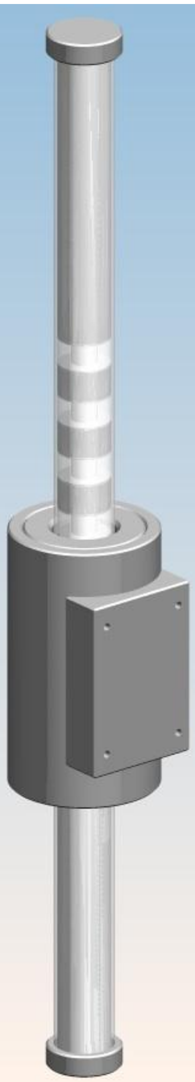
A linear generator power take-off system for the VIVACE hydrokinetic energy converter



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Executive Summary

Problem Statement

Power take-off systems that are readily available, such as rotational generators, are not cost effective and/or efficient for implementation into the VIVACE system. Only a custom made linear generator, based on the inputs of a particular VIVACE system, can effectively collect energy at a relative high density from a given current. The implementation of a linear generator was the conclusion of the previous ME 450 group of winter 2008. The problem with their generator was a high counter-electromotive force that caused a non-continuous motion throughout the cycle. The stronger the counter-electromotive force is from the generator, the more energy you can harness from each cycle, but too much force will disrupt the vortex shedding and take energy away from the process. This in turn results in a low energy density that is collected from the incoming current. In collaboration with Professor Bernitsas, our team will design a power take-off system that will be optimized and scalable to a given VIVACE apparatus to which it will be attached.

Customer Requirements

Professor Bernitsas has expressed the need to for a power take-off linear generator that is scalable, cost effective and reduces the back electromagnetic force of the previous groups design.

Concept Generation and Final Design

The final design was compiled after brainstorming sessions and meetings with our sponsors. The final design builds off of the alpha design and consists of a series of Halbach magnetic arrays enclosed in a collar that is affixed to the VIV cylinder. The magnetic array collar moves in a vertical oscillating motion along the PTO device tube. The collar's sliding movement is eased by the addition of bearings in series with the magnet arrays. Within the tube are multiple inductor coils series that harness the magnetic flux imposed on them and create electrical energy.

Project Plan

Ordering of all of the parts and raw stock will be conducted in the next few days. Manufacturing of the off-shelf components will be conducted primarily in the University of Michigan undergraduate machine shop. Assembly and validation of the prototype will be conducted prior to the final design expo preparation.

Test Results and Conclusion

The test of the generator was proven successful by an electrical output reading. The manufacturing is complete on the prototype, but an additional rectifier circuit will be needed to harness the electricity from all of the coils simultaneously. However, we believe the prototype has achieved the customer's requirements and initial goals we set out to achieve.

Table of Contents

1. Motivation/Intro

With an ever-growing world population comes an even higher demand for energy production. Energy needs are among top concerns for developed countries now and in the future. A higher amount of energy production brings more environmental pollution that is adversely affecting our climate worldwide. Energy production is also becoming more expensive to produce with resources slowly dwindling from the earth's reserves. Future efforts are being made to try and develop clean renewable energy sources that minimize waste and pollution while still being cost effective to recover.

One of the largest mediums of stored energy are the vast oceans and rivers on earth. This energy storage comes in the form of currents, waves, tides, thermal gradient, and salinity gradient. Currently, wave and current/tidal energy pilot devices are environmentally obtrusive and complex. Simpler devices that emulate natural phenomena and fish kinematics are needed. Energy from currents can be harnessed using turbines, which require an average speed of 5-7 knots to be financially viable. However, the vast majority of currents flow at speeds less than 3 knots.

2. Background on VIVACE

The CEO/CTO of Vortex Hydro Energy, Professor Michael M. Bernitsas, is the inventor of the VIVACE (Vortex Induced Vibration Aquatic Clean Energy) concept along with being our sponsor on this project. VIVACE is not a turbine: it is an all-together novel concept. Flexible bluff structures (particularly cylinders), from fishnet filaments to 120ft diameter SPAR offshore platforms and anything in between, such as car antennas, flagpoles, marine cables, heat exchanger tubes, experience VIV (Vortex Induced Vibration) in a steady flow. Engineers seek to suppress VIV because it causes large motions leading to fatigue and structural failure. The VIVACE (VIV for Aquatic Clean Energy) Converter is designed to do the opposite: maximize and utilize VIV to harness the hydrokinetic energy of flows. Thus, VIVACE takes this natural, destructive, instability phenomenon and transforms it into means of taping into a vast and virtually untapped energy source. VIV is further enhanced using turbulence stimulation and fish-biomimetics. VIVACE is modular and scalable from 1kW-1GW. VIVACE is also capable of harnessing energy from currents slower than 3 knots. The active VIVACE system is being tested in the Naval Marine Lab at the University of Michigan. The motion of the VIVACE requires a linear generator that is built around what type of forces and range of motion the VIVACE is capable of to recover the energy efficiently.

3. Abstract

Power take-off (PTO) devices such as rotational and hydraulic generators currently available are expensive to purchase and maintain. They are also not efficient in recovering a high energy density from low currents that VIVACE can operate at. Energy density is measured by the amount of recovered or stored energy we can capture related to the potential kinetic energy can be recovered by a VIVACE convertor. Our team designed and built a power take-off system for a small VIVACE Converter on the order of 1-5kW. Our system is a linear generator that is scalable to accommodate different sized VIVACE convertors. We optimized the linear generator created by the ME 450 project team of winter semester 2008, to create a more continuous system, which is better apt to capture wave and tidal energy from bodies of water. Our engineering efforts concentrated on producing the most voltage at low water speeds, while keeping the cost of production and maintenance low.

4. Problem Description

The decision to make a linear generator was based on the previous work of the ME 450 Winter 2008 team. While working with our Sponsor Professor Bernitsas, they concluded that a linear generator was the best means of recovering a high level of efficient energy from the VIVACE convertor. The problem with their generator was a high counter-electromotive force that caused a non-continuous motion throughout the cycle. The stronger the counter-electromotive force is from the generator, the more energy you can harness from each cycle, but too much force will disrupt the vortex shedding and take energy away from the process. This in turn results in a low energy density that is collected from the incoming current. In collaboration with Professor Bernitsas, our team will designed a power take-off system that was able to be optimized and scalable to a given VIVACE apparatus to which it will be attached. On site customization of the electromotive force was key in the success of the linear generator. A finite element analysis on the linear generator prototype will allow for total customization and scalability for numerous VIVACE applications.

5. Information Sources and Patent Search

We have narrowed our patent search down to more relevant ideas and discuss them in further detail. There are two patents that are useful for our project that are listed as follows;

1. Wave Energy Convertor (WEC) with US Patent# 7,140,180

This is an assembly created to harvest electrical energy from waves. It consists of two cylinders over each other which is used a linear generator. The electrical energy is harvested by the mono-axial sliding motion of these two cylinders, created by the wave. This concept is really similar to ours. In the patent information it is claimed that the higher the length of the cylinders, which increases the area where the energy can be harvested, the higher the energy output. However, it is also claimed that this increase in efficiency decreases and eventually settles as length increases because the material and water that has to be lifted by the wave increases. This increases the force required to be applied by the wave which decreases the efficiency.

2. Linear Generator Apparatus with US Patent#7,250,697

This patent explains the possible construction of a linear generator. Since are design consist of optimizing a linear generator it is useful to know the fundamentals of its design. The patent explains how can two cylinders are used in the creation of a linear generator and which one can be fixed and in what condition. This information is useful in the optimization of our design

We have also researched different concepts such as; Faraday's Law of Induction, and Halbach Array. These concepts help us understand the fundamentals of electric generators. We have used textbooks, Internet sources (in References) and the previous ME 450 teams report for this research.

6. Customer Requirements

Because our product is not on the market yet we don't have any customers except for our sponsor, Professor Bernitsas. Engineering targets and customer requirements were determined based on Professor's Bernitsas knowledge of comparable energy gathering systems and his ideas for improvements on the current VIVACE model. Because only one model of the VIVACE power take off system has been made, by the ME 450 design team of winter semester 2008, we will compare our design to the model built in winter 2008. The comparison process for harnessing marine energy versus other methods was completed by the winter 08 team, refer to their report for such information.

The focus of our redesign will be the magnet and coil system. Creating a smoother, more continuous motion of the magnet over the coils is the main customer complaint from professor Bernitsas about winter 08's design. Besides creating a more continuous motion, improving the overall manufacturing of the model was his only other customer complaint.

The table below lists our customer requirements determined during the conception of the VIVACE system and based on professor Bernitsas comments. The requirements are listed in order of importance with their relative weights according to the customer.

Smoother motion (A smoother motion of the magnets over the coils)	10
Wet and dry components (The ability of system to keep internal components separated from water and moisture)	9
Stack ability (The ability to add and remove magnets or coils to the system as needed)	7
Few Moving Parts (Keeping the total number of parts in the system to a minimum)	6
Environmentally Compatible (Quality of the system owing to its low environmental impact on its surroundings)	5
Scalability (The ability of the system to scale to different sizes for different applications)	5
Battery (Desire for the prototype to include a battery)	5
Cost (The total cost of the system)	4
Easy to maintain (The system requires little maintenance, and is easy to service)	4
Easy to install (The system is easy to place and begin operation)	4
Easy to transport (The system is easy to move from manufacturing site to location of operation)	1

Customer Attributes	Importance 1(low) – 10(high)	Induced EMF	Length of cylinder	Design Life	Minimum speed	Efficiency	Orientation of magnets	Weight	Field Strength	Back EMF	Cylinder friction	Wraps of coil	Winter 08
Easy to maintain	4			9	3		1	3	3		3	3	3
Scalability	5		9		9	3	9	3				9	2
Cost	4	3	3	9	9	3	3	3			3	9	2
Environmentally Compatible	5			9	9	3		3					2
Few Moving Parts	6	9		3	3	9			3				5
Stack ability	7	3	1		3	9	3	1	9				5
Wet and Dry Components	9	9		9		3			9	1		3	2
Smoother motion	10	9	3		9		9	3	9	9	3	3	1
Easy to transport	1		3					9				1	4
Easy to install	4	3	3					9	3		3	1	2
Battery	5	9			9				3			3	1
Technical Difficulty		**45**	**22**	**39**	**54**	**30**	**25**	**34**	**39**	**10**	**12**	**32**	
Technical Benchmarking	Units	V	M	Yrs	RPM	%	Vert. or Hor.	N	T	V		d, L (m)	
	Current Unit	8 V @ 0.62	0.5	10	5000	0.22	Hor.	?	0.604	?	0.28 (HDP)	0.05, 0.048	
	Linear			10-20	60-100	0.80	Hor.						

1 = doesn't satisfy at all, 5 = satisfies all

Table 1: QFD Diagram

Explanation of QFD

The QFD shows that capturing a useable amount of energy at very low water speeds will be the most challenging engineering task for our team. This engineering specification is followed closely by the magnitude of induced EMF (electro-motive force), or voltage, our magnet coil arrangement can produce while maintaining a smooth, continuous motion. There are many areas of improvement on the previous design according to the QFD, the most obvious being a smoother motion of the magnet over the coils. Our engineering efforts should concentrate on producing the most voltage at low water speeds, while keeping the maintenance of our product low.

Translating customer requirements to engineering specifications

Through research, large counter EMF, the voltage which opposes the direction of the current and the induced voltage, and the coefficient of friction on the outside of the cylinder were identified as the engineering specifications related to improving the continuity of magnet coil system. Also relating to counter EMF and the inductance of the magnet coil system, field strength, wraps of coil, orientation of the magnets and the amount of induced EMF were also identified as engineering specifications which largely influence the models ability to capture energy. Other engineering specifications pertaining to the installation and transportation of the VIVACE system, total weight of the system and the length of the main cylinder were chosen as engineering specifications.

7. Engineering Specifications

Our engineering specifications were derived from meetings with our sponsor, our research, and our own brainstorming sessions. Below are the engineering specifications listed in order of technical difficulty as determined by our QFD.

1. Ability to operate well in minimum water speeds	Most currents in the world are lower than 3 knots; the power take off system should not create a lot of force so that VIVACE can still be functional and efficient at lower water speeds.
2. Induced EMF	By creating the highest possible EMF from our design we would be harvesting more electrical energy which would make VIVACE more efficient. However we must balance the desire to induce large EMF with keeping a low counter EMF to maintain a continuous motion of the magnet.
3. Long design life	VIVACE can have a very fast oscillating motion and will be placed underwater in areas not easily accessible. Therefore it will be important design our model with parts which have large resistance to fatigue. The power take-off system needs to be able to withstand marine life.

4. Magnetic field strength	Induced EMF has direct connection with magnetic field strength thus; to increase induced EMF we need the highest magnetic field strength possible without major drawbacks.
5. Weight	The power take-off system should be light weight because it will be lifted up and down at every cycle. If it is heavy, it will decrease the overall efficiency of the system.
6. Wraps of coil	This is directly related to amount of EMF, voltage, our system is able to induce. The more turns of wire in our coils the larger the magnetic flux will be as the magnet passes over the coil.
7. High efficiency	After all the improvements we aim for a minimum of 80% efficiency. This is only 5% more efficient than the previous team's target, but we plan to actually test the efficiency of our model, something not done by the previous team.
8. Orientation of magnets	If we use multiple magnets to get a higher magnetic field strength, orientation for magnets is critical.
9. Length of cylinder	The length of the cylinder is an important consideration for scalability and transportation.
10. Low cylinder friction	Lower friction between the cylinder and the magnet will increase efficiency.
11. Low counter-EMF	Counter-EMF resists the magnetic flux and therefore the motion of the magnet over the coils. Because counter EMF is directly proportional to the amount of induced EMF, keeping counter EMF low is one of the main engineering specifications we need to optimize around.

Quite possibly the largest difficulties we face in the design of this device is maximizing the continuity of the linear inductors movement while getting the highest EMF possible. Getting a higher EMF will increase the force working against the movement of the magnet and possibly the cost.

8. Concept Generation and Concept Selection

In the concept generation process there were four main stages that took place. First, the team held brain storming sessions were one team member recorded the sketches. During the brainstorming sessions the PTO device was decomposed down into five main function groups and within in each group, the pertaining subcomponents were conceptualized. The five function groups are: energy harnessing, VIV cylinder mounting system, PTO device mounting system, magnet collar bearing system, and energy transmission. These groups will be explained in further detail in the subsequent sections. Once all the subcomponents of the function groups were created and recorded the most feasible and inventive ideas were selected. Finally, with the function group components selected the whole PTO device alpha design was compiled to produce the best possible design.

Brainstorming and Function Decomposition

Our team's first step was to critically think about not only what the PTO device needs to accomplish, which is harness energy underwater, but also how we will go about achieving this goal. Since we already had a basis to start from, a linear inductor generator, we knew we had to optimize the system as a whole. To make the task of optimizing the whole device easier and a more logical process we broke it down to five function groups. These function groups will be explain in detail in the following section. During the brainstorming sessions many ideas in each group were created and recorded. All of the different ideas can be seen in Appendix A. For each function group below, only the best two ideas were selected and shown.

Energy Harnessing

Energy harnessing accounts for how the power is harvested from the VIV motion and how smooth the motion is along the axis of the device. In generating ideas for this group three separate sub sections were acknowledged to play into what this group accounts for. Those subsections are: magnet design, inductor design and magnet/inductor configuration. For the magnet design the two best solutions were to use a solid one piece round magnet or to utilize a Halbach magnet array to create the same type of magnetic flux seen in the solid magnet but with smaller magnets in a circular configuration. These two ideas can be seen below in Figures 1 and 2.

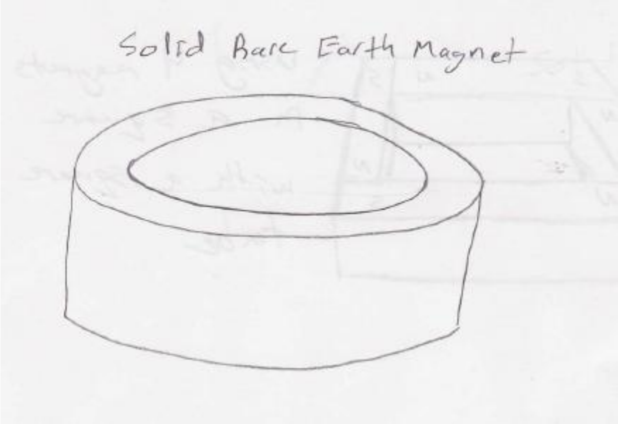


Figure 1: Solid magnet

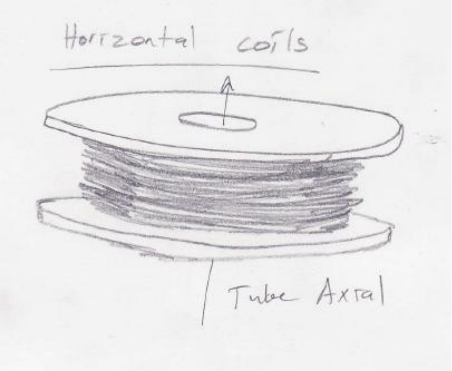


Figure 2: Horizontal wire coil

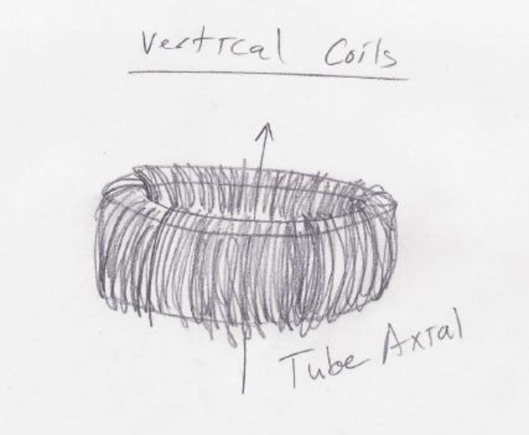


Figure 3: Vertical wire coil

The inductor design broke down to essentially two ideas as seen in Figures 4 and 5. Figure 4 shows a horizontal wire coil configuration and Figure 5 shows a vertical wire coil configuration. The two different wire coil configurations work differently depending on the magnetic flux lines that are imposed on them by the magnets. Because the magnetic field induced by our design runs perpendicular with the horizontal coils it creates more flux in the system. Lastly, the magnet/inductor configuration ideas came up with only two ideas, seen below in Figures 6 and 7below. The two ideas are simple, both one magnet and one long inductor are used or a series of magnets in junction with a series of smaller inductors are used. The selection processes of these ideas are listed by pros and cons of each idea in Table 2.

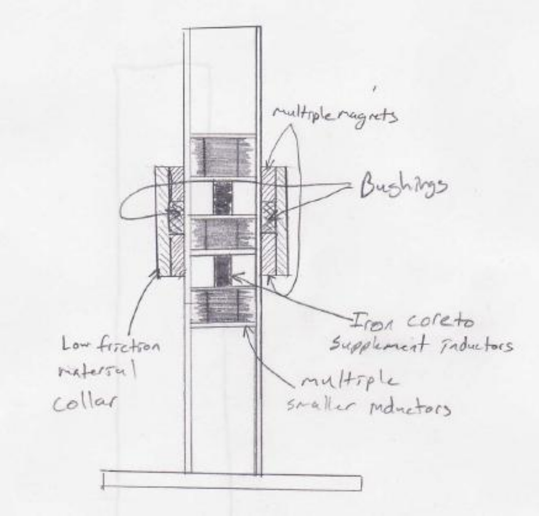


Figure 4: Single magnet and single inductor configuration

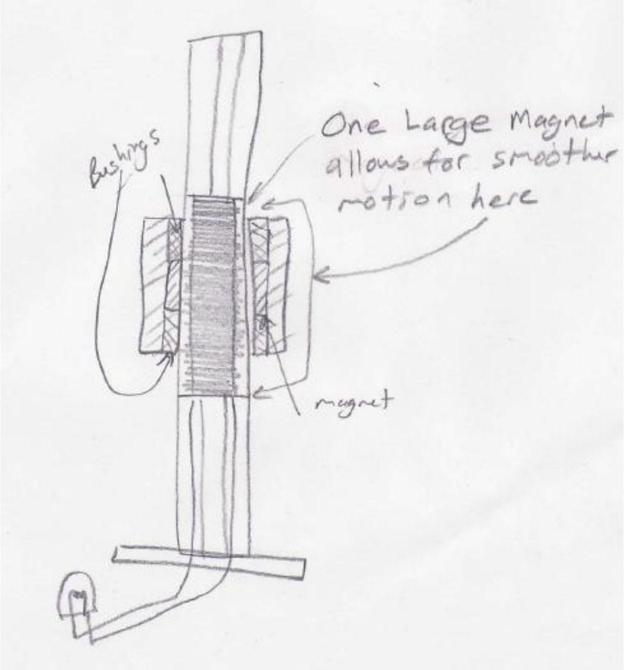


Figure 5: Series of magnets and inductor configuration

VIV Cylinder Mounting System

The VIV cylinder mounting system is the component that physically takes the VIV cylinder end and affixes it to the PTO device. This component seems simple enough but in reality has to support varying loads in a hostile environment. The ideas generated and shown below in Figures 8 and 9 both attach themselves to the magnet collar and then use the existing square bracket on the VIV cylinder to attach to it. The pros and cons of these are listed in Table 2.

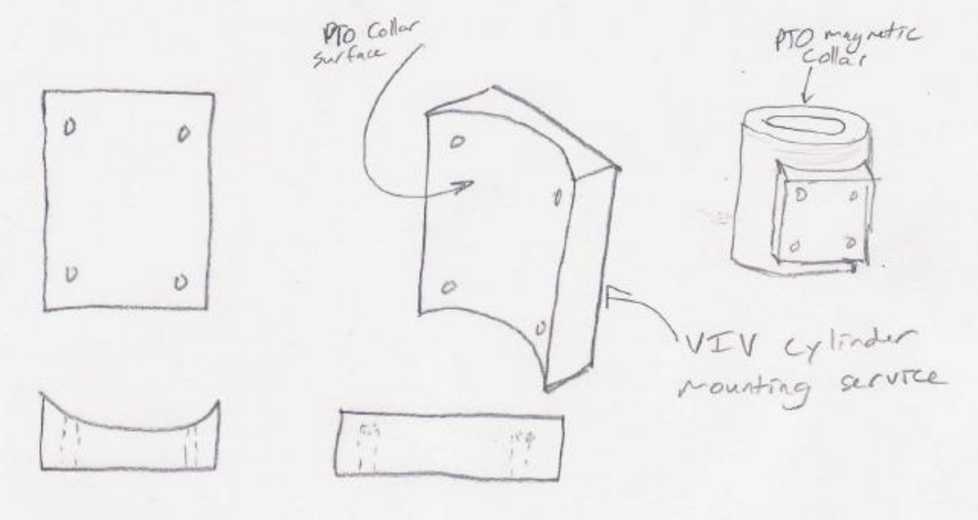


Figure 6: One piece mount

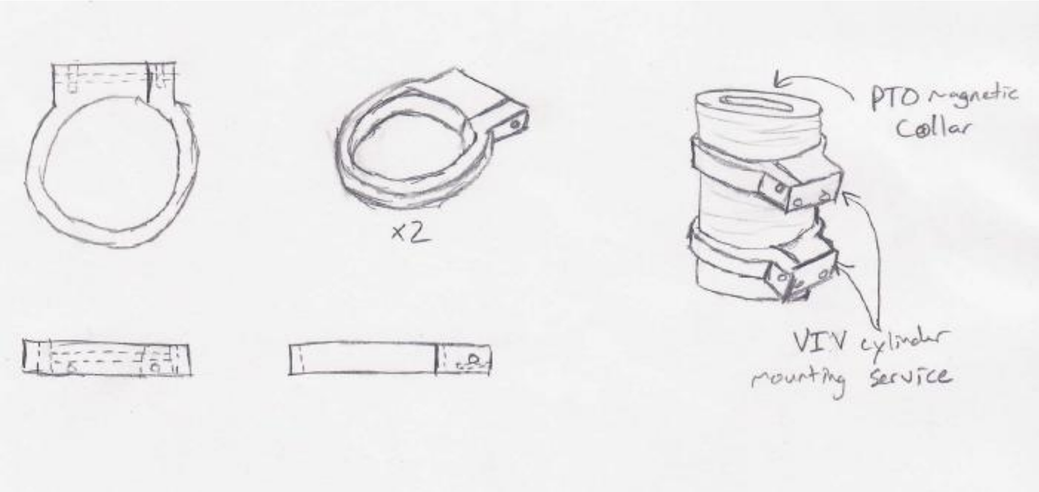


Figure 7: Two piece clamp mount

PTO Device Mounting System

The PTO device mounting system is the bracket that connects the entire device to the surrounding environment. In our idea generation more attention was placed on the importance of sealing the joint as much as possible as oppose to physical packaging constraints. The two best ideas generated are listed below in Figures 10 and 11 below. The pros and cons of each bracket and their respective sealing methods are listed in Table 2.

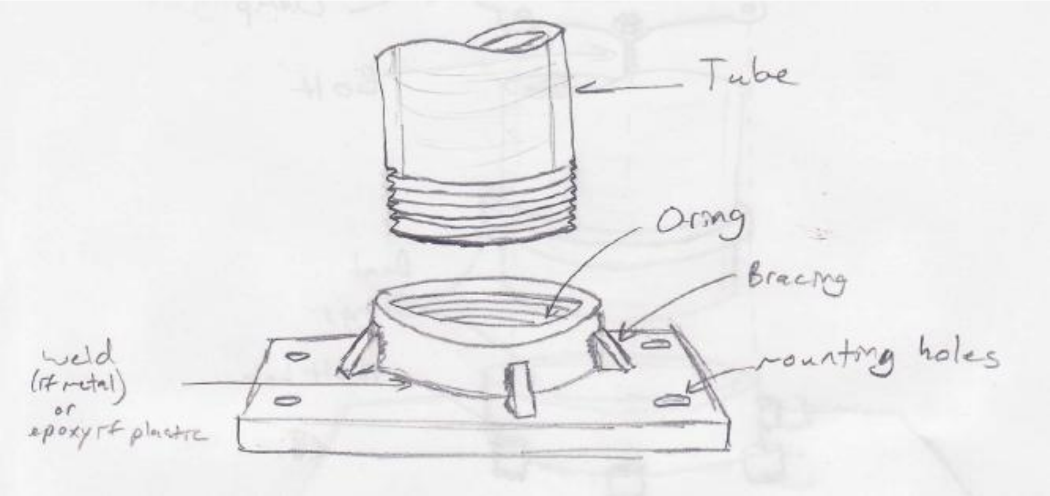


Figure 8: Threaded mount

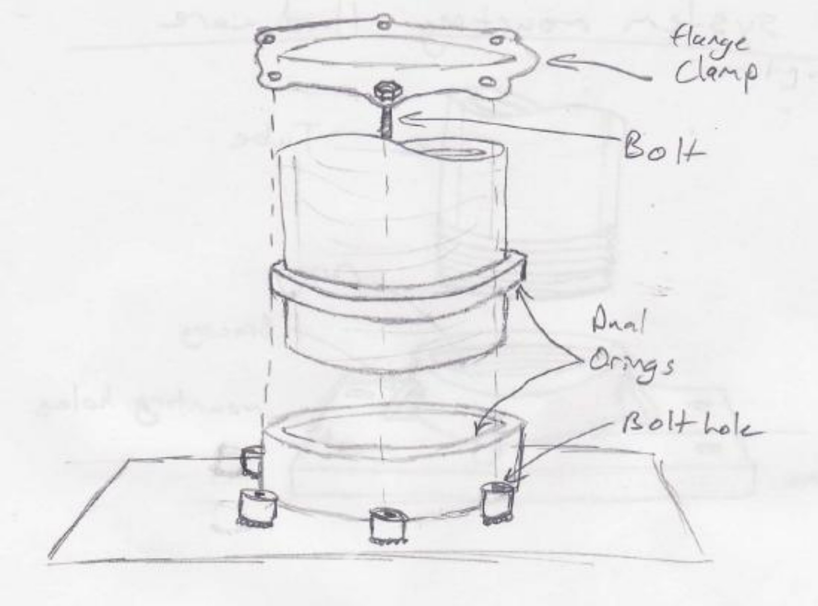


Figure 9: Flange clamp mount

Magnet Collar Bearing System

In this group the magnet collar bearing system consists of a novel bearing that will be used to aid in the continuous motion of the magnet collar relative to the PTO tube by having a lower friction coefficient, ensure proper alignment of the magnets to the inductor coils and safeguard the PTO device's life expectancy by reducing physical wear. The two best ideas are shown below in Figures 12 and 13. The pros and cons of each bearing are listed in Table 2.

