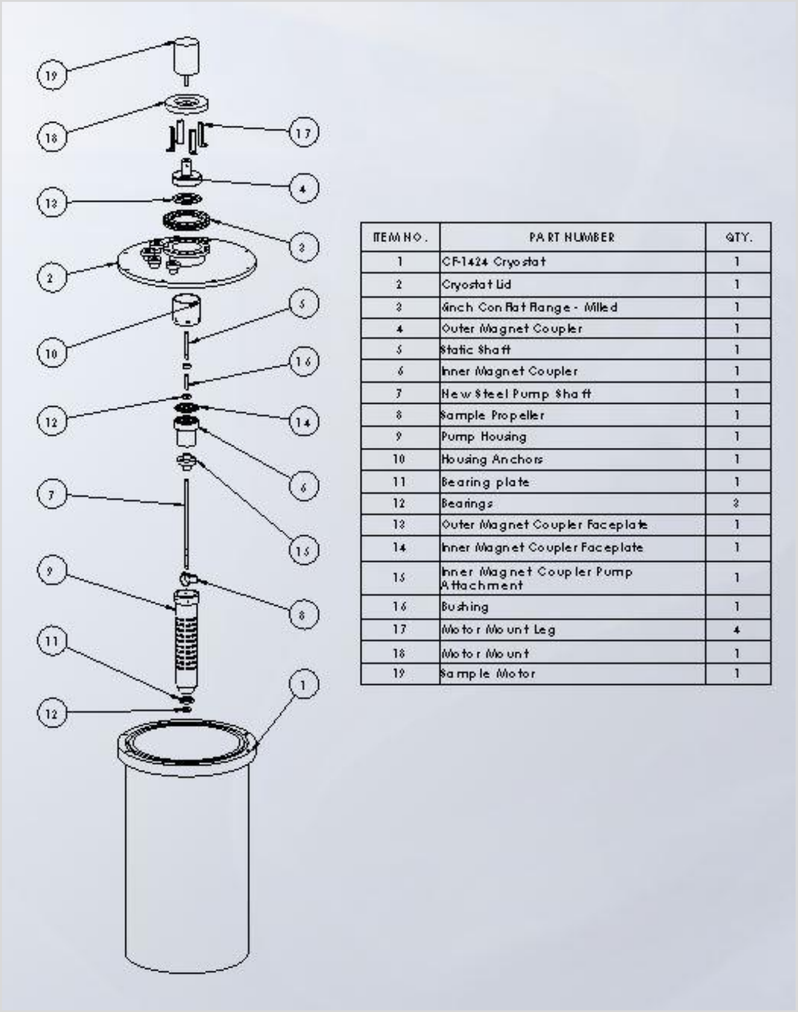
$$F_e = XVF_r + YF_a \tag{10}$$

Using this new equivalent a new dynamic load can be calculated using. This process is then repeated until the dynamic load does not change when the process is performed. Sample calculations for the bearings can be viewed in Appendix C-1.

4.3. Design for Manufacturing

In the following section, the assembly and manufacturing of the system is discussed. The total installation time was around 1.5 hours. Much of the assembly time was taken up by the welding process needed for connecting the static shaft and the pump housing anchor to the flange and the bearing plate to the pump housing, as well as the time needed for the epoxy to set on the motor mount legs. This welding assembly can be seen in Figure 24. However the total assembly time after the welding can be done in less than 4 hours. As far as the complexity of our design, our design was kept as simple as possible as per our sponsor’s request.

The entire prototype can be seen in the Figure 22 below with the components labeled. This design however has many components and can be broken down into several more comprehensive sub-assemblies. These sub-assemblies are the outer coupler motor sub-assembly (Fig 23), the inner coupler sub-assembly (Fig 25), the pump housing sub-assembly (Fig 26), and the previously mentioned welding sub-assembly (Fig 24).



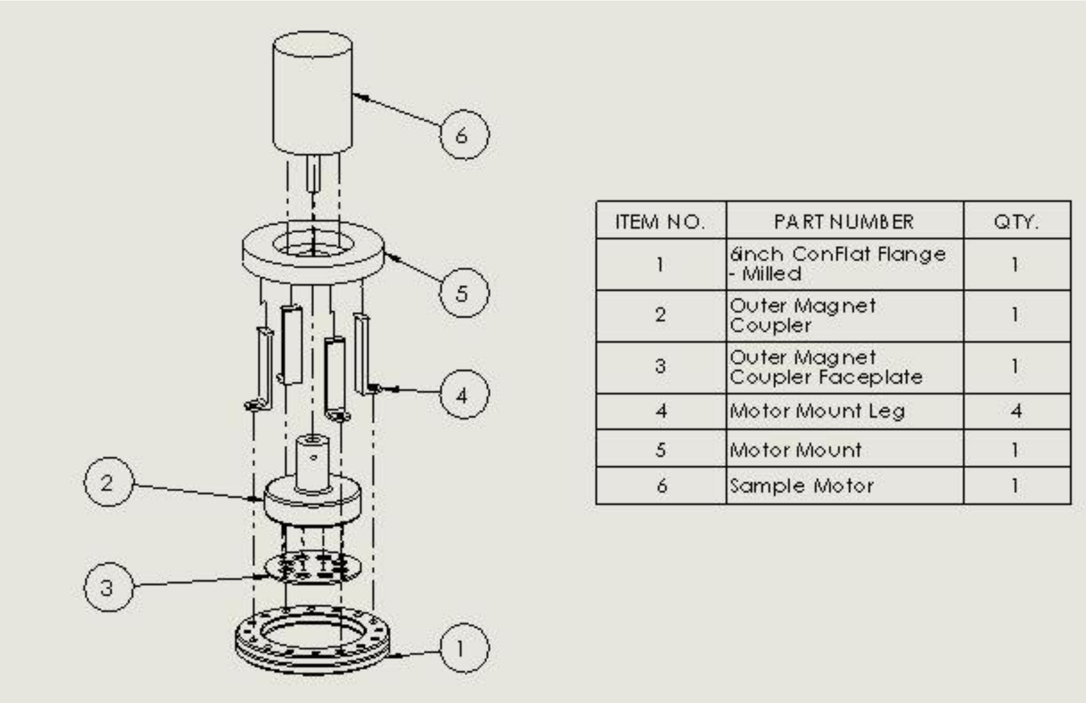
ITEM NO.	PART NUMBER	QTY.
1	CF-1424 Cryostat	1
2	Cryostat Lid	1
3	6inch ConFlat Flange - Milled	1
4	Outer Magnet Coupler	1
5	Static Shaft	1
6	Inner Magnet Coupler	1
7	New Steel Pump Shaft	1
8	Sample Propeller	1
9	Pump Housing	1
10	Housing Anchors	1
11	Bearing plate	1
12	Bearings	3
13	Outer Magnet Coupler Faceplate	1
14	Inner Magnet Coupler Faceplate	1
15	Inner Magnet Coupler Pump Attachment	1
16	Bushing	1
17	Motor Mount Leg	4
18	Motor Mount	1
19	Sample Motor	1

Figure 22: Prototype System Assembly

The first sub-assembly, the outer coupler and motor sub-assembly, consists of the motor, motor mount, the four motor mount legs, the outer coupler, outer coupler faceplate, and the flange. It can be seen in Figure 23. The first step of the assembly consists of inserting the four magnets into the outer magnet coupler. This must be done with the poles alternating to ensure maximum coupling between the two couplers. The method for the easiest insertion of the magnets is as follows.

1. Attach the outer coupler faceplate with one of the outer screws.
2. Insert one magnet into its appropriate hole.
3. Rotate the faceplate so that it holds the inserted magnet in place.
4. Insert the next magnet with the opposite poles facing outwards.
5. Rotate the faceplate so that it now holds both magnets in place.
6. Repeat steps 4 and 5 until all the magnets are in place and the faceplate lines up with its screw holes.
7. Screw the faceplate in securely.

Now that the outer magnet coupler is fully assembled the next step is to make epoxy the motor mount legs to the motor mount. This was done using a guide part indicating where the legs needed to be located and the flange itself. After attaching the legs to the flange they are the put into the indicator spots on the motor mount plate with epoxy. The motor mount system then needed to set for 24 hours.

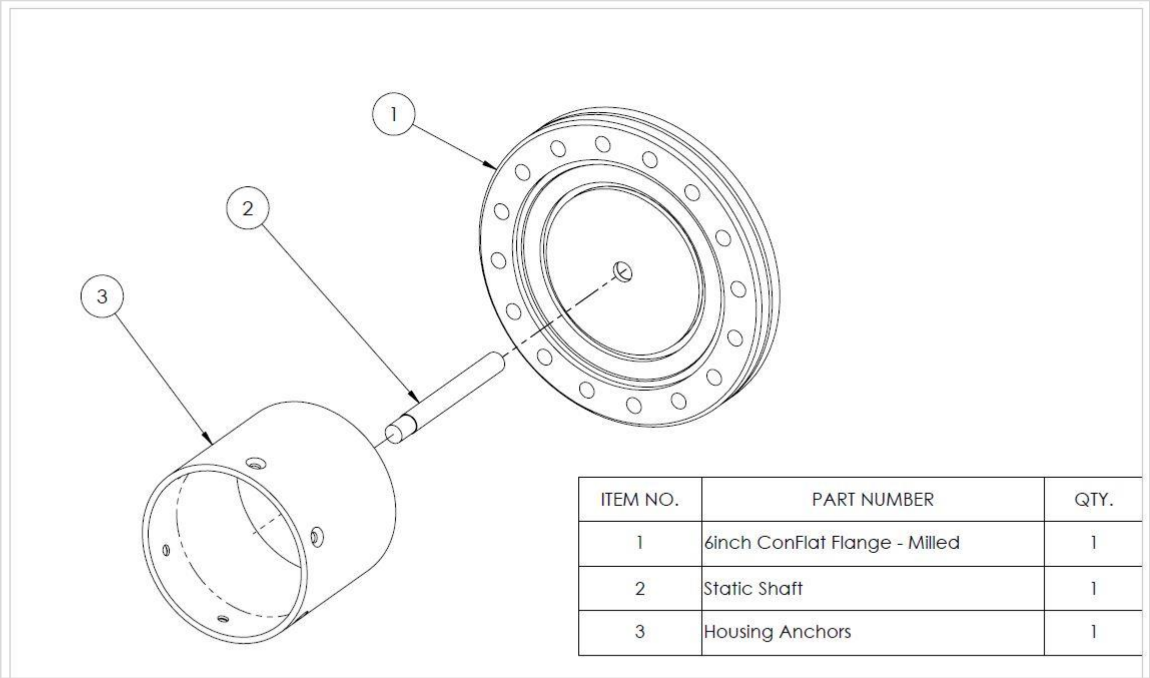


ITEM NO.	PART NUMBER	QTY.
1	6inch ConFlat Flange - Milled	1
2	Outer Magnet Coupler	1
3	Outer Magnet Coupler Faceplate	1
4	Motor Mount Leg	4
5	Motor Mount	1
6	Sample Motor	1

Figure 23: Outer Coupler and Motor Sub-Assembly

With the coupler and motor mount fully assembled the two components can then be attached to the motor. Using the provided screws the motor can be attached to the motor mount. The outer coupler is then put over the motor shaft with the key in place. The coupler is the offset about 3/16 inches from the motor to ensure that the outer coupler does not scrape against the flange, and set in place using the two set screws. Finally the motor mount is then attached to the flange. With this the outer coupler motor mount sub-assembly is complete.

The next sub-assembly to be constructed would be the welding sub-assembly (Fig 24). The welding was done in the machine shop by the machinist working there. The parts that needed welding were the static shaft and the pump housing anchor, and the pump housing and bearing plate. The static shaft and pump housing anchor were welded into the appropriate grooves cut into the milled down flange. With the shaft and pump housing anchor welded in place the other two internal sub-assemblies can be placed over the static shaft. In addition to the required flange welding, the bearing plate had to be welded to the pump housing. To ensure that the welding was perfectly level a step was cut into the bearing plate. The bearing plate needed to be added to the end of the pump housing to have the shaft secured on two ends to cut down the wobble of the system.

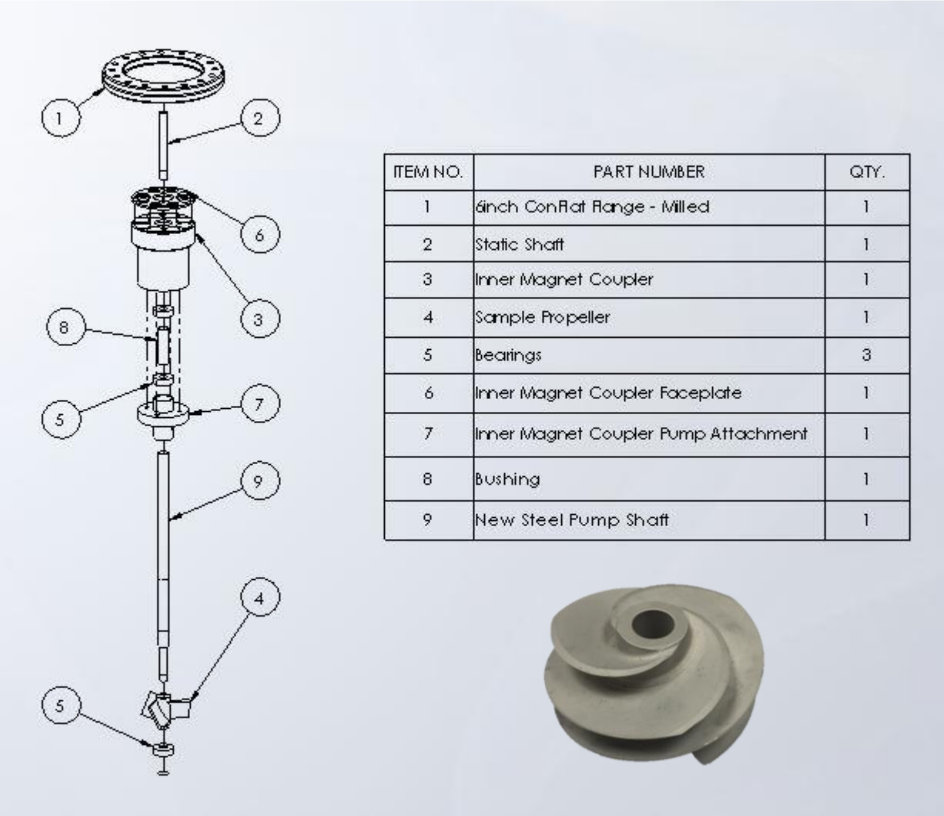


ITEM NO.	PART NUMBER	QTY.
1	6inch ConFlat Flange - Milled	1
2	Static Shaft	1
3	Housing Anchors	1

Figure 24: Welding Sub-Assembly with the pump housing anchor and static shaft

The next sub-assembly to be made would be the inner coupler sub-assembly (Fig 25). This assembly is composed of the flange, static shaft, inner coupler, inner coupler faceplate, bearings, bushings, inner coupler pump attachment, steel pump shaft, and the impeller. The first step of the assembly consists of inserting the four magnets into the inner magnet coupler. This must be done with the poles alternating to ensure maximum coupling between the two couplers. The method for the easiest insertion of the magnets is the same as it was stated earlier.

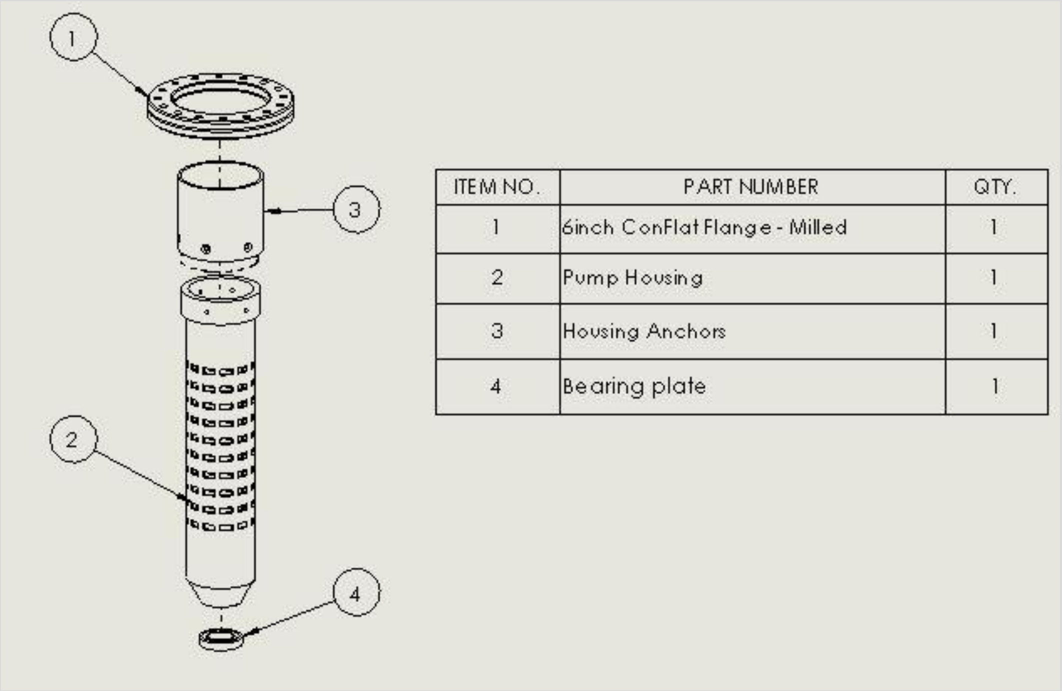
The rest of the inner magnet coupler assembly is the most complex of the assembly of the prototype. Once the inner coupler is fully assembled with the magnets, the coupler is placed over the static shaft. The first bearing is then press fitted all the way down until it makes contact with the lip of the inner coupler. Place the spacing bushing over the shaft. Then place the other bearing onto the static shaft. Screw the locking nut onto the static shaft along with a washer to hold the bearings in place. The next step would be to press fit the steel pump shaft into the inner coupler pump attachment. This is done by heating the inner coupler so that it thermally expands; the pump shaft is then inserted and left to cool. After cooling the shaft is firmly in place. Now that the shaft is in place the impeller provided to us by NASA, shown is Figure 25, can be attached onto the pump shaft. The impeller is press fitted to the stop 2.25” down the shaft. A 7/16 locking nut is then tightened down onto the impeller to ensure that the impeller is secured. Finally install the inner coupler pump attachment, now with the pump shaft and impeller attached, using the provided four 10-32 screws. The cylinder extending from this part will brace against the second bearing and through installation will guarantee spacing between the inner coupler and the flange and completing the bearing system. Finally attach the bearing onto the end of the pump shaft until it reaches the stop. This bearing is then secured in place using a washer and a 10-32 bolt that is tightened into the tapped ole at the end of the pump shaft. This completes the inner coupler sub-assembly as seen in Figure 25.



