Final Report
Design of a Power Take Off System for the VIVACE Generator

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Section 3: Professor Hulbert

Team 10: Jeff Bondalapati, Kevin Crimmins,
Quang Nguyen, Kevin Wolf, and Zhili Zuo

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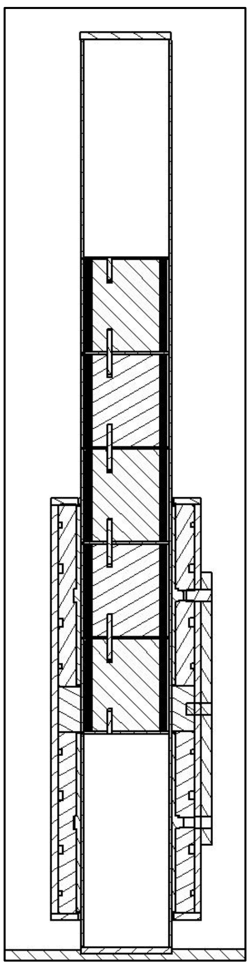
EXECUTIVE SUMMARY

The VIVACE Converter, which is invented by Professor Michael M. Bernitsas of the University of Michigan, converts ocean/river hydrokinetic energy to electricity by Vortex Induced Vibration (VIV). The overall objective of this project is to design and build a Power Take Off (PTO) system for a VIVACE Converter. This system will be comprised of four sub-functions. First it must convert the oscillatory motion of the VIVACE into motion that is usable for energy conversion. Second it must convert the kinetic energy into electrical energy. Third it must be able to transmit the electrical energy so that it can be used. Finally it must seal electrical equipment in a dry environment.

The PTO must reconcile the desired characteristics of being cost competitive, easy to maintain, environmentally friendly, modular, scalable, able to seal wet and dry components, and stackable with the need for a large generating capacity, small volume, and long design life. The PTO system must have power output of greater than 1 Watt with an efficiency of greater than 0.50. The entire system must fit within 4’x2’x2’ constraint. The systems design life must exceed 10 years.

After breaking down the PTO into its major functions, we developed different concepts for each component. We met with Professor Bernitsas, who offered advice for our design. Once we had a sufficient number of possible designs, we chose our final design using Pugh charts. However, Professor Bernitsas later informed us of a change to the VIVACE system which altered our design to as it stands now.



Our final design will use the VIV oscillations to pass a neodymium magnet over coiled wire segments to produce electrical current through induction. An iron rod will be inserted into the coils to increase the magnetic field strength and the output power. The coiled wire will be housed in a non-corrosive PVC tube sealed at each end. The magnet and two linear bearings will be housed in a second PVC tube connected to the VIVACE cylinder. PVC was chosen because it is non-corrosive and strong enough to withstand the pressure of the water environment, and it is a non-conductive, non-magnetic material.

We have developed a manufacturing process for our design which has been refined so that it is financially viable. In this process, the housings are made through injection molding, the spacers are die-cast from aluminum, and it is all assembled with a water tight adhesive sealant.

A prototype was made as a proof of concept, which it displayed in tests. However, it also brought to light some unexpected problems with the final design. The wire was too fragile, the magnet’s field size was too big, and we found that we could have refined the size of the iron core to better suit the power of the VIV motion.

Through validation testing, the prototype power output was found to be of 0.04 W. While this result yields an output power substantially less than desired by the customer, the overall efficiency of the PTO will yield a system capable of achieving such goals when scaled up. The results of the prototype fabrication and final design generation prompt further research in the PTO system.

INTRODUCTION

Water is the world's largest energy storage medium. Marine energy, which is clean, renewable, abundant and available worldwide, comes in five forms: currents, waves, tides, thermal gradient, and salinity gradient. [1] To extract the water energy, various devices such as watermills, tidal dams, and turbines have been made over the past hundreds of years. Recently Professor Michael M. Bernitsas and his group at the University of Michigan Marine Renewable Energy Lab have come up with a new idea to extract water energy. They built six working models of the VIVACE (Vortex Induced Vibration for Aquatic Clean Energy) Converter. The converter generates clean hydrokinetic energy from slow-moving water currents, taking advantage of the natural instability phenomenon of Vortex Induced Vibrations (VIV).