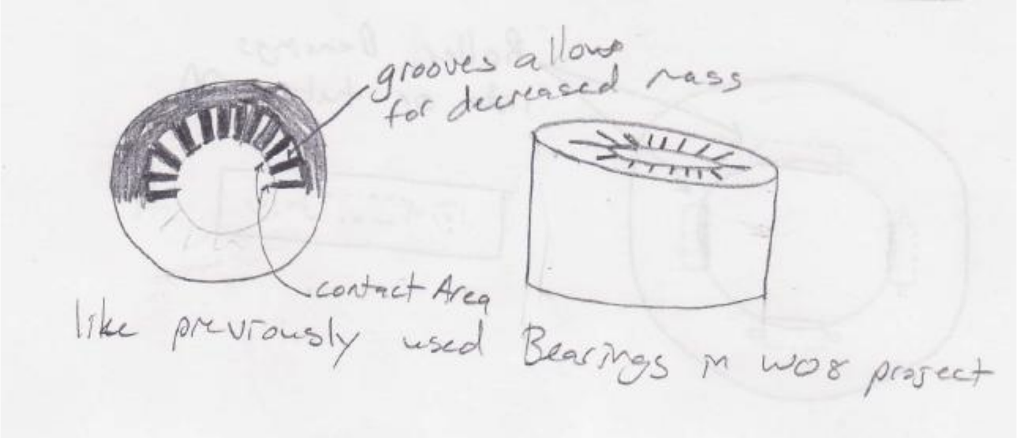


Figure 10: Groove bearing

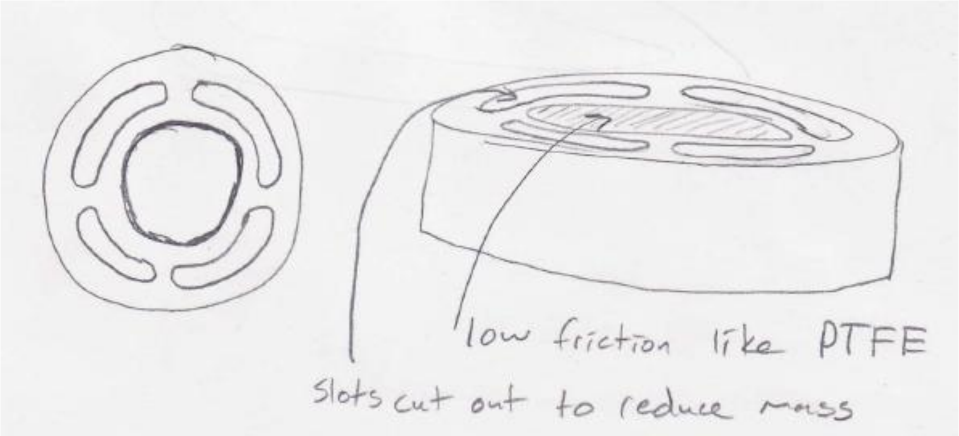


Figure 11: PTFE bearing

Energy Transmission

In this final group, energy transmission is a key design concern because we need to assure that the wiring harness in the PTO device is robust enough to handle the required electrical loads, endure the dynamic loading of the cyclic forces Imposed on the entire system and that it is simple enough to allow for easy manufacturing and maintenance. The two ideas are to either utilize a series circuit configuration or a parallel circuit configuration. The pros and cons of each idea are listed in Table 2.

Function	**Idea**	**Pros**	**Cons**	**Pick for Alpha Design**
Energy Harnessing: Magnet Design	Solid magnet	• Even magnetic flux throughout center	• Heavy • Fragile • Higher cost • Limited size	Halbach Array
	Halbach array	• Lower cost • More concentrated flux in center • Scalable • More durable	• More manufacturing required	
Energy Harnessing: Inductor Design	Horizontal coils	• Creates inductance for tube axial magnetic flux		Horizontal Coils
	Vertical coils	• Creates inductance for tube perpendicular magnetic flux	• Is not effective in this application due to the tube axial direction of the magnetic flux	
Energy Harnessing: Magnet/Inductor Configuration	One magnet, long inductor	• Lower cost • Easier to manufacture • Lower cost	• Less inductance/ energy is generated • High back EMF at start of the inductor creating non continuous motion	Multiple magnets, multiple inductors in series
	Multiple magnets, multiple inductors in series	• More inductance/ energy is generated • More continuous motion is observed	• Higher cost • Longer collar and tube is needed	
VIV Cylinder Mounting System	Solid one piece bracket	• Easier to manufacture • Lower cost • Ability to attach more securely to collar due to larger contact area • Smaller overall profile in fluid flow • Simpler, few parts	• Heavier	Solid one piece bracket
	Circular clamp	• Lower weight	• Higher Cost • More manufacturing required • Higher number of parts • Higher likely hood of loosening over time and becoming detached from the collar • Larger profile in fluid flow	

PTO Device Mounting System	Threaded mount	Simpler, fewer parts Seals out water by threads locking and O-ring Lower cost	Assembly might prove to be difficult due to twisting of wiring harness	Threaded Mount
	Flange clamp mount	Two O-ring sealing Tube does not rotate causing concerns over the wiring harness	Higher cost More parts More assembly steps	
Magnet Collar Bearing System	Grooved bearing	Lower cost Lower weight	Higher friction than PTFE	Grooved Bearing
	PTFE Bearing	Lower friction	Higher Cost	
Energy Transmission	Parallel circuit	Less possibility of complete circuit failure	More wire means higher cost More complicated	Parallel
	Series circuit	Simpler	Higher risk of failure	

Table 2: Pros and Cons of each function group and their respective subsections

9. The Alpha Design

Using the information tabulated from Table 2, the alpha design was then assembled. The CAD models, seen below in Figures 14 and 15, show the complete alpha design assembled and exploded for easier understanding of how all the components fit together. For more in depth pictures of each component of the alpha design please refer to Appendix B.

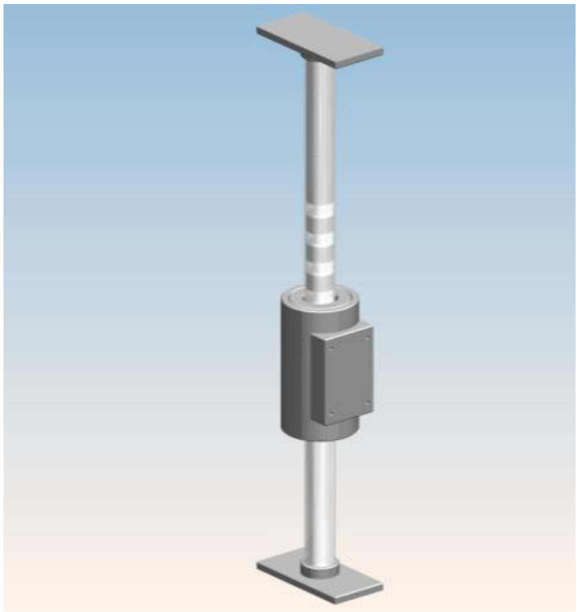


Figure 12: Assembled view of the Alpha design

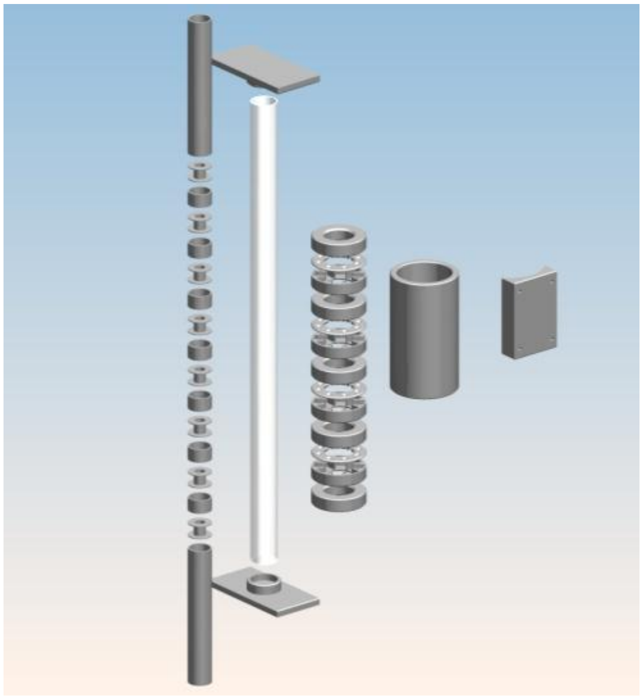


Figure 13: Exploded view of the Alpha design

In the figures above it is visible the how the horizontal coil inductors are assembled in series within the main tube. The main tube is encircled by the magnetic collar that moves axially along the tubes length. The Halbach array magnets in series are clearly visible in Figure 15. With the Halbach array magnets in series along with the inductors in series one can see how the magnetic flux created by the magnets is imposed on the inductors. Along with the oscillating axial movement of the VIV cylinder attached to the VIV mounting bracket energy is created and outputted by the PTO device. The energy transmission components of the alpha design are not shown in the CAD models in the above figures to simplify the CAD modeling. The above design created by selecting the best ideas from each function group should yield the best design that best fits the engineering specifications and the customer requirements.

10. Engineering Design Parameter Analysis

Electromagnetic Induction

Faraday's Law is the main theory we researched in to develop an understanding of electric generators. Faraday's law states that a change in magnetic flux (Φ) along a conductor creates Electromotive Force (EMF), which results in a current flow along the conductor. In a case of coil with several turns we multiply the general equation by the number of turns (N). This concept is shown in the Equation below.

$$EMF = N * \frac{\delta\phi}{\delta_t} \qquad \text{Eq. 1}$$

$$\Phi_B = B * A * \cos(\phi) \qquad \text{Eq. 2}$$

(Eq. 2) is the equation for Magnetic Flux, which is used in Faraday's Law. (B) is the magnetic field strength, (A) is the area and (ϕ) is the angle between the direction of (B) and the normal of area (A). These two factors (B) and (A) are depended on our magnet design and coil optimization. Increasing the magnetic field strength (B) would result in a higher flux difference and therefore a higher EMF.

Halbach Array

Halbach Array discovered by Klaus Halbach is a phenomenon which concentrates the magnetic field to a specific location using a predesigned magnet configuration. This concentration does not change the overall flux however it helps you focus the magnetic strength to a more useful area.

This phenomenon can be applied to circular shapes to focus the magnetic field inside and minimize the field outside. This would be perfect case for us since we would like to increase our magnetic field strength effective our coils which would be in the inside of a circular magnet. Also even though single piece magnets are limited by size, Halbach arrays are fully scalable.

To be able to do this we are planning on using 8 N42 neodymium cube magnets (3/4'' * 3/4'' * 3/4'') and arrange them to focus the flux inside as shown in Figure 1. Each magnet has a magnetic field strength of 5940 Gauss. When 2 magnets are stuck together and the fields are acting the same direction with double the area, the magnetic field strength approximately doubles. In our arrangement of 8 magnets there only 2 magnets that act amplifies each other's fields. However, since we have air gaps between these magnets and also the supporting frame, there would be some loses. We are assuming that the overall magnetic field strength inside our arrangement is approximately 1.5 times the strength of 1 magnet which is 8910 Gauss.

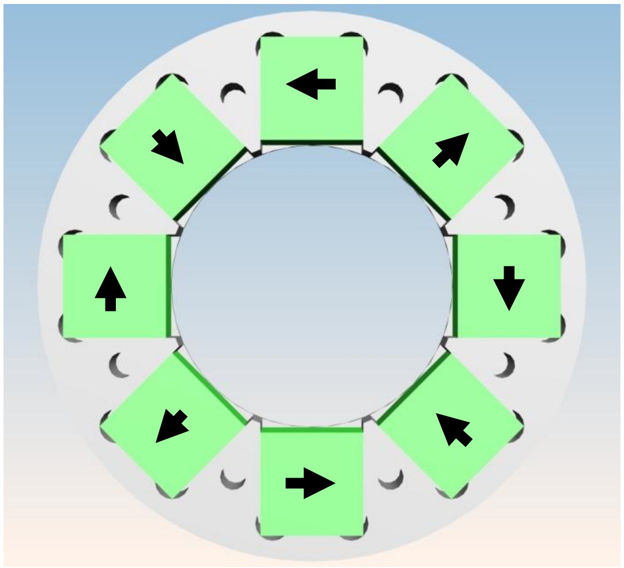


Figure 14: Halbach array magnet orientation

The strength of the Halbach array inside the magnet is higher than the single piece version which had a magnetic field strength of 6040 Gauss used by the previous 450 team, Winter 08. At the same time Halbach array configuration is cost effective. It is almost 1.5 times the cost, and it is totally scalable for any size unlike a single piece magnet.

Magnet field calculations

Calculating the magnetic flux in a region is not an easy task. Given our budget and time constraints, we don't have the resources to measure the strength of the magnetic field experimentally. Therefore to approximate the magnetic field strength inside the Halbach array we used ANSYS finite element software to simulate the magnetic field. We believe this model is valid because its input parameters are good, and its field lines match those of other rare earth magnet Halbach arrays. ("Bowden")

Simulation Settings

Because all we care about in this simulation is the magnitude of the magnetic field, we only needed to fill out the electromagnetic properties of the materials. The magnets in our final design are made of sintered N42 Neodymium Iron Boron material, and the shaft of the inductor is made of grey cast iron.

N42 Neodymium Iron Boron (Ref. "Alliance")

These are the material properties required to model the Neodymium magnets as 'Linear hard magnetic material' in ANSYS.

Magnetic coercive force = 11600 Oersted ≈ 923098.6699 A/m

The magnetic coercive force is the magnetic intensity (H) required to remove all magnetization within the material. Oe is the English unit for magnetic field intensity. 1 Oersted is equal to $\frac{1000}{4\pi}$ A/m, the SI unit for magnetic field intensity.

Residual Induction = 13000 Gauss = 1.3 T

Residual induction is the amount to magnetic flux remaining in a material after the magnet has been removed. 10000 Gauss = 1 Tesla.

Grey Cast Iron

ANSYS has material properties for some electromagnetic materials built in to the program, gray cast iron being one of them. It provides a B-H for the material which shows how much flux density (B) is produced from an increase in flux intensity (H). This allows ANSYS to calculate the magnitude of the magnetic flux.

Environment

To model the electric field as most accurately as we are capable, the eight neodymium magnets are in an enclosure of solid gray cast iron. This is the only way we could see the field lines throughout the environment. The simulation does not include the magnet array base, which holds the cube magnets in place. However this would not affect the simulation results in the case of our prototype because this piece will be made of nylon. The permeability of nylon is equal to that of air ($\sim 1.25 \times 10^{-6}\ N/A^2$), meaning it will have no effect on the magnetic field. There is a ¼ of an inch air gap between the iron core and the array of magnets which is not included in the simulation because we could not get the simulation to work when including it.

Average magnetic strength

For our calculation of the voltage created by the system we needed an average value of the magnetic field produced by the Halbach array. To calculate the average field in ANSYS we sampled the field in 24 equally spaced points, and averaged these points. The average magnetic produced by our Halbach array according to ANSYS is ~ 4200 Gauss. Refer to Figure 1 in Appendix H for a visual of the magnetic field.

General idea of electromagnetic flux

The principles that are used in the analysis are all based on Faradays law (Eq. 1).

$$\varepsilon = -N * \frac{d\Phi_{\mathrm{B}}}{dt} \qquad \text{Eq. 1}$$

Faraday's Law states that a change in flux around a connector creates electromotive force on that connector, which creates a current on that connector. The faster the change in flux and the larger the number of turns of wire, the EMF created is increased. All generators have this same concept. There are regulating parameters that affect the overall efficiency of the coil system such as; coil placement/design, inductance of the coil and permeability of the inner core.

Coil Design

The general formula for flux in our example is given below (Eq. 2):

$$\Phi_{\mathrm{B}} = \int\int_{\Sigma(\mathrm{t})} \mathrm{B}(\mathrm{r},\mathrm{t}) * \mathrm{dA} \qquad \text{Eq. 2}$$

Where Φ_{B} is the magnetic flux, B is the magnetic field strength and A is the area for which the flux is found. From this formula we can see that the maximum flux is achieved when the magnetic field is perpendicular to the area we are calculating the flux upon.

The change in flux depends on the speed of the cylinder. This value is continuously changing, but for our calculations we decided to take a constant value to get consistent results so that we can compare other variables. We decided to take the speed "v" for cylinders speed to be 0.5 $\frac{m}{s}$. The formula used in the calculation of change in flux is given (Eq.3).

$$\frac{d\Phi_{\mathrm{B}}}{dt} = \frac{\Phi_{\mathrm{B}}}{\frac{h}{v}} \qquad \text{Eq. 3}$$

Where $\frac{d\Phi_{\mathrm{B}}}{dt}$ is the change in flux and Φ_{B} is the maximum flux that can be obtained, h is the height of the winding and "v" is speed of the cylinder.

The copper wires that are used for the windings are insulated. This allows them to be adjacent to each other with minimal or no space in between them. This will allow us to put approximately 40 windings into the length our prototype is going to be. The outer diameter of the iron core is 1" and the core with the coil windings 1.5" in diameter.

The number of turns in a coil depends on the notch width the depth and the gauge of the wire. The notch width and the depth are 0.25 and 0.375 inches respectively. This will allow us to put necessary number turns without sacrificing a lot of the core material. We have chosen the gauge for the wire to be 28. Gauge 28 wire thickness is 0.014 inches. The formula for the calculation of number turns is given below (Eq. 4).

$$N = \frac{r_C - a}{g} * \frac{w_n}{g} * 0.8 \qquad \text{Eq.4}$$

Where "N" is the number of turns, r_C is core diameter, "a" is the inner diameter, "g" is the gauge of the wire and "w_n" is the width of the notch. We have also multiplied the result with "0.8" which would be our error value. We have found the number of turns we can put into one winding to be 472.

The calculation for the length of the wire was fairly complicated because even though the length of one turn is equal to the circumference of that layer, each subsequent layer will increase the radius of the iron core plus coil. The formula for the calculation of the wire is given below (Eq. 5).

$$\frac{w_n}{g} * 0.8 * \sum_{n=0}^{n=\frac{r_C - a}{g}} 2 * \pi * (a + n * g) \qquad \text{Eq. 5}$$

Using this formula we have found the length of copper wire required for one winding to be approximately 180 feet. Using Faraday's Law given in (Eq.1) and the change in flux which we assumed constant, we found that our system with 472 turns of coil wire will create 127 V of EMF on one winding.

Inductance

The inductance of a material is a measure of how it will react to a change in current passing through it. A large inductance will slow the change in current down. Windings and coils have an inductance which affects the overall system. From our research we have found the formula for a multi-layer multi-row coil with an air core to be the following (Eq. 6)

$$L_0 = \frac{0.8*r^2*N^2}{6*r+9*l+10*d} \qquad \text{Eq.6}$$

Where "L_0" is the Inductance, N is the number of turns and r is the radius of the coil, "l" is the length of the coil and "d" is the dept. Since the radius of the coil is different depending on the layer we used the average value for "r". This formula is for coils with an air core.

Permeability

Permeability is defined as the degree of magnetization of a material that responds to an applied magnetic field. It can be considered a resistance to a magnetic field just as a resistor is to an electrical circuit. Permeability depends on the magnetic field. However, when the change of magnetic field is included the calculation becomes too complex. That is why estimation is often used for permeability calculations.

A high permeability core is necessary for transformers, motors and generators. A high permeability core material allows the magnetic field created to pass thorough the core easier, which increases the overall magnetic flux that affects the coils.

Increasing the permeability also increases the inductance and the time constant, but this is not a big concern for us. The advantage gained from the increase in overall flux is more beneficial.

Iron based materials have high permeability. Materials such as air, water, plastic and wood anything that is not Iron based has a low permeability. For our generator system we can use any material that is iron based, such as pure iron, ferrites and steel. For cost purposes we are going to use iron in our prototype however, an electrical steel core (Iron and Silicon) should be used for maximum permeability and price ratio.

The inductance formula (Eq. 6) is for a coil that has an air core. The relationship which would help us implement the effect of the iron core is given below. (Eq. 7)

$$L = \frac{\mu}{\mu_0} * L_0 \qquad \text{Eq. 7}$$

Where "L" is the inductance of one winding, "μ" is the permeability of the core and "μ_0" is the permeability of air. Using this equation we have found the inductance of one winding to be 6080 Henries.

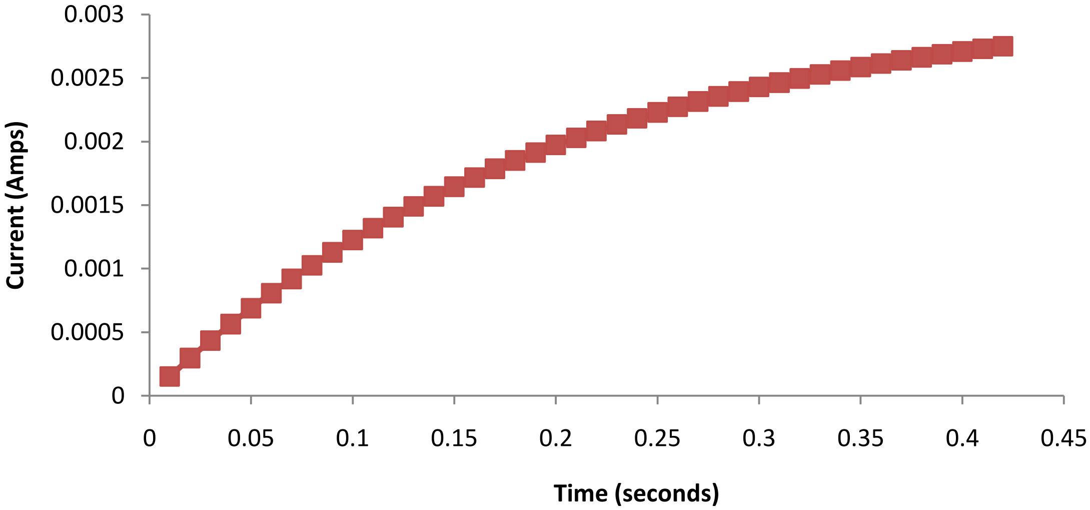
Permeability directly affects the inductance of any inductor. Any inductor in a circuit resists a change in current. When the current is constant it stores energy fairly smaller than the overall energy being used and then releases this energy as current when there is no current applied anymore. High inductance increases the time constant of the electrical system, which is an increase in the time it takes for the current to reach its maximum value. The time constant is approximately half the time where the current reaches its maximum value. The formula of the time constant is given below. We found that for a 3000 Ohm resistance circuit the time constant is approximately 0.164 sec. Since this value is very small is does not need to be taken into consideration.

Power output

For a generator to produce electrical power it must contain a closed circuit. A coil itself is not a closed circuit. The power also depends on the amount of resistance there is in the system. This is why, for calculation and verification purposes we have assumed our system has 3000 Ohms of total resistance. A winding and resistance circuit is an RL circuit. The current output for an RL circuit is given below.

$$I(t) = \frac{V}{R} * (1 - e^{\left(-\frac{t}{\tau}\right)}) \qquad \text{Eq. 8}$$

Where "I" is the current at time "t", "τ" is the time constant, "V" is the EMF and R is the resistance. The current "I" increases until it settles down in a constant value. The graph below shows this increase.



Fiqure 15: voltage ramp up

The resistance in our calculation can be anything from a lamp, to a cities energy grid. To get an output value we have calculated the power at the resistance R. First we have found the current "I". We have taken the settled down value in graph 0.0028 Amps shown above. Using this I value we have calculated the output at the resistance to be 0.248 Watts.

For maximum output power, “The maximum power” theorem states that to get the maximum power out of a power source, the internal resistance of the power source should be equal to the load.

Stress Analysis

Our project does not have any major stresses on it, especially for the prototype and also smaller scale versions. We weren’t able to get any specific value for these forces because the system is always in motion and the forces are constantly changing. However we have identified some components on the design that might have comparatively higher stresses acting on them. These components are listed below:

- Caps for the inner tube (Base): These caps will constrict the inner part of the tubes, which has the coils inside, from any movement. There will be forces acting on these components due to magnetism.

- Bushings for the magnet assembly: These are the end caps for the magnet assembly. Just as the inner tube caps these bushings prevent the magnetic arrays from falling apart or moving inside.

- VIV Cylinder Bracket: This component will not have any major magnetic force acting on it but the VIV cylinder will be connected to this component. Even though the Magnetic Array can freely move thus decreases the stresses on the bracket, there will still be forces acting on it due to the sinusoidal movement.

- Main Tube: This is an area for concern since the inside of the main tube needs to remain dry. Making sure that the main tube can withstand water pressures for a given application is important. Due to the widely varying applications for the VIVACE device, in-depth analysis of hydrostatic pressure gradients will need to be completed before manufacturing of the final design will be completed.

There will be competitively higher forces acting on these components listed above this is why these components are design to be more durable.

Magnet

As we put magnets into the Halbach array the force acting on the next magnet that needs to be inserted increases. This force can get considerably high and make this process risky and hard. While putting these magnets in their slots we need to be careful. Also for scaled up versions of the final design special equipment might be required for the placement of these magnets.

For the strength of the material we have estimated a value, however since it is estimation the value we found can be off. This can be fixed by getting direct measurements using special tools in the future. Also a mistake in manufacturing can cause the magnets to be closer to each than planned or cause them to be misaligned which would affect the overall efficiency of the system.

We have also made the assumption that there is no gap. This is not the reality we have gaps and the since the permeability air is almost 750 times less than the permeability of iron, there will be some loss of magnetization in air and this is not accounted for in our analysis because of complexity.

Coils

If the system is overloaded, it might burn out the coil wires. Even though this would not be a problem for our prototype it might be a problem for bigger systems. This can be prevented by using thicker wires however this will decrease the number of turns which will decrease the overall efficiency.

We are planning on connecting the windings in parallel. This will allow the system to still work even if one of the windings fails. However due to electrical circuit system restriction there might some problems with the transmission of power. This problem requires more research.

11. Final Design Description

The final design for the VIVACE system is shown below in Figure 16, and an exploded view of the PTO system is shown in Figure 17. More detailed diagrams and schematics of the final PTO device and all of the sub components can be seen in Appendix D. The fundamental purpose of our design is to generate electrical power by having a series of circular magnetic arrays pass over a series of wire coil inductors. The series of magnetic arrays move up and down along the main tube of the PTO device due to VIV forces imposed on the VIV cylinder that is bolted to a collar and bracket, items 9 and 10 on Figure 17. The movement of the collar causes the magnetic arrays to move axially along the main tube. This axial movement and the magnetic flux created by the magnetic arrays allow the inductors inside of the main tube, to create electrical power. The full list of on-shelf and off-shelf materials can be found in Appendix E. The following sections explain, in greater detail, the subgroups of the final PTO design.

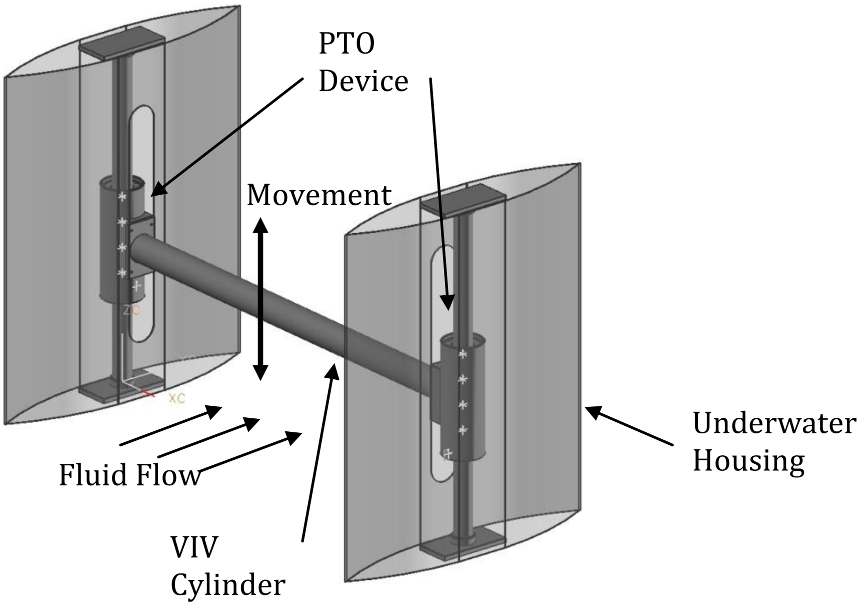


Figure 16: Final Design with VIV Cylinder and Underwater Housing

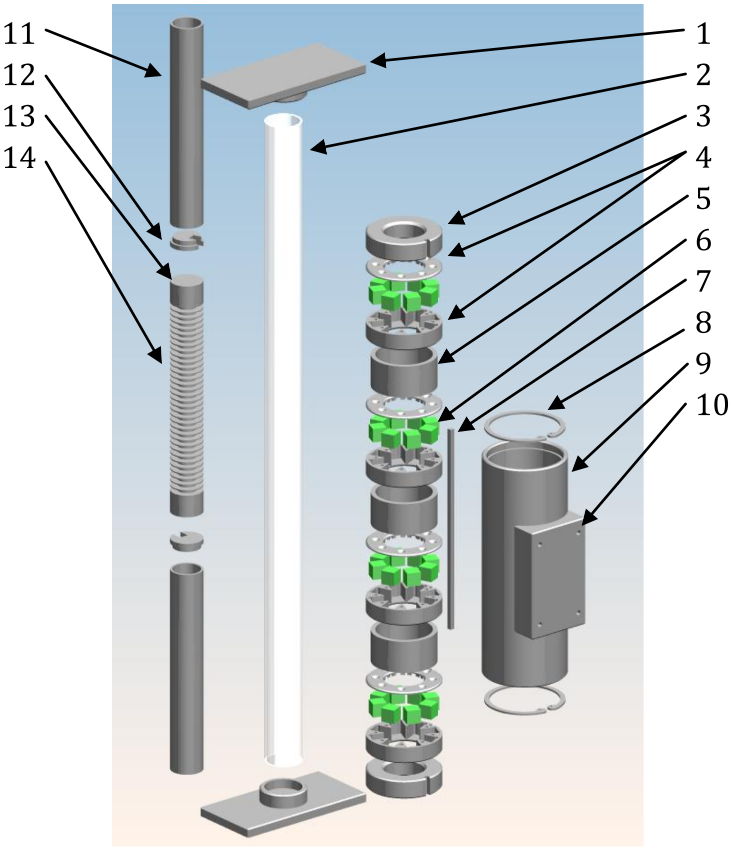


Figure 17: Exploded View of the PTO System

Figure Number	Nomenclature	Purpose	Quantity
1	Base	Allows for PTO device to be mounted to its environment.	2
2	Main Tube	Encases the inductors and wiring, ensuring a water tight seal with the Base.	1
3	Bushing	Maintains proper alignment and low friction movement of the magnetic arrays with main tube and inductors.	2
4	Magnetic Array Housing (Top and Bottom)	Holds the individual magnets in the Halbach circular array pattern.	4
5	Magnetic Array Spacer	Maintains proper spacing between magnet arrays.	3
6	Magnet	Individual ¾”x¾”x¾” magnet that produces magnetic flux and creates inductance in the wire coils.	24
7	Key	Locks into the magnetic array housings and bushings to prevent any rotational movement.	1
8	Retaining Ring	Locks the bushings, magnetic arrays, and magnetic array spacers within the magnetic array collar.	2
9	Magnetic Array Collar	Encloses the bushings, magnetic arrays, and magnetic array spacers.	1
10	VIV Cylinder Bracket	Mounts the VIV cylinder to the PTO device.	1
11	Large Spacer	Provides the proper distance within the main tube to ensure that the inductors are in the proper position.	2
12	Large Spacer End Cap	Provides a robust bracket that can support the Iron core of the inductor.	2
13	Iron Core	Provides a highly magnetic permeable core for the wire inductors.	1
14	Wire Spacer	Creates a space between each inductor.	41
*Not shown: Inductor wire, wiring harness, EMF spring, wave spring and other assorted small hardware.			