ITEM NO.	PART NUMBER	QTY.
1	6inch ConFlat Flange - Milled	1
2	Static Shaft	1
3	Inner Magnet Coupler	1
4	Sample Propeller	1
5	Bearings	3
6	Inner Magnet Coupler Faceplate	1
7	Inner Magnet Coupler Pump Attachment	1
8	Bushing	1
9	New Steel Pump Shaft	1

Figure 25: Inner Coupler Sub-Assembly and the impeller that was provided by NASA

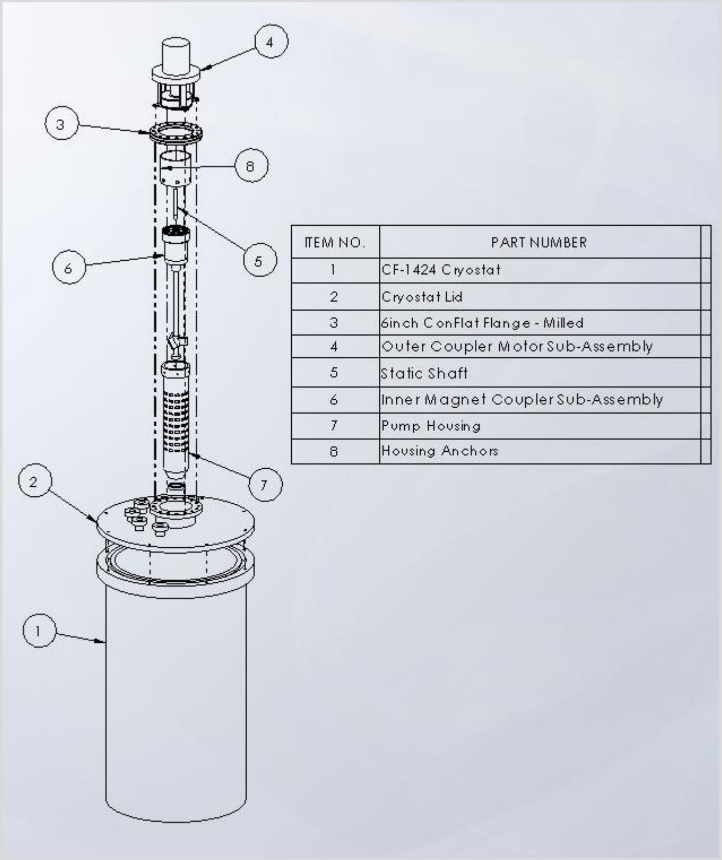
The final sub-assembly to be made would be the pump housing sub-assembly (Fig 26). This sub-assembly consists of the flange, pump housing anchor, pump housing, and bearing plate. Once the pump housing anchor is welded onto the flange, the inner coupler sub-assembly is placed onto the static shaft as described above. The bearing plate then needs to be welded onto the end of the pump housing using the cutout lip as a welding guide. Once welded the pump housing and bearing plate then had more holes cut into it to allow more fluid flow to reach the required volumetric flow rate. Once these holes are cut and the bearing plate attached, the pump housing can be placed over the inner coupler sub-assembly. At this point the bearing at the end of the pump shaft is force fit into the bearing plate at the end of the pump housing. At this point the pump housing then needs to be aligned with the pump housing anchor and then attached to it using the six provided 10-32 countersink screws.



ITEM NO.	PART NUMBER	QTY.
1	6inch ConFlat Flange - Milled	1
2	Pump Housing	1
3	Housing Anchors	1
4	Bearing plate	1

Figure 26: Pump Housing Sub-Assembly

This final assembly shows how each sub-assembly fits together to fully assembly the prototype and can be seen in Figure 27. With the Outer Coupler Motor Sub-Assembly, Inner Coupler Sub-Assembly, and the Pump Housing Sub-Assembly all attached to the flange through the welded static shaft, pump housing anchor and the motor mount the prototype pump mixer system is complete. For testing the prototype system must then be installed into the NASA provided testing cryostat. This final step consists of attaching the flange to the cryostat top using the 16 proved 13 mm bolts. The cryostat top is then firmly attached to the provided cryostat. With this complete the prototype has been fully assembled into the testing cryostat.



ITEM NO.	PART NUMBER	
1	CF-1424 Cryostat	
2	Cryostat Lid	
3	6inch ConFlat Flange - Milled	
4	Outer Coupler Motor Sub-Assembly	
5	Static Shaft	
6	Inner Magnet Coupler Sub-Assembly	
7	Pump Housing	
8	Housing Anchors	

Figure 27: Complete System Assembly for Manufacturing

4.4.Operation Procedure

The assembly drawing can be seen back in Figure 27. The total assembly time after the welding certain components and epoxying the motor mount legs to the motor mount can be done in less than 2 hours. The assembly is done in a series of steps with five different sections.

1. Pre Assembly

Before any assembly of the pump system can begin certain components of the pump need to be prepared.

a. The motor mount consist of five parts. The motor mount plate and the four legs. These components are made out of PVC and need to be epoxied together before assembly. Once epoxied, the motor mount needs to sit for at least twelve hours so the epoxy can cure.

b. The static shaft that will mount the inner coupler needs to be welded to the flange. As seen in Figure 28.

c. Once the static shaft is welded to the flange, the pump anchor will also need to be welded to the same side of the flange as the static shaft. Also seen in Figure 28

d. Lastly, the bearing plate will need to be welded to the end of the pump housing using the lip as a guide.

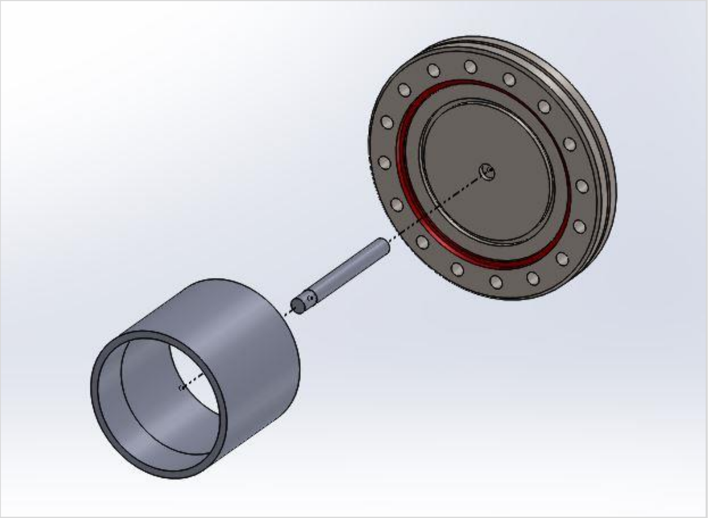


Figure 28: Welding Sub-Assembly with the pump housing anchor and static shaft

2. Magnet Insertion and Coupler Assembly

a) When inserting the magnets into both couplers, make sure they are alternating poles using the faceplate as a guide and to keep the magnets in place (Fig. 29).

b) Attach the outer coupler faceplate with one of the outer 10-32 x 0.5”screws.

c) Insert one magnet into its appropriate hole.

d) Rotate the faceplate so that it holds the inserted magnet in place.

e) Insert the next magnet with the opposite poles facing outwards.

f) Rotate the faceplate so that it now holds both magnets in place.

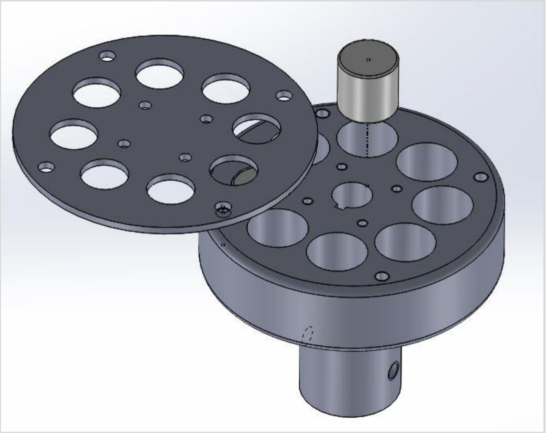


Figure 29: Magnet installation into the Outer Magnet Coupler Illustration

g) Repeat steps 4 and 5 until all the magnets are in place and the faceplate lines up with its screw holes.

h) Screw the faceplate in securely.

3. Outer Coupler and Motor Sub-Assembly

a. Secure the motor to the motor mount using for 8/32 ½” screws (Fig 30)

b. Attach the outer coupler to the motor shaft and securing it with two ¼-20 set screws

c. Do NOT attach the motor mount to the flange

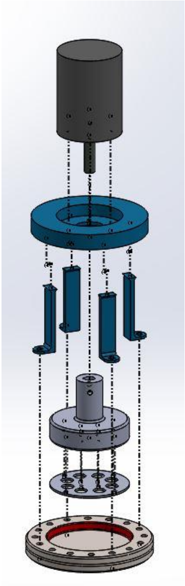


Figure 30: Outer Coupler and Motor Sub-Assembly

4. Inner Coupler Sub-Assembly

a. Make sure the flange is on a flat surface with the static shaft and pump anchor facing up (Fig. 31)

b. Place one ball bearing into the inner coupler and place on the static shaft. Once on the static shaft, insert the bushing and the second ball bearing securing it with a washer and 10-32 locking nut.

c. After the bearings and bushing is secure, press fit the stainless steel pump shaft into the inner coupler pump attachment.

d. Once the pump shaft is attached to the inner coupler pump attachment, attach the impeller to the rotating shaft by force fitting the impeller to the stop, then screw the 7/16 locking nut until it secures the impeller.

e. Once secured, attach the inner coupler pump attachment to the inner magnet coupler using the four 10-32 x 1.25” screws with the impeller facing up.

f. After the inner coupler pump attachment is secured to the inner coupler, attach the bearing to the end of the pump shaft and secure it in place using the 10-32 1” bolt and washer.

g. Finally, put the pump housing over the pump shaft, press fitting the bearing into the bearing plate at the end of the pump housing. Now attach to the pump anchor using the six 10-32 x 3/8” countersink screws.

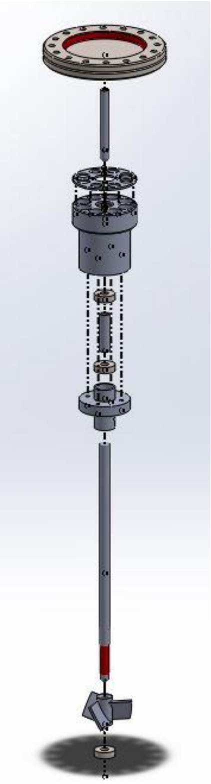


Figure 31: Inner Coupler Sub-Assembly

5. Final Assembly

a. Once the inner coupler sub-assembly is complete, place the inner coupler assembly inside the 3.75” port on top of the cryostat lid with the copper gasket.
b. Mount the outer coupler and motor sub-assembly to the flange using the four 13mm bolts provided and continuing to seal the flange with the remaining twelve bolts

4.4.2. Operating Instructions

a. Using the wiring diagram below (Fig 32) to wire the motor to the driver. A However the positive and negative wires going to the motor must be reversed to have the motor rotate the correct direction to have successfully pumping. Before wiring the battery or other power source to the driver make sure the driver is in the OFF position.
b. Wire the battery or power sourced to the driver, double checking the voltage and the ground are in the right ports
c. Wire battery to the motor driver and rotate the motor driver knob clockwise SLOWLY. If done to quickly the starting torque immediately causes the magnet coupling to slip, and while this is not damaging to the system, it should be avoided. As the knob continues to turn clockwise, the speed increases causing the pump to produce higher flow rates.
d. To turn off the motor, rotate the knob on the driver counter clockwise until it makes a “clicking” noise. Remove the system after the motor has completely stopped.

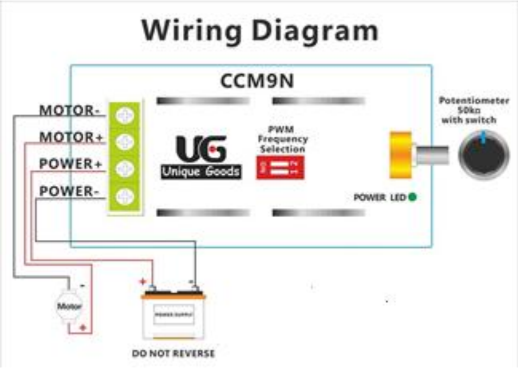


Figure 32: Wiring diagram for motor driver

4.5.Design for Reliability

Sustainability

Although this project was proposed to show proof of concept of magnetic coupling technology, great care was taken when considering the life span of the design. Due to the nature of this project we were very judicious when selecting materials and components of the design. Many of the components were designed to outlast the electrical components such as the motor and motor controller that were purchased. Additionally the materials used to make each component of the design were selected to ensure they were non-magnetic and their strength would not be compromised when submerged in the cryogenic fluids. The main components that were considered for reliability include: bearings, magnets, and materials.

Bearing

The bearings used for this design were carefully selected to consider the life span as well as the nature of the project. Calculations were performed in order to select a suitable bearing that would withstand the forces applied to each bearing. These calculations considered a life span of 8000hrs with a factor of safety of four. A sample calculation for the bearings can be viewed in the Appendix C-1. Great consideration was also used when selecting the material the bearings were made of. This is due to the fact that the bearings were significantly close to the magnets. Additionally the bearings would be subjected to extremely cold conditions (77K). Due to these concerns stainless steel was used because it is non-magnetic and does not display the phenomenon of ductile to brittle transition when introduced to extreme colds. In addition to these concerns, the bearings were cleaned of all lubricants to ensure that when exposed to cryogenic temperature, the prototype will run. Since the bearings used in the design were selected so carefully it is not unreasonable for the bearing to last in excess of 16000hrs.

Magnets

Due to the fact that the coupling magnets are the essence of our project special attention was taken when selecting them. The magnets the team selected are made of the rare earth metal neodymium. This type of magnet was selected due to its exceptional magnetic strength of 1 T, or 10,000 gauss. Additionally neodymium magnets are known to lose less than 1% of their magnetic strength over a time span of 10 years. Another reason why these magnets were selected is because they do not lose strength when subject to extreme colds, as is the case in this application. For the reasons stated above the team believes that the magnets will be one of the longest lasting components of the design.

Materials

The materials used in the design were another component that needed to be selected with great thoughtfulness. This is because of the magnetic forces as well as the extreme colds the materials are exposed to. In order for the materials to have a respectable life span in the extreme colds a metal that did not display the phenomenon of ductile to brittle transition was needed. For this reason aluminum was the first material of choice. Unfortunately due to the eddy currents introduced by the magnetic forces aluminum could not be used in areas that moved relative to the magnets. This lead us to choose stainless steel as the material used in these situations. Both of the metals used will outlast any other component in the design due to their high strength and the minimal stresses felt in this application.

Failure

Although many of the components were designed to last a great deal longer then what is needed for this project some failure can still occur. Failure Mode Effects Analysis (F.M.E.A) was performed for all the major components of the design to account for these possible mishaps. The F.M.E.A for this design can be viewed in Appendix D-1. After performing the F.M.E.A three main concerns of failure were found Bearing wear, tolerance of the pump, and the cryogenic behavior of the project. These possible mishaps were corrected for and the appropriate action was taken to avoid these issues.

4.5.2. Troubleshooting

Sources of improper operation

1. Electrical – After an extended period of time of operation running at the maximum setting could cause the motor to burnout and requires a new motor to be installed to continue operation. Additionally, batteries should be checked for proper voltage and electric current rates to ensure that the motor controller and motor function properly.
2. Magnetic Error – The slippage of the magnets improperly rotates the pump shaft and creates improper mixing of the cryogenic fluid. Be sure to ramp up the motor speed slowly to avoid magnet slippage while the inner coupler builds up speed. In order to ensure the best coupling strength four magnets with alternating poles must be used in each coupler. Also to ensure greatest coupling strength ensure that the design is properly installed to minimize distance between the couplers
3. Excessive Vibration and Collisions – Excessive vibration and collisions will alter the path of the rotating components of the system and cause failure eventually due to un-alignment of these components. If any components scrape against the pump housing or flange, the parts have been improperly installed. If the motor mount begins to excessively vibrate, then not enough epoxy has been used to secure the motor mount legs. All forms of vibration and collision with other objects should be avoided to prevent failures and ensure operation.
4. Improper Sealing – Improper sealing allows evaporated cryogenic fluid to leak out. Make sure the tank is sealed correctly and the pressure check value is operating to regulate the amount of evaporated fluid within the tank. This allows the tank to store the cryogenic fluid properly without unwanted discharge which alters the enclosure of the tank.
5. Pressure Check Value – The pressure check value needs to be operating correctly to monitor the pressure within the tank. This eliminates uncontrollable discharge of vapor from the surroundings of the tank.

4.5.3. Regular Maintenance

Although this is a continuous operating system, sporadic maintenance is required to ensure proper operation and a high level of performance. This alleviates the risk of malfunctions with long term use of this product and increases the life span of the product significantly. With proper maintenance, the possibilities of malfunctions can be eliminated or significantly reduced to make this product perfect for any application and the optimal level of performance can be maintained to produce excellent results.

The maintenance procedure should include all the functions/sub-functions listed below and should be performed after each long continuous projects. For shorter projects, the maintenance procedure should be performed discretionary with a recommended monthly period of time. This allows smooth and safe operation of the product. Immediate maintenance should be performed after extremely hazardous environments such as storm conditions or significant changes in the environment.

1. Electrical Components
   a. Observe motor and electric controller conditions
   b. Charge battery after depleted 20 Ah
   c. Replace the battery after lifetime
2. Electrical Wires
   a. Check the wires for improper connections, damages in the wire, and more.
   b. Check harnesses, connectors, solders, and all other connection points for security
3. Mechanical Components for Wear
   a. Rust and corrosion of metal components creates potential area of leak and material failure. Replace any mechanical components if necessary.
   b. Search for dents in pump housing
   c. Replace bearings after they have reached the rated lifetime of 8000 hours
   d. Check bushings, screw, bolts, and washers
   e. Evaluate welds and pressed components
4. Magnets
   a. Check the condition of the magnets to ensure no chipping
5. Fasteners are Tighten
   a. Check for loosen screws that holds components together within the system
   b. Tighten bolts, nuts, and all fasteners as well
6. Complete Overall System
   a. Perform analysis of the complete working system
   b. Relate data from previous analysis
   c. Relate to theoretical results

5. Design of Experiment

It is important when prototyping to accurately test the design to achieve tangible evidence that the prototype does indeed work. In order to obtain this evidence experimental procedures must first be designed. When testing this prototype three different experimental procedures were formulated to test the success of the prototype. The first experiment was designed to test the coupling strength of the magnets. Next an experiment was devised to test the volumetric flow rate of the cryogenic pump. Lastly it was desired to ensure the design worked in the extreme environments of liquid nitrogen. Although it is extremely important to acquire tangible evidence of the prototypes success due to time constraints some quantitative numbers were not found.

5.1.Magnetic Coupling

In order to ensure the motor would properly couple with the pump the team needed to know how the magnetic fields would react in torsion. Unfortunately no previous experiments found on the Internet performed this type of test. This caused the team to design an experiment to test the coupling strength of the magnets. This was a very important test as it showed the maximum distance the magnets could be apart before slippage occurred. Additionally this test helped the team optimize the number of magnets required to achieve sufficient torque.