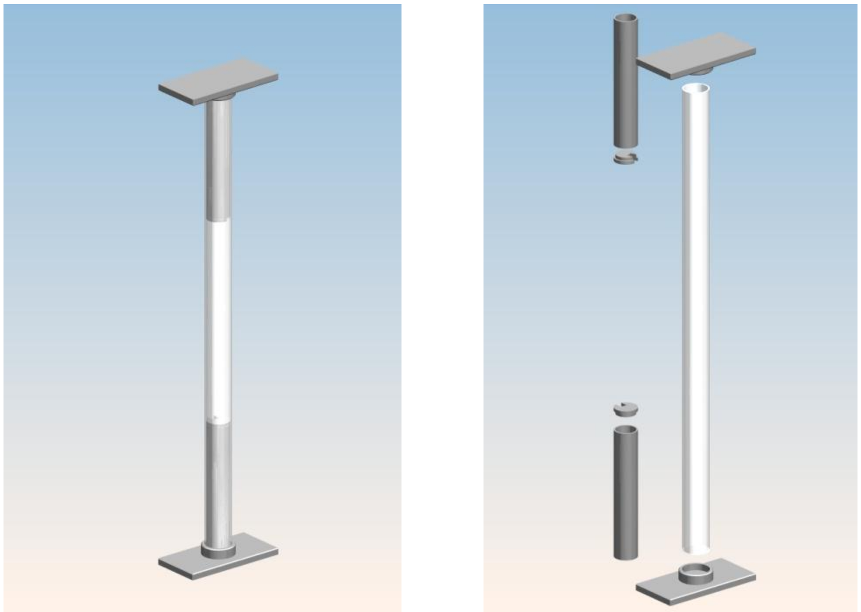
Table 3: List of Items from Figure 17

Main Tube Group

The main tube group consists of the base, main tube, large spacer and large spacer end cap. The three main functions of this group are (1) to provide the spine of the

PTO, (2) to provide a water tight housing for the inductors, wiring, and electronics and (3) to output the voltage created by the inductor via a connector located at the base. The main tube will be made of 2 inch O.D. and 1.75 inch I.D aluminum tube cut to a 36 inch length and hard anodized (for corrosion resistance). The base will be made of case aluminum, and the main tube mating surface will be machined to ensure a smooth surface for the best water tight seal. The main tube will have a wall thickness of 0.25 inches, which is thick enough to with stand the operating water pressure and any moments that the PTO device might encounter during normal operation. The base is designed to mount the PTO device to either the floor or onto another VIVACE device (when in a stacked configuration). The base has a thickness of 0.5 inches and is designed to be able to withstand moments applied to the PTO during normal operation. Aluminum was chosen for its high strength to withstand high water pressures, light weight to keep transportation and installation costs low, and high corrosion resistance compared to steel.

The large spacer and large spacer end cap will be located within the main tube, as seen in Figures 3Aa and 3Ab. The large spacer will be made of 1.75 inch PETG polyester tube cut to length. The large spacer end cap will be injection molded with a relief notch built in, visible in Figure 12 in Appendix D. The end cap is necessary to support the weight of the iron core, and the relief notch allows for the wiring harness to be routed through. Additionally, the rectifier circuits are a part of the final design but are outside of the scope of this project and are omitted from our final design.



(a) (b)

Figure 18: Main Tube Group

Inductor Group

The inductor group consists of a 1 inch O.D. by 13 inch iron rod, a series of polyester spacers, and 28 gauge enamel coated copper wire coils. The iron core is used to increase the magnetic permittivity of the wire coils to create a higher EMF that in turn produces more electrical power. The spacers will be adhered to the iron core using extreme adhesives 300, seen in Appendix G. The spacers will be adhered maintaining a 0.25 inch gap. The copper wire will then be wound onto the iron core in the gaps are created by the polyester spacers. The wire must be wound uniformly to ensure that the gaps are most efficiently filled to create an effective inductor coil. As stated in the engineering design parameter analysis, there will be a series of inductor coils, and each inductor will consist of a horizontal component. Seven coils are created in series along the iron core, as seen in Figure 19. Multiple inductors in series are used to compensate for the varying amplitudes of motion that the VIV cylinder creates. Finally, enamel coated wire is used to prevent unwanted electricity transfer between the windings.

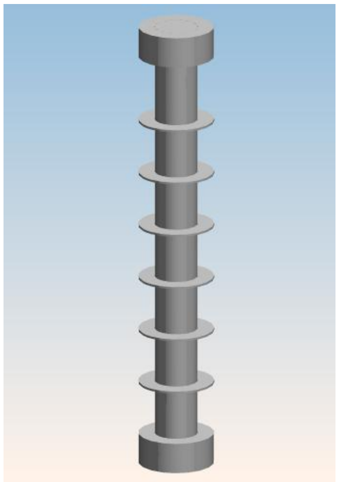


Figure 19: Inductor Group

Magnetic Array and Bracket Group

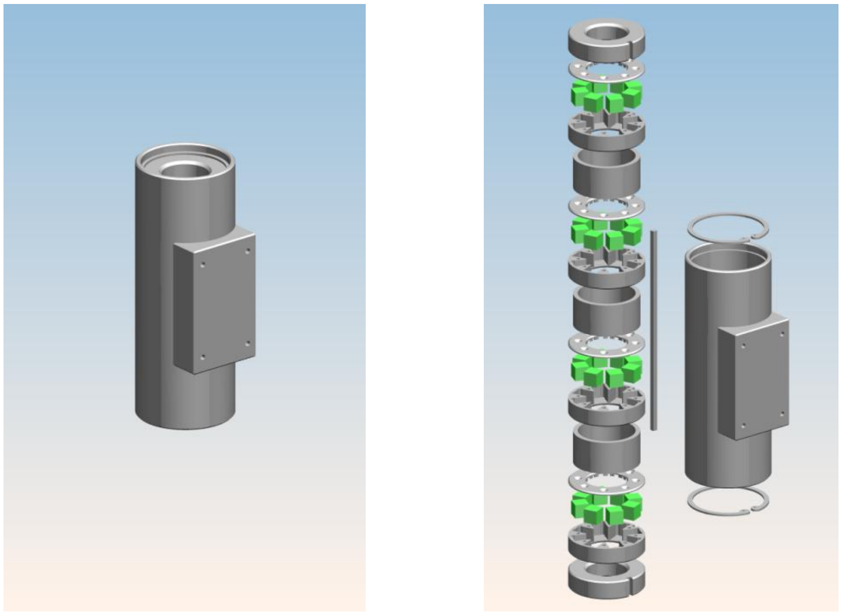
The magnetic array and bracket group consists of the magnetic array collar, VIV cylinder bracket, retaining rings, key, bushings, spacers, magnetic array housings, and the magnets. Figure 20 shows the magnetic array and bracket group. The magnetic array collar and VIV cylinder bracket are one piece of cast hard anodized aluminum that has a 4 inch I.D., a 4.5 inch O.D., and a 12.25 inch length. The VIV cylinder bracket is what the VIV cylinder is affixed to on the PTO device. This transfers the force generated by the VIV cylinder and makes the magnetic collar oscillate up and down, which induces the magnetic flux onto the inductor. The bracket and collar were chosen to be one cast piece to ensure that it can withstand long cyclic loading and fatigue stress.

The two bushings are located at each end of the collar because those are the only two locations where a moment on the collar could create alignment problems with the main tube. The bearings chosen are linear self-aligning bearings, shown Appendix B1. These bearings are designed specifically for underwater use and are well suited for the normal work environment of the VIVACE system.

In series beyond the bearings are the four magnetic array housings and the magnets located within the housings. The housings are made of Cast Nylon 6 material due to its low permittivity and high strength. The housings will be injection molded, and both the top and bottom of the housing will be sealed together to create a water tight and dry environment for the magnets enclosed within. The magnets are neodymium N42 grade 0.75 inch square magnets. Neodymium magnets were chosen due to their excellent magnetic strength relative to their size and their high resistance to demagnetize over time. However, these magnets are highly susceptible to corrosion, which is why the housing must be sealed to prevent water from corroding the magnets.

In between the magnetic array housings are cast acrylic spacers that have a 3.5 inch O.D., a 3 inch I.D., and a 1.75 inch length. The length of the spacer is determined by the length of an inductor. The purpose of the space between the magnetic arrays is to allow for the magnetic field from one magnetic array to not interfere with another magnetic array.

When the bushings, magnetic arrays, and spacers are assembled and inserted into the collar; a wave spring (seen in Figure 2 Appendix E) is sandwiched between the lower bushing and the first magnetic array. Then a 0.25 inch by 0.25 inch by 11.25 inch key is inserted into the keyways located on the bushings and magnetic arrays. The wave spring is used to compensate for any stack-up tolerance gaps, and the key is used to prevent any possible torsion effects that occur. Lastly, all of the components located within the collar are secured in place by a 4.25 inch internal retaining ring on each end of the collar.



(a) (b)

Figure 20: Magnetic Array and Bracket Group

EMF Spring Group

This final design will also include electromagnetic springs on each end of the main tube. The electromagnetic springs, in addition to a closed feedback loop, will be used to create restoring force springs that have a higher fatigue life and lower susceptibility to wet environments than traditional mechanical springs. These springs will be designed with the assistance of Professor Nikos Xiros of Florida Atlantic University. These electromagnetic springs are beyond the scope of this project and will be omitted from our final design.

Underwater Housing Group

The final design will include a housing that will be used underwater and will surround the PTO device on each side of the entire VIVACE device, as seen in Figure 1A. The housing is necessary to provide protection of the PTO device from possible debris and to create a more laminar cross section for the PTO device in the fluid flow. The specifics of the housing was never discussed or asked for by our sponsor, so it is outside the scope of this project. It will be designed and produced elsewhere later in the production process.

12. Prototype Description

The prototype design for this project will be much simpler and more cost effective than the finished product because the prototype is not required to be water submersible, since it will not be tested under water. Due to this omission, the prototype will not have some of the same materials chosen for the final design, and some of the component designs will be simpler. Although there are some differences between the final design and the prototype, a good proof of concept will be conveyed through the prototype.

Since the prototype does not need to be water submersible, all of the aluminum components in the final design can be made of cheaper and easier to manufacture plastics. For a full list of each part and its corresponding material and price, please refer to Table 4 below. The magnetic array housing is no longer required to be sealed, which allows for a two piece housing that will be attached together with fasteners. The main tube will be made from clear acrylic tube to be able to show the inductor arrangement. Additionally, the bearings chosen for the final design will not be needed. A simpler, more cost effective bushing will be made out of low friction Ultra-High Molecular Weight (UHMW) polyethylene 4 inch O.D rod. All of these changes are made to reduce the time and cost of the manufacturing of the prototype.

Part	Material	On or Off Shelf	Price
Base	Polypropylene	Off	$24.48
Main Tube	Cast Acrylic	On	$45.75
Bushing	UHMW Polyethylene	Off	$8.65
Magnetic Array Housing (Top and Bottom)	Cast Nylon 6	Off	$107.08 26” length
Magnetic Array Spacer	Cast Acrylic	On	$25.18
Magnet	¾” cube N42 grade Neodymium Magnet	On	$7.70 each
Key	PVC, Type I	On	$0.86 per foot
Retaining Ring	Carbon Steel	On	$7.17 each
Magnetic Array Collar	Cast Nylon 6	Off	$85.26 26” length
VIV Cylinder Bracket	Cast Nylon 6	Off	$51.30
Large Spacer	PETG Polyester	On	$4.20 per foot
Large Spacer End Cap	Polypropylene	Off	Prince included in Base price
Iron Core	Cast Gray Iron	On	$30.64
Wire Spacer	PETG Polyester	Off	$4.20 per foot
Wave Spring	High Carbon Steel	On	$11.91
Electrical Wire	Enamel-Coated Copper	On	$41.78 per 4000 foot spool

Table 4: Prototype List of Parts and Their Corresponding Materials

The manufacturing of the prototype is also different from the production manufacturing of the final design. This is due to the prototype budget constraints and the available tools to manufacture the prototype. Instead of making the base and magnetic array collar from cast aluminum, they will be both machined from cut to length plastic, and the pieces from each component will be adhered together. All of the injection molded components indicated in the final design description will be machined from stock pieces of plastic.

Even though there are differences between the final design and the prototype, the prototype proves the most important elements of the final design. Our prototype will strengthen the proof of the concept for linear inductors by increasing the PTO device's ability to continuously harness energy. In addition, our prototype will prove that the Halbach magnet array is a viable, economical, and scalable alternative to the solid hoop magnet used in the previous PTO device.

To help evaluate the performance of our final design and validate our design, we will wire our linear inductors to a series of LED lights to show that power is, in fact, generated. This will allow us to easily show that power is generated without the need for a rectifier circuit. In addition to showing that power is generated, the next most important customer requirement that can be validated is the continuity of motion from the magnetic array collar. As the magnetic array collar moves up and down axially along the main tube, there is a back EMF created when a magnet nears an inductor. Since the two piece inductor design in series in the prototype is identical to the final design the prototype will represent the same motion and forces that the final design would produce. Finally, the prototype can validate the final design's feasibility by just using one PTO device. The final design calls for two PTO devices on either side of the VIV cylinder, which is unnecessary since we are just showing proof of concept.

13. Initial Manufacturing Plan

This section will describe how we will manufacture the device. Due to the differences between our final design and prototype, the manufacturing plans do not reflect the mass production procedures. This tends to be true for most prototypes. The prototype manufacturing will be conducted primarily using the University of Michigan mechanical engineering undergraduate machine shop. Depending on availability and budget constraints, two components will be made using a CNC mill, outside of the undergraduate machine shop.

The manufacture of the prototype is going to be broken down into three sections: inductor group, main tube group, and the magnetic array and bracket group. The details for the manufacturing of each group are in the following sections. Schematics for each component can be found in Appendix D.

Inductor Group

The inductor group consists of the iron core, plastic spacers, and the inductor coil wire. These components can be seen in Figure 19 above or in greater detail in Appendix D. The iron core will have to be rough cut down close to the nominal dimension using a band saw. The final length of the iron core will be cut by a lathe. The 8 spacers will be cut from on-shelf plastic tube that will be cut to the required spacer thickness using a lathe parting cutoff tool. Once all the spacers are cut, the first spacer will be adhered onto the iron shaft at one end. Each subsequent spacer will be adhered with a 1.5 inch spacing from the last spacer. This is continued along the entire length of the iron rod until all the spacers have been affixed in their proper positions. Each wire inductor is then made by slowly spinning the iron rod in a lathe and winding the rod until the coil is complete. Each of the seven coils is manufactured in the same manner described previously until they are all completed. The inductor group is then set aside until it is ready to be inserted in the main tube. The details for this operation are listed in the next section.

Main Tube Group

The main tube group consists of the main tube, bases, large spacers, and large spacer end caps. These pieces can be seen in Figure 18b or in greater detail in Appendix D. The base will consist of two sub- components, which will be: (1) a piece of flat plastic stock that will be first rough cut using a band saw then machined to its final dimensions using a mill and (2) a piece of round stock that will be machined on a lathe down to the proper O.D. the interior portion of the end cap will then be machined using a boring bar to the proper dimensions for insertion of the main tube. After both pieces are completed, they will be adhered together to create one piece.

The large spacer will be on-shelf plastic tube that will be cut to the proper length using a parting cutoff tool on the lathe. The large spacer end cap will be machined down to the proper dimensions using a lathe, and the relief notch on the end cap will be machined out using a mill.

The entire assembly is manufactured around an on-shelf 36 inch clear acrylic tube. One of the end caps is inserted into one large spacer. The spacer is then inserted into the main tube. One of the base pieces is then affixed to the end of the main tube with small set screws. The final design calls for a threaded coupling, but due to time constraints and no longer having the need to make it water tight, small set screws will be used to attach the base to the main tube ends. From the other end the tube, the inductor group will be inserted inside the main tube until it makes contact with the end cap already in the tube. The second large spacer and end cap will be inserted making sure that the inductor group’s wiring harness is properly routed within the large spacer. The second base will be attached to the main tube only after the magnetic array and bracket group is placed over the main tube.

Magnetic Array and Bracket Group

The magnetic array and bracket group is the most time consuming and costly group to manufacture. This group consists of the magnetic array collar, VIV cylinder bracket, retaining rings, key, bushings, spacers, magnetic array housings, and the magnets. These components can be seen in the above Figures 20b and in greater detail in Appendix D. The first component to be manufactured is the magnetic array collar; this will start off as a stock plastic tube that will have to be cut down to the nominal length using a lathe. Next, the retaining ring grooves will be cut out from the bore of the collar using a boring bar operation. The VIV mounting bracket will then be cut down to the required outer dimensions using a mill; the curved collar mounting surface will then be cut out by a fly-cutter operation on the mill. Mounting holes will then be drilled into the bracket using a drill press. Lastly, the VIV bracket is adhered to the collar. The bushings will be made from stock 4 inch rod of low friction UHMW Polyethylene. The rod will be drilled and bored to the proper dimensions using a lathe boring operation. Once the bore is finished, a parting cutoff tool will be used on the lathe to cut the bushings to their required length. The magnetic array spacers will then be cut to length from stock plastic tube using the lathe parting cutoff tool. This process will be repeated until all three spacers are created.

The magnetic array housing is the most complicated sub-component of the entire device and is shown in Figure 21. This sub-component consists of ten parts: the lower housing, upper housing, and eight magnets. Both the upper and lower housing components will be made from the same 4 inch O.D. and 2 inch I.D. nylon tube stock. The tube stock's bore will be widened using a boring operation to allow for a 0.0625 inch clearance between the magnet housing and the main tube. The bottom housing component will then be cut to a 0.875 inch length. The upper component of the housing will first be cut to length by using the lathe parting cutoff tool. The pattern shown in 21b will then be cut out using a mill and rotary table. Once both top and bottom parts of the housing are machined, they will be sandwiched together, and bolt holes will be drilled and tapped so that both pieces can be attached to one another. Finally, eight ¾ inch cube magnets will be placed in the bottom housing in the pole configuration shown in Figure 14 and bolted together.

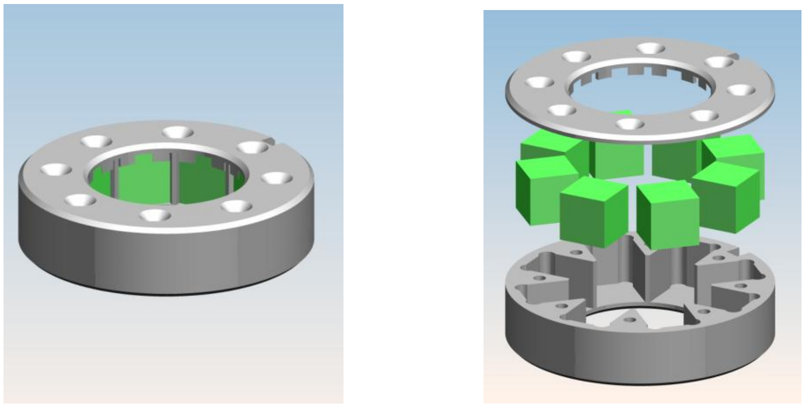
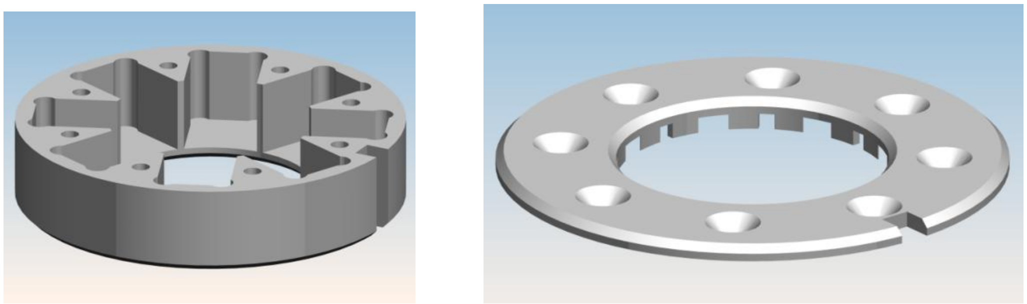

(a) (b)

Figure 21: Magnetic Array



(a) (b)

Figure 22: Magnetic Array Housing Top and Bottom Detail

The entire group will then be assembled by installing one of the retaining rings into the collar, inserting a bushing, wave spring, magnet array, spacer, magnet array, spacer, magnet array, spacer, magnet array, and bushing. To keep all of those components from rotating, a key will be inserted into the keyway cut out of each bushing and magnetic array housing. Lastly, the final retaining ring will be installed. The magnetic array and bracket group will then be finished.

The main tube will be inserted through the magnetic array and bracket group, and the second base will be installed, ensuring that the inductor wiring harness is properly routed. This process will complete the manufacturing of our prototype. Below Table 5 lists the type of machine used, operations, tool speed and feed rate for each component.

Component	Machine	Operation	Tool Speed	Feed Rate
Base	Band Saw	Cutting	300 FPM	3 IPM
	Mill	Face Milling	1500 RPM	1.5 IPM
	Lathe	Turning	200 RPM	2 IPM
	Lathe	Parting	200 RPM	0.5 IPM
Bushing	Lathe	Boring	300 RPM	2 IPM
	Lathe	Parting	150 RPM	0.5 IPM
Magnetic Array Housing Top	Lathe	Boring	300 RPM	2 IPM
	Lathe	Parting	150 RPM	0.5 IPM
	Mill	Face Milling	1500 RPM	1.5 IPM
Magnetic Array Housing Bottom	Lathe	Boring	300 RPM	2 IPM

	Lathe	Parting	150 RPM	0.5 IPM
	Mill	Face Milling	1500 RPM	1.5 IPM
Magnetic Array Spacer	Lathe	Parting	200 RPM	0.5 IPM
Magnetic Array Collar	Lathe	Parting	150 RPM	0.5 IPM
	Lathe	Boring	150 RPM	2 IPM
VIV Cylinder Bracket	Mill	Face Milling	1500 RPM	1.5 IPM
	Mill	End Milling	1500 RPM	1.5 IPM
	Mill	Fly Cutting	300 RPM	1.5 IPM
Large Spacer	Lathe	Parting	300 RPM	0.5 IPM
Large Spacer End Cap	Lathe	Turning	300 RPM	2 IPM
	Lathe	Parting	200 RPM	0.5 IPM
	Mill	End Milling	1500 RPM	1.5 IPM
Iron Core	Band Saw	Cutting	100 FPM	1.5 IPM
	Lathe	Parting	150 RPM	0.5 IPM

Table 5: List of Machining Operations

14. Validation Plan

The engineering specifications that will be tested are the amount of induced EMF and smoother motion. The validity of the device can either be tested by attaching the VIV cylinder bracket to the VIVACE module in the Low Turbulence Free Surface Water Channel in the University of Michigan Marine Hydrodynamics Lab or by manually oscillating the magnetic collar up and down with roughly the same average frequency seen by the VIVACE module.

The amount of induced EMF from the inductors can be tested by attaching the output wiring harness to an oscilloscope. The oscilloscope will be able to graphically show how much voltage is being output at a given location of the magnetic collar along the main tube. To measure smoother motion, the magnetic collar will be moved up and down and compared to the previous prototype to show the difference in continuous motion. The best approach to test this would be to use a force meter to plot the force alone the path of the inductor. However, due to budget constraints, this is not a feasible option.

Other specifications of the final design would be validated, such as longevity and waterproofing ability. Since this prototype is designed to show proof of concept, the validation of the two specifications above will not be conducted.

15. Project Timeline and Plan

Here is a list a chronological list of the objectives we need to complete before December 4th. Many of these things can be completed simultaneously, for example multiple people could be putting in orders for parts at the same time, but this is a good laundry list which shows us the path to completion.

1. Order the magnet array base and top to be manufactured
2. Order reduced friction bearing for inside of magnet housing
3. Order the magnets
4. Order iron core
5. Order the clear plastic tube to go around iron core and coil windings
6. Order copper wire
7. Purchase lights
8. Machine
    a. Spool
    b. Large spacer
    c. Bushings
    d. End cap
    e. Collar VIV cylinder bracket
    f. Bracket for lights
9. Turn wire onto spools
10. Assemble spools and spacers on iron core
11. Wire lights to inductor
12. Assemble Halbach arrays
13. Assemble VIV cylinder
14. Prepare final report
15. Prepare design expo poster and visual material
16. Submit final report/analysis to section instructor and sponsor

16. Problem Analysis

The VIVACE system uses linear inductance to convert kinetic energy into stored electrical energy. In order to optimize this system we are going to need to have a good understanding of inductors and electromagnetism to produce valuable design concepts and our alpha design. Having knowledge of fluid mechanics will also be necessary if we want to fully optimize the VIVACE system because it is currently a marine application. While a design is being selected, we will need to use our material science knowledge and resources, like Cambridge Engineering Selector, to choose the best materials for our prototype, and allow plenty of time for the materials to arrive. The most critical decisions to be made on our design are the number and the size of the wire coils we are going to have, and what type of magnet will we use.

To keep costs down we are going to try an array of magnets as opposed to a solid circular magnet. Besides the cost benefits, an array of magnets also has a weaker magnetic field outside the magnet while maintaining a large magnetic field inside the magnet. This will be beneficial as it will reduce the magnets interference with its surroundings.

To optimize the design we plan to use the ANSYS Emag Finite Element Analysis (FEA) software, which is especially for the analysis of electromagnetic systems. This modeling software will help us simulate different scenarios and choose the optimum values for our engineering specifications such as, wraps of coil in each inductor, orientation of magnets, and field strength. By creating a Design of Experiments (DOE) to eliminate the number of tests needed to identify optimal settings for our VIVACE system, we can compare the different coil and magnet setups to select the optimal design for this marine application.

Major problems in our project will come from need for knowledge. Although some group members have statistical and FEA experience, consulting with an expert in these fields may be required to maximize the ability of our model and results.

17. Test results

For our first mode of testing we wanted to figure out a special circuitry to get the maximum power possible from all of the coils put together. However, due to the phase differences generated by the coils we were unable to build a circuit with our lack of knowledge on circuitry and were not successful.

As a second option we decided to calculate the current created by one coil only. We connected a rectifier to one coil and then the rectifier to a multi-meter. The rectifier was used to turn the AC current to DC which would allow us to test it easier. The result we got from the multi-meter for one coil came up to be approximately 3 volts max. We had higher spikes however they were for a really short time. This value also depends on the speed the magnets were moved.

The overall energy output would be more because we have more coils and more magnets. The correct phase setup and circuitry could be implemented possibly by an electrical engineer in the future.