The experiment the team formulated utilized a torsion-testing machine. This allowed the torque and the angle of rotation to be recorded. These parameters were very important because they showed at what angle and how much applied torque the coupler would reach before slipping ensued. The tests were performed at three different distance 1”, .75”, and .5”. For both the 1” and .75” distance four tests were executed two tests without a steel medium between the couplers and two test with a steel medium between the couplers. This showed if the steel flange would affect the coupling strength, which was necessary for liquid nitrogen tests. Unfortunately only two tests without a steel medium were carried out at .5”. This was due to the couplers slightly touching the steel plate causing inaccurate readings.

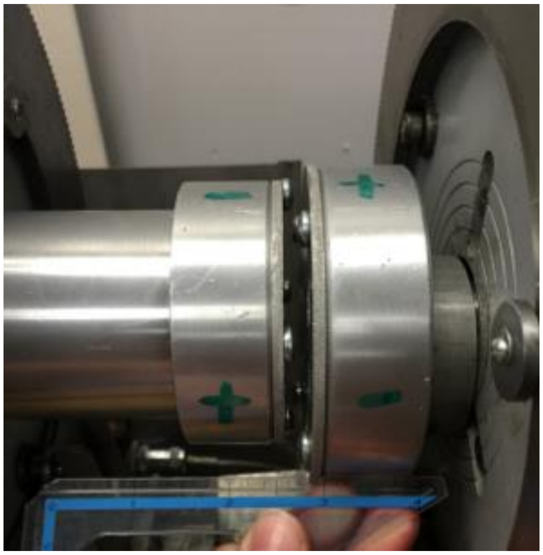


Figure 33: Experimental setup of magnetic coupling.

The experiment was setup by first inserting the couplers into the chucks of the torsion machine. Once the couplers were securely in the chucks the couplers were aligned axially so the center of each coupler were perfectly centered. Next the couplers were moved to the desired distance, which was 1” for the first test. The magnets were then aligned so the positive pole of one magnet was centered to the negative pole of the other this can be seen in Figure 33. This alignment ensured there was no torque on the couplers before testing began. The torsion machine was then set to rotate at a rate of 20°/min. The machine was then turned on and the torque was recorded every 5° for 180°. The machine was then turned off and a steel plate was placed in between the couplers. This process was then repeated for each distance.

Initially the couplers were tested with eight magnets in each coupler as the team thought that the coupling strength would increase with increasing magnets. This proved to be an incorrect assumption. When the couplers were tested in the torsion machine with eight magnets no torque was observed. This was due to the fact that the magnetic field lines were smearing together causing the alternating poles to be ineffective. Four magnets were then remove from each coupler and the experiment was run again. With less magnets the magnets were able to have a greater degree of attraction with its complimentary coupling magnet in the opposite coupler. Due to this greater degree of attraction to the complimentary magnets and the increased repulsion from its neighboring magnets a larger torque could be achieved. The reduction in magnets proved to be effective and an observable torque was recorded.

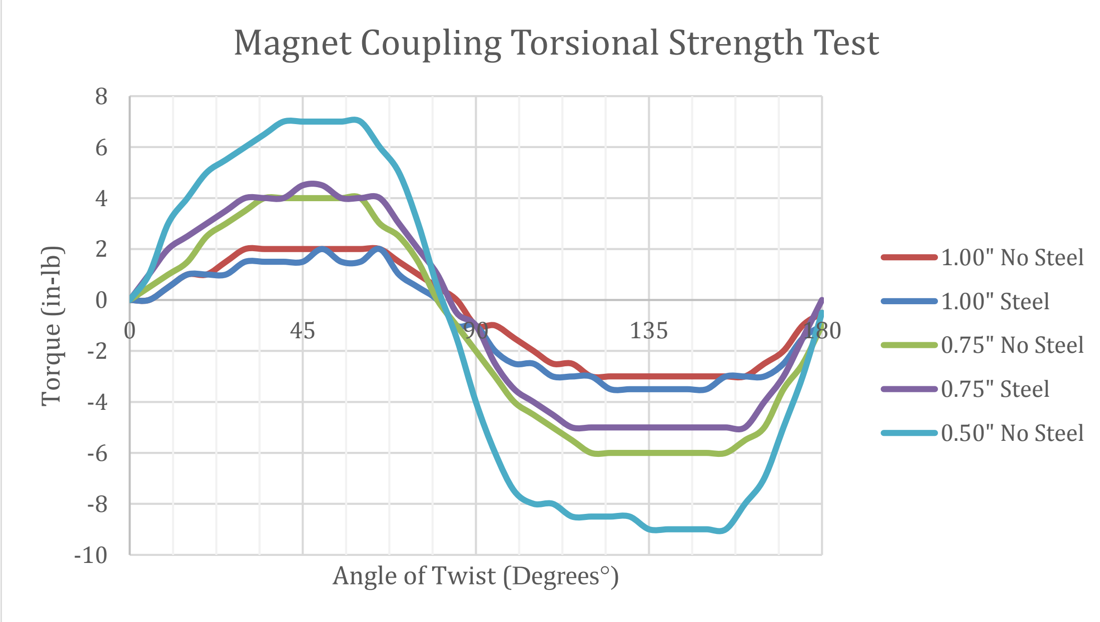


Figure 34: Experimental data comparing the coupling strength at different distances.

The data the team received from this experiment can be seen in Figure 34. The results the team observed were almost identical to the expected results. The data shows that the magnetic coupling slips when the positive pole is at a 45deg angle from the negative pole. Additionally it showed that the steel had no observable effect on the coupling strength. At the maximum distance of 1" it can be seen that the magnets would begin to slip at roughly 2in-lbs of force. This is extremely desirable because the torque calculated for the motor to move the pump was found to be 0.1in-lbs. Considering that the prototype would be run at the .75" distance it was determined that the coupling strength was well beyond the required torque. This experiment proved that magnetic fields are a viable mechanism to couple a motor to a pump.

5.2. Volumetric Flow Rate

A very important part of the teams design was to reach a flow rate of 5-15gpm. This is to guarantee that the cryogens are mixing sufficiently to maintain a homogeneous temperature throughout the cryostat. Due to the harsh environments of cryogenics, time constraints, and limited resources the flow rate could not be tested in liquid nitrogen. Instead the volumetric flow rate was recorded using water as the operating fluid.


Figure 35: Setup for volumetric flow rate test

In order to test the flow rate an experiment was formulated utilizing a flow meter and a piping system. The flow meter measured the volumetric flow rate in gpm using a simple gravity flow meter. The piping system was designed to pipe the water out of the tank in order for the flow meter to be observable. The piping system was made of 2” diameter PVC that was then reduced to 1” to fit the flow meter. The system consisted of an 180deg bend that led into a 1’ long straight pipe. This 1’ straight pipe was then connected to a 90deg bend and then reduced to 1” in diameter. At this point the flow meter was connect to the piping system another 1” diameter pipe was connected to the other end of the flow meter leading to a 90deg bend. The 90deg bend was then connected to a 1”x1’ pipe that returned the flow to the tank. This setup can be seen outside the tank in Figure 35.

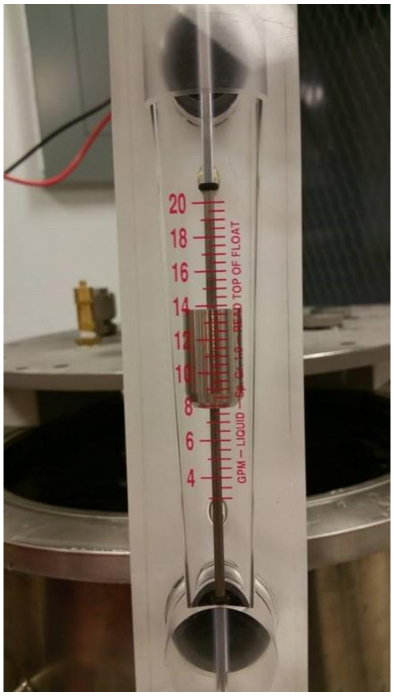


Figure 36: Achieved flow rate of 14gpm

Once the experiment was designed a procedure was formulated in order to record the results. This procedure was somewhat rudimentary due to the time constraints and lack of resources. The pump and piping system were first submerged in the cryogenic tank provided by NASA. The tank was then filled with water in order to cover the majority of the inlet holes of the pump. The experiment was then conducted by simply bringing the motor up to speed until the maximum volumetric flow rate was measured. This experiment was performed several times in order to achieve an accurate reading for the maximum volumetric flow rate.

After the experiment was performed several times it was observed that the maximum volumetric flow rate reached 14gpm as seen in Figure 36. Additionally the piping system the team designed introduced significant losses due to friction and gravity. These losses decreased the flow rate by roughly 2-3gpm. This is an extremely favorable result as NASA set a goal to achieve an upper limit of 15gpm.

5.3.Cryogenic Testing

The last step in prototype testing was to ensure the design worked properly in liquid nitrogen. This was an important aspect of the design because the design is intended to destratify cryogenic fluids. Due to extreme time constraints the testing was just intended to make sure the individual components did not break under the extreme conditions of a cryogenic chamber. However some simple data was recorded during the cryogenic testing.

All of the cryogenic testing was done at the National High Magnetic Field Laboratory. The tests were conducted inside the Cryofab CF 1424-f provided by NASA. In order to conduct the testing the cryostat lid was first securely fastened to the cryostat. Next, the copper gasket and the 6” conflat flange were cleaned thoroughly using acetone. Once the flange and the gasket were free of all contaminants the gasket was placed on the cryostat lid followed by the prototype. The design was then securely fastened to the lid using 13mm bolts in a star fashion. Next fittings wrapped in Teflon were attached to the lid in order to fill the cryostat and to reduce the pressure in the tank when filling. A stainless steel hose was then connected to the filling attachment and the pressure valve was opened. A dewar was then transported to the testing area and the other end of the hose was connected to it. The dewar’s valve was slowly opened and liquid nitrogen was slowly transferred to the testing tank. The setup of this experiment can be seen in Figure 37.

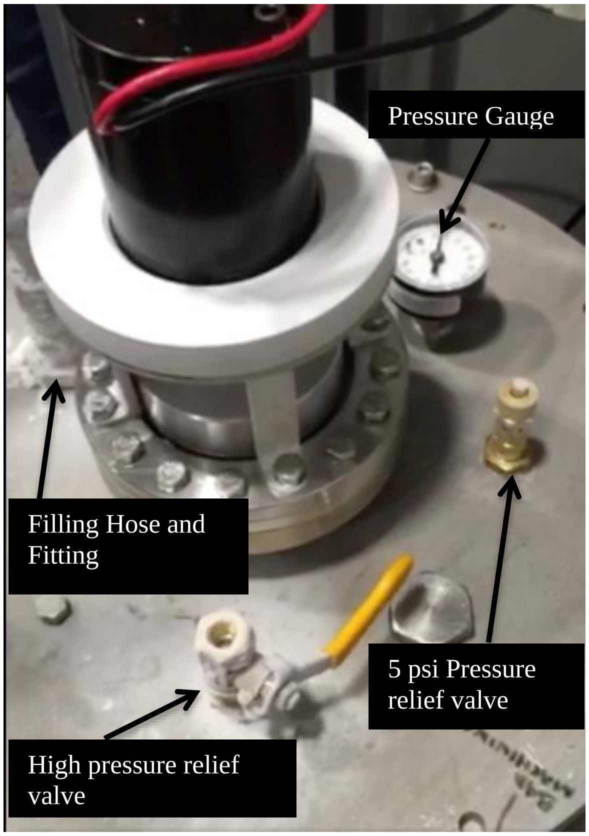


Figure 37: Experimental setup of liquid nitrogen tests.

Once the experiment was properly setup the testing of the design began. The high pressure relief valve was first closed in order to record how many times the 5psi pressure valve was engaged. A control test was first performed and the frequency of pressure relief was recorded. Next a test was performed while running the magnetically coupled cryogenic pump. The frequency of pressure relief during the control test was observed to be 0.4Hz. Conversely when the pump was running a pressure relief frequency of 0.15Hz was observed. This proves that the cryogenic pump successfully destratified the cryogens and reduced the pressure rise in the cryogenic tank by 63%.

5.4.Experimental Improvements

As stated earlier many of the experiments used to test the success of the prototype were done under extreme time constrains and lacked the necessary resources to provide concrete data. Given the right resources and the proper amount of time significant results could be obtained. The first major results that would be necessary to achieve these results would be to construct a pressure vs. flow diagram. This diagram would show how the flow rate affects the flow rate of the fluid. These tests could be done using a flow meter rated for cryogenic temperatures. The while pressure would then be recorded at different volumetric flow rates and then plotted in order to obtain the pressure vs. flow diagram. Another improvement that could be made to the testing of the prototype would be to expand on the magnetic torsion testing. This would be done by varying the size, strength and number of magnets in each coupler at a specified distance. These results would allow for the couplers to be expertly optimized for the maximum amount of magnetic coupling.

6. Considerations for Environment, Safety, and Ethics

In our project there were not many considerations needed for the environment, considering that the tested cryogen is nitrogen which is readily available in nature, nor in ethics since the idea we have were entirely original and not plagiarized. However there are several safety measures that need to be taken into account during manufacturing and testing of our prototype system.

Liquid Nitrogen:

Handling liquid nitrogen is one of the biggest safety hazards of the project. The project requires testing with liquid nitrogen which temperatures range from 63K to 77K. Due to the extremely low temperature of this cryogen, contact with this fluid causes rapid frost bite and should be avoided at all cost. Safety precautions have to be taken in order to ensure no member of the team comes in contact with the substance. These precautions included wearing safety glasses, closed toe shoes and thick gloves when working with the LN dewar and the prototype tank. Along with following the National High Magnetic Field Laboratory's cryogenic safety procedure, we always had a graduate student of our faculty advisor present while working with the cryogen.

Pressure Build-up:

To ensure the testing cryostat does not become over pressurized, which could cause a catastrophic failure of the tank, a five psi pressure relief valve was installed for venting the ullage out of the tank. Along with this a valve was installed to allow for rapid de-pressurization of the tank whenever necessary. The reliability of the valve is essential since over time the liquid nitrogen will eventually boil off and become vapor. If this valve were to fail (not vent the vapor), the tank would become over pressurized and overstressed which could potentially cause the tank to rupture. To ensure that the tank is completely sealed to prevent cryogen/vapor loss copper gaskets were used on the flange that the prototype was attached to as well as a large O-ring used in between the cryostat and the cryostat lid. Before installation the flange, gasket and lid were cleaned with acetone to ensure the best possible seal.

High Velocity Components:

The system involves a large magnet coupler which is directly attached to our motor. The motor is capable of reaching 5600 RPM. While this top speed is not generally used, at such high speeds the outer coupler becomes a safety concern. At such high speed touching the coupler will result in bodily such as cuts, abrasion, and blood blisters. While the motor mount legs partially shield the operator from the spinning coupler, all activity around the outer coupler should be avoided. While the inner coupler also operates at a high RPM the pump housing anchor shield this part entirely. The impeller at the other end of the pump shaft is also operating at a high speed and touching this component can cause cuts due to its sharp edges. However the impeller is completely covered by the pump housing during operation.

Electrical Components:

Whenever one works with there is a possibility of faulty wiring causing errors or even injury, therefore a consideration for the safety of the installation and operation of the wiring in our project was considered. To insure that they system is not wired correctly consult our Operational Procedure section that shows the wiring diagram. If these directions are not followed the motor or the motor controller could fry which could cause a small fire. Also possible is the shorting of the motor controller board which could shock the operator.

Magnets:

The essential component of our system are the eight 1 Tesla magnets used in the magnet couplers. These are very powerful magnets that must be handled with care during installation. Magnets of this strength must be kept far from each other, any magnetic metal, and any electronics. If the magnets are placed too close together or too close to magnetic material and care is not taken the magnet could have the potential to cause personal injury. If place too close to any electronics, these magnets could possibly cause damage to the internal components of the device. During installation of the magnets into the magnet coupler, as previously discussed, a procedure has been set in place using the coupler's faceplate as a way of holding the magnets in their placement hole ensuring that they do not jump out and cause injury to the individual assembling the coupler. This procedure should be carefully followed to avoid injury.

7. Project Management

The management of this project was a very important aspect of the overall design process. The scheduling, resources, procurement process, and communications were handled with great care due to the constraints set forth by the College of Engineering and the NASA Marshal Space Flight Center.

7.1.Schedule

In order for the project to stay on track and be completed in the allotted amount of time a schedule was formulated at the beginning of the semester. This timetable was meant to be a tentative schedule as to account for any unforeseen circumstances. The schedule the team came up with can be seen in Appendix F-1. A sizeable amount of time was allotted for the fabrication, assembly, and testing phases. Three weeks were apportioned for the fabrication stage. Originally the team thought this would be an ample amount of time to complete this process. However due to the overloaded machine shop this proved to be an incorrect belief. The fabrication of the parts took over seven weeks to complete which significantly delayed the project objectives. To make up for this lost time the assembly process was shortened from an allotted ten days to less than two days. Unfortunately the team was still behind schedule and the testing and compiling data was cut short by over two weeks. The testing was completed in two days and the compiling of data was finished in less than a day.

7.2.Resources

During the course of the year numerous resources were utilized in order to aid in the success of the project. One major resource we used during the project was our advisor Dr. Guo. Dr. Guo helped us formulate some of the governing equations of our design and was involved in the brainstorming process during the early stages of the design. In addition to the helped we received from our faculty advisor we also sought help from other faculty members not assigned to our group. Dr. Hollis helped us design the bearing system used to stabilize and support our design. Dr. Gupta and Dr. Chuy helped us select an appropriate motor to accompany the necessary power required for the design. Another major resource the team utilized was our sponsor and liaison engineer Jim Martin. Jim provided much needed direction when calculating the power required in order to achieve the necessary volumetric flow rate. Additionally our sponsor NASA Marshal space flight center provided important materials that were needed to design and test the prototype. All of the fabrication implemented in the design was done at the College of Engineering’s machine shop free of charge. This significantly reduced the cost of the overall design and helped keep the budget within reason. Lastly the National High Magnetic Field Laboratory provided liquid nitrogen in order to test our design in a safe and controlled manner.

7.3. Procurement

When selecting components for the design of this project the economics were of utmost importance. An initial budget of $500 was proposed for this project. Many of the materials procured for this design were extensively researched in order to find the best market price while still producing a reliable product. However, it was determined that a budget increase was required in order to ensure the success of the design. The budget was raised by $100 bringing the total budget up to $600. A breakdown of the budget can be seen in Figure 38. A more detailed breakdown of the budget can be seen in Appendix E Table E-1 which shows the bill of materials for all the components purchased for the design, testing and assembly. Evident in the bill of materials the design stayed well within the given budget of $600. The overall cost of the design was $373.48, which was only 62% of the budget. The rest of the budget was used to purchase the necessary materials used to test the design. These materials totaled $213.29 bringing the overall cost of the prototype to $586.77. However, some materials were donated in order to assist in the project's success such as a 6" flange, an inducer, bearings, raw materials, and a cryostat used for testing the design. Additionally all of the machining of the design was done at the FAMU-FSU College of Engineering free of charge.

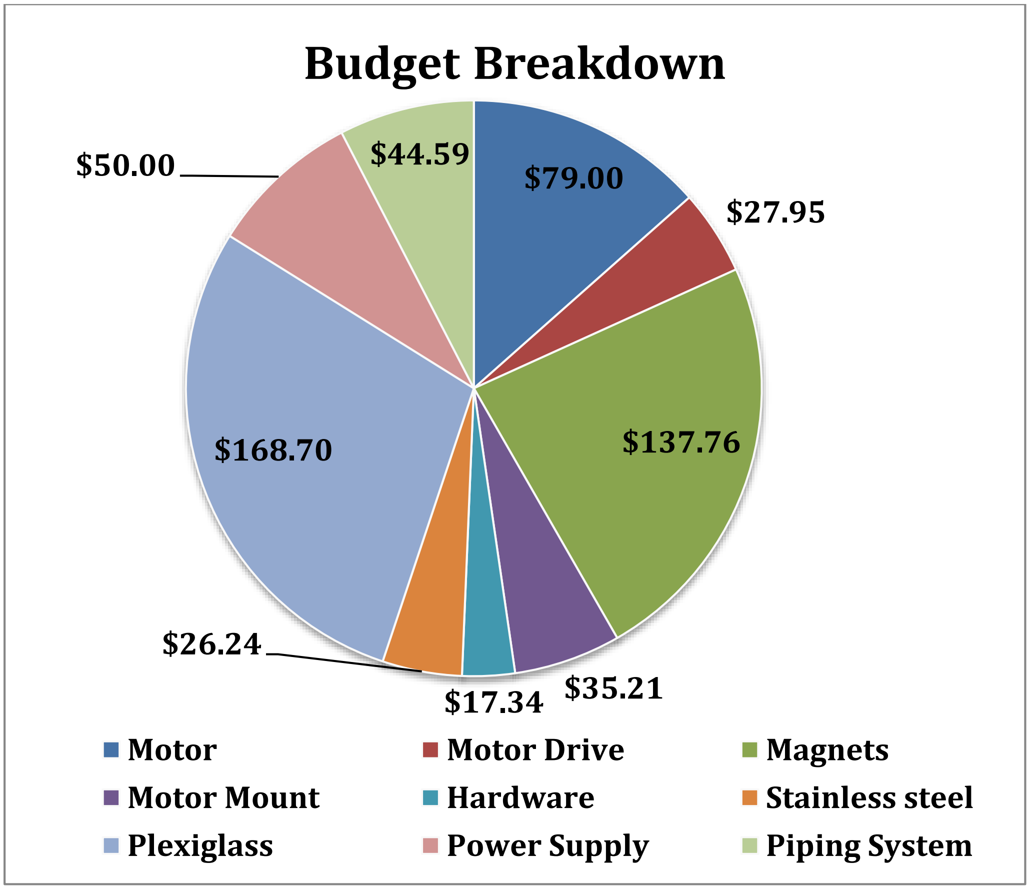


Figure 38: Breakdown of the budget for the components used in the design.

7.4.Communications

The communication between group members throughout the course of the project ran exceptionally smooth. A Facebook page was created to keep the group members updated on the progression of the project. Additionally a Dropbox was used in order to share files during times when group meetings were not feasible. These two systems allowed the group members to work seamlessly together providing a quick and effective form of communication.

Additionally weekly meetings were scheduled with the team's advisor Dr. Guo to keep him updated on our project goals and success. Biweekly teleconference calls were also organized with the team's sponsor to update them on the project objects. In addition to keeping the teams sponsor and advisor up to date these meetings also provided the team with opportunities to seek guidance in problematic situations.

8. Conclusion

In summary of our senior design project, a complete and functional magnetically coupler pump system for cryogenic tank propellant destratification has been manufactured. As stated before, destratification is necessary to reduce the amount of pressure venting in a cryogenic tank in low gravity environments. This destratification is currently achieved with systems that have their motors fully submerged in cryogens, which causes the system to be expensive and introduces heat into the system. Our design removes this motor from the tank, keeping the system completely sealed using magnetic coupling.

The design was constructed in the design software Solid Works before fabrication and consists of three main sub-assemblies; the outer coupler motor sub-assembly, inner coupler and pump sub-assembly, and the pump housing assembly. Calculations were conducted using the geometry of the pumping system to determine the power and speed requirements for the prototype's motor as well as the bearing system used. Upon the completion of the fabrication of all the design components the prototype was assembled using the manufacturing procedure. The prototype was then dry tested to ensure that the couplers rotated together and that there was no scraping. The operational procedure of the prototype pump was then devised and was followed for the experimental section of the project.

Testing was then conducted both in water and liquid nitrogen. The system was found to successfully pump water and using a piping system and a flow meter provided to us by our faculty advisor. During these tests a maximum flow rate of 14 gpm was consistently achieved and during tests values of up to 16 gpm were observed. The system was then tested at the National High Magnetic Field Laboratory in liquid nitrogen using the cryostat provided to the group by our sponsor. All cryogenic safety procedures of the NHMFL were followed to ensure a safe test. The system functioned while being fully submerged in liquid nitrogen. To test that the pump successfully destratified the liquid nitrogen and reduced the amount of pressure venting the frequency at which the five psi pressure relief valve was engaged. Comparing to a control test where the pump was off, the frequency of pressure relief decreases from 0.4 Hz to 0.15 Hz, a 63% decrease in the amount of venting. This test shows that the system successfully destratifies the liquid nitrogen while using magnetic coupling.

This project went behind schedule after fabrication times took almost twice as long as previously intended by the original Gantt chart. The project was under-budget even with the addition of the experimental testing materials, but the design itself was able to be constructed well under the supplied budget of $600.

Future recommendations to continue this project on for multiple years would mostly be in improving the errors in the current design. Vibrational analysis could be conducted on the system and dampening of the motor mount could be done to make the system run at higher speeds for long periods of time. An improved design would also reduce the amount of friction in the bearing system to allow for a smoother system operation. Overall the system could be designed to run more smoothly while still meeting the project requirements. If given more time more in depth experiments of the magnet torsional strength could be done to determine the optimum achievable spacing between the couplers as well as the optimal number of magnets to use in each coupler. Also if allowed more time, more testing could be conducted to systematically construct an in-depth flow rate vs. pressure plot for the pump system for operational use. In addition to this type of testing, a method for testing the flow rate in liquid nitrogen could also be conducted to more accurately show the operation of the system in cryogens.

9. References

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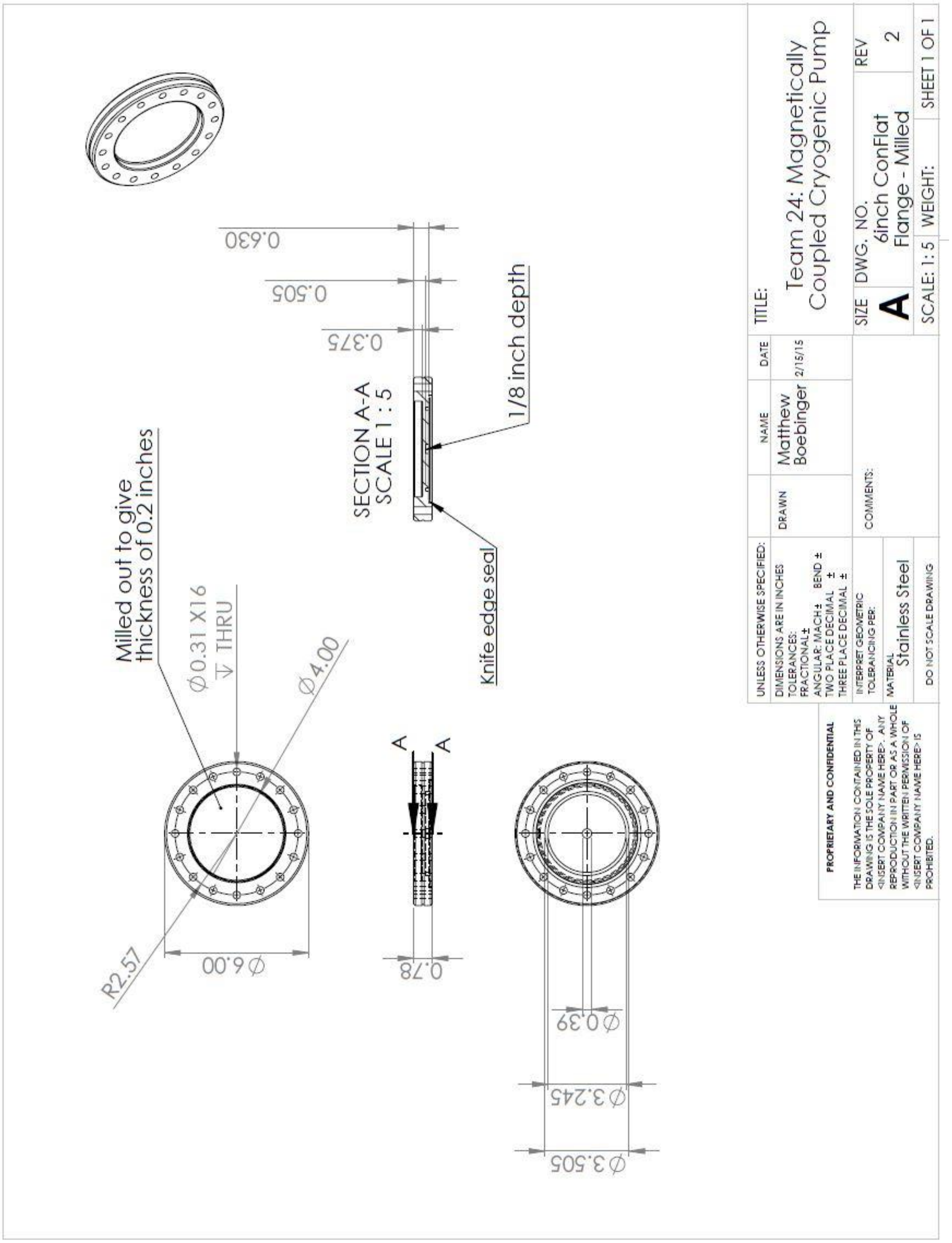
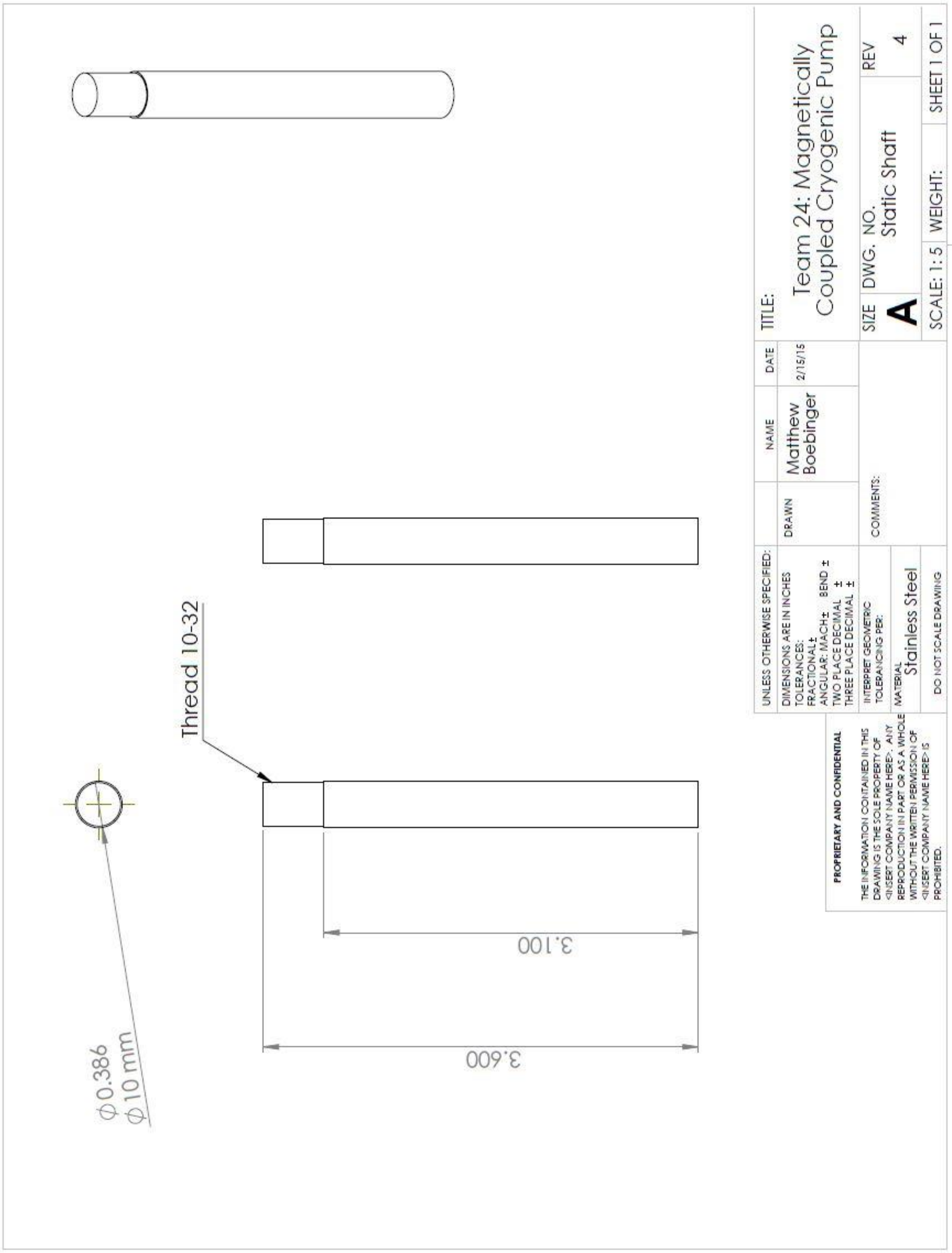
[5] "Axial Flow Pumps Information." *On GlobalSpec*. N.p., n.d. Web. 25 Oct. 2014.

[6] Norton, Robert L. *Machine Design: An Integrated Approach*. Boston: Prentice Hall, 2011. Print.