17. Conclusion

Power take-off systems that are readily available, such as rotational generators, are not cost effective and/or efficient for implementation into the VIVACE system. Only a custom made linear generator, based on the inputs of a particular VIVACE system, can effectively collect energy at a relative high density from a given current. The implementation of a linear generator was the conclusion of the previous ME 450 group of winter 2008. The problem with their generator was a high counter-electromotive force that caused a non-continuous motion throughout the cycle. The stronger the counter-electromotive force is from the generator, the more energy you can harness from each cycle, but too much force will disrupt the vortex shedding and take energy away from the process. This in turn results in a low energy density that is collected from the incoming current. In collaboration with Professor Bernitsas, our team will design a power take-off system that will be optimized and scalable to a given VIVACE apparatus to which it will be attached. On site customization of the electromotive force will be key in the success of the linear generator.

Using brainstorming sessions within our group and with our sponsor we created many innovative ideas. By using functional decomposition to break the entire system down into five function groups. The function groups are: energy harnessing, VIV cylinder mounting system, PTO device mounting system, magnet collar bearing system and energy transmission. All of our ideas were placed into their respective functional groups and then narrowed down by listing their pros and cons.

After the best ideas were chosen the Alpha design concept was chosen and created in a CAD environment. We recommend moving further with the chosen Alpha design concept. We believe that this current Alpha design will allow for the best fit to our engineering specifications, customer requirements and will prove to be the simplest and most cost effective design.

Upon conducting further meetings with our sponsors and building off of the alpha design, the final design was chosen. The final design addresses all of the customer requirements by encompassing the engineering specifications in our engineering analysis. Due to expertise and time constraints the final design prototype will not be operational in all coils simultaneously. A rectifier circuit that addresses the problem of alternating electrical phases throughout the different coils will allow you to harness the generators power. Although the prototype differed from the final design, it validated the customer requirements of a scalable, cost effective PTO that greatly reduced the back electromagnetic force of the previous groups design.

18. Recommendations

As a result of our research and experience from this project we came up with several recommendations for future considerations.

We have realized the magnetic field force decreases significantly around the coils due the air gaps, and low permeability material. To encounter this issue we recommend using high permeability material for any part that is between the magnets and the coil and the inner core of the coils. These high permeability materials are ferrous materials. However high carbon steel alloys or stainless steel alloys might not have high permeability depending on their content.

Even though we want to maximize the magnetization inside the magnetic array we want to minimize it outside because of environmental effects. Halbach array is a good phenomena for this application however to be on the safe side we recommend using low permeability materials for the outer shell of the magnetic array casing. The material choices are not limited by a lot because any material other than ferrous materials does have low permeability. We also recommend painting any part that is in contact with water to prevent it from corrosion.

In our design we have arranged the magnets and coils as close as possible without making two magnets are in line with one coil at a time. However, someone more experienced and knowledgeable in phases and how they work can put the magnets and the coils in phase and possibly increasing the total output of the system. Also to get the maximum output possible from all of the coils, proper circuitry should be designed and implemented. If a proper circuit could be implemented smaller and more windings can be used which would increase the total electricity created. These tasks would be most suitable for an electrical expert.

18. Acknowledgements

We would like to thank Professor Michael M. Bernitsas for his sponsorship, time, and inspirational ideas in this project. Also, a special thanks to our Section Instructor, Professor Bogdan Epureanu, for his tireless efforts to make sure we had every available resource to design, build and complete a working prototype that would please our sponsor. He also helped us in having great design reviews to prepare us for the final design expo.

19. References

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Biographies

Robert Shaun McKee

Shaun was born in Dearborn, Michigan on March 14, 1981. He currently resides in Northville, Michigan with his girlfriend and their two cats, Isis and Osiris. A senior in Mechanical Engineering he has attended over six different colleges and hopes to complete his degree in under a decade. Prior to his studies at Michigan he was in the United States Marine Corps and spent time in California and Japan during his active tour. Sergeant McKee held numerous jobs to include; paralegal for the Judge Advocate General's Corps, Military Police Officer and a Marksman's coach. He is the first of his family to attend college and has funded his own education through the Montgomery G.I. bill and sales on eBay. In his free time he likes to play tennis and work out at the local gym when his girlfriend doesn't have him completing domestic tasks at home.

Peter Avram

Peter was born and raised in Ann Arbor, MI. He is the first child from his family born in the United States and the first to complete his college degree. After graduating high school, he joined the United States Army and became an anti-tank missile repairman. While in the service he excelled at his job and after completing one year of combat in Iraq he attained the rank of Sergeant just before he left the service in the summer of 2004. That following fall semester he started his school career at Washtenaw Community College and completed his engineering prerequisites. Upon completing enough credits at he transferred to the University of Michigan. He is now a senior in Mechanical Engineering and is planning to graduate in December of 2008. After his graduation he plans to find a job in the aerospace and defense industry utilizing his engineering skills and military experience.

Brandon Geiger

Brandon is from Cincinnati, OH. He is a mechanical engineer at the University of Michigan along with his younger brother Derek. As a re-founding father of Delta Tau Delta at UM he spends most of his extracurricular time managing university, community, and Greek relations for the fraternity. He has two years intern experience at Cummins Diesel and most recently at Procter and Gamble Co. His career interests include technical design and energy systems, one of the reasons he choose the VIVACE system as his senior design project. After living in the midwest his entire life he hopes to find work on the west coast after graduation.

TolgaTuzun

Tolga was born in Ankara, Turkey on March 20, 1987. He lived in Turkey most of his life. His parents and he had to move to France for a year and a half when he was in third grade because of his dad’s work. He studied third grade in France and move back to Turkey. While he was in France he has been to almost all of Europe. He stayed in Turkey until he came to USA for college with his parents in 2004. He is currently staying and studying mechanical engineering in Ann Arbor. He hopes to work and then get an MBA degree. He likes cars, snowboarding, swimming, playing computer games, going to the movie theater and travelling.