Appendix A: Component Engineering Drawings

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ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
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DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
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Matthew Boebinger
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Static Shaft
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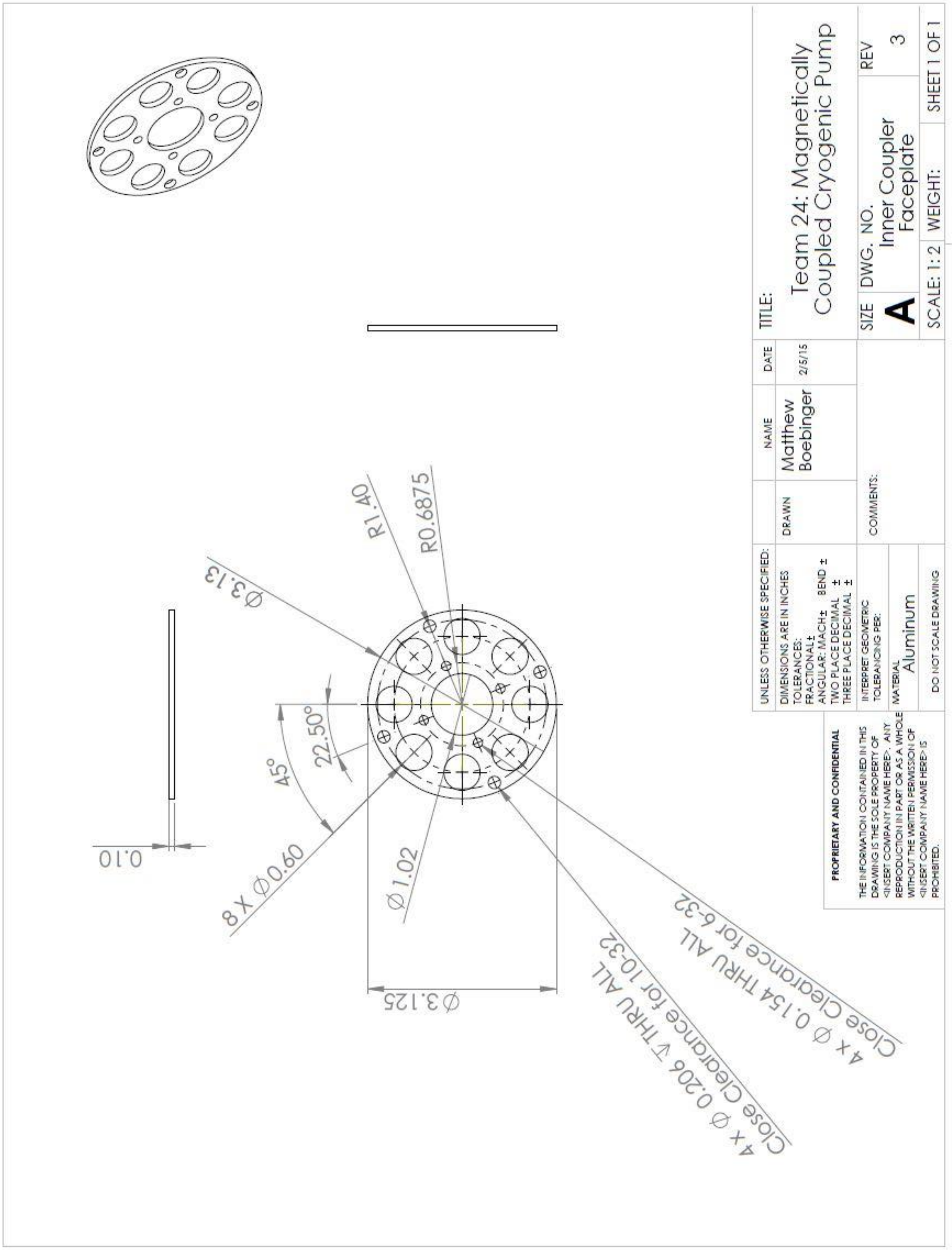
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Matthew Boebinger
2/5/15
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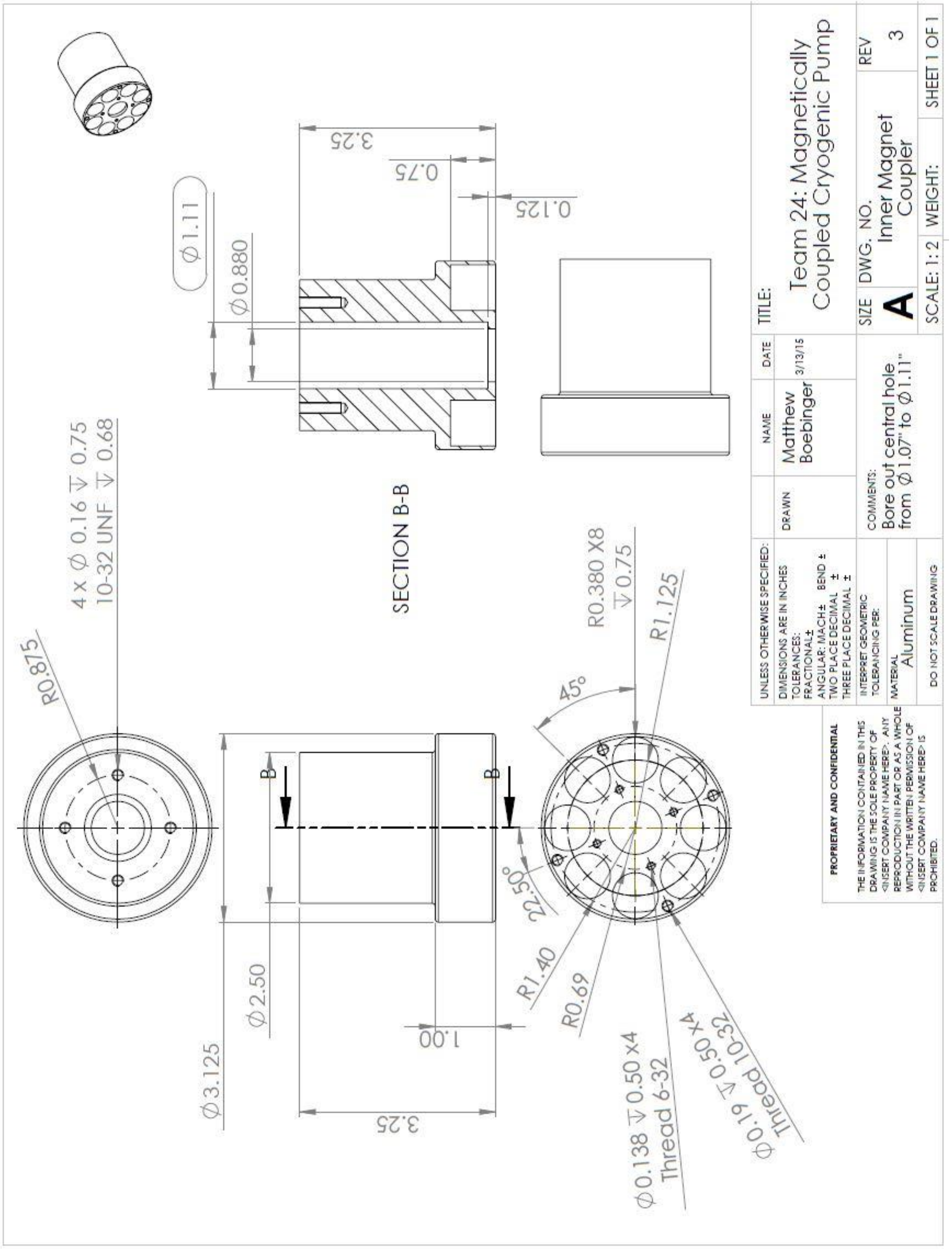
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0.125
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↧0.75
R1.125
45°
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B
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3/13/15
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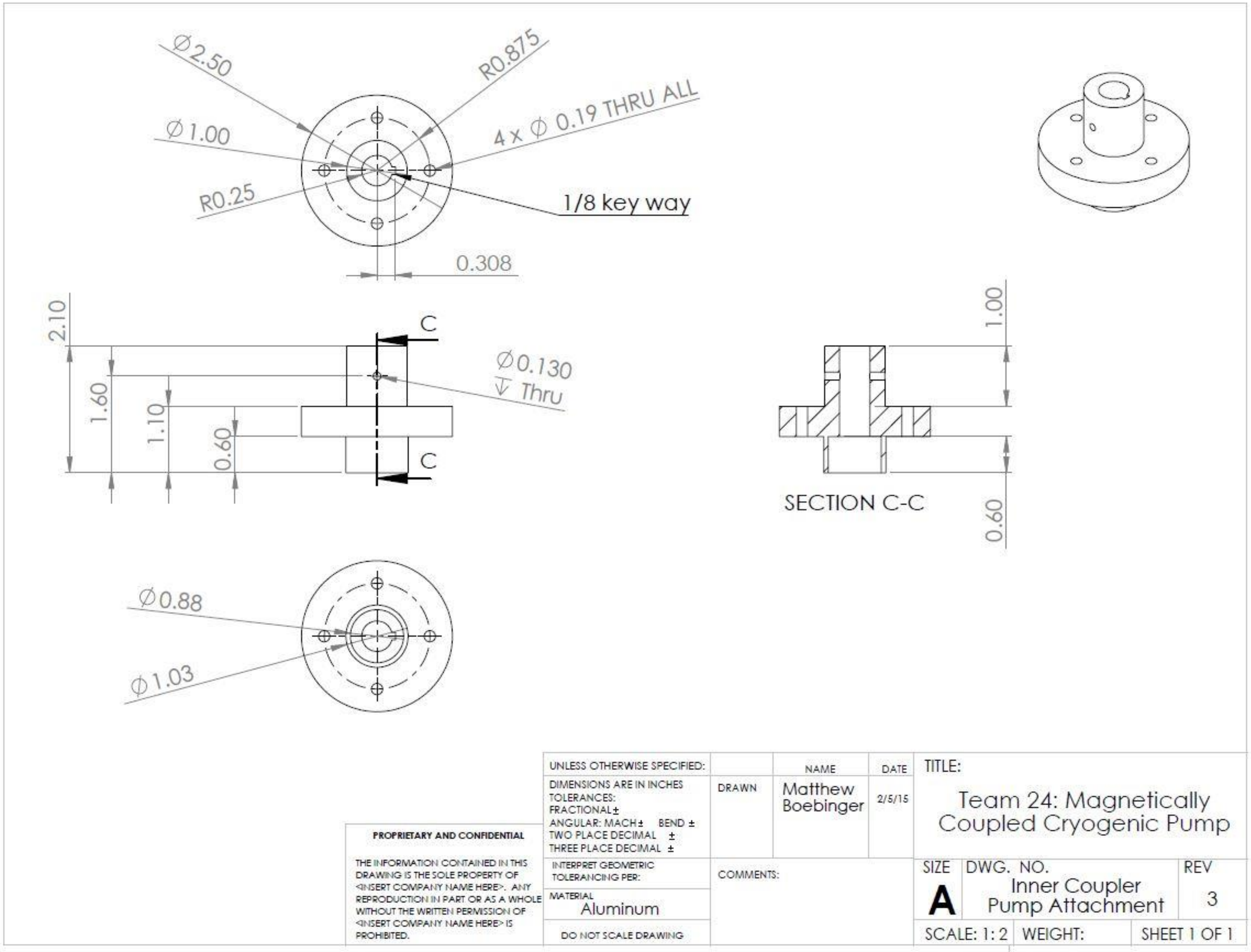
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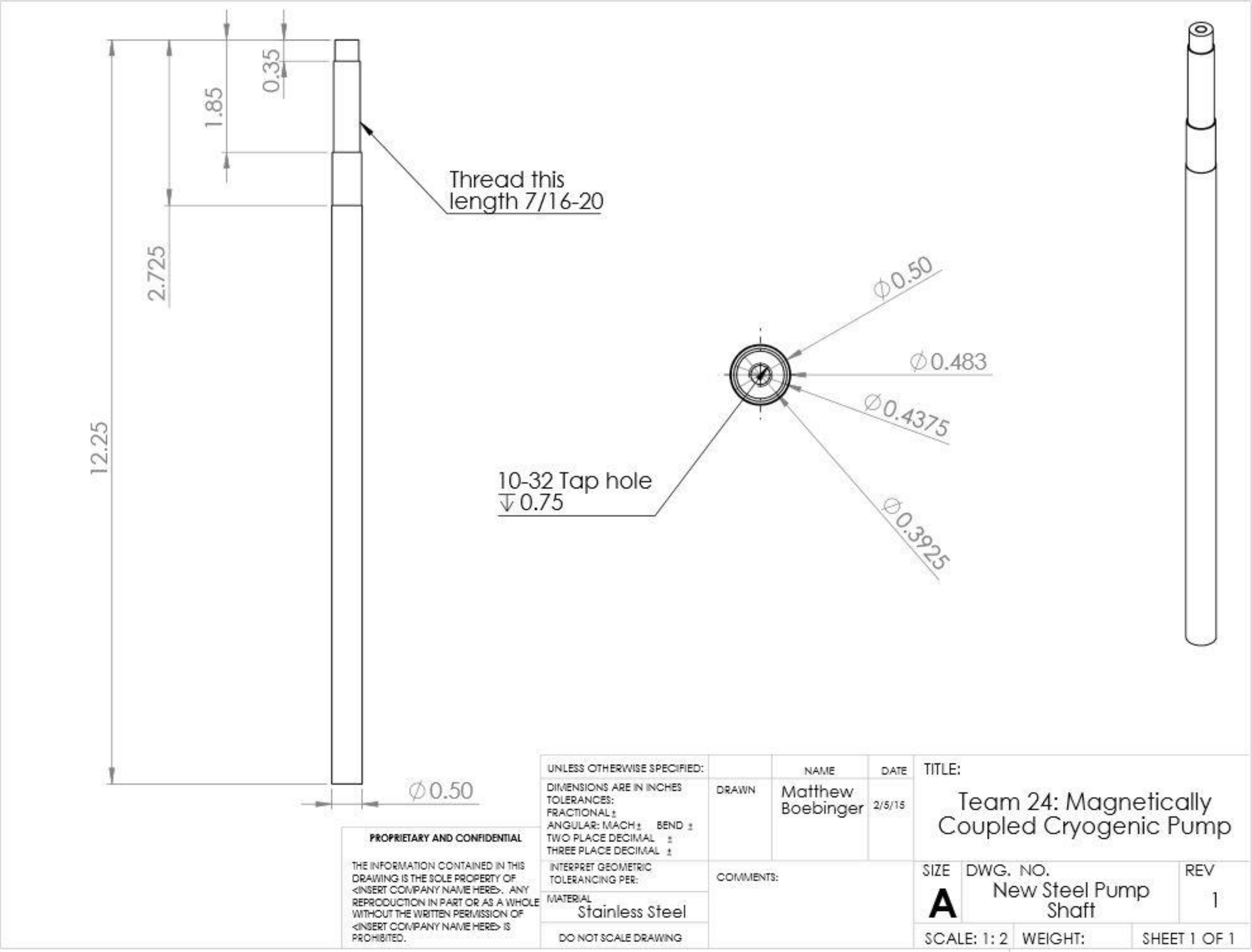
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Matthew Boebinger
2/5/15
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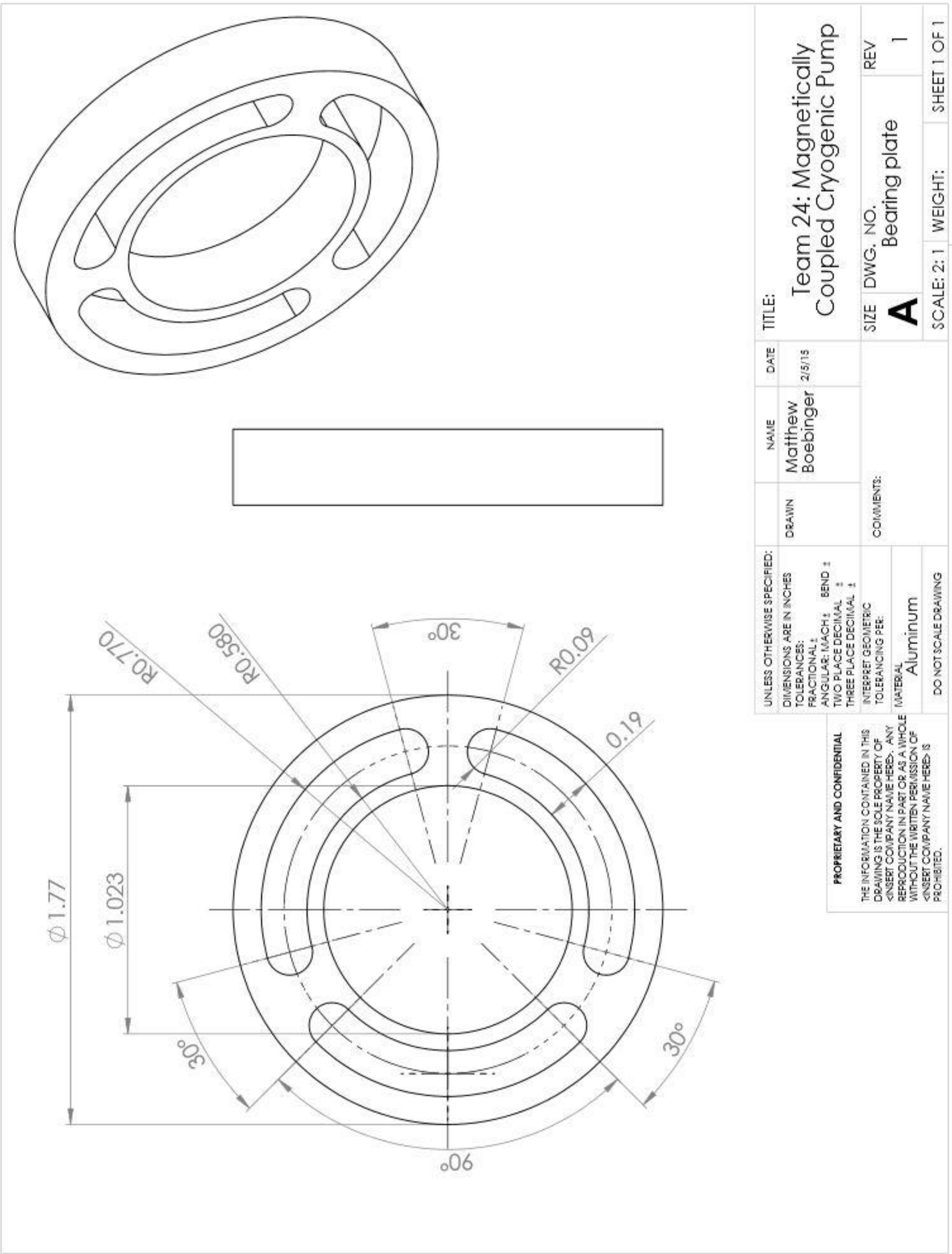
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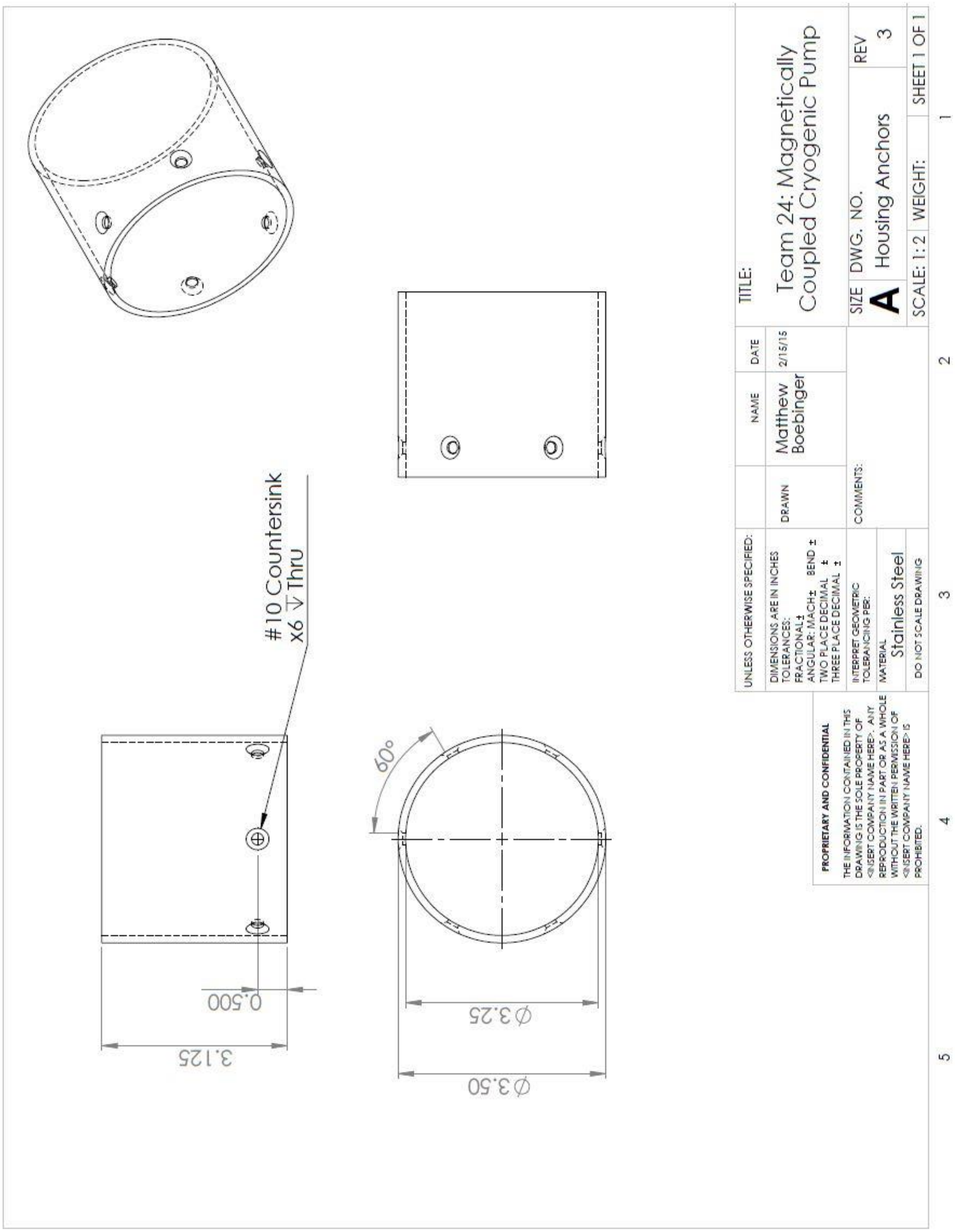
NAME
DATE
DRAWN
Matthew Boebinger
2/5/15
COMMENTS:
TITLE:
Team 24: Magnetically Coupled Cryogenic Pump
SIZE
A
DWG. NO.
Bearing plate
REV
1
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1


#10 Countersink
x6 ⫟ Thru
60°
0.500
3.125
⌀3.25
⌀3.50
TITLE:
Team 24: Magnetically Coupled Cryogenic Pump
NAME
DATE
DRAWN
Matthew Boebinger
2/15/15
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Stainless Steel
DO NOT SCALE DRAWING
COMMENTS:
SIZE
A
DWG. NO.
Housing Anchors
REV
3
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
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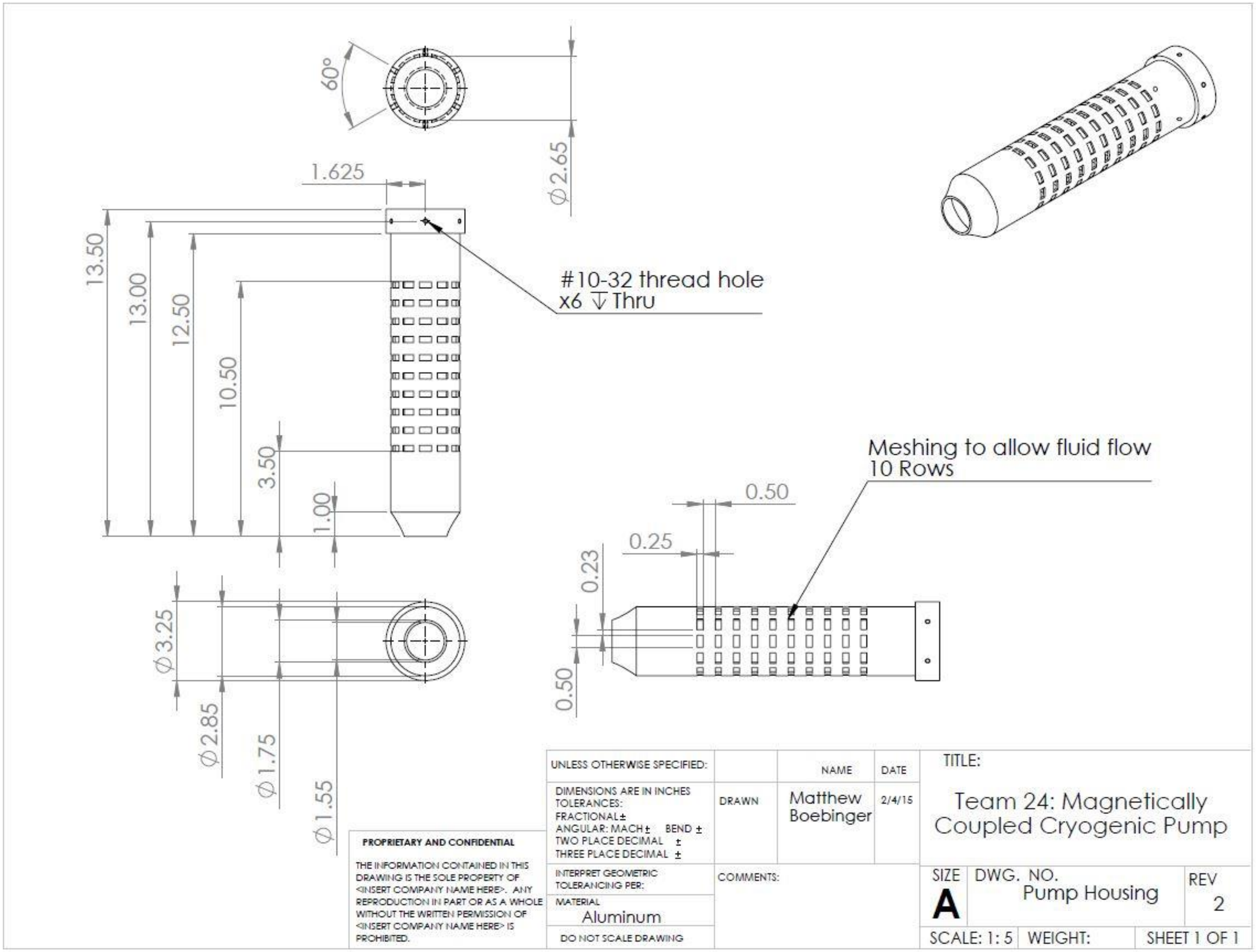
1
2
3
4
5


60°
Ø2.65
1.625
13.50
13.00
12.50
10.50
3.50
1.00
#10-32 thread hole
x6 ⊽ Thru
Ø3.25
Ø2.85
Ø1.75
Ø1.55
Meshing to allow fluid flow
10 Rows
0.50
0.25
0.23
0.50
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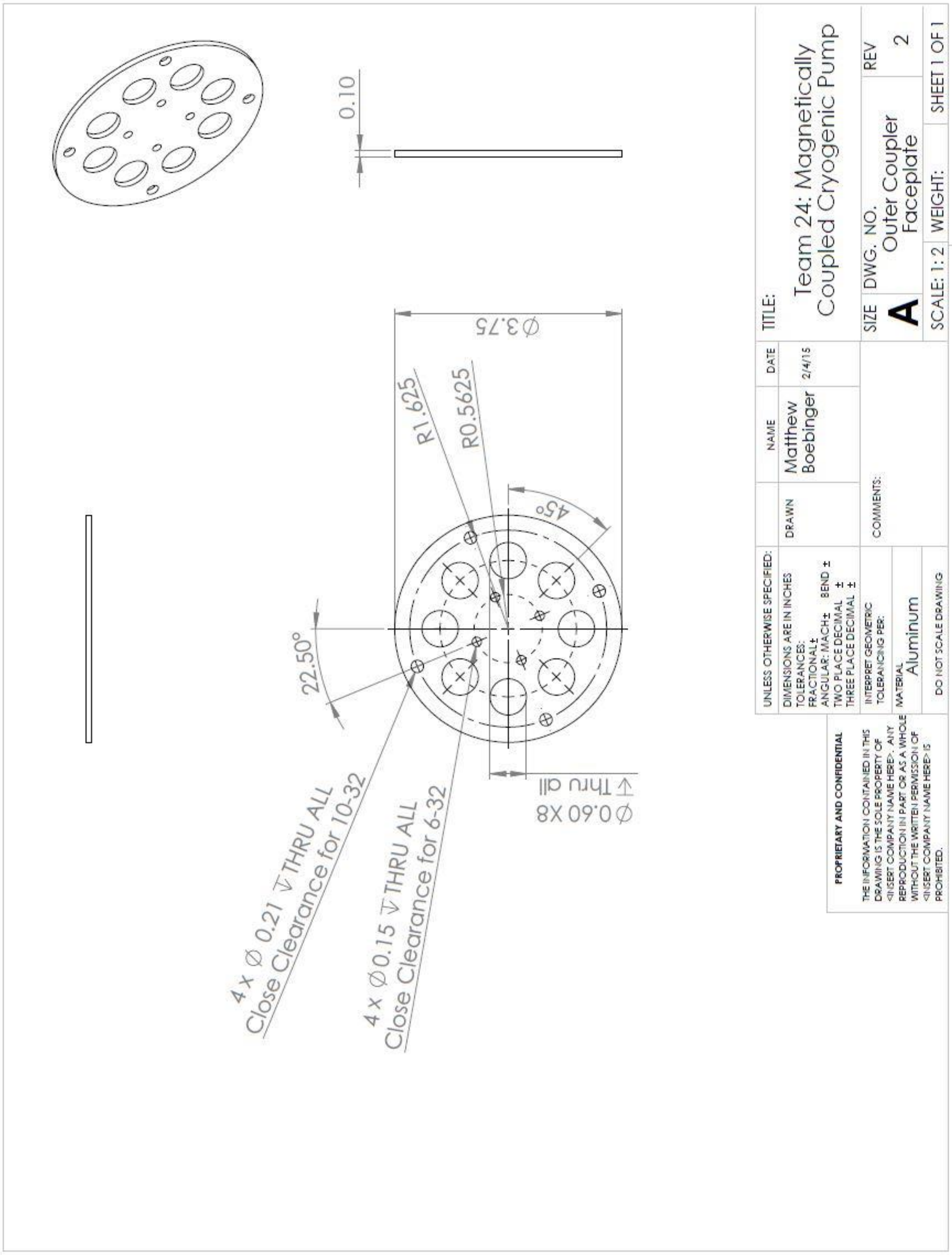
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
Matthew Boebinger
2/4/15
COMMENTS:
TITLE:
Team 24: Magnetically Coupled Cryogenic Pump
SIZE
A
DWG. NO.
Pump Housing
REV
2
SCALE: 1: 5
WEIGHT:
SHEET 1 OF 1



TITLE: Team 24: Magnetically Coupled Cryogenic Pump

SIZE: A
DWG. NO.: Outer Coupler Faceplate
REV: 2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

	NAME	DATE
DRAWN	Matthew Boebinger	2/4/15

COMMENTS:

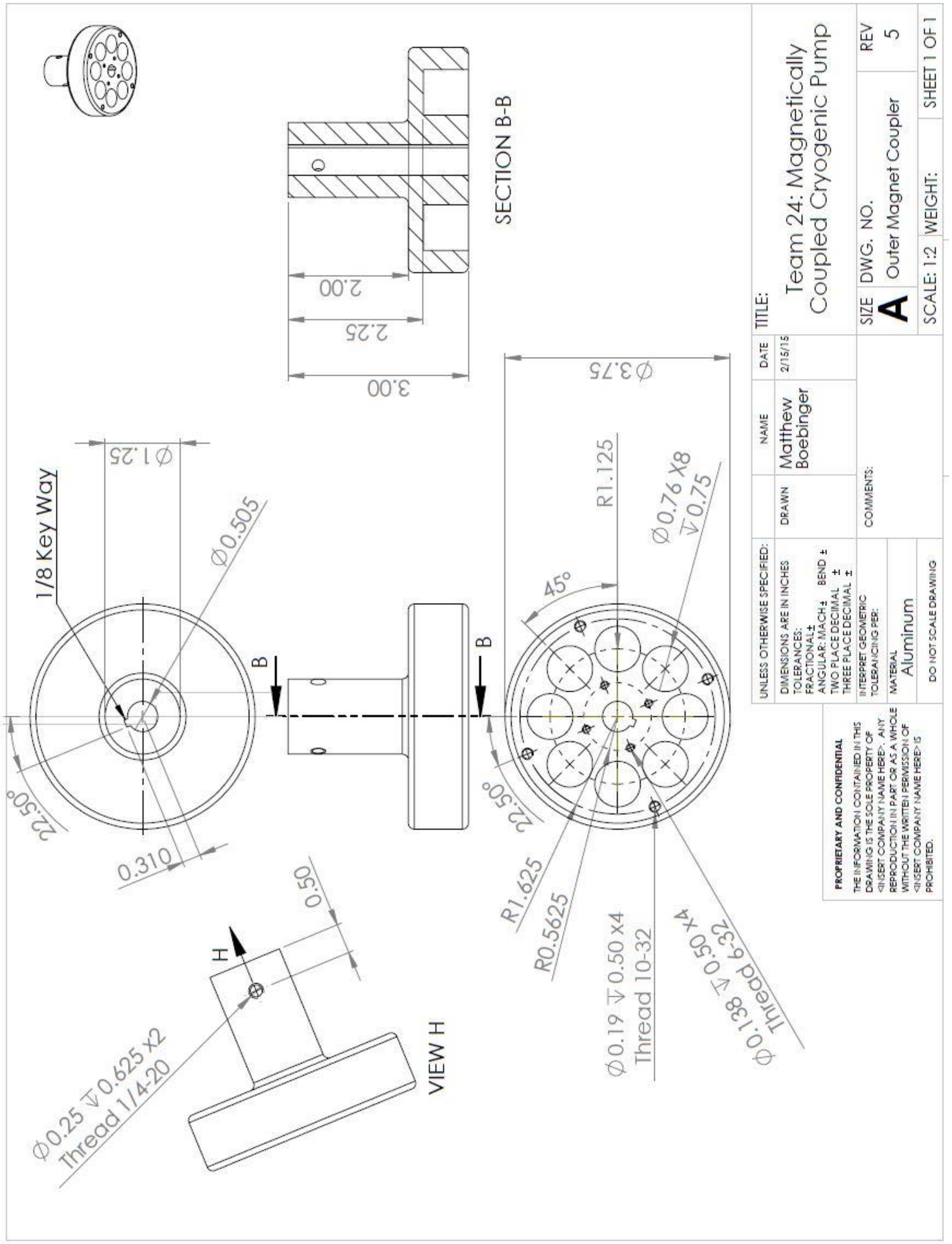
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Aluminum

DO NOT SCALE DRAWING

PROPRIETARY AND CONFIDENTIAL


SECTION B-B
3.00
2.25
2.00
Ø3.75
Ø1.25
1/8 Key Way
Ø0.505
R1.125
Ø0.76 X8
↧0.75
45°
B
B
22.50°
22.50°
0.310
0.50
H
VIEW H
Ø0.25 ↧0.625 x2
Thread 1/4-20
R1.625
R0.5625
Ø0.19 ↧0.50 x4
Thread 10-32
Ø0.138 ↧0.50 x4
Thread 6-32
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum
DO NOT SCALE DRAWING
DRAWN
NAME
Matthew Boebinger
DATE
2/15/15
COMMENTS:
TITLE:
Team 24: Magnetically Coupled Cryogenic Pump
SIZE
A
DWG. NO.
Outer Magnet Coupler
REV
5
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
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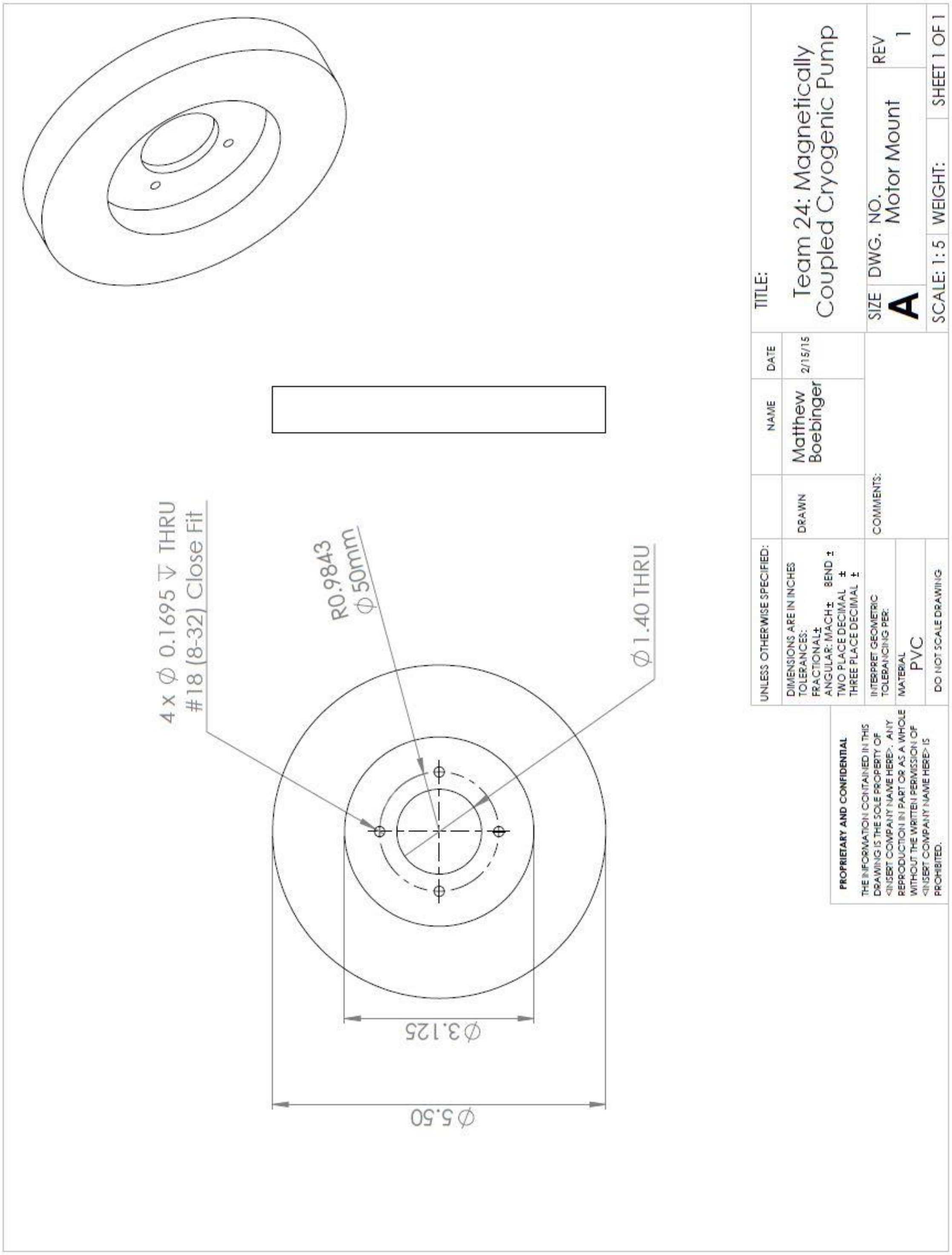


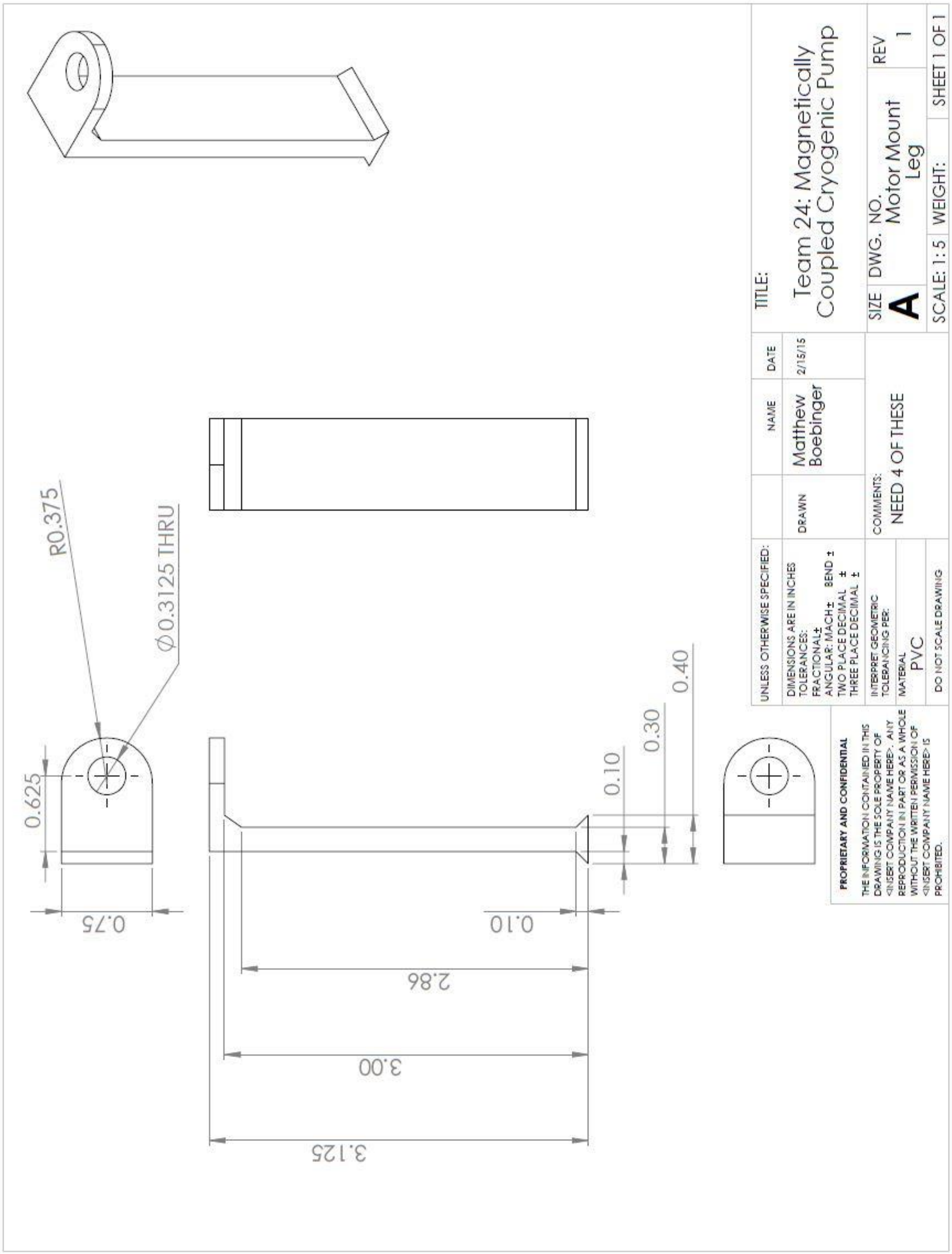
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PVC
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Matthew Boebinger	2/15/15