University of Michigan Design Expo Fall 2008

Appendix A: Function Group Concept Ideas

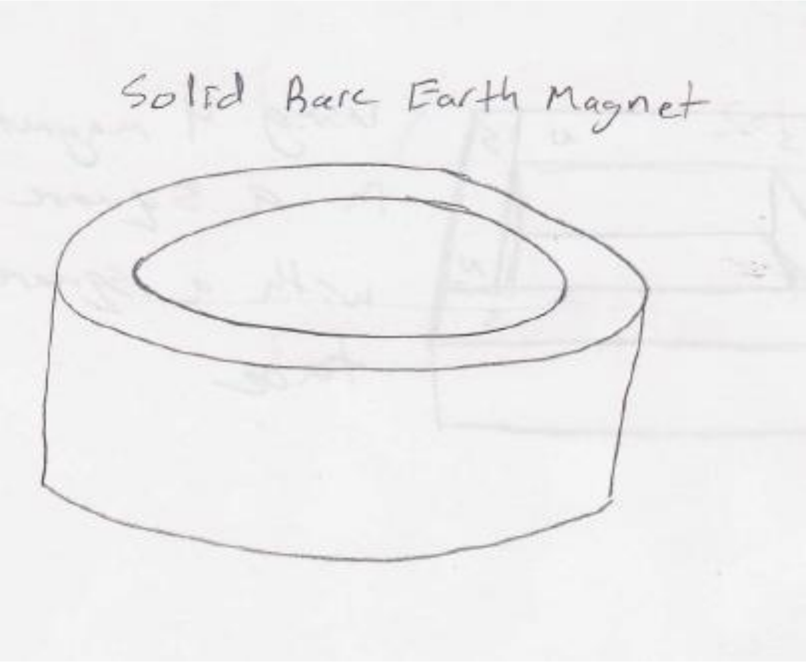


Figure 1: Solid Magnet Concept

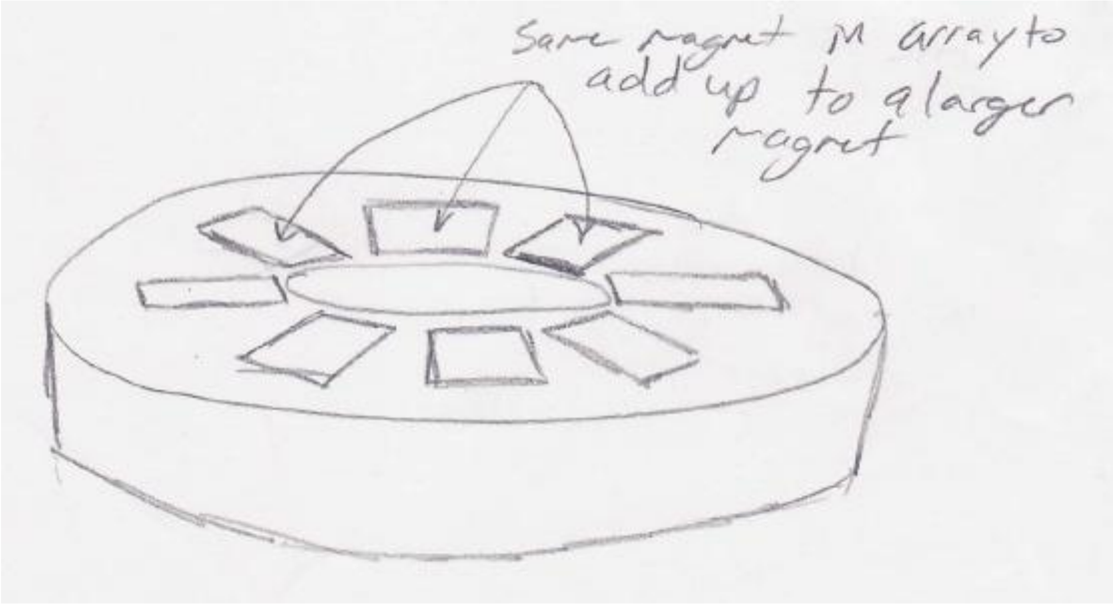


Figure 2: Halbach Array Magnet Concept

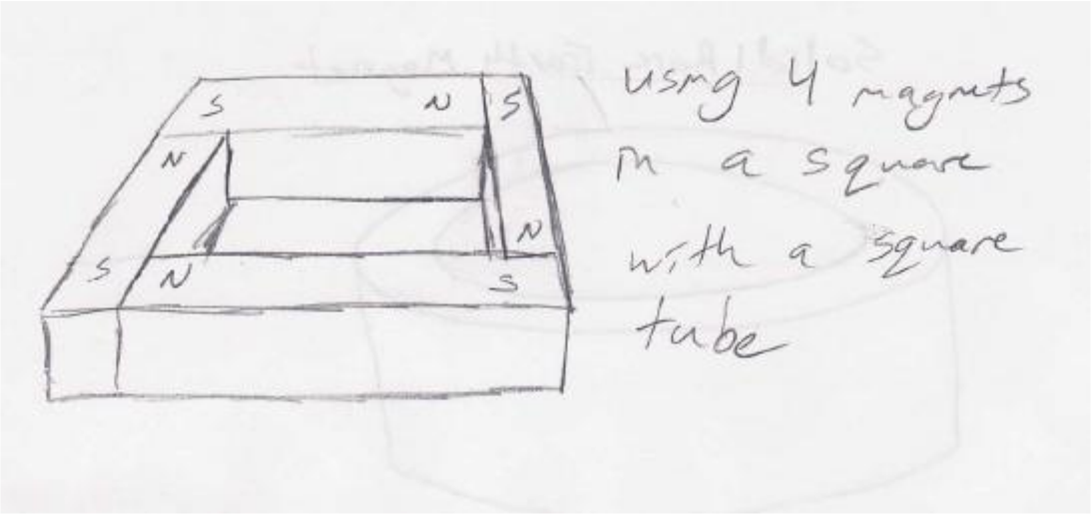


Figure 3: Square Magnet Concept

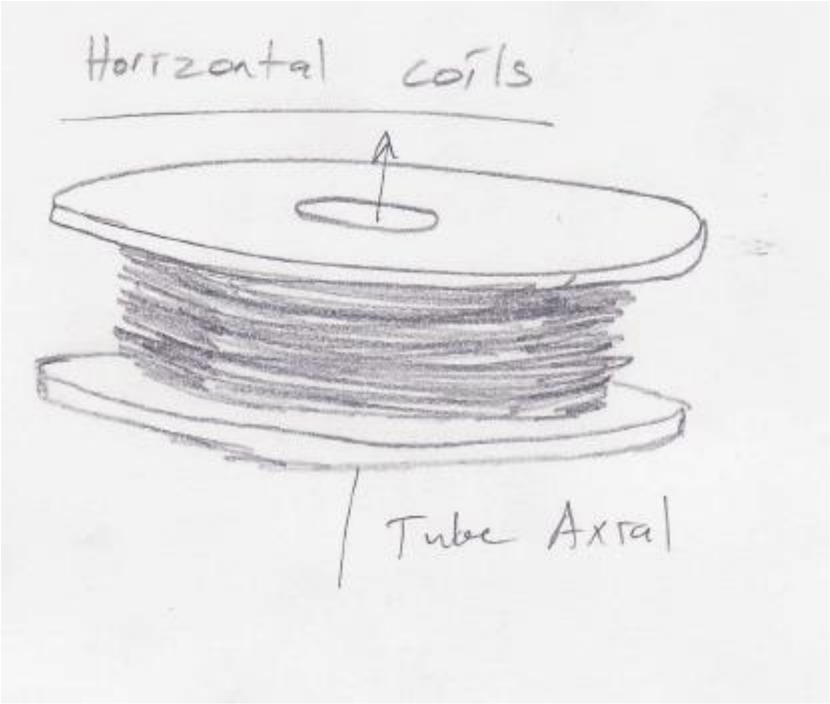


Figure 4: Horizontal Inductor Coil Concept

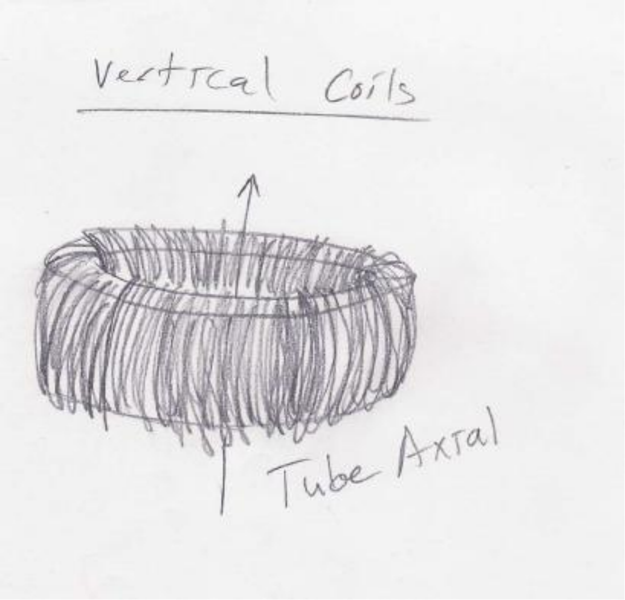


Figure 5: Vertical Inductor Coil Concept

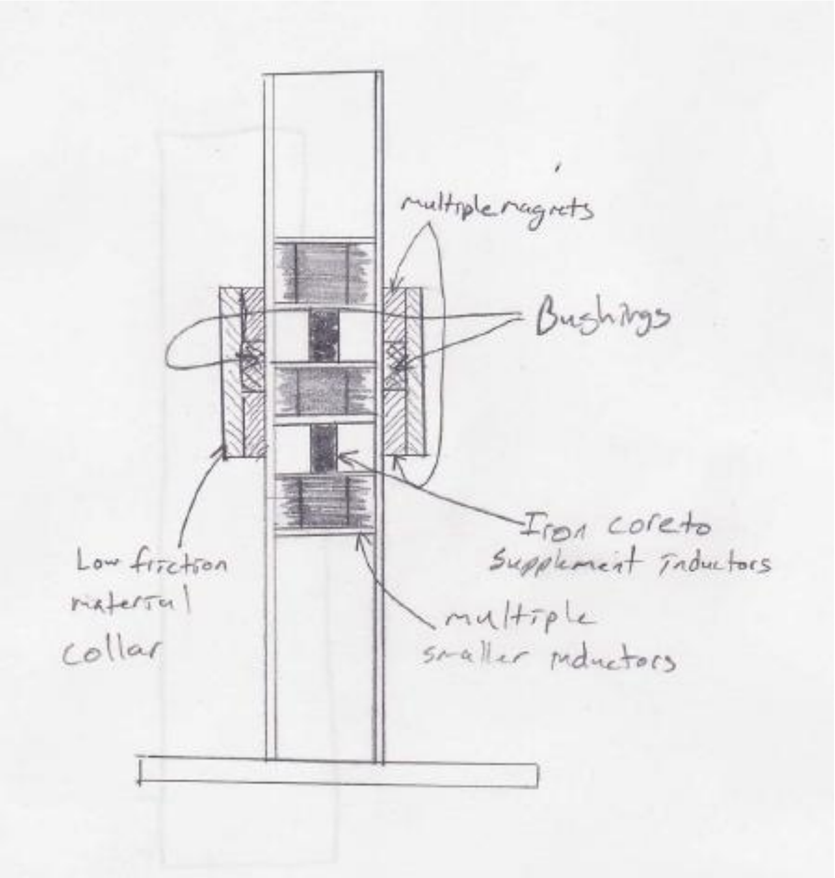


Figure 6: Multiple Inductor PTO Concept

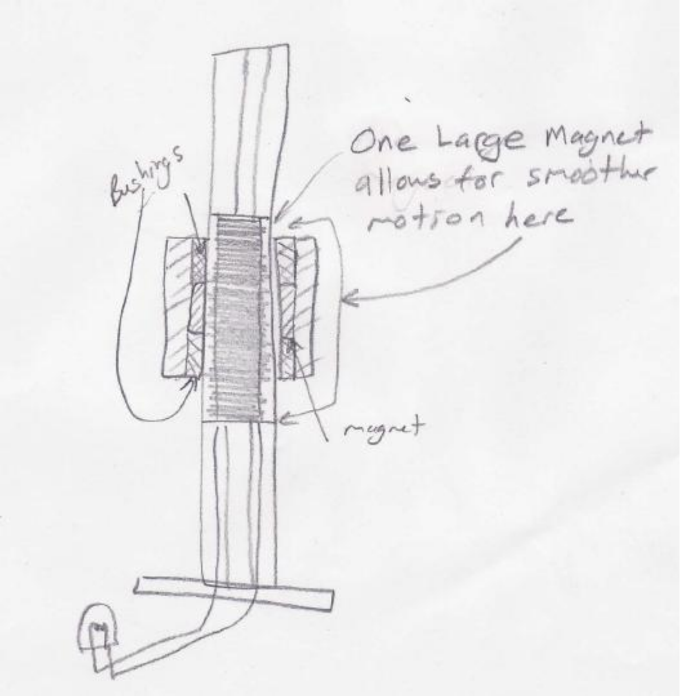


Figure 7: Single Magnet PTO Concept

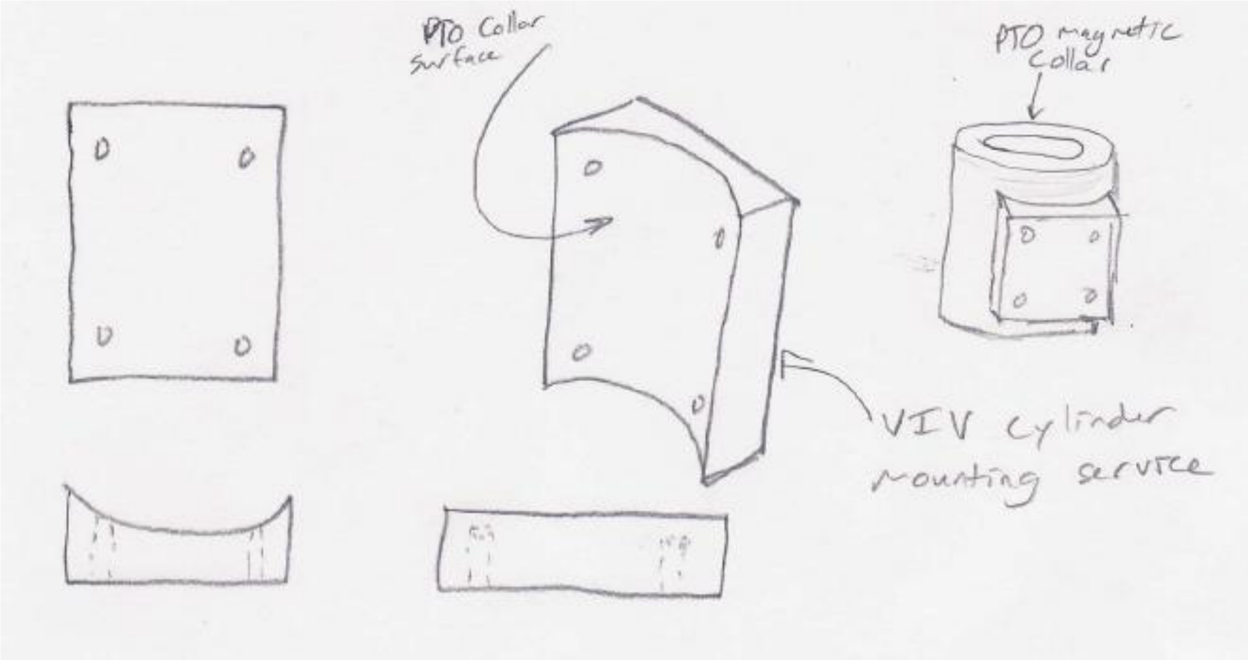


Figure 8: VIV Cylinder Bracket Adhered Concept

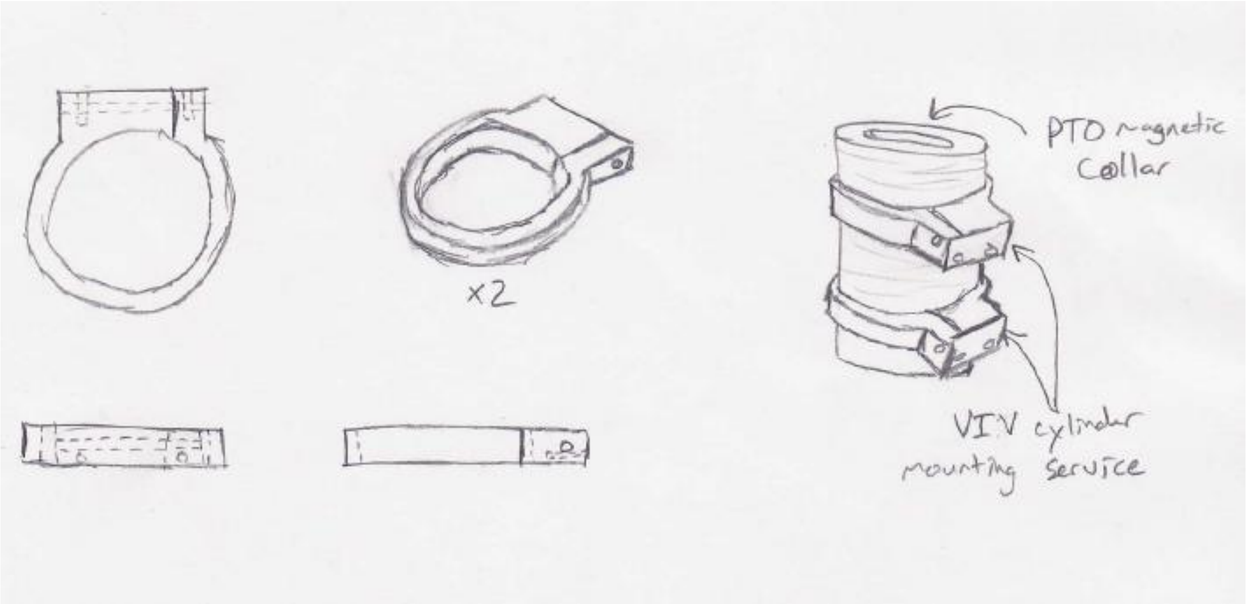


Figure 9: VIV Cylinder Bracket Ring Concept

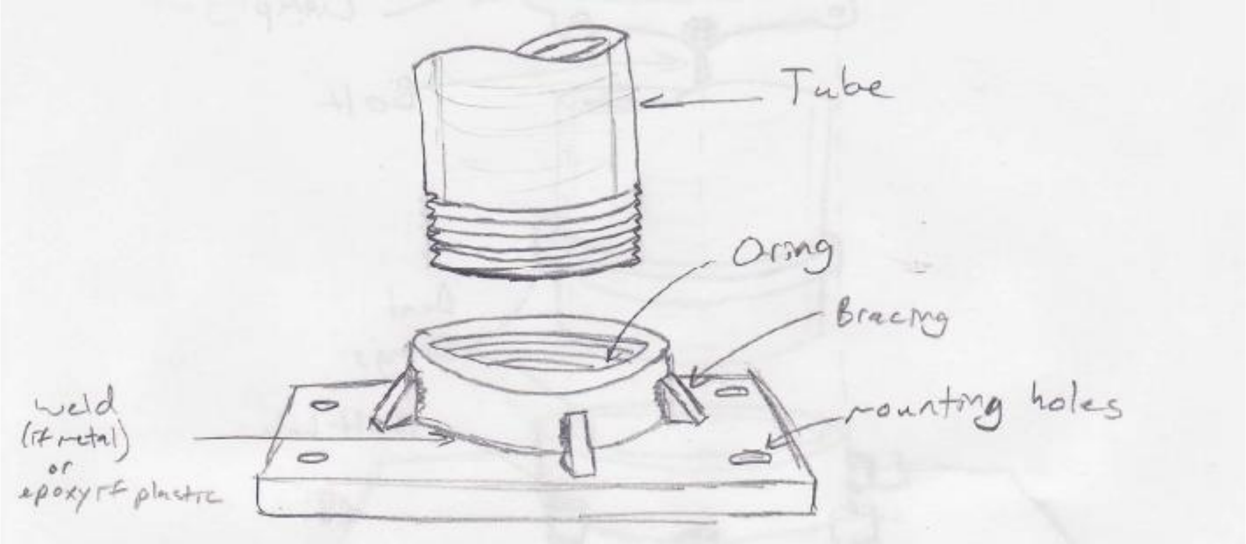


Figure 10: Base Thread Concept

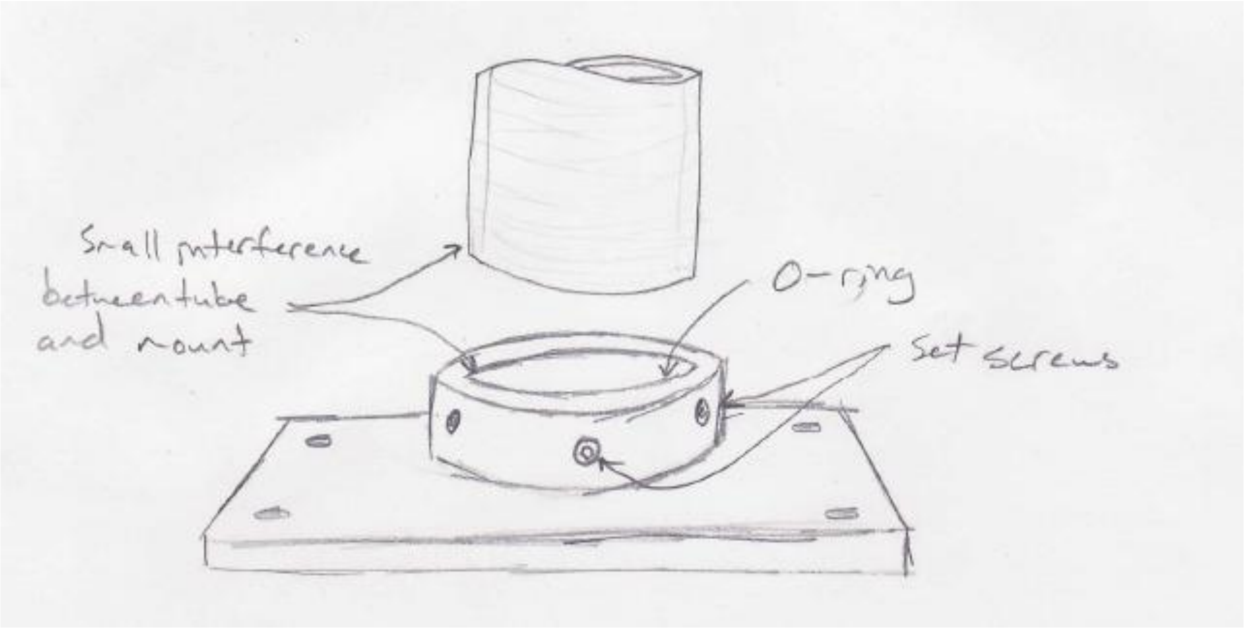


Figure 11: Base Set Screw Concept

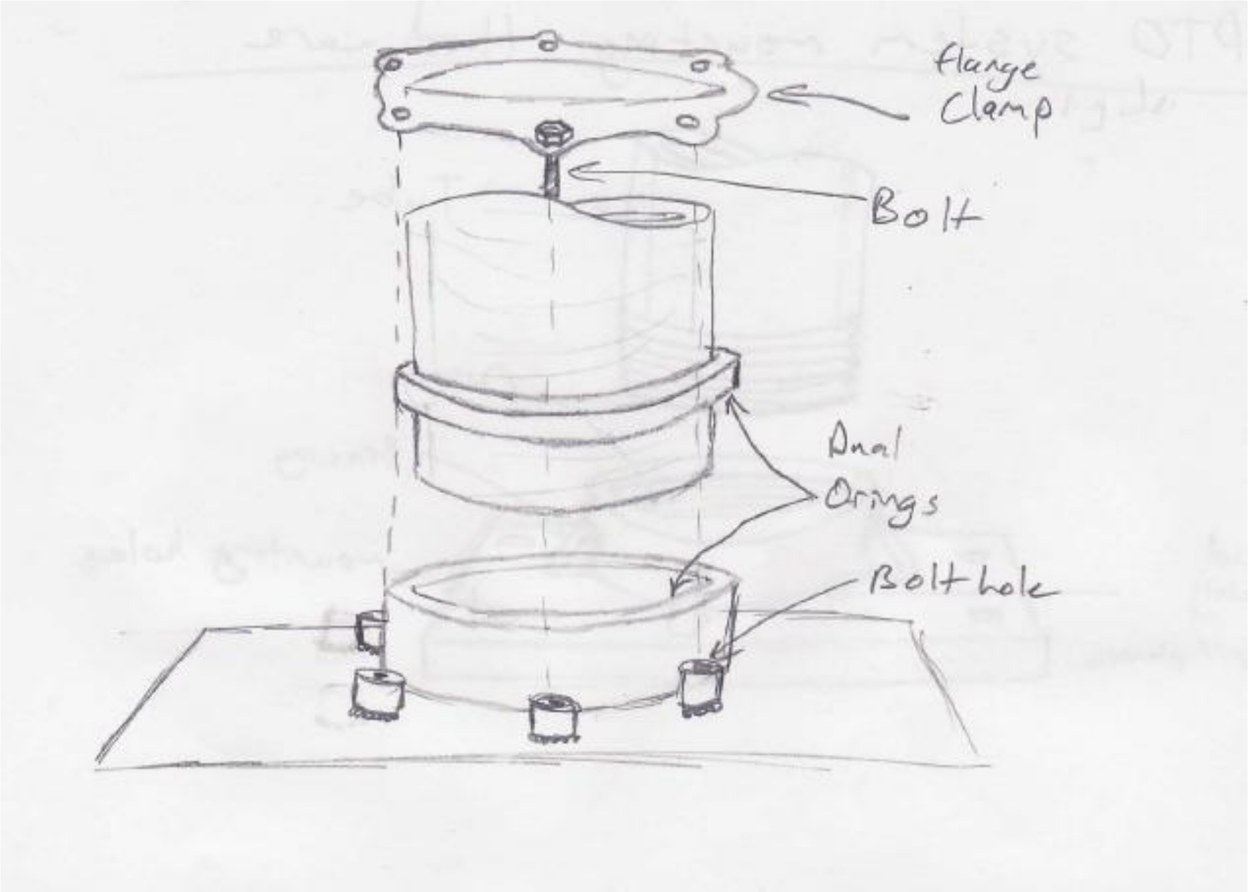


Figure 12: Base Flange Clamp Concept

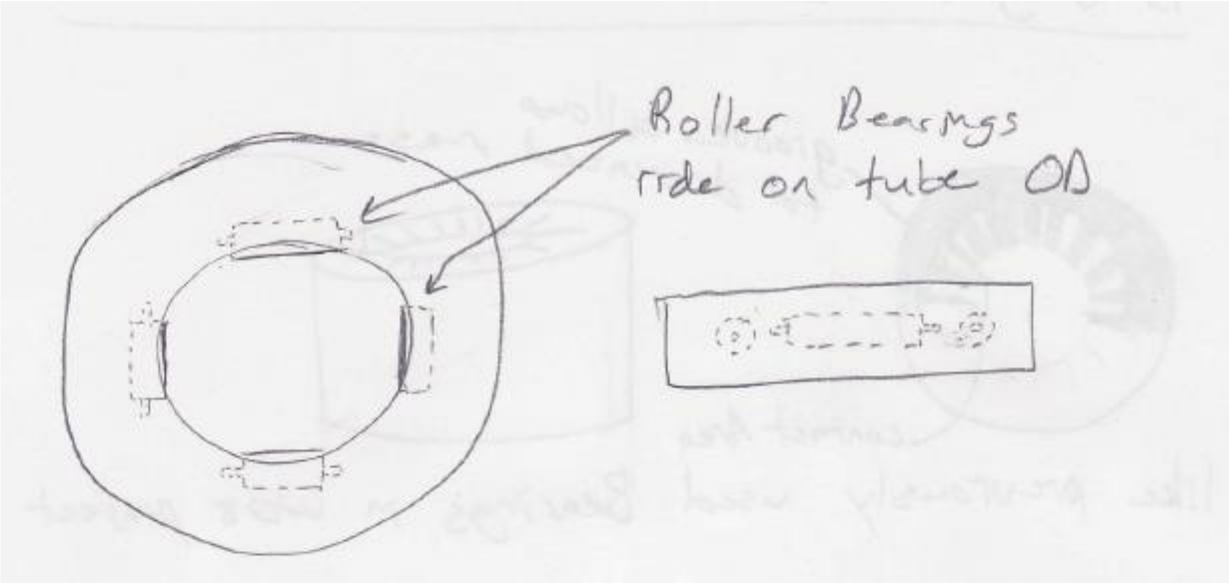


Figure 13: Roller Bearing Concept

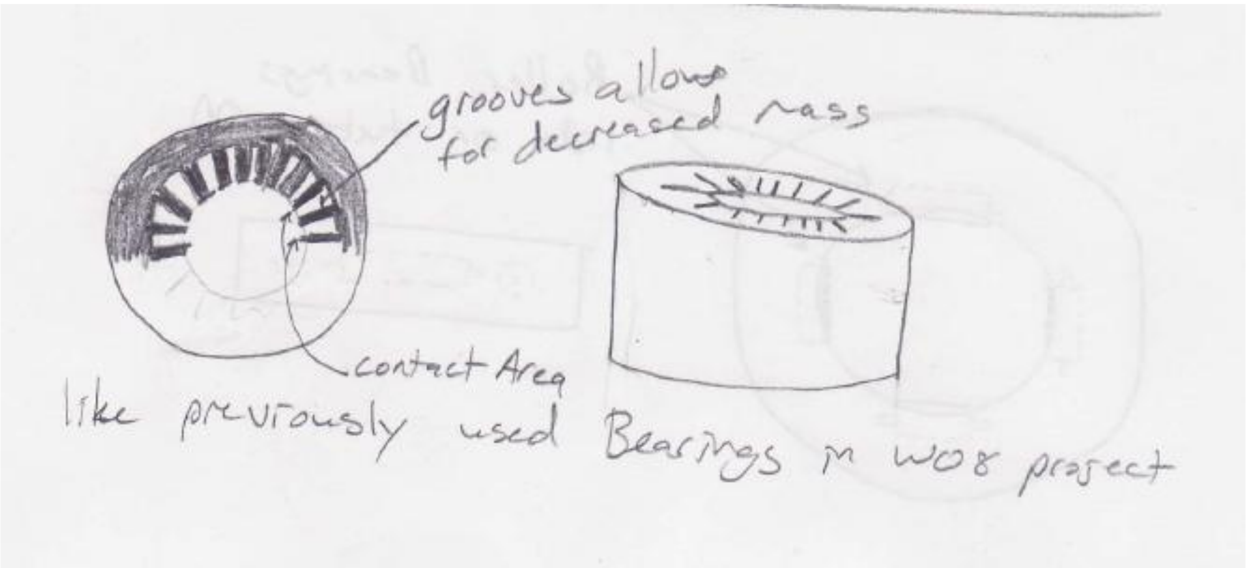


Figure 14: Low Friction Fin Concept

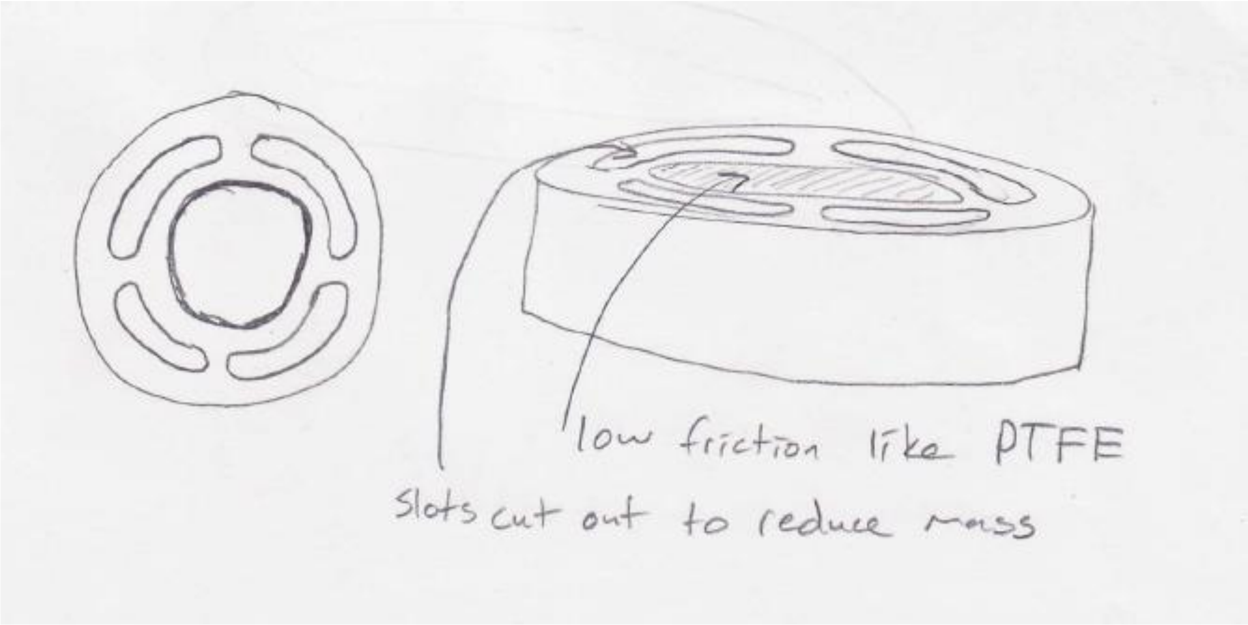


Figure 15: Low Friction Material Concept

Appendix B: Alpha Design CAD Images

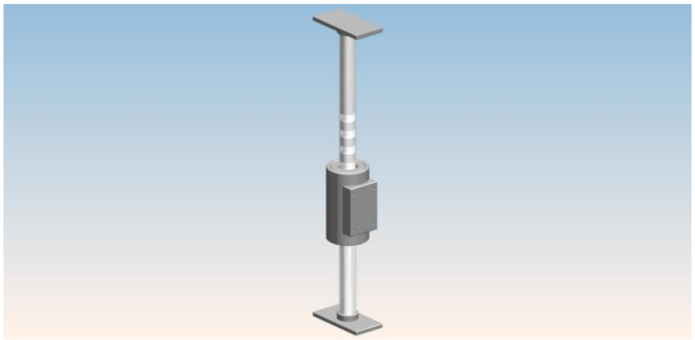


Figure 1: Assembled View of Alpha Design

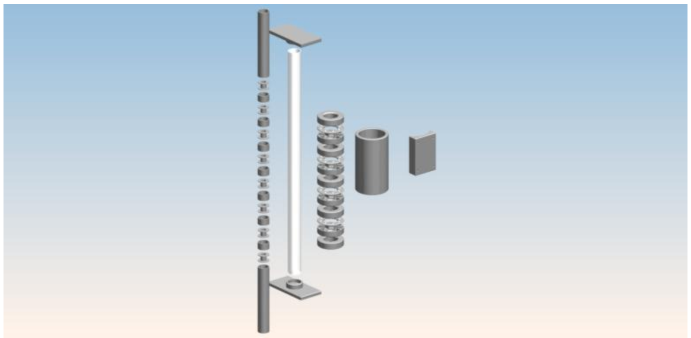


Figure 2: Exploded View

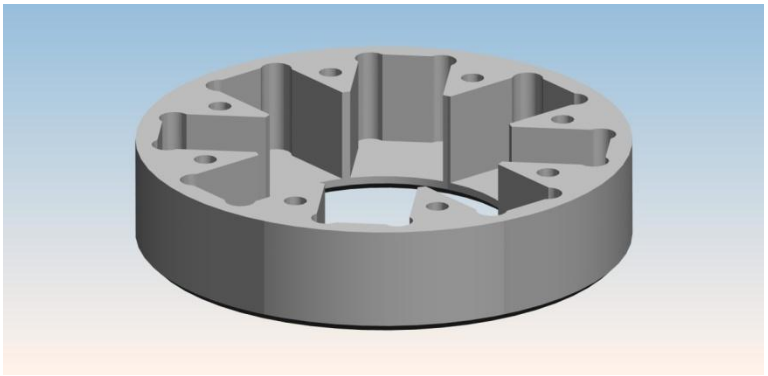


Figure 3: Magnetic Array Base

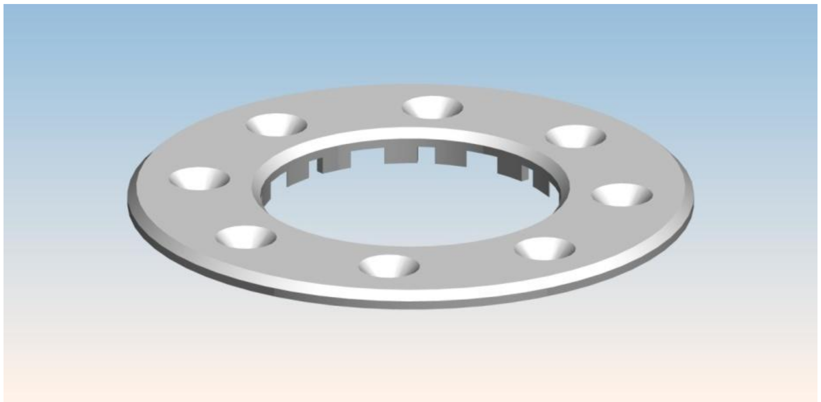


Figure 4: Magnetic Array Top

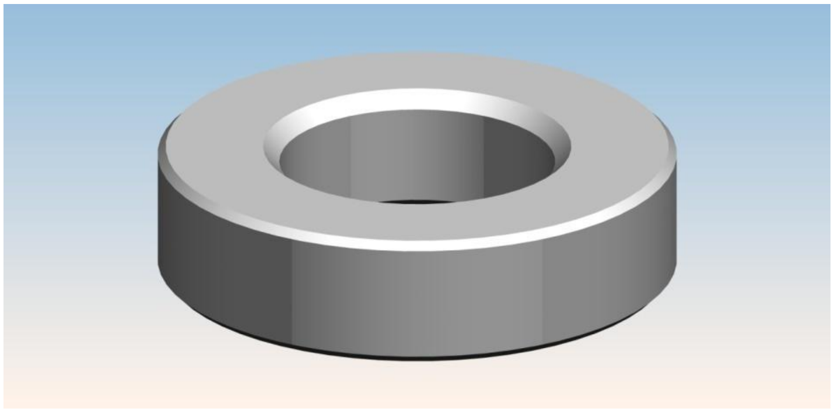


Figure 5: Bushing

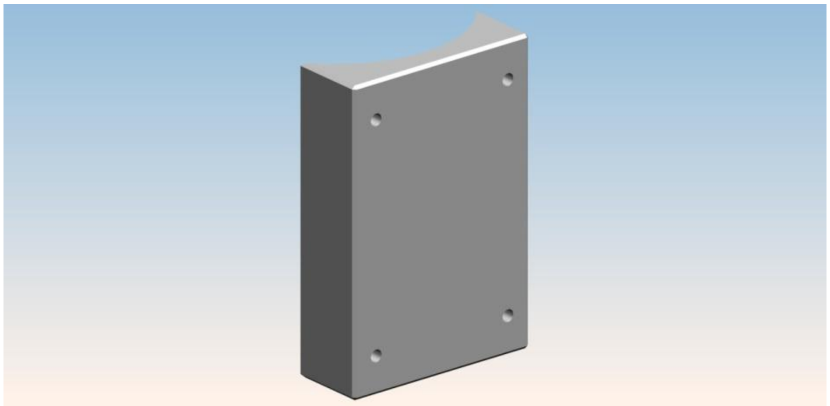


Figure 6: Collar VIV Cylinder Bracket

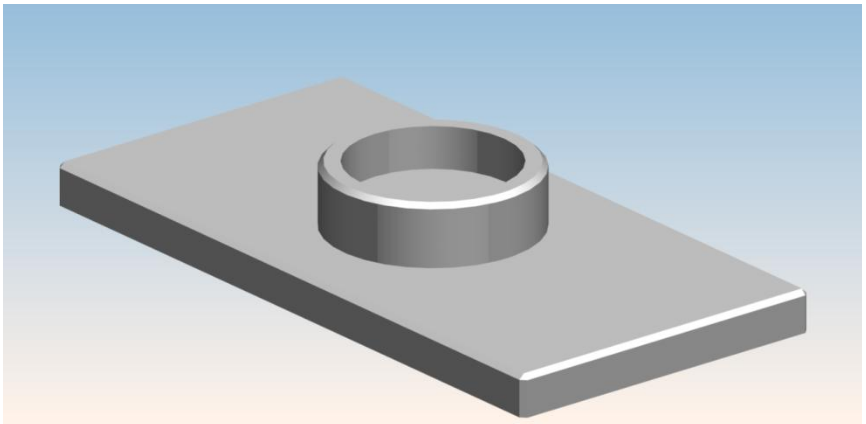


Figure 7: End Cap

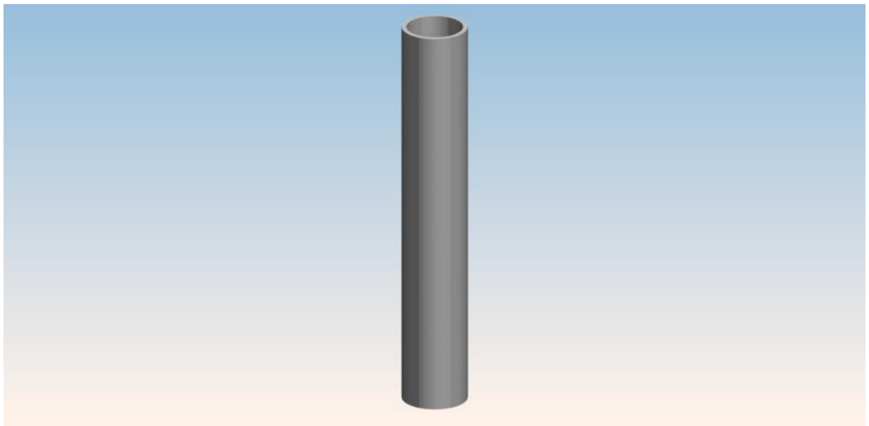


Figure 8: Large Spacer

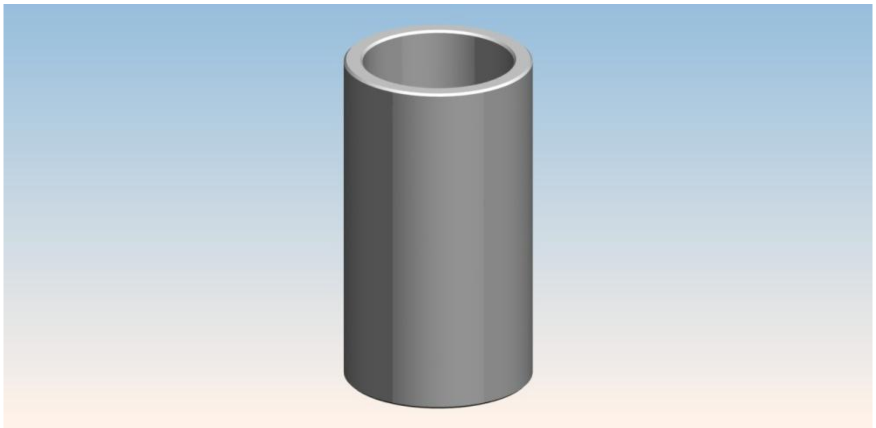


Figure 9: Magnetic Collar

Figure 10: Outer Tube

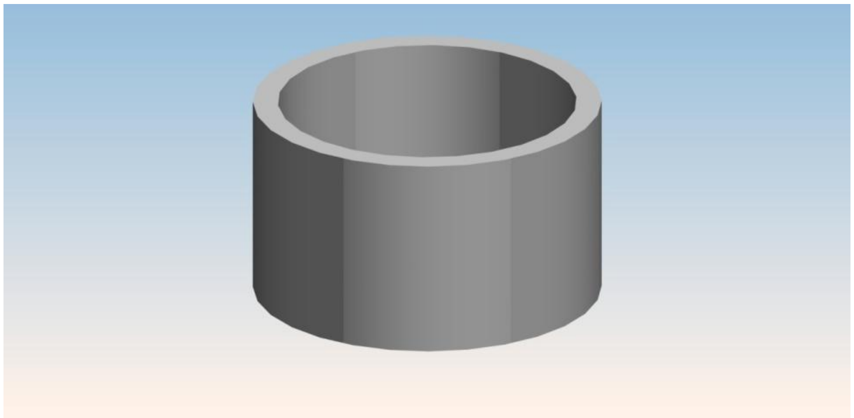


Figure 11: Small Spacer

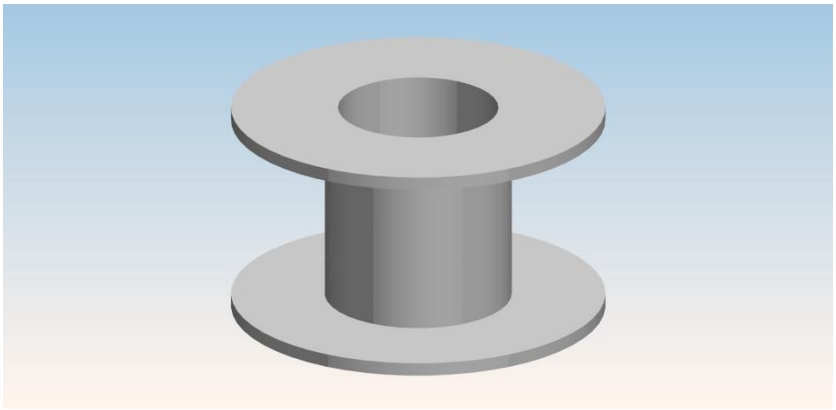
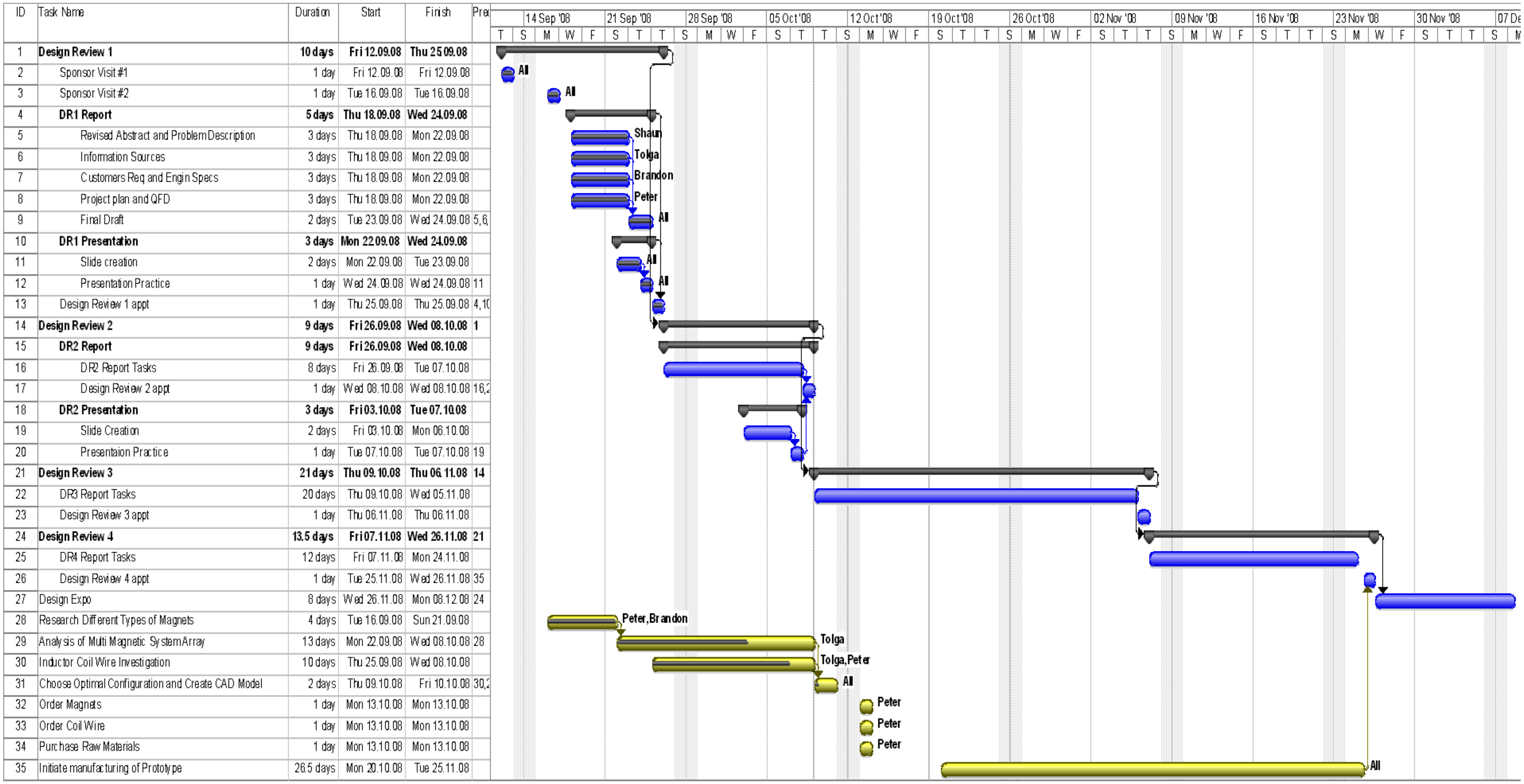


Figure 12: Spool

Appendix C: Gantt Chart



ID	Task Name	Duration	Start	Finish	Pre
1	**Design Review 1**	**10 days**	**Fri 12.09.08**	**Thu 25.09.08**	
2	Sponsor Visit #1	1 day	Fri 12.09.08	Fri 12.09.08	
3	Sponsor Visit #2	1 day	Tue 16.09.08	Tue 16.09.08	
4	**DR1 Report**	**5 days**	**Thu 18.09.08**	**Wed 24.09.08**	
5	Revised Abstract and Problem Description	3 days	Thu 18.09.08	Mon 22.09.08	
6	Information Sources	3 days	Thu 18.09.08	Mon 22.09.08	
7	Customers Req and Engin Specs	3 days	Thu 18.09.08	Mon 22.09.08	
8	Project plan and QFD	3 days	Thu 18.09.08	Mon 22.09.08	
9	Final Draft	2 days	Tue 23.09.08	Wed 24.09.08	5,6,
10	**DR1 Presentation**	**3 days**	**Mon 22.09.08**	**Wed 24.09.08**	
11	Slide creation	2 days	Mon 22.09.08	Tue 23.09.08	
12	Presentation Practice	1 day	Wed 24.09.08	Wed 24.09.08	11
13	Design Review 1 appt	1 day	Thu 25.09.08	Thu 25.09.08	4,10
14	**Design Review 2**	**9 days**	**Fri 26.09.08**	**Wed 08.10.08**	**1**
15	**DR2 Report**	**9 days**	**Fri 26.09.08**	**Wed 08.10.08**	
16	DR2 Report Tasks	8 days	Fri 26.09.08	Tue 07.10.08	
17	Design Review 2 appt	1 day	Wed 08.10.08	Wed 08.10.08	16,2
18	**DR2 Presentation**	**3 days**	**Fri 03.10.08**	**Tue 07.10.08**	
19	Slide Creation	2 days	Fri 03.10.08	Mon 06.10.08	
20	Presentaion Practice	1 day	Tue 07.10.08	Tue 07.10.08	19
21	**Design Review 3**	**21 days**	**Thu 09.10.08**	**Thu 06.11.08**	**14**
22	DR3 Report Tasks	20 days	Thu 09.10.08	Wed 05.11.08	
23	Design Review 3 appt	1 day	Thu 06.11.08	Thu 06.11.08	
24	**Design Review 4**	**13.5 days**	**Fri 07.11.08**	**Wed 26.11.08**	**21**
25	DR4 Report Tasks	12 days	Fri 07.11.08	Mon 24.11.08	
26	Design Review 4 appt	1 day	Tue 25.11.08	Wed 26.11.08	35
27	Design Expo	8 days	Wed 26.11.08	Mon 08.12.08	24
28	Research Different Types of Magnets	4 days	Tue 16.09.08	Sun 21.09.08	
29	Analysis of Multi Magnetic System Array	13 days	Mon 22.09.08	Wed 08.10.08	28
30	Inductor Coil Wire Investigation	10 days	Thu 25.09.08	Wed 08.10.08	
31	Choose Optimal Configuration and Create CAD Model	2 days	Thu 09.10.08	Fri 10.10.08	30,2
32	Order Magnets	1 day	Mon 13.10.08	Mon 13.10.08	
33	Order Coil Wire	1 day	Mon 13.10.08	Mon 13.10.08	
34	Purchase Raw Materials	1 day	Mon 13.10.08	Mon 13.10.08	
35	Initiate manufacturing of Prototype	26.5 days	Mon 20.10.08	Tue 25.11.08	

Appendix D: Final Design Drawings

(All dimensions are in inches)

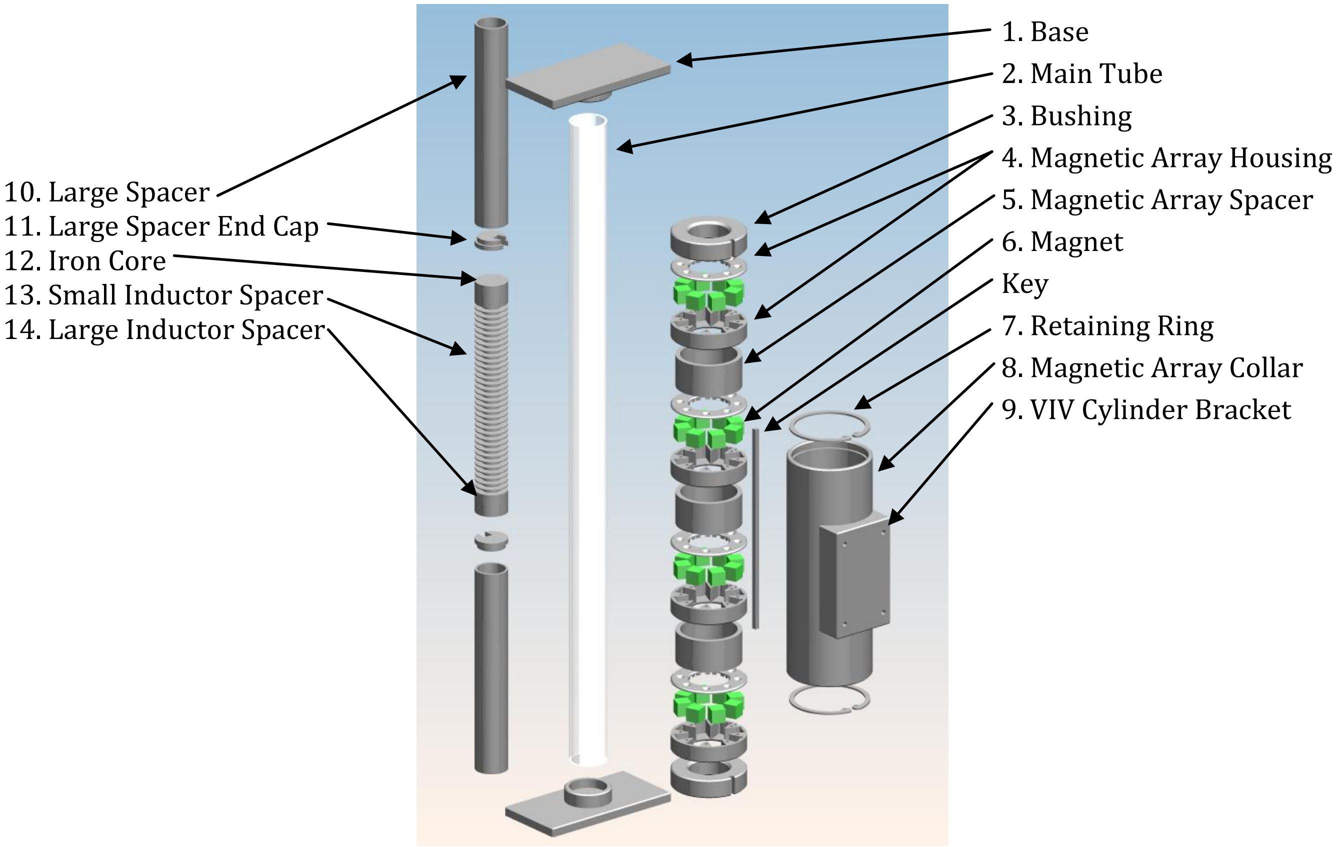


Figure1: Component Part Reference

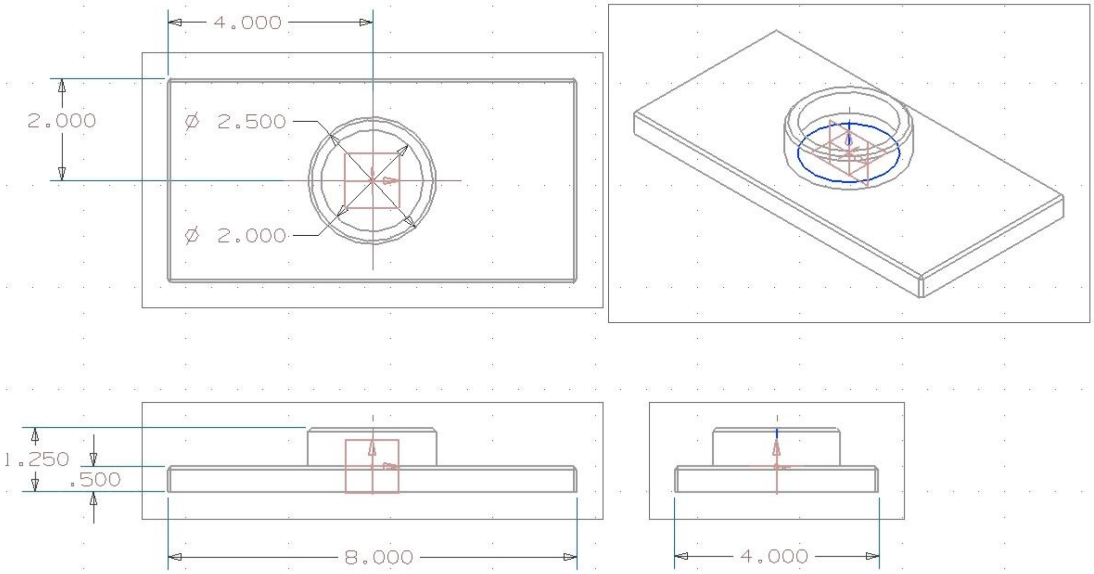


Figure 2: Base Dimensions

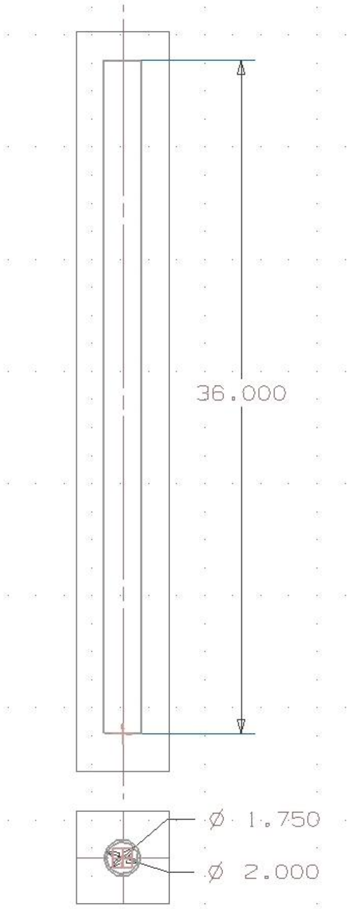


Figure 3: Outer Tube Dimensions

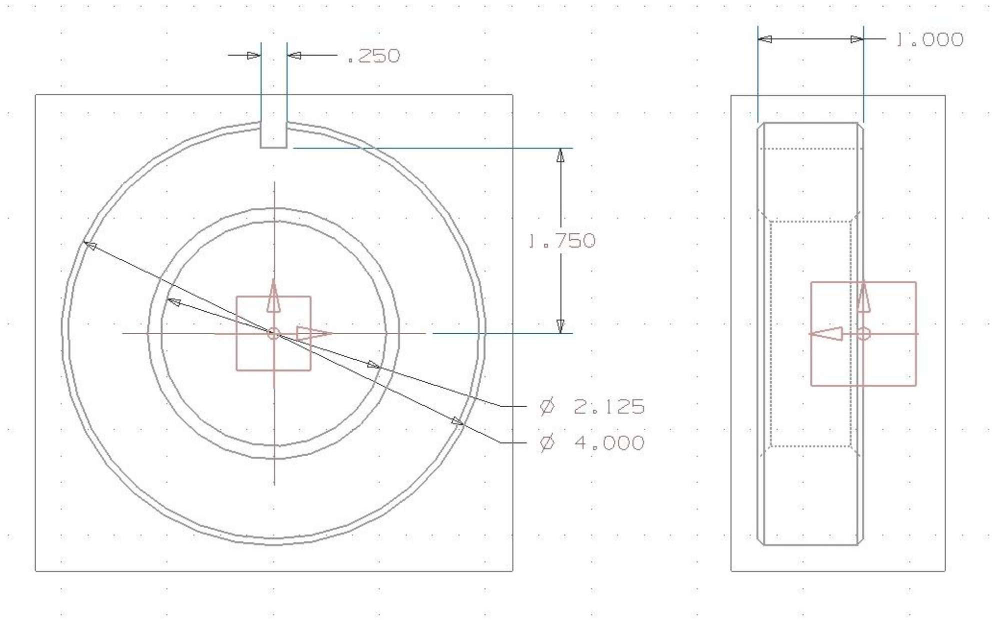


Figure 4: Bushing Dimensions

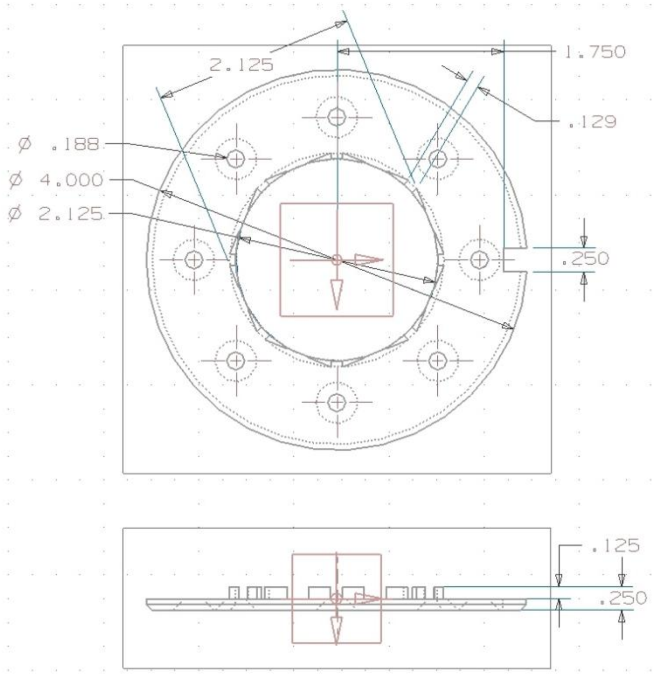


Figure 5: Magnet Array Housing Top Dimensions

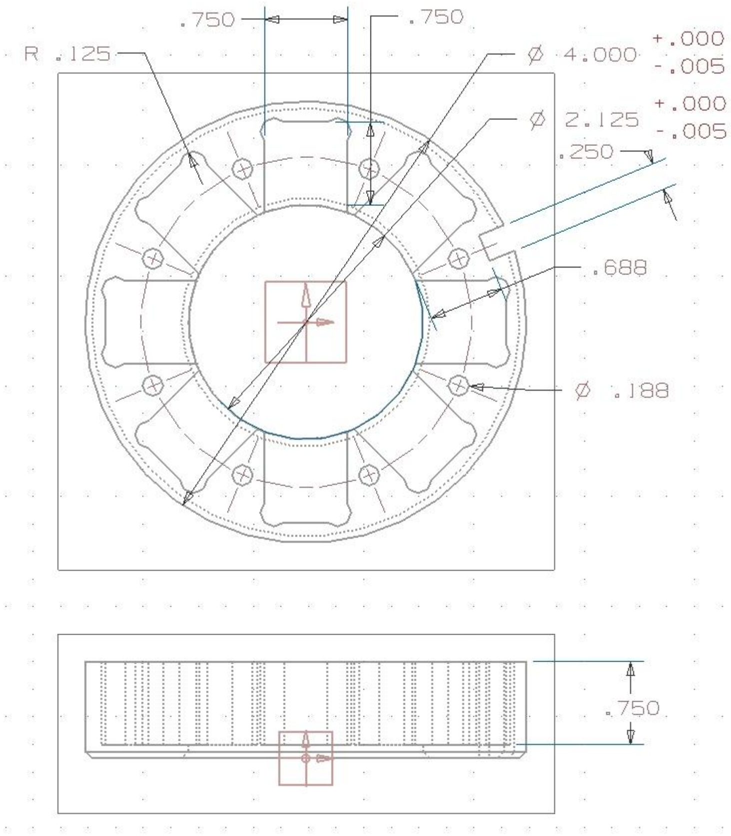


Figure 6: Magnet Array Housing Base Dimensions

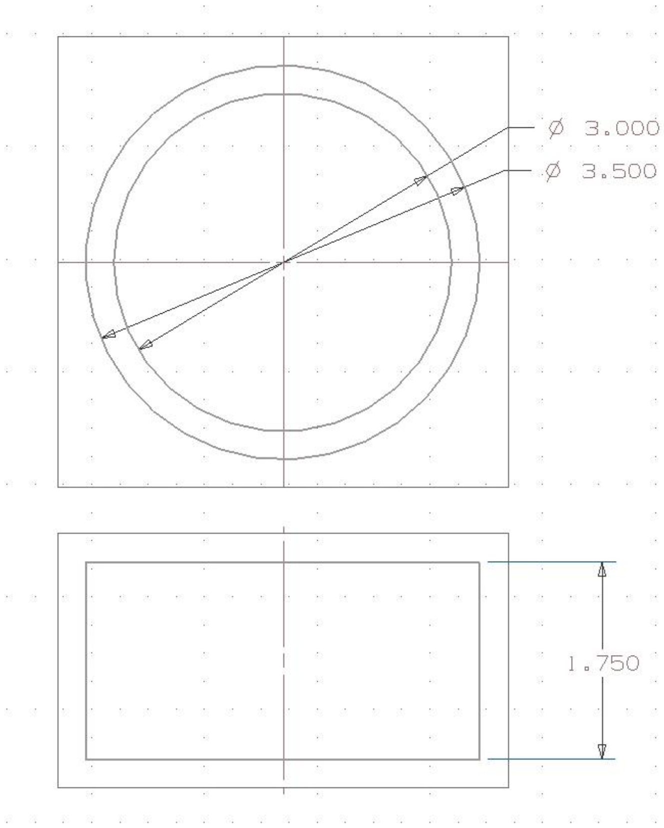


Figure 7: Magnet Array Spacer Dimensions

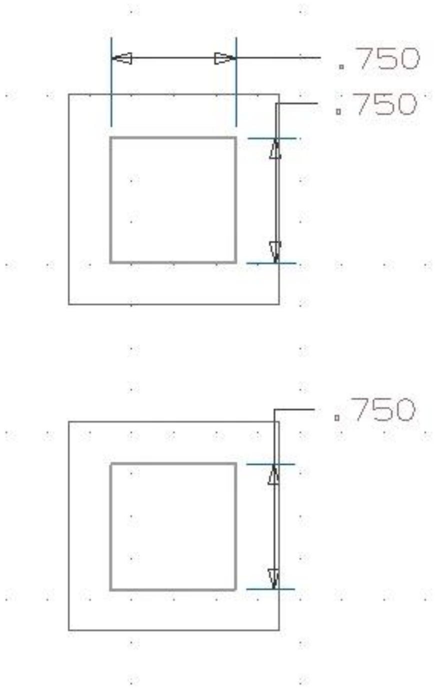


Figure 8: Magnet Dimensions

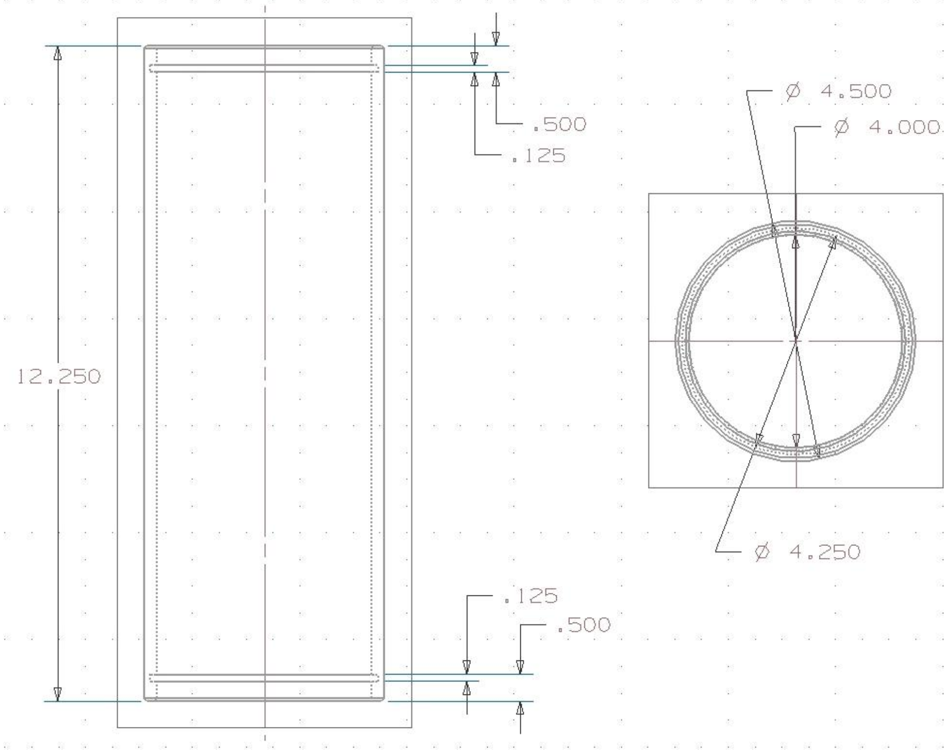


Figure 9: Magnetic Array Collar Dimensions

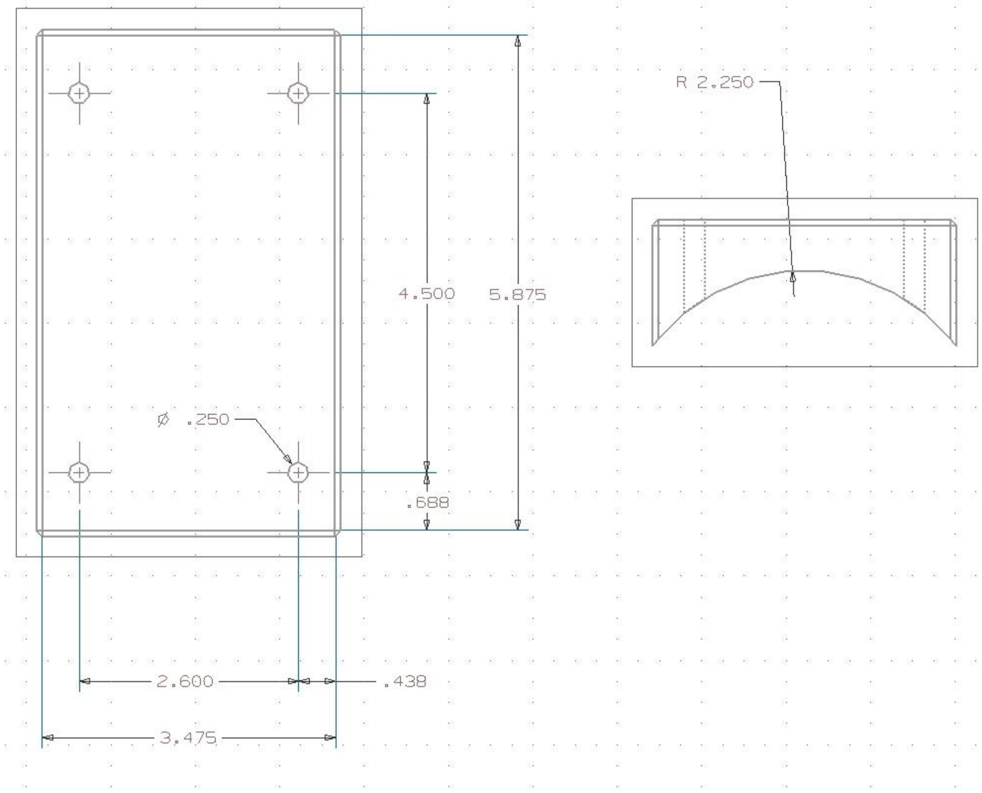


Figure 10: VIV Cylinder Bracket Dimensions

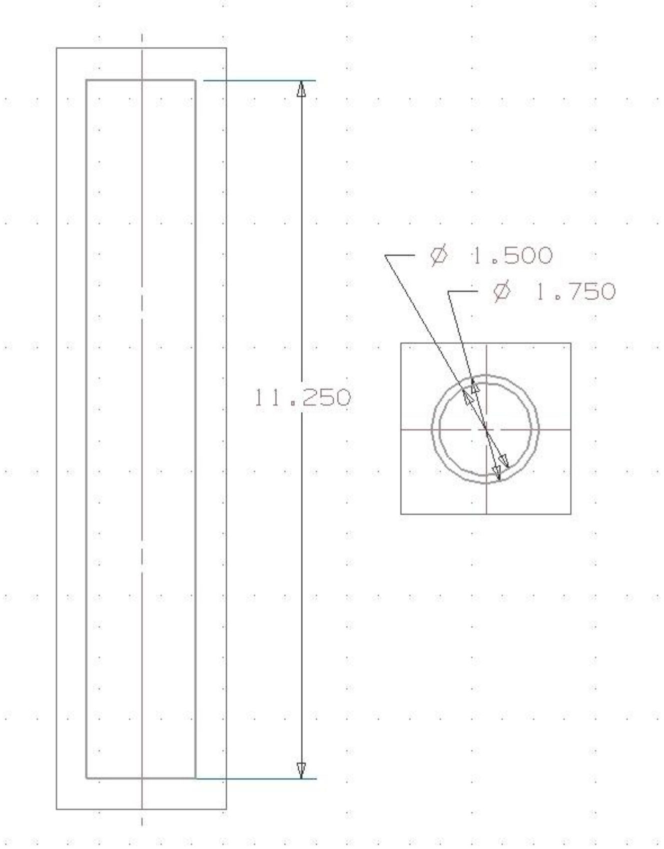


Figure 11: Large Spacer Dimensions

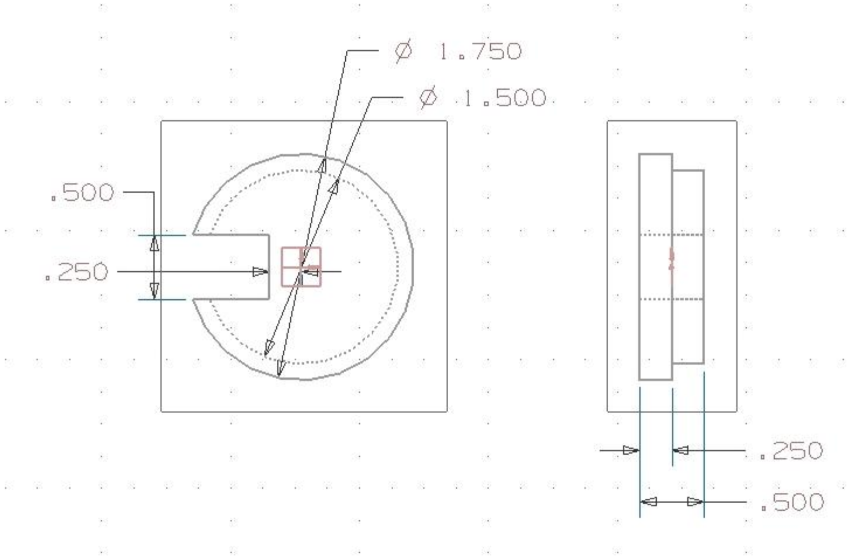


Figure 12: Large Spacer End Cap Dimensions

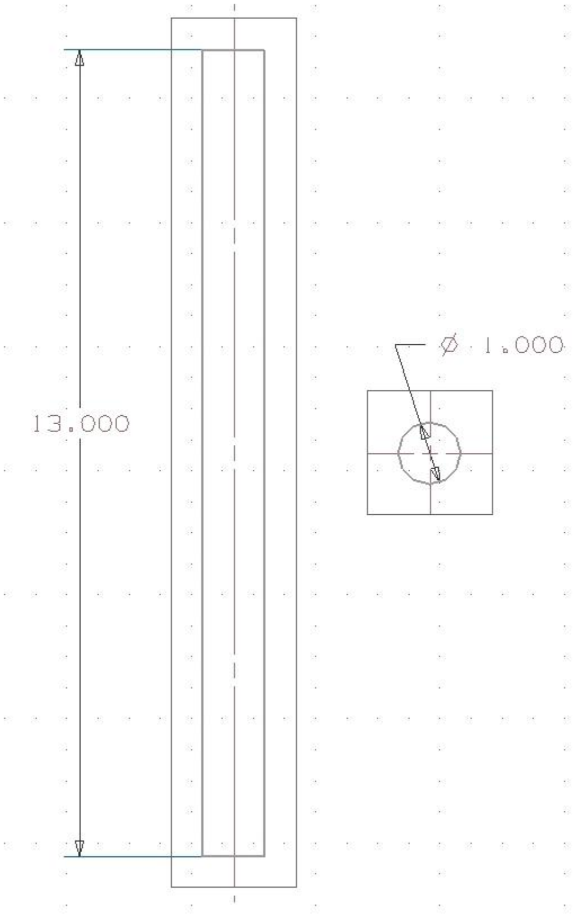


Figure 13: Iron Core Dimensions

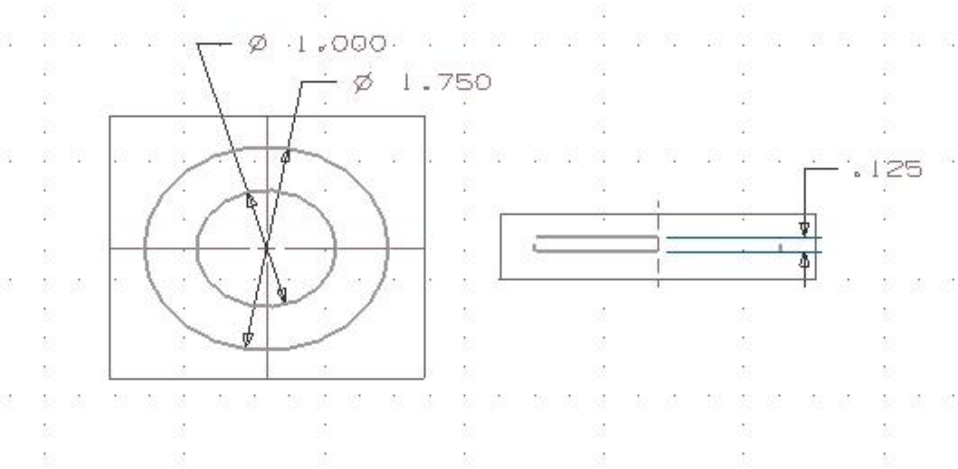


Figure 14: Small Wire Spacer Dimensions

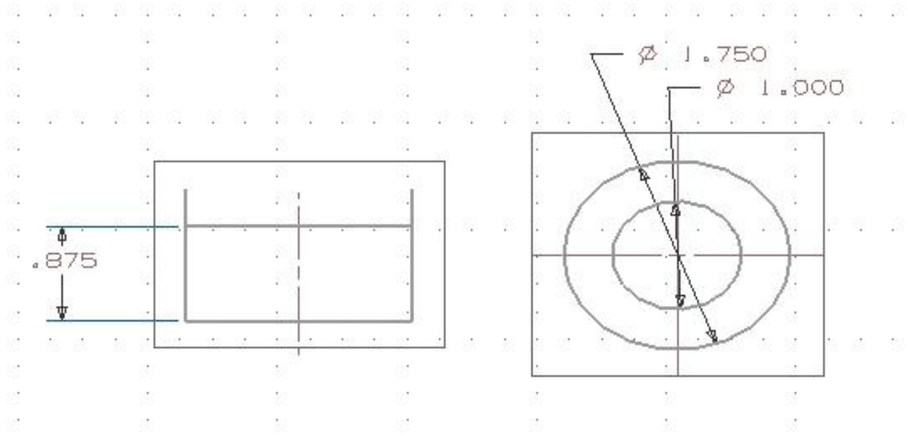
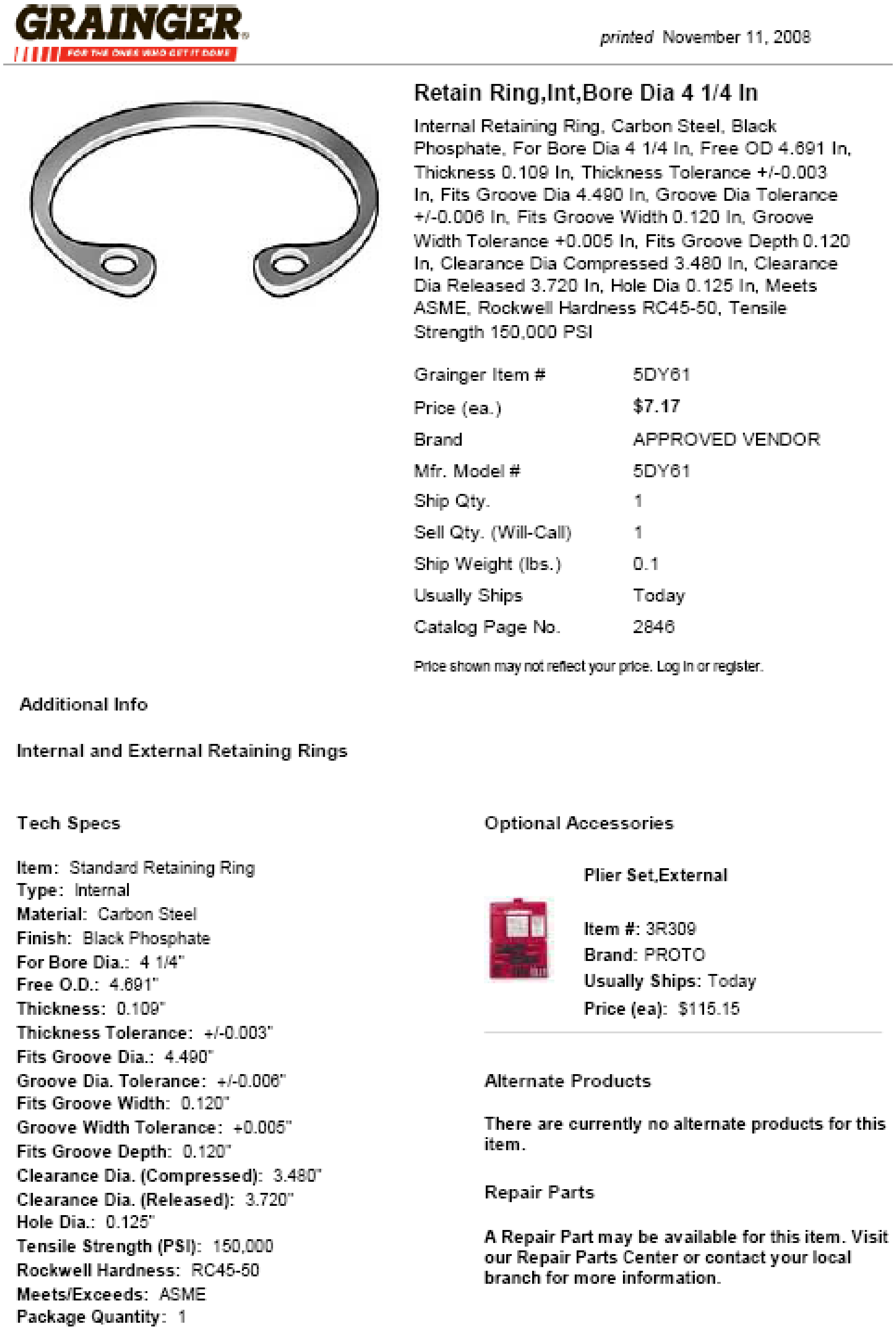