COMMENTS:

TITLE:
Team 24: Magnetically Coupled Cryogenic Pump

SIZE A
DWG. NO. Motor Mount
REV 1
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1


R0.375
⌀0.3125 THRU
0.625
0.75
0.10
0.30
0.40
0.10
2.86
3.00
3.125
TITLE:
Team 24: Magnetically Coupled Cryogenic Pump
SIZE A
DWG. NO. Motor Mount Leg
REV 1
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
NAME
DATE
DRAWN
Matthew Boebinger
2/15/15
COMMENTS:
NEED 4 OF THESE
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PVC
DO NOT SCALE DRAWING
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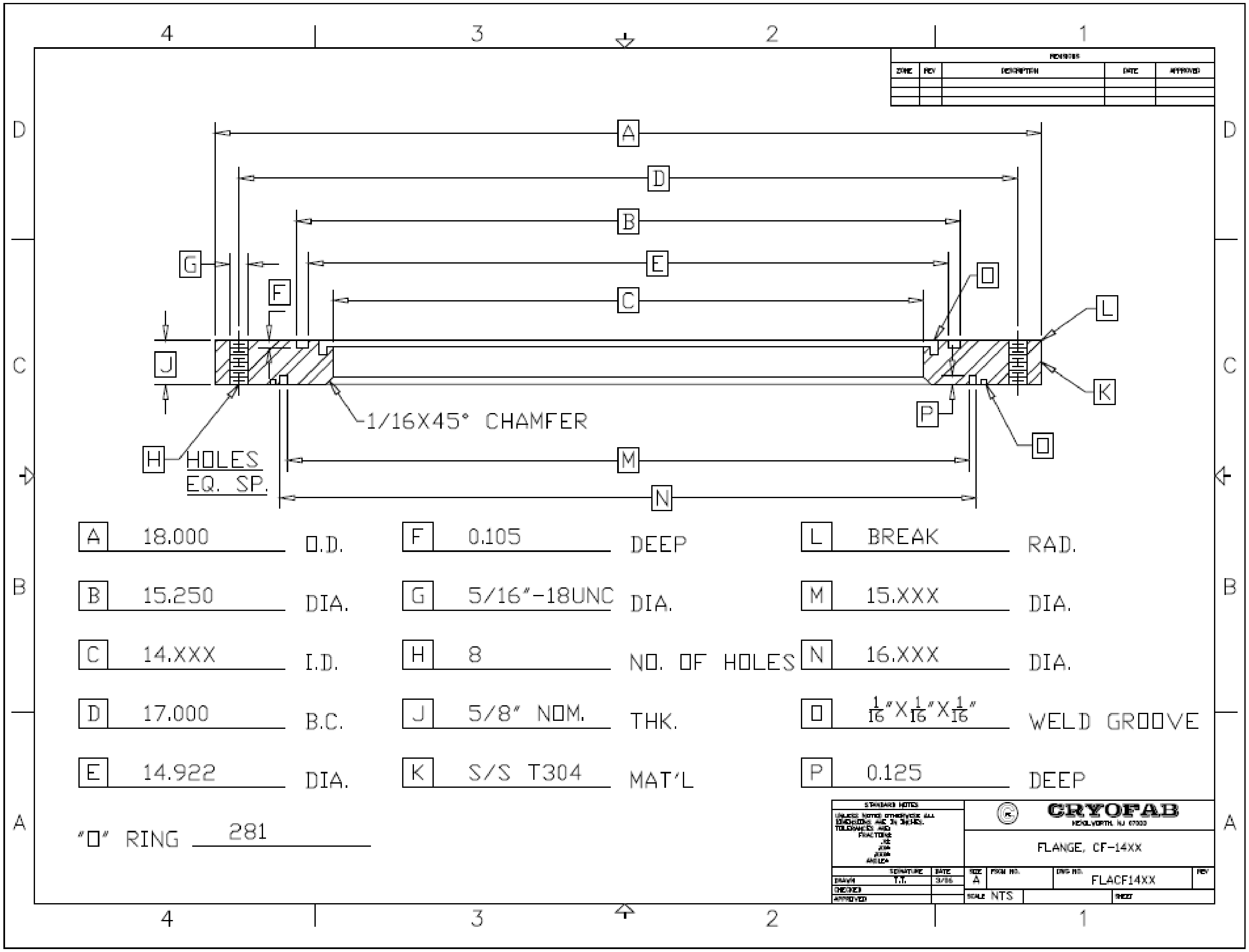
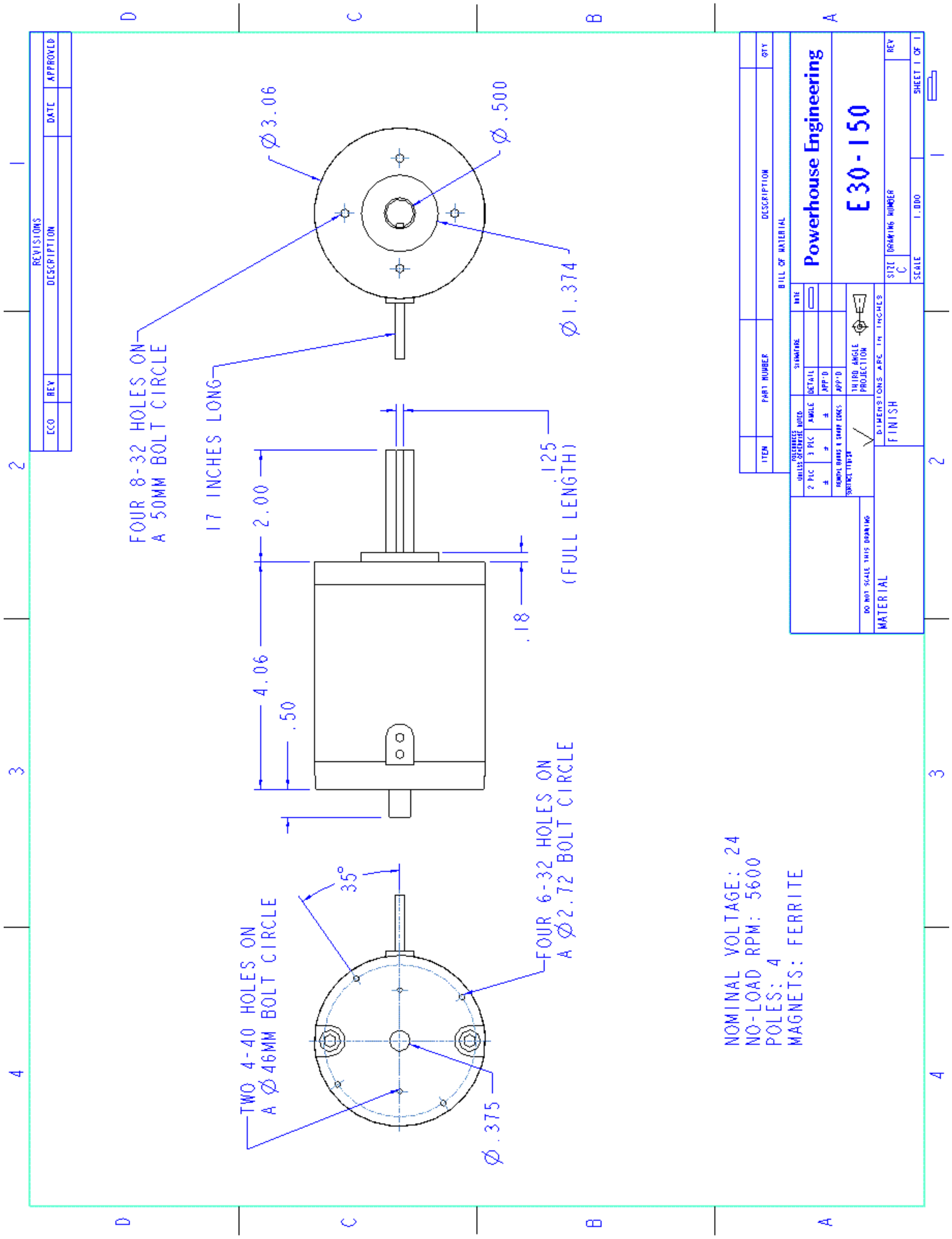
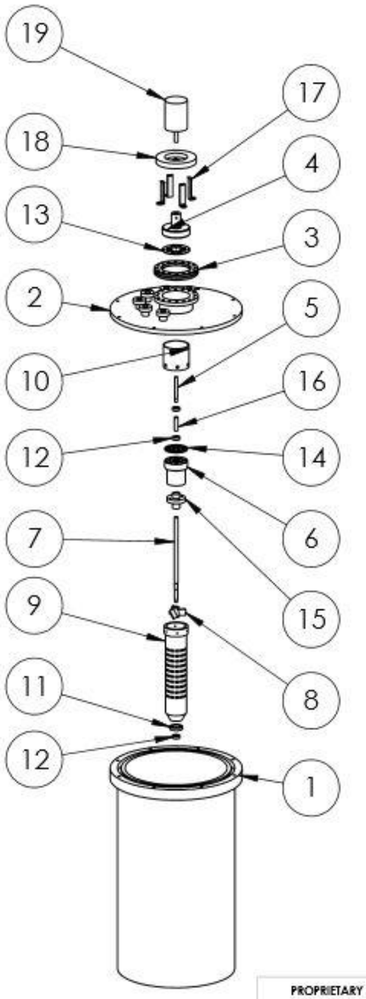

A
D
B
E
C
G
F
J
H HOLES EQ. SP.
1/16X45° CHAMFER
M
N
O
L
K
P
O
A 18.000 O.D.
B 15.250 DIA.
C 14.XXX I.D.
D 17.000 B.C.
E 14.922 DIA.
F 0.105 DEEP
G 5/16"-18UNC DIA.
H 8 NO. OF HOLES
J 5/8" NOM. THK.
K S/S T304 MAT'L
L BREAK RAD.
M 15.XXX DIA.
N 16.XXX DIA.
O 1/16"X1/16"X1/16" WELD GROOVE
P 0.125 DEEP
"O" RING 281
REVISIONS
ZONE
REV
DESCRIPTION
DATE
APPROVED
STANDARD NOTES
UNLESS NOTED OTHERWISE ALL DIMENSIONS ARE IN INCHES.
TOLERANCES AND FRACTIONS
SIGNATURE
DATE
DRAWN T.T. 3/06
CHECKED
APPROVED
CRYOFAB
KENILWORTH, NJ 07033
FLANGE, CF-14XX
SIZE A
FSCM NO.
DWG NO. FLACF14XX
REV
SCALE NTS
SHEET
4
3
2
1
D
C
B
A


Ø3.06
Ø.500
Ø1.374
FOUR 8-32 HOLES ON A 50MM BOLT CIRCLE
17 INCHES LONG
2.00
4.06
.50
.125 (FULL LENGTH)
.18
35°
TWO 4-40 HOLES ON A Ø46MM BOLT CIRCLE
FOUR 6-32 HOLES ON A Ø2.72 BOLT CIRCLE
Ø.375
NOMINAL VOLTAGE: 24
NO-LOAD RPM: 5600
POLES: 4
MAGNETS: FERRITE
REVISIONS
ECO
REV
DESCRIPTION
DATE
APPROVED
BILL OF MATERIAL
ITEM
PART NUMBER
DESCRIPTION
QTY
Powerhouse Engineering
E30-150
SIZE C
DRAWING NUMBER
REV
SCALE 1.000
SHEET 1 OF 1
TOLERANCES UNLESS OTHERWISE NOTED
2 PLC ±
3 PLC ±
ANGLE ±
REMOVE BURRS & SHARP EDGES
SURFACE FINISH
DETAIL
APP'D
APP'D
SIGNATURE
DATE
THIRD ANGLE PROJECTION
DIMENSIONS ARE IN INCHES
FINISH
DO NOT SCALE THIS DRAWING
MATERIAL
D
C
B
A
1
2
3
4

Appendix B: Assembly Drawings



ITEM NO.	PART NUMBER	QTY.
1	CF-1424 Cryostat	1
2	Cryostat Lid	1
3	6inch ConFlat Flange - Milled	1
4	Outer Magnet Coupler	1
5	Static Shaft	1
6	Inner Magnet Coupler	1
7	New Steel Pump Shaft	1
8	Sample Propeller	1
9	Pump Housing	1
10	Housing Anchors	1
11	Bearing plate	1
12	Bearings	3
13	Outer Magnet Coupler Faceplate	1
14	Inner Magnet Coupler Faceplate	1
15	Inner Magnet Coupler Pump Attachment	1
16	Bushing	1
17	Motor Mount Leg	4
18	Motor Mount	1
19	Sample Motor	1

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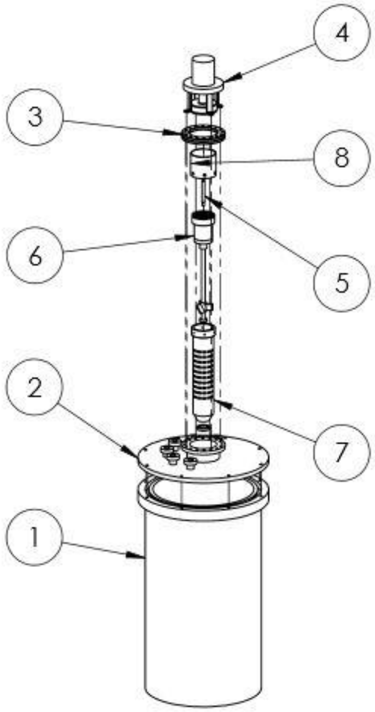
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Matthew Boebinger	2/4/15

COMMENTS:
Exploded for Labeled Components

TITLE:
Team 24: Magnetically Coupled Cryogenic Pump

SIZE A
DWG. NO. System Design Assembly
REV 4
SCALE: 1: 20 WEIGHT:
SHEET 1 OF 1



ITEM NO.	PART NUMBER
1	CF-1424 Cryostat
2	Cryostat Lid
3	6inch ConFlat Flange - Milled
4	Outer Coupler Motor Sub-Assembly
5	Static Shaft
6	Inner Magnet Coupler Sub-Assembly
7	Pump Housing
8	Housing Anchors

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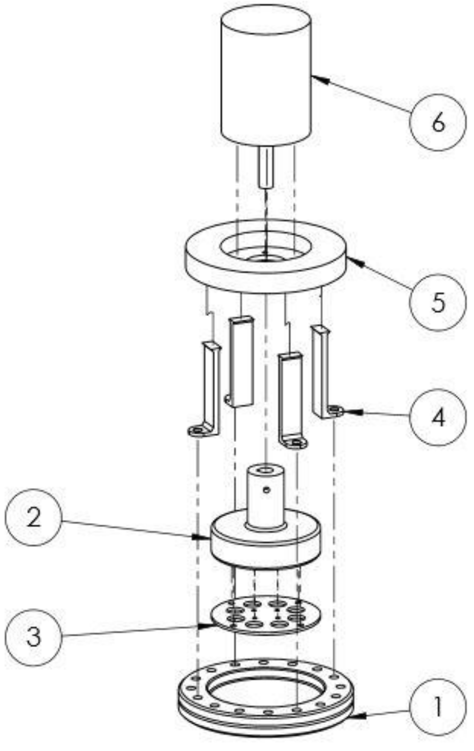
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Matthew Boebinger	3/20/15

COMMENTS:
Exploded with Sub-Assemblies for Manufacturing

TITLE:
Team 24: Magnetically Coupled Cryogenic Pump

SIZE A
DWG. NO. System Design Assembly for Manufacturing
REV 1
SCALE: 1: 20 WEIGHT:
SHEET 1 OF 1



ITEM NO.	PART NUMBER	QTY.
1	6inch ConFlat Flange - Milled	1
2	Outer Magnet Coupler	1
3	Outer Magnet Coupler Faceplate	1
4	Motor Mount Leg	4
5	Motor Mount	1
6	Sample Motor	1

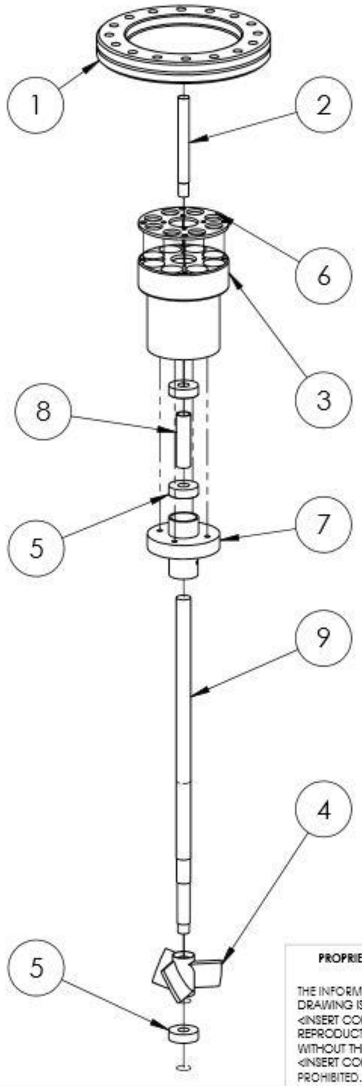
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Matthew Boebinger	3/20/15

COMMENTS:

TITLE:
Team 24: Magnetically Coupled Cryogenic Pump

SIZE A
DWG. NO. Outer Coupler Motor Sub-Assembly
REV 1
SCALE: 1: 5
WEIGHT:
SHEET 1 OF 1



ITEM NO.	PART NUMBER	QTY.
1	6inch ConFlat Flange - Milled	1
2	Static Shaft	1
3	Inner Magnet Coupler	1
4	Sample Propeller	1
5	Bearings	3
6	Inner Magnet Coupler Faceplate	1
7	Inner Magnet Coupler Pump Attachment	1
8	Bushing	1
9	New Steel Pump Shaft	1

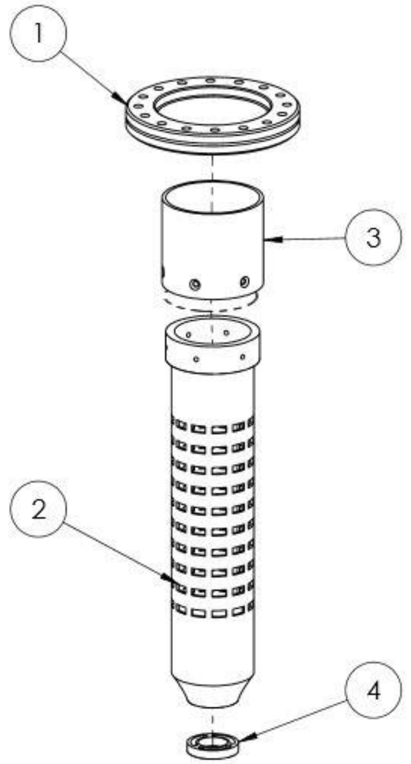
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Matthew Boebinger	2/4/15