Figure 15: Large Wire Spacer Dimensions

Appendix E: Final Design Material List

Table 1: Materials List for Each Part of the Final Design

Part	Material
Base	6061 Aluminum, Hard anodized
Main Tube	6061 Aluminum, Hard anodized
Bushing	Spec Sheet In Appendix F
Magnetic Array Housing (Top and Bottom)	Cast Nylon
Magnetic Array Spacer	Cast Nylon 6
Magnet	¾” cube N42 grade Neodymium Magnet , Spec Sheet In Appendix F
Key	Cast Nylon 6
Retaining Ring	Powder Coated Carbon Steel, Spec Sheet Below
Magnetic Array Collar	6061 Aluminum, Hard anodized
VIV Cylinder Bracket	6061 Aluminum, Hard anodized
Large Spacer	PETG Polyester
Large Spacer End Cap	Polypropylene
Iron Core	Cast Gray Iron
Wire Spacer	PETG Polyester
Wave Spring	Powder Coated High Carbon Steel, Spec Sheet Below
Electrical Wire	Enamel-Coated Copper, Spec Sheet Below



GRAINGER

FOR THE ONES WHO GET IT DONE

printed November 11, 2008

Retain Ring,Int,Bore Dia 4 1/4 In

Internal Retaining Ring, Carbon Steel, Black Phosphate, For Bore Dia 4 1/4 In, Free OD 4.691 In, Thickness 0.109 In, Thickness Tolerance +/-0.003 In, Fits Groove Dia 4.490 In, Groove Dia Tolerance +/-0.006 In, Fits Groove Width 0.120 In, Groove Width Tolerance +0.005 In, Fits Groove Depth 0.120 In, Clearance Dia Compressed 3.480 In, Clearance Dia Released 3.720 In, Hole Dia 0.125 In, Meets ASME, Rockwell Hardness RC45-50, Tensile Strength 150,000 PSI

Grainger Item #	5DY61
Price (ea.)	**$7.17**
Brand	APPROVED VENDOR
Mfr. Model #	5DY61
Ship Qty.	1
Sell Qty. (Will-Call)	1
Ship Weight (lbs.)	0.1
Usually Ships	Today
Catalog Page No.	2846

Price shown may not reflect your price. Log in or register.

Additional Info

Internal and External Retaining Rings

Tech Specs

Item: Standard Retaining Ring
Type: Internal
Material: Carbon Steel
Finish: Black Phosphate
For Bore Dia.: 4 1/4"
Free O.D.: 4.691"
Thickness: 0.109"
Thickness Tolerance: +/-0.003"
Fits Groove Dia.: 4.490"
Groove Dia. Tolerance: +/-0.006"
Fits Groove Width: 0.120"
Groove Width Tolerance: +0.005"
Fits Groove Depth: 0.120"
Clearance Dia. (Compressed): 3.480"
Clearance Dia. (Released): 3.720"
Hole Dia.: 0.125"
Tensile Strength (PSI): 150,000
Rockwell Hardness: RC45-50
Meets/Exceeds: ASME
Package Quantity: 1

Optional Accessories

Plier Set,External

Item #: 3R309
Brand: PROTO
Usually Ships: Today
Price (ea): $115.15

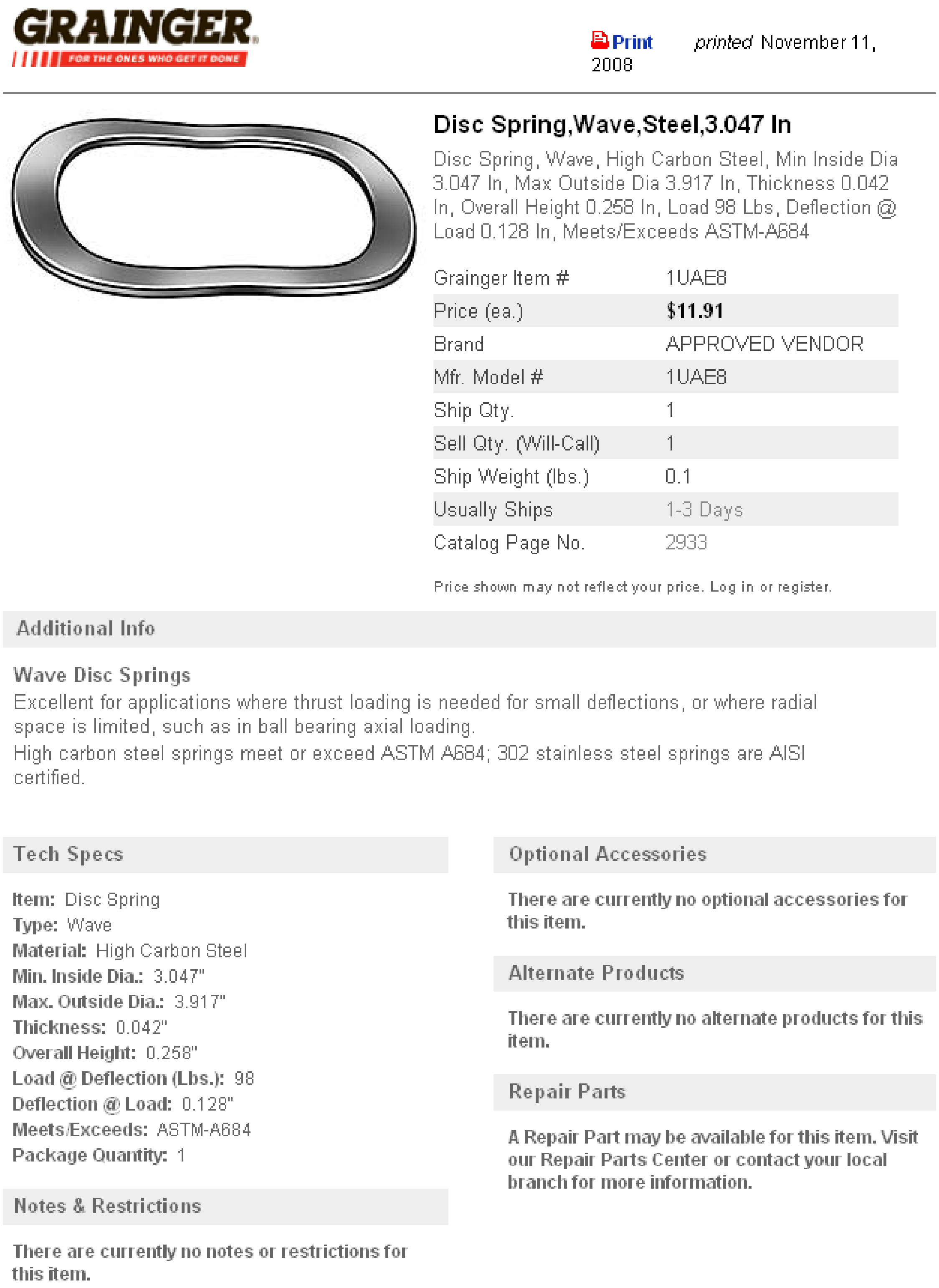
Alternate Products

There are currently no alternate products for this item.

Repair Parts

A Repair Part may be available for this item. Visit our Repair Parts Center or contact your local branch for more information.

Figure 1: Data Sheet on Retaining Ring



GRAINGER
FOR THE ONES WHO GET IT DONE

Print *printed* November 11, 2008

Disc Spring,Wave,Steel,3.047 In

Disc Spring, Wave, High Carbon Steel, Min Inside Dia 3.047 In, Max Outside Dia 3.917 In, Thickness 0.042 In, Overall Height 0.258 In, Load 98 Lbs, Deflection @ Load 0.128 In, Meets/Exceeds ASTM-A684

Grainger Item #	1UAE8
Price (ea.)	**$11.91**
Brand	APPROVED VENDOR
Mfr. Model #	1UAE8
Ship Qty.	1
Sell Qty. (Will-Call)	1
Ship Weight (lbs.)	0.1
Usually Ships	1-3 Days
Catalog Page No.	2933

Price shown may not reflect your price. Log in or register.

Additional Info

Wave Disc Springs
Excellent for applications where thrust loading is needed for small deflections, or where radial space is limited, such as in ball bearing axial loading.
High carbon steel springs meet or exceed ASTM A684; 302 stainless steel springs are AISI certified.

Tech Specs

Item: Disc Spring
Type: Wave
Material: High Carbon Steel
Min. Inside Dia.: 3.047"
Max. Outside Dia.: 3.917"
Thickness: 0.042"
Overall Height: 0.258"
Load @ Deflection (Lbs.): 98
Deflection @ Load: 0.128"
Meets/Exceeds: ASTM-A684
Package Quantity: 1

Notes & Restrictions

There are currently no notes or restrictions for this item.

Optional Accessories

There are currently no optional accessories for this item.

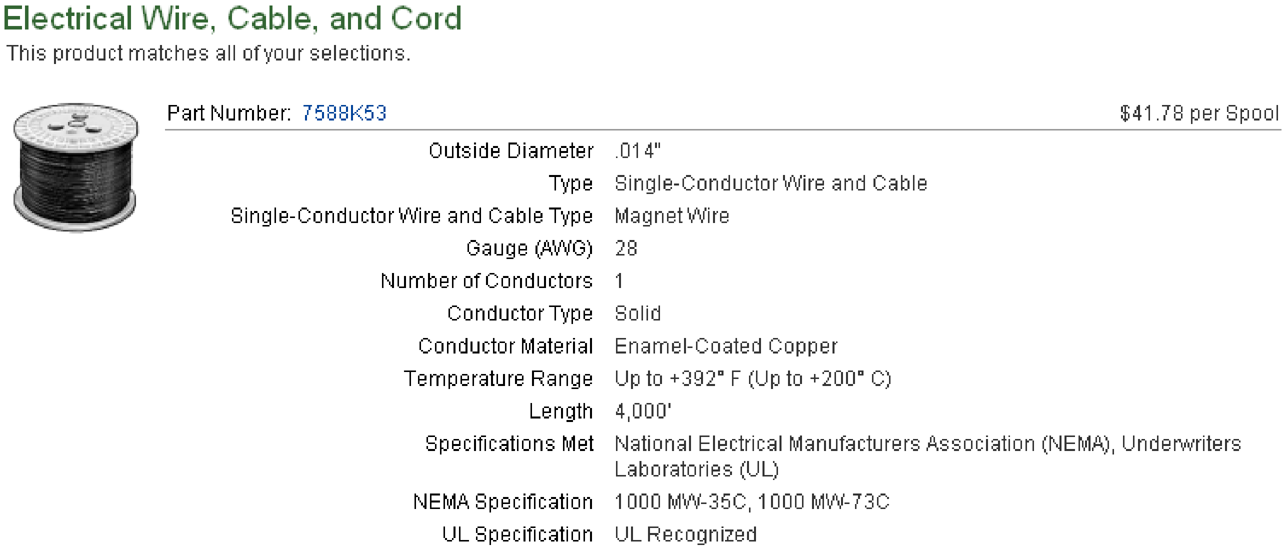
Alternate Products

There are currently no alternate products for this item.

Repair Parts

A Repair Part may be available for this item. Visit our Repair Parts Center or contact your local branch for more information.

Figure 2: Data Sheet on Wave Spring



Electrical Wire, Cable, and Cord

This product matches all of your selections.

Part Number: 7588K53 $41.78 per Spool

Outside Diameter	.014"
Type	Single-Conductor Wire and Cable
Single-Conductor Wire and Cable Type	Magnet Wire
Gauge (AWG)	28
Number of Conductors	1
Conductor Type	Solid
Conductor Material	Enamel-Coated Copper
Temperature Range	Up to +392° F (Up to +200° C)
Length	4,000'
Specifications Met	National Electrical Manufacturers Association (NEMA), Underwriters Laboratories (UL)
NEMA Specification	1000 MW-35C, 1000 MW-73C
UL Specification	UL Recognized

Figure 3: Data Sheet on Electrical Wire

Appendix F: Magnet and Underwater Bearing Information

K&J Magnetics, Inc.

Your Source for the World's Strongest Magnets

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Monday November 10th 2008

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- Custom Magnets

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BCCC

- Dimensions: 3/4" x 3/4" x 3/4" thick
- Tolerances: ±0.002" x ±0.002" x ±0.002"
- Material: NdFeB, Grade N42
- Plating/Coating: Ni-Cu-Ni (Nickel)
- Magnetization Direction: Thru Thickness
- Weight: 1.83 oz. (51.86 g)
- Pull Force: 48.50 lbs
- Surface Field: 5940 Gauss
- Brmax: 13,200 Gauss
- BHmax: 42 MGOe

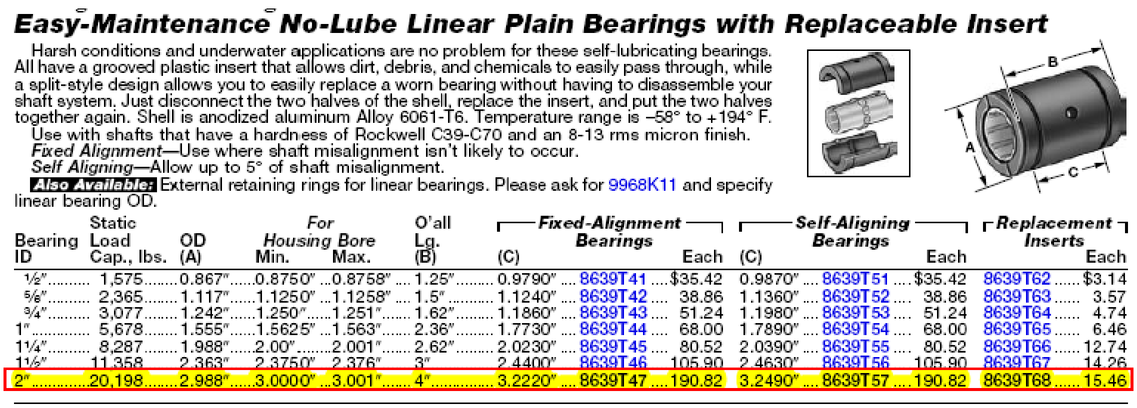
These 3/4" cubes are wicked strong. They are great for holding metal in place for welding. They can also be used as that "extra set of hands" often needed when working with metal. These blocks are incredibly powerful and must be handled with care.

BCCC: 1 for $7.70

Quantity: 1

Add to cart

Figure 1: Magnet Information



Easy-Maintenance No-Lube Linear Plain Bearings with Replaceable Insert

Harsh conditions and underwater applications are no problem for these self-lubricating bearings. All have a grooved plastic insert that allows dirt, debris, and chemicals to easily pass through, while a split-style design allows you to easily replace a worn bearing without having to disassemble your shaft system. Just disconnect the two halves of the shell, replace the insert, and put the two halves together again. Shell is anodized aluminum Alloy 6061-T6. Temperature range is –58° to +194° F.

Use with shafts that have a hardness of Rockwell C39-C70 and an 8-13 rms micron finish.

Fixed Alignment—Use where shaft misalignment isn't likely to occur.

Self Aligning—Allow up to 5° of shaft misalignment.

Also Available: External retaining rings for linear bearings. Please ask for 9968K11 and specify linear bearing OD.

Bearing ID	Static Load Cap., lbs.	OD (A)	*For Housing Bore* Min.	Max.	O'all Lg. (B)	***Fixed-Alignment Bearings*** (C)		Each	***Self-Aligning Bearings*** (C)		Each	***Replacement Inserts***	Each
½"	1,575	0.867"	0.8750"	0.8758"	1.25"	0.9790"	8639T41	$35.42	0.9870"	8639T51	$35.42	8639T62	$3.14
⅝"	2,365	1.117"	1.1250"	1.1258"	1.5"	1.1240"	8639T42	38.86	1.1360"	8639T52	38.86	8639T63	3.57
¾"	3,077	1.242"	1.250"	1.251"	1.62"	1.1860"	8639T43	51.24	1.1980"	8639T53	51.24	8639T64	4.74
1"	5,678	1.555"	1.5625"	1.563"	2.36"	1.7730"	8639T44	68.00	1.7890"	8639T54	68.00	8639T65	6.46
1¼"	8,287	1.988"	2.00"	2.001"	2.62"	2.0230"	8639T45	80.52	2.0390"	8639T55	80.52	8639T66	12.74
1½"	11,358	2.363"	2.3750"	2.376"	3"	2.4400"	8639T46	105.90	2.4630"	8639T56	105.90	8639T67	14.26
2"	20,198	2.988"	3.0000"	3.001"	4"	3.2220"	8639T47	190.82	3.2490"	8639T57	190.82	8639T68	15.46

Figure 2: Bearing Information

Appendix G: Extreme Adhesive 300 Information

GET IT TOGETHER.™
EXTREME
ADHESIVES™

Extreme 300

High Peel \ High Impact Metal \ Plastics Bonder

Product Description

Extreme 300 is a medium viscosity, **solvent-free** structural adhesive system that provides flexibility, toughness and surface adhesion for bonding plastics and metals in any combination. Cured performance shows excellent adhesion and bond strength to nylons, polystyrenes, fiberglass, reinforced plastics, stone, ceramics and most plain and plated metal components. This material can withstand thermal cycling and shock loading between dissimilar materials.

Although it is always best to clean and prepare most bonded surfaces for improved adhesion. ***Extreme 300*** will work successfully in many applications **without preparation.**

Extreme 300 is moderate cure speed, two-component product with an open time of 5-6 minutes at 72º F after thorough mixing. For a longer open time consider product number ***Extreme 310.***

Why You Should Select this Adhesive

- Toughness and Durability
- Excellent Adhesion to Plastics and Metals
- Impact Resistance
- Peel Strength
- 100% Reactive Solids Formulation for VOC Compliance and Safety
- Fast Cure Speed and Excellent Gap Cure

Contact an ***EXTREME ADHESIVES***® Adhesive Applications Specialist for further recommendations on adhesive selection.

Physical Properties

Typical Uncured Properties (liquid)

	Part A	Part B	Mixed A+B
Color	Off White	Off White	Amber
Mix Ratio by volume	1	1	
Mix Ratio by weight	1.05	1	
Viscosity	100,000	120,000	
Density, grams/ml	1.02	0.94	0.98
Unit weight, lb/gallon	8.49	7.83	8.17

Typical Cured Properties (solid)

Tensile strength psi (mpa)	2,500-3,300 (27-34)
Maximum Tensile Elongation (%)	>80
Modulus psi (mpa)	70,000-80,000 (965-1172)
Lap Shear strength psi (mpa)	2,800-3,500 (24-27)
Service Temperature, °F (°C)	-67 to 250 (-55 to 121)
Working time (minutes)	5
Fixture time (minutes)	<15

Instructions for Use

Combine resin and activator in equal volume and mix thoroughly. For convenience and accuracy use pre-measured cartridges with disposable static mixers.

Shelf Life

Shelf Life is at least 6 months when properly stored in an unopened original container in a cool, dark area at least 55°F to 75°F.

EXTREME ADHESIVES, INC. • 15 BATCHELDER ROAD • PO BOX 2449 • SEABROOK, NH 03874
TEL: 603-474-3070 • TOLL FREE: 800-888-GLUE • FAX: 603-474-2750 • WWW.EXTREMEADHESIVES.COM

Appendix H: ANSYS Model

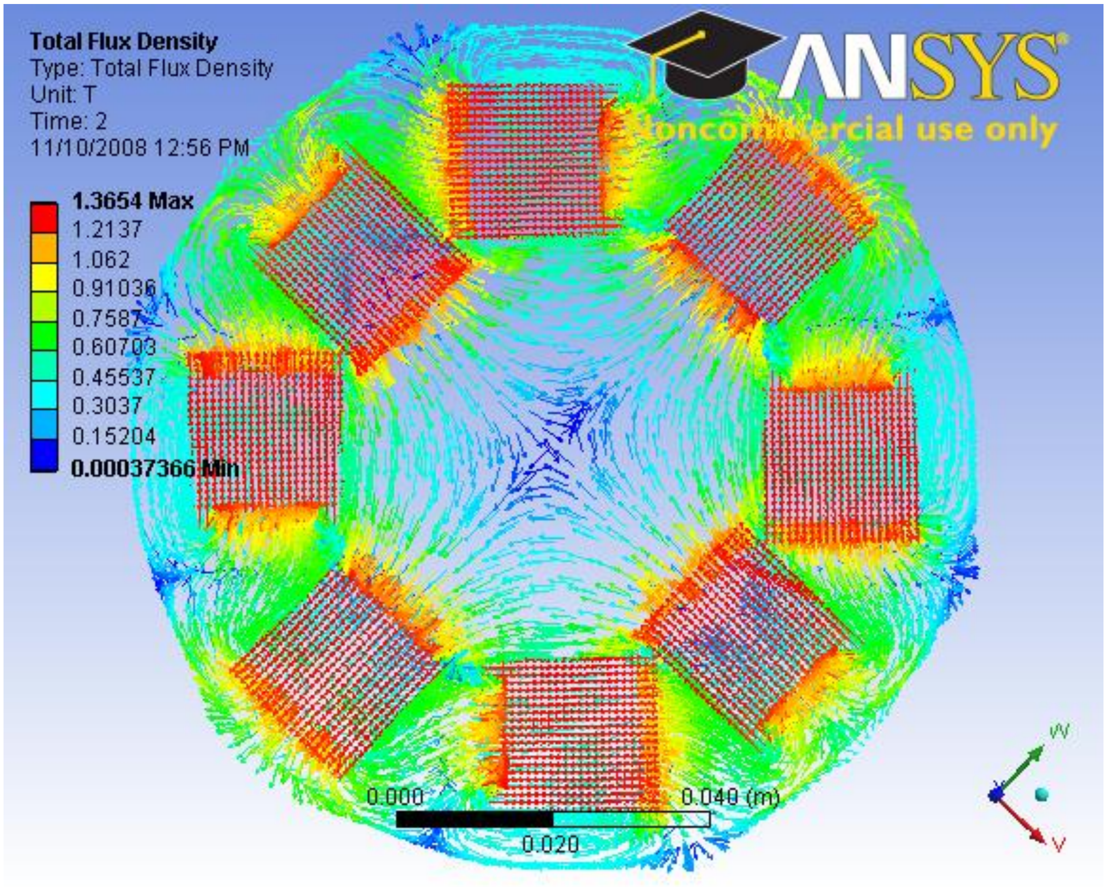


Figure 1: Resulting vector field of magnetic flux simulation in ANSYS

Appendix I: Description of engineering changes since design review #3

There were no major changes to our design and what we set out to build after design review #3. One small change was the number and the size of coil windings. In our design we had 40 small windings each being 0.25 inches wide, however in the creation of the prototype we realized that would have been time consuming and unnecessary for prototyping purposes. We then decided to make 7 windings each being 1.5 inches wide along the iron core. This is the only difference we have between our design and our final prototype.

Appendix J: Design Analysis

Material Selection

For the final design to be installed in sea and river beds across the world, we used GRANTA's Cambridge Engineering Selector (CES) material selection software to determine what material would be best for the main tube (for part names refer to Appendix D). The main goal of our linear generator is to induce the greatest EMF in the copper coil windings and thereby store the most energy. The amount of EMF's induced depends on the change in magnetic flux as the coils pass through magnetic field. In order to have the greatest amount of magnetic flux possible, we need the magnetic field to be as strong as possible. In order to preserve the magnetic field coming off the face of the magnets it is important for the main tube should be made up of mostly iron so that it permits the magnetic field to move through it easily.

Other important criteria are high abrasion resistance because the magnet array assembly will be moving up and down along the cylinder millions of times. The main tube should also be made of a non-ferrous material because we don't want the main tube's material to affect the magnetic field of the magnets passing over the coils of wire. In the end, it is also important to do all this at the lowest cost possible. Entering CES with the criterion above we can produce several graphs which show the best materials for our application. Abrasion resistance is a function of the materials ability to withstand shear stress and scratches.

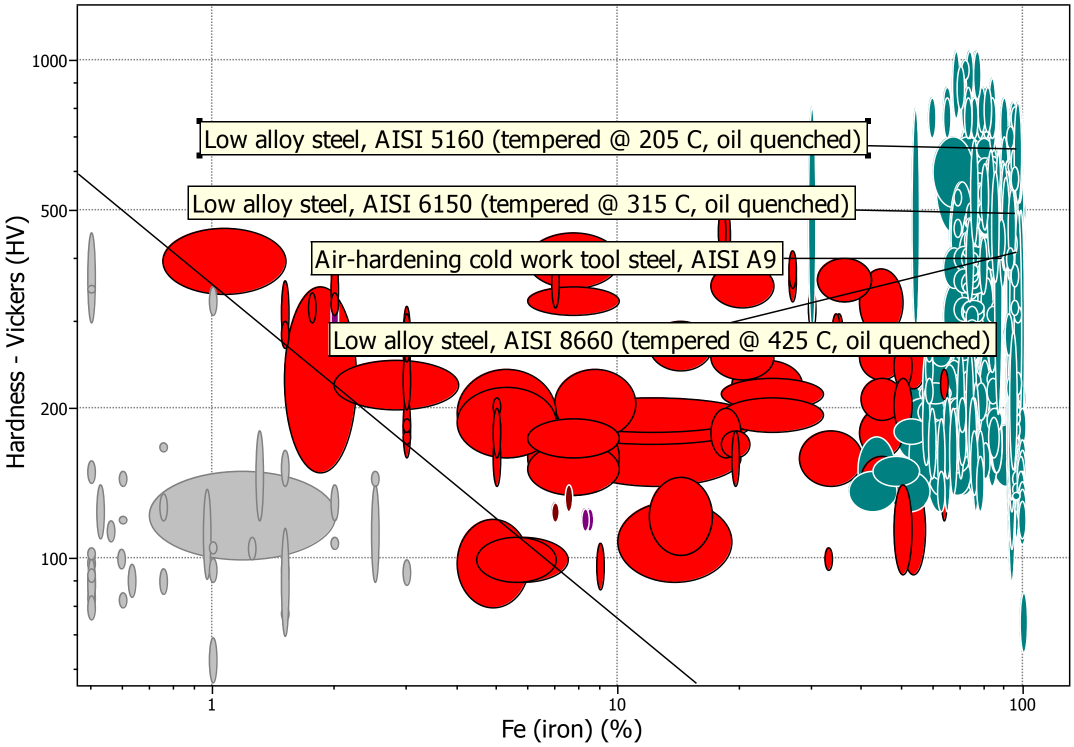


Figure 1: Many steels have high hardness and iron percentage

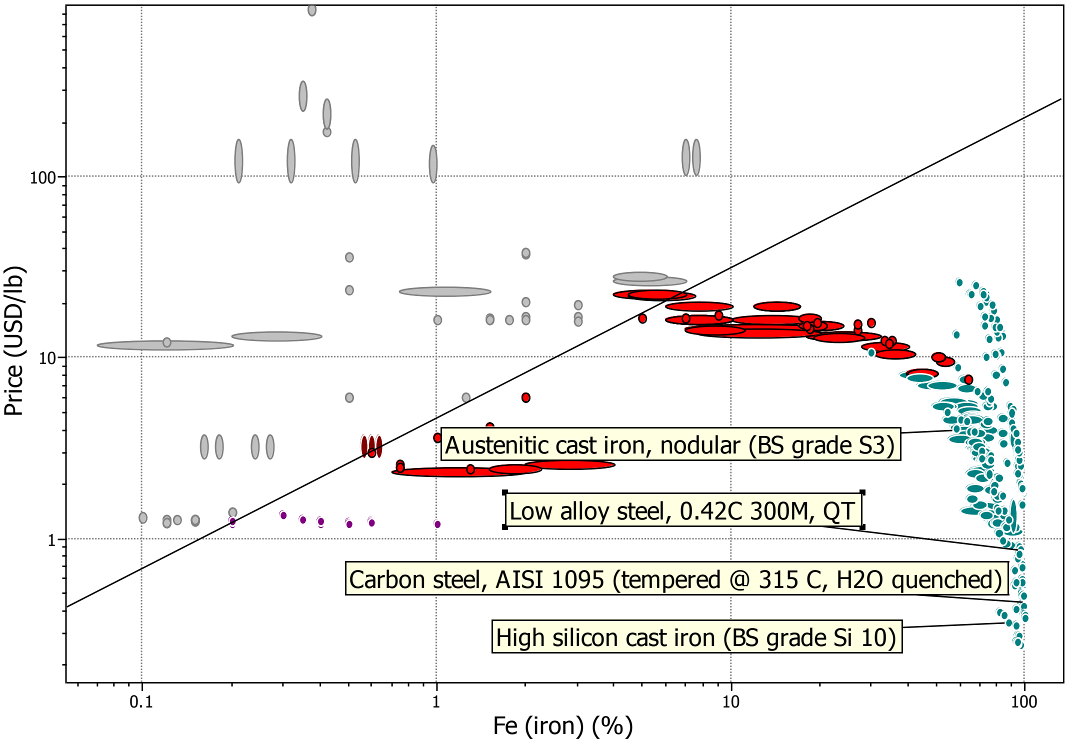


Figure 2: Large range of steel prices

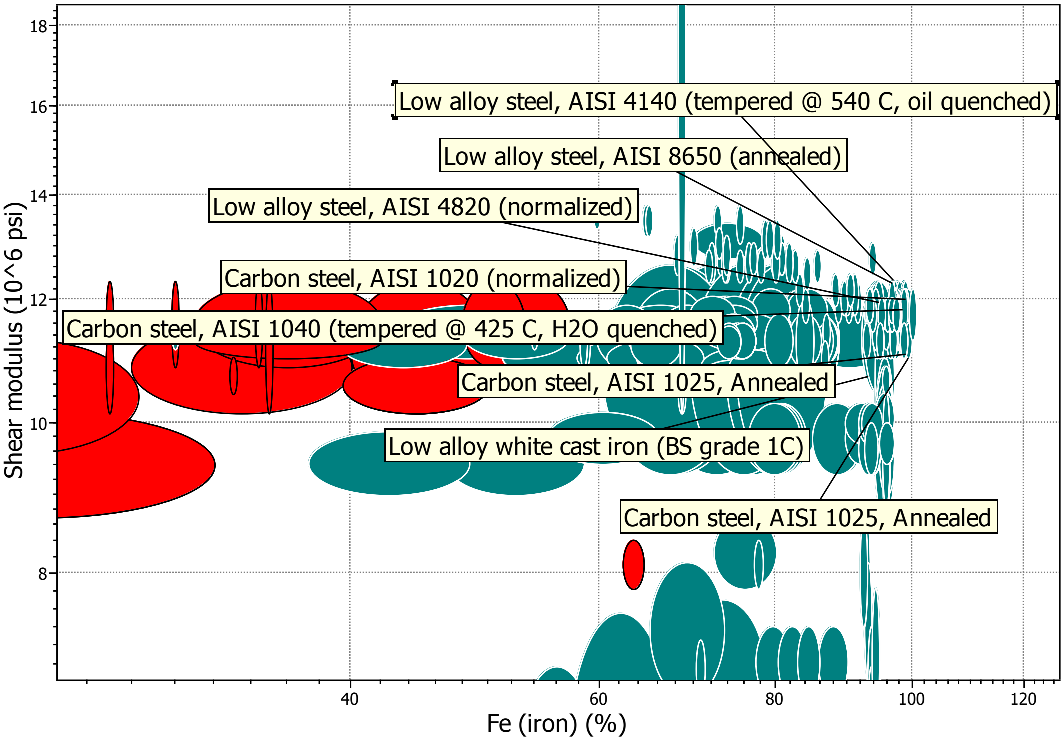


Figure 3: Many steels with high shear modulus

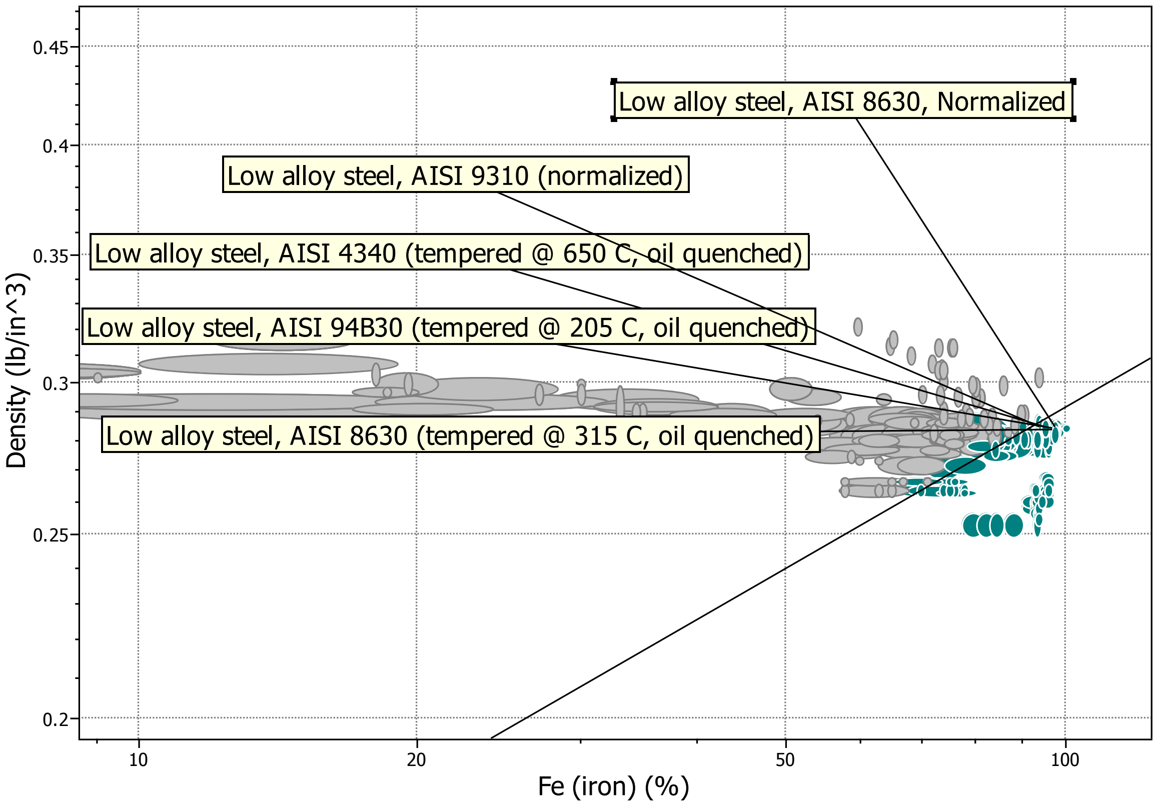


Figure 4: Low alloy steel has good properties in all our areas of concern

There are many choices to take, as indicated by all the circles, and there is no clear choice as to a single material that would work best for our application. After studying all the graphs, it appears low alloy steel would work best because it would be made of mostly iron, have a good shear modulus, high hardness, and be relatively inexpensive.

Because our final design will be in a marine environment, resistance to corrosion and oxidation are important criterion for the main tube's material. Iron is one of the main elements of rust, so to guard against this the main tube we would want to galvanized steel.

Design for environmental sustainability

The materials that will be chosen for the production model based on our prototype will almost likely vary from the almost all plastic construction we used. Considering the case of the cylinder that holds the magnetic arrays, the prototype used Cast Nylon 6. We have decided to compare this Nylon with a good substitute for the cylinder housing; wrought aluminum alloy.

AlCuMg1 (2017) : Wrought Al alloys represent about 85% of all Aluminum applications. Compared to steel, both density and Young's modulus of Al are a factor 3 lower. Precipitation hardening can bring the strength in the range of carbon steels; dependent on alloy type, but precipitation hardened alloys can show drawbacks in corrosion resistance, formability and weldability. Generally, corrosion resistance is good, especially for pure Al and Al-Mg alloys, as a result of a closed protective oxide layer. The crystal structure of Al is FCC, which offers a good (cold) formability. The structure of wrought alloys offers better mechanical properties than cast alloys, caused by anisotropy (SimaPro 7).

Cast Nylon 6 : Nylon 6 is a semi-crystalline polymide. Its fibers are tough possessing a high tensile strength. It is highly resistant to abrasion and chemicals such as acids and alkalis.

The mass used to compare and calculate each materials impact was based on their respective densities and using a volume of 1 m^3, thus giving AlCuMg = 2.7kg and Nylon 6 = 1.148 kg.

The software used to compare these materials was SimaPro 7. Figure 1 below is a graph of the data produced by SimaPro and shows that Aluminum would require more raw materials to produce, but Nylon produces more water emissions or pollutants. Figures 6-8 show the relative impacts in disaggregated damage categories, normalization plot and single score comparisons. As you can see from the plots the choice to use Aluminum alloy for not only the cylinder housing, but for many other parts for the linear generator would result in a greater impact on the environment.

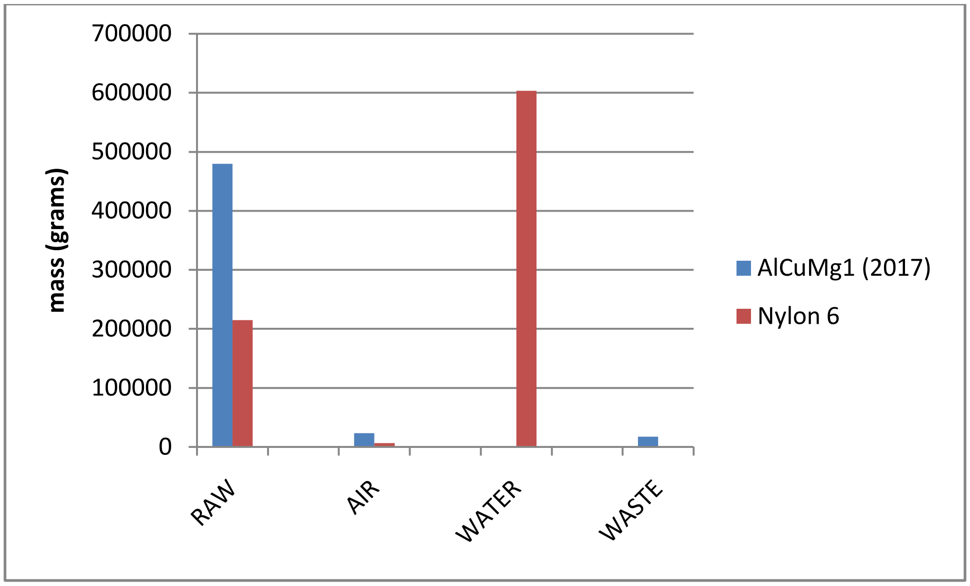


Figure 5: Comparing total mass use of raw materials, air emissions, water emissions and solid waste from the creation of 1.148kg Nylon 6 and 2.7kgAlCuMg (2017).

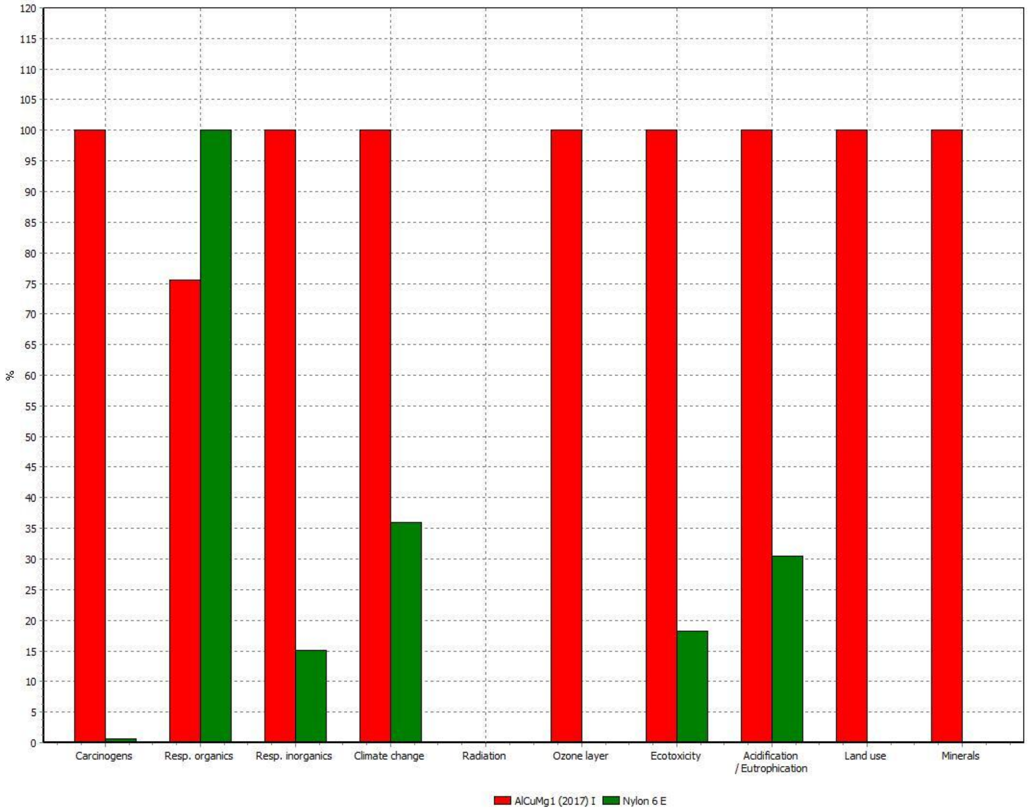


Figure 6: Comparing 2.7kg AlCuMg (2017) with 1.148kg of Nylon 6: Method indicator 99 (I) V2.02 / Europe EI 99 I/I/characterization

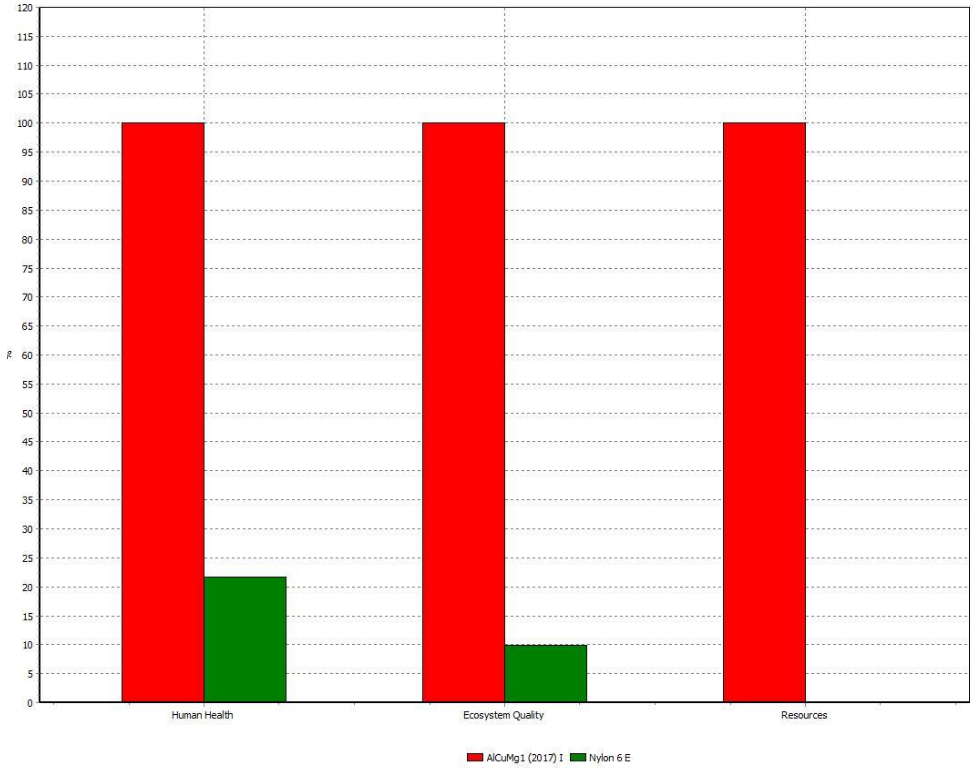


Figure 7: Comparing 2.7kg AlCuMg (2017) with 1.148kg of Nylon 6: Method indicator 99 (I) V2.02 / Europe EI 99 I/I/ damage assessment

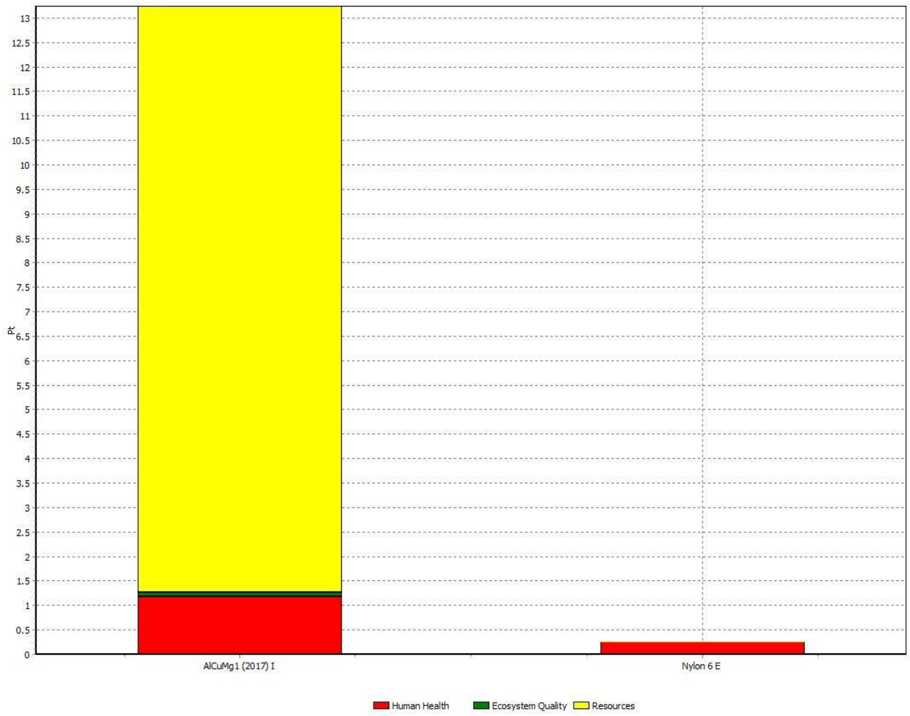


Figure 8: Comparing 2.7kg AlCuMg (2017) with 1.148kg of Nylon 6: Method indicator 99 (I) V2.02 / Europe EI 99 I/I/single score

In additional environmental impact to consider are the electricity and magnetism effects on marine life. One interesting aspect about the Halbach array arrangement of magnets is that the magnetic force is almost all directed to the center of the tubing, thus almost no magnetic field is around the outside of the cylinder (Appendix H figure 1). This is a favorable side-effect because we don't know how the field would affect marine life around it.

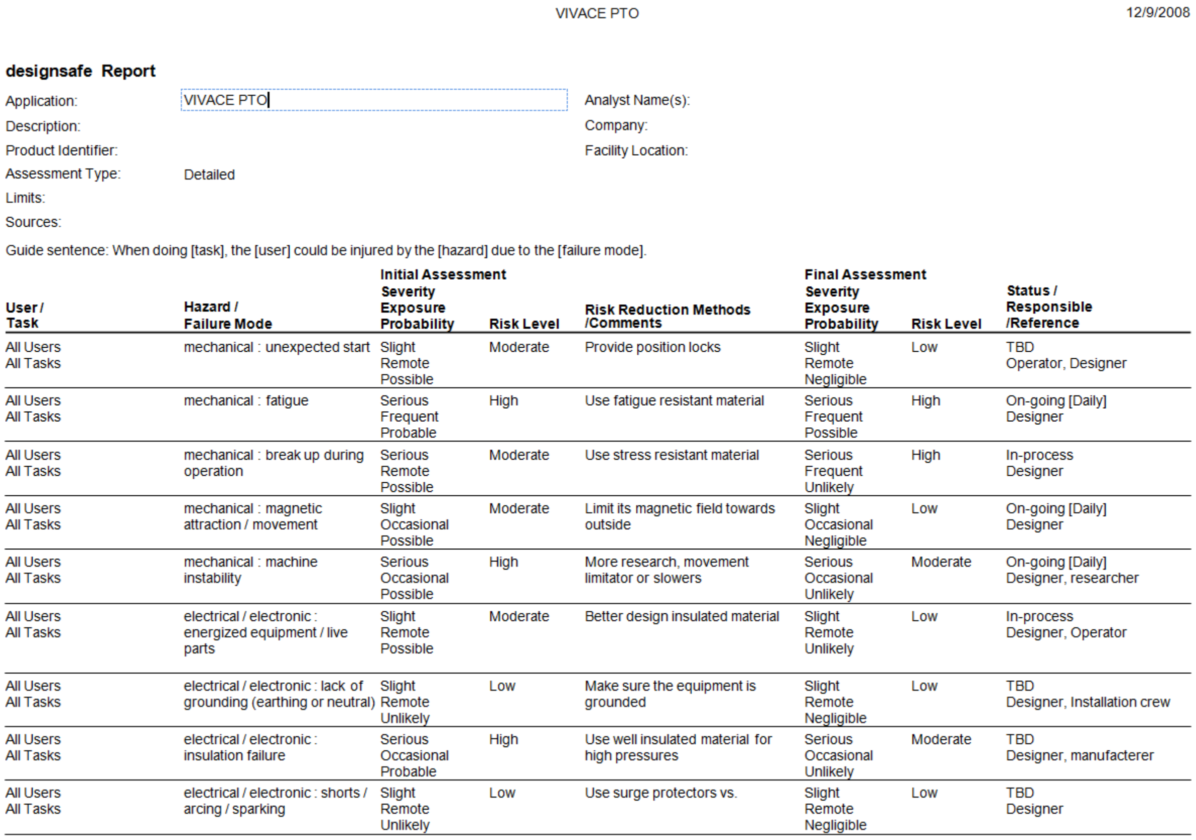
Design for safety

We have made an FMEA analysis using the Designsafe 3 software. The report created by the software is included in this appendix (figure 9-10). This report shows the possible failure that can occur and possible ways to reduce its risk. Most of the failure risk could be reduced to low or moderate, but some stayed at high risk levels. The High risk levels were fatigue, break up during operation and deep water pressure.

Break up during operation is mainly due to fatigue. VIVACE would be cycling up and down at all times due to the vortex shedding forces acting on the cylinders. These forces also would be changing in sign and amplitude. VIVACE's operation can approach high frequencies and due to the changing stresses on the equipment fatigue will probably be one of the main issues for any break up. To minimize the effect of fatigue and break up a high fatigue resistant material should be used.

Deep water pressure stayed as a high risk as well because VIVACE will be implemented underwater sometimes in deep water. Since a PTO has little wiring water leaks would always be an issue. In addition to water pressure, VIVACE is always moving and under constant fatigue stress, these factors increase the possibility of having a leak. To minimize water leaks proper sealing should be used. Also these seals should be able to work properly under constant stress and strain conditions.

We believe that these three factors; fatigue, break up during operation and deep water pressure, are high risk possible failures and they should be addressed in.



VIVACE PTO 12/9/2008

designsafe Report

Application:	VIVACE PTO	Analyst Name(s):	
Description:		Company:	
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	mechanical : unexpected start	Slight Remote Possible	Moderate	Provide position locks	Slight Remote Negligible	Low	TBD Operator, Designer
All Users All Tasks	mechanical : fatigue	Serious Frequent Probable	High	Use fatigue resistant material	Serious Frequent Possible	High	On-going [Daily] Designer
All Users All Tasks	mechanical : break up during operation	Serious Remote Possible	Moderate	Use stress resistant material	Serious Frequent Unlikely	High	In-process Designer
All Users All Tasks	mechanical : magnetic attraction / movement	Slight Occasional Possible	Moderate	Limit its magnetic field towards outside	Slight Occasional Negligible	Low	On-going [Daily] Designer
All Users All Tasks	mechanical : machine instability	Serious Occasional Possible	High	More research, movement limitator or slowers	Serious Occasional Unlikely	Moderate	On-going [Daily] Designer, researcher
All Users All Tasks	electrical / electronic : energized equipment / live parts	Slight Remote Possible	Moderate	Better design insulated material	Slight Remote Unlikely	Low	In-process Designer, Operator
All Users All Tasks	electrical / electronic : lack of grounding (earthing or neutral)	Slight Remote Unlikely	Low	Make sure the equipment is grounded	Slight Remote Negligible	Low	TBD Designer, Installation crew
All Users All Tasks	electrical / electronic : insulation failure	Serious Occasional Probable	High	Use well insulated material for high pressures	Serious Occasional Unlikely	Moderate	TBD Designer, manufacterer
All Users All Tasks	electrical / electronic : shorts / arcing / sparking	Slight Remote Unlikely	Low	Use surge protectors vs.	Slight Remote Negligible	Low	TBD Designer

Figure 9: Design safe chart (1)

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	electrical / electronic : improper wiring	Slight Remote Possible	Moderate	Better design + double check	Slight Remote Negligible	Low	TBD Designer, manufacterer, installation crew
All Users All Tasks	electrical / electronic : overloading	Slight Occasional Possible	Moderate	Movement and load limitators	Slight Occasional Negligible	Low	TBD Designer
All Users All Tasks	electrical / electronic : water / wet locations	Serious Frequent Probable	High	High pressure water proofing	Serious Frequent Unlikely	High	In-process Designer, manufacterer
All Users All Tasks	electrical / electronic : unexpected start up / motion	Slight Occasional Possible	Moderate	Provide position locks	Slight Occasional Negligible	Low	TBD Designer, operator
All Users All Tasks	electrical / electronic : overvoltage /overcurrent	Serious Occasional Probable	High	Implement current/voltage limitators	Serious Occasional Unlikely	Moderate	TBD Designer
All Users All Tasks	electrical / electronic : electromagnetic susceptibility	Slight Occasional Possible	Moderate	Minimize its electromagnetic effects towards outside	Slight Occasional Negligible	Low	TBD Designer
All Users All Tasks	ergonomics / human factors : human errors / behaviors	Serious Occasional Probable	High	Double check all the work, get qualified personal for installation	Serious Remote Possible	Moderate	TBD Installation Crew
All Users All Tasks	ergonomics / human factors : deviations from safe work practices	Serious Occasional Possible	High	Provide safety distances, and equipment for installation	Serious Remote Unlikely	Moderate	TBD Installation crew
All Users All Tasks	noise / vibration : equipment damage	Serious Occasional Unlikely	Moderate	Double check the installation plan and think about possible problems that might occur	Serious Remote Unlikely	Moderate	TBD Installation Crew
All Users All Tasks	ingress / egress : inadequate means of evacuation	Serious Remote Unlikely	Moderate	Provide safety routes and openings during installation	Serious Remote Unlikely	Moderate	TBD Installation Crew
All Users All Tasks	None / Other : Deep Water Pressure	Serious Frequent Probable	High	Provide high pressure insulation and water proofing for the equipment	Serious Frequent Unlikely	High	In-process Designer, manufacterer

Figure 10: Design safe chart (2)