COMMENTS:

TITLE:
Team 24: Magnetically Coupled Cryogenic Pump

SIZE A
DWG. NO. Inner Coupler Sub-Assembly
REV 2
SCALE: 1: 5
WEIGHT:
SHEET 1 OF 1



ITEM NO.	PART NUMBER	QTY.
1	6inch ConFlat Flange - Milled	1
2	Pump Housing	1
3	Housing Anchors	1
4	Bearing plate	1

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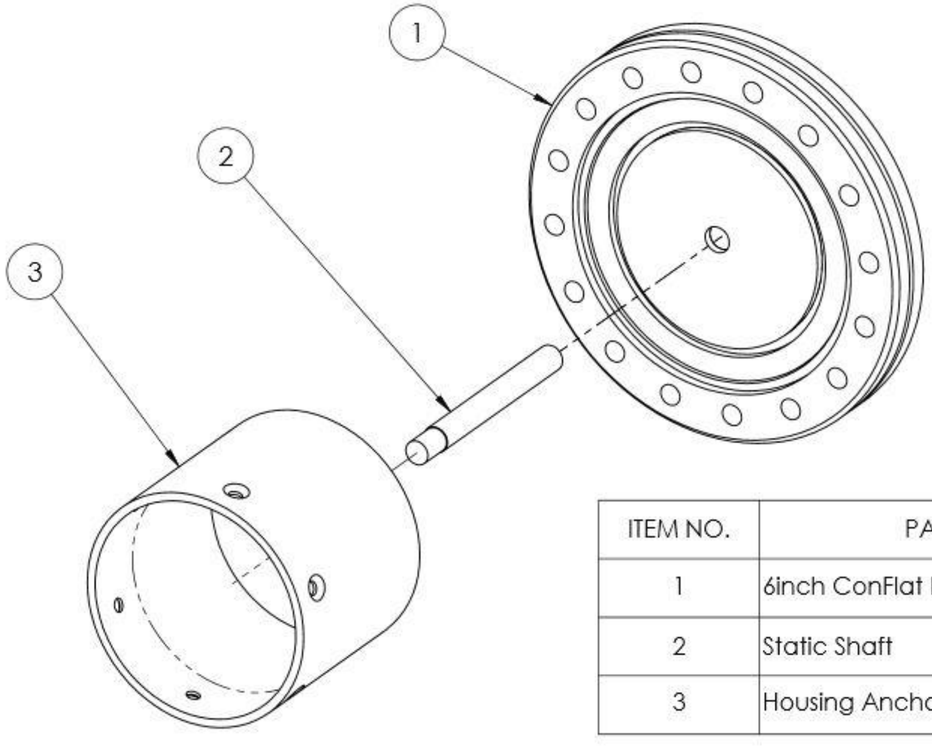
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Matthew Boebinger	2/4/15

COMMENTS:

TITLE:
Team 24: Magnetically Coupled Cryogenic Pump

SIZE A
DWG. NO. Pump Housing Sub-Assembly
REV 1
SCALE: 1: 5
WEIGHT:
SHEET 1 OF 1



ITEM NO.	PART NUMBER	QTY.
1	6inch ConFlat Flange - Milled	1
2	Static Shaft	1
3	Housing Anchors	1

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Matthew Boebinger	2/15/15

COMMENTS:

TITLE:
Team 24: Magnetically Coupled Cryogenic Pump

SIZE A
DWG. NO. Welding Sub-Assembly
REV 1
SCALE: 1: 2
WEIGHT:
SHEET 1 OF 1

Appendix C: Sample Calculations

Bearing Calculations

$Fr := 6\text{lbf}$

$Fa := 10.5\text{lbf}$

$L_h := 8000\text{hr}$

$\omega := 1500\text{rpm}$

$$Fe := \left(Fr^2 + Fa^2\right)^{\frac{1}{2}} = 53.794\,\text{N}$$

$$C\_ := Fe \cdot L_{10}^{\frac{1}{3}} = 482.146\,\text{N}$$

From SKF bearing catalog

$C_0 := 193\text{N} = 43.388\,\text{lbf}$

From Table 11-24

$$\frac{Fa}{C_0} = 0.242$$

Linear Interpolation

$$e := .34 + (.38 - .34) \cdot \frac{.242 - .17}{.28 - .17} = 0.366$$

$V := 1.2$

$$\frac{Fa}{V \cdot Fr} = 1.458$$

$$Y := 1.15 + (1.31 - 1.15) \cdot \frac{.242 - .17}{.28 - .17} = 1.255$$

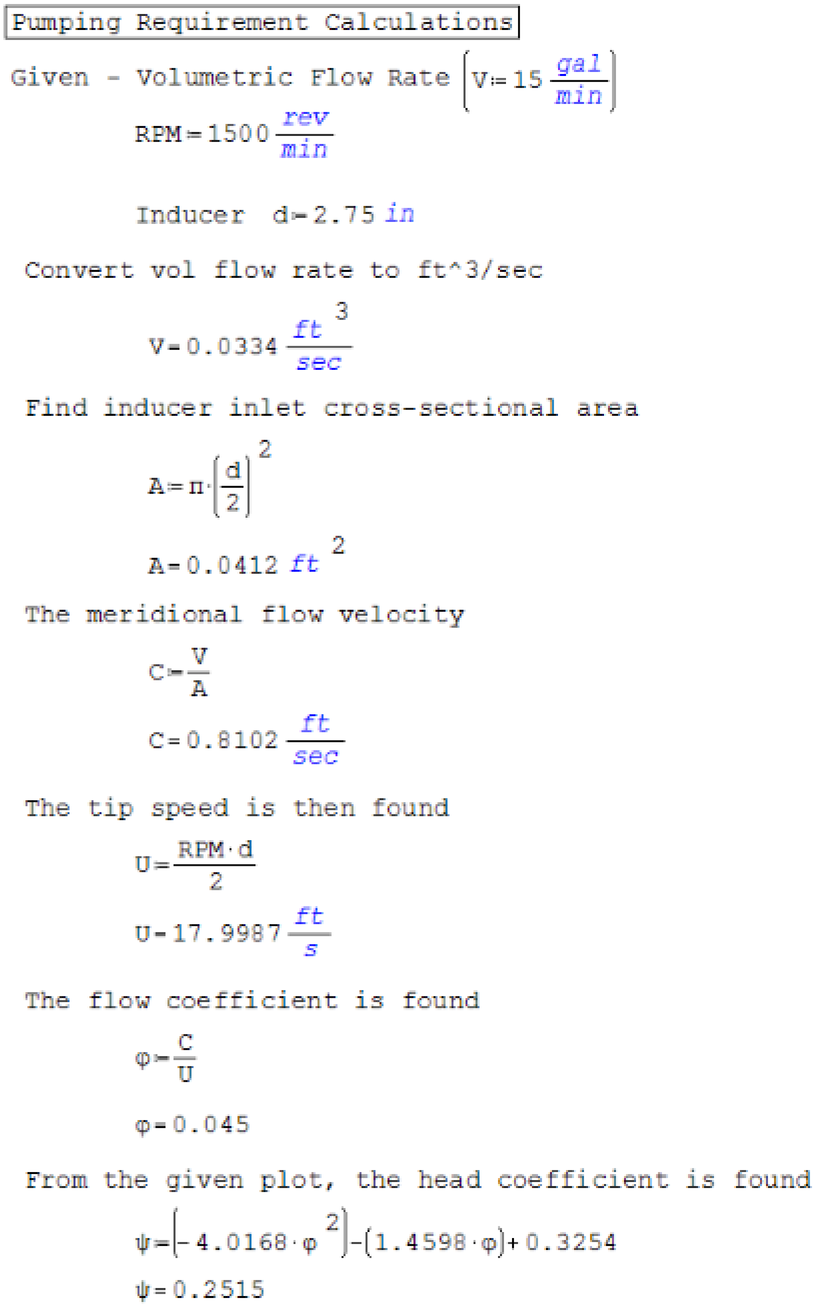
$X := .56$

$F_e := X \cdot V \cdot Fr + Y \cdot Fa = 76.539\,\text{N}$

$$C\_\_ := F_e \cdot L_{10}^{\frac{1}{3}} = 686.004\,\text{N}$$

Repeat process Until C does not change

Power Calculations



Pumping Requirement Calculations

Given - Volumetric Flow Rate $\left(V := 15\,\frac{gal}{min}\right)$

$RPM := 1500\,\frac{rev}{min}$

Inducer $d := 2.75\,in$

Convert vol flow rate to ft^3/sec

$V = 0.0334\,\frac{ft^3}{sec}$

Find inducer inlet cross-sectional area

$A := \pi\cdot\left(\frac{d}{2}\right)^2$

$A = 0.0412\,ft^2$

The meridional flow velocity

$C := \frac{V}{A}$

$C = 0.8102\,\frac{ft}{sec}$

The tip speed is then found

$U := \frac{RPM\cdot d}{2}$

$U = 17.9987\,\frac{ft}{s}$

The flow coefficient is found

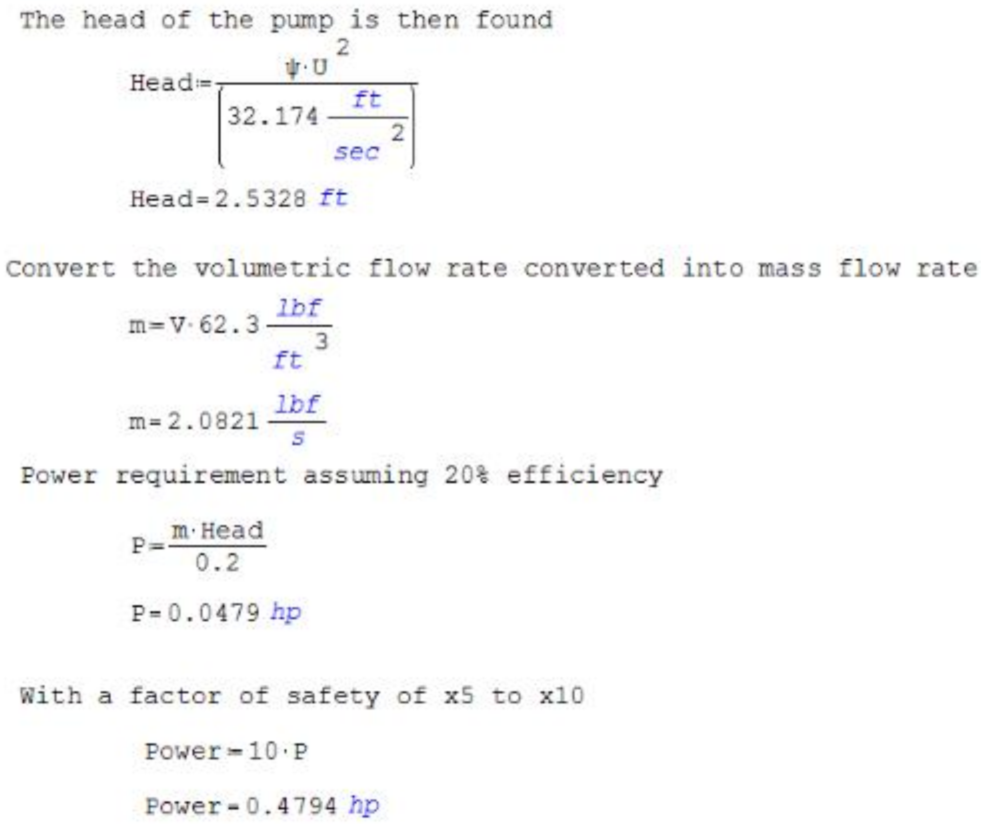
$\varphi := \frac{C}{U}$

$\varphi = 0.045$

From the given plot, the head coefficient is found

$\psi := \left(-4.0168\cdot\varphi^2\right) - (1.4598\cdot\varphi) + 0.3254$

$\psi = 0.2515$



The head of the pump is then found

$$\mathrm{Head} := \frac{\psi \cdot U^2}{\left(32.174\,\frac{ft}{sec^2}\right)}$$

$$\mathrm{Head} = 2.5328\ ft$$

Convert the volumetric flow rate converted into mass flow rate

$$m := V \cdot 62.3\,\frac{lbf}{ft^3}$$

$$m = 2.0821\,\frac{lbf}{s}$$

Power requirement assuming 20% efficiency

$$P := \frac{m \cdot \mathrm{Head}}{0.2}$$

$$P = 0.0479\ hp$$

With a factor of safety of x5 to x10

$$\mathrm{Power} := 10 \cdot P$$

$$\mathrm{Power} = 0.4794\ hp$$

Appendix D: Failure Mode Effects Analysis

Key Process Step or Input	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN	Actions Recommended	Resp.	Actions Taken
What is the Process Step or Input?	In what ways can the Process Step or Input fail?	What is the impact on the Key Output Variables once it fails (customer or internal requirements)?	How **Severe** is the effect to the customer?	What causes the Key Input to go wrong?	How **often** does cause or FM **occur?**	What are the existing **controls** and procedures that prevent either the Cause or the Failure Mode?	How well can you **detect** the Cause or the Failure Mode?		What are the actions for reducing the occurrence of the cause, or improving detection?	Who is Responsible for the recommended action?	Note the actions taken. Include dates of completion.
Bearing Wear	Bearings have more friction or wobble	Will require more power from the motor, or cause more heat from friction	5	Extended use without replacement	3	Monitor use. Bi-monthly maintenance	9	135	Maintain system. Keep log of use to determine when system requires maintance	User	bearing calculations were performed to ensure a life of 8000 hr of use with a factor of safety of 4. 11/2/14
Magnet Seperation	Magnets in respective couplers are too far apart to couple	Pump will no longer work/pump fluid	4	improper assembly	2	Following proper instructions for assembly and measuring the correct operating distance	2	16	Monitor the system when srating it up to ensure a 1:1 coupling if slippage occurs move the couplers closer together	Manufacturer	Tested the couplers in torsion machine to find the maximum operating distance 3/20/15
Number of Magnets	sufficient torsional strength for coupling is not achieved	Pump will no longer work/pump fluid	5	To many magnets close together causes the magnetic fields to smear together therfore no torque is generated	1	Following the instucions for proper amount of magnets for a given coupler	2	10	Follow instruction manuel and monitor system when first starting up to ensure the coupling is 1:1	Manufacturer	Tested the couplers for the optimized amount of magnets for a 3.5" coupler 3/20/15
Magnetic Materials	Coupling may fail if torque exceeds the rated amount	Increased tourque on motor and couplers. The rtequired volumetric flow rate is not met	3	Pump housing anchor material magnetic.	1	Procuring the proper non magnetic material	1	3	Checking the material for magnetic properties using a high strength magnet	manufacturer	Checked materials for magnetic properties. Returned the magnetic material and recived proper material. 2/10/15
Motor Connection	motor overheats or shorts out. Insufficient power	Motor will stop working as well as pump. Volumetric flow rate not achieved	4	Incorrect electrical assembly/ short circuit	4	Following the instruction manuel on proper connection of motor to driver and driver to battery	1	16	Follow the operaation manuel step by step or hire certified electrician to install motor	user	discussed proper connection with electrical engineers and seeked help from faculty. 3/1/15
Motor Drive Failure	Overheats	Motor will stop working as well as pump	5	Incorrect electrical assembly, short circuit, and exsessive voltage	2	Following instruction manuel on proper connection and voltage input	2	20	Follow operation manuel test output voltage of battery or outlet hire electrician to install	user	discussed proper connection with electrical engineers and seeked help from faculty. 3/1/15
Cryogenic Behavior	Bearing lubricant freezes/stiffens	Increase torque on motor possibly seize the pump	6	lubricant not fully removed from bearing or incorrect bearing assembly	4	Ensure all lubricant is stripped from the bearing or buy non lubricated bearings	4	96	start the system slowly to ensure the bearings run smoothely without seizure	Manufacturer	ordered non lubricated bearings from the store to ensure no lubrication was applied to the bearings. 12/10/14
Tolerancing of Pump	Coupler screws/ impeller scrapes against pump housing	Increase friction and damage parts	6	improper assembly. Machine tolerance not tight enough	4	Follow the operation manuel exactly for assembly and ensure machines have high tolreances	1	24	use looser tolerances.	Manufacturer	tolerances of machine shop was checked and proper assembly was ensured. 3/31/15

Appendix E: Bill of Materials

Table E-1 Bill of Materials

Part	Vendor	Purpose	Quantity	Cost per Item	Total Cost
Magnets	K&J Magnets	Magnetic coupling	16	$8.61	$137.76
Motor	Amazon	Motor	1	$79.00	$79.00
Motor Drive	Amazon	Control Motor Speed	1	$27.95	$27.95
PVC 12"x12"x 1"	Amazon	Motor Mount	1	$35.21	$35.21
6-32 x 1/2"	Fastenal	Assembly	10	$0.20	$2.00
10-32x1/2"	Fastenal	Assembly	10	$0.20	$2.00
10-32x3/4"	Fastenal	Assembly	5	$0.40	$2.00
10-32 Nyloknut	Fastenal	Assembly	10	$0.30	$3.00
1/4-20x3/8"	Fastenal	Assembly	10	$0.30	$3.00
8-32X1.5"	Fastenal	Assembly	5	$0.40	$2.00
Key stock 1/8"x1/8"x1'	Fastenal	Assembly	1	$0.65	$0.65
3/16x1.25" clevis pin	Fastenal	Assembly	1	$0.23	$0.23
3/16x7/8" clevis pin	Fastenal	Assembly	1	$0.24	$0.24
3/16X3/4" clevis pin	Fastenal	Assembly	1	$0.20	$0.20
Cotter pin 1/16 x1	Fastenal	Assembly	20	$0.10	$2.00
12v Battery	FourAcre	Power supply	1	$50.00	$50.00
Stainless Steel	Online Metals	Pump Anchor	1	$26.24	$26.24
				Design Cost	$373.48
12"x24"x.5" Plexiglas	Professional Plastics	Testing Tank	4	$35.80	$143.20
12"x12"x.5" Plexiglas	Professional Plastics	Testing Tank	1	$25.50	$25.50
1'x1" PVC Pipe	Home Depot	Testing system	2	$2.23	$4.46
1'x2" PVC Pipe	Home Depot	Testing system	2	$3.36	$6.72
2" 180deg Bend PVC	Home Depot	Testing system	2	$3.23	$6.46
PVC glue	Home Depot	Testing system	1	$8.26	$8.26
Silicon sealant	Home Depot	Testing system	2	$6.75	$13.50
Rubber PVC Reducer	Home Depot	Testing system	1	$3.63	$3.63
2" to 1" PVC reducer	Home Depot	Testing system	1	$1.56	$1.56
				Testing Cost	$213.29
				Total Cost	$586.77

Appendix F: Gantt Chart