Vortex Induced Vibration (VIV) is the resultant phenomena occurring when a current flows over a stationary object. During this process, vortices form and shed on the downstream side of bluff bodies in a current as shown in Figure 1. Vortex shedding alternates from one side to the other, thereby inducing oscillation or vibration of a body in an up and down motion. Vortex Induced Vibration (VIV) usually occurs in many engineering situations, such as bridges, stacks, transmission lines, offshore structures, buoyancy and spar hulls, and other hydrodynamic and hydroacoustic applications [2]. Since Leonardo da Vinci first observed VIV in 1504AD, engineers have always been seeking to suppress VIV because it causes large motions leading to structural fatigue and failure. The VIVACE Converter, however, is designed to do the opposite: (a) maximize rather than suppress VIV and (b) harness rather than mitigate VIV energy. [3]

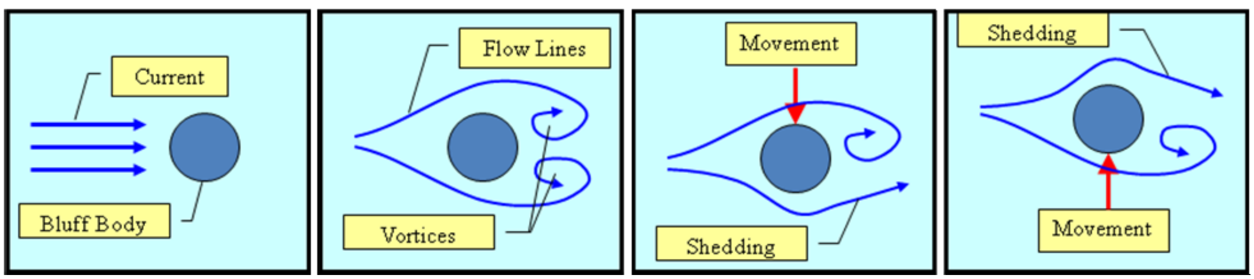


Figure 1: Vortex Induced Vibration oscillates objects in fluid current. [4]

The elements of a single module of the VIVACE Converter are: a circular rigid cylinder, two supporting linear springs, one or more generators, and one transmission mechanism [3]. A prototype of the VIVACE Converter module has been built, which operates in the University of Michigan Low-Turbulence Free Surface Water (LTFSW) Channel. A computer 3D model of the prototype is shown in Figure 2. Properties of the prototype as part of the final design are shown in Appendix A.

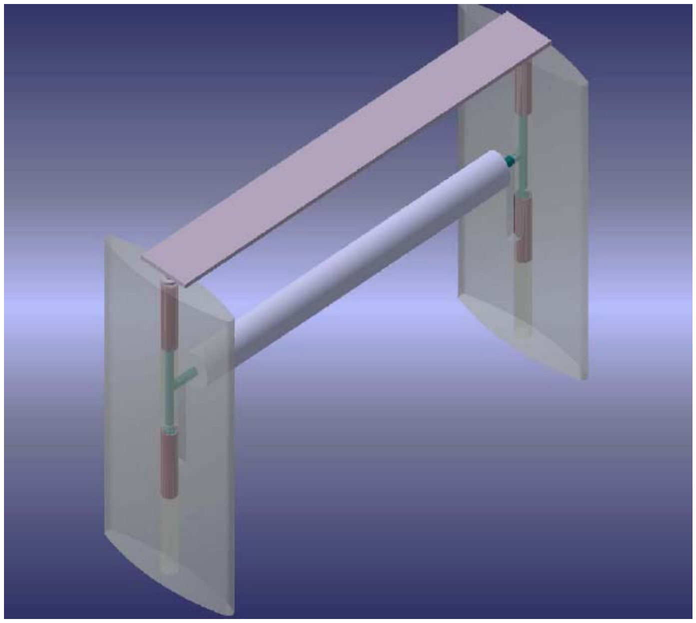


Figure 2: VIVACE Converter Module [5]

To convert the hydrokinetic energy into usable electrical energy, a Power Take Off (PTO) system is needed. The PTO system is also related to parameters such as the optimized power output, efficiency, energy density, and cost, which are important for widening the application of the VIVACE technology. Thus, the design of a PTO system of the VIVACE Converter becomes an important issue.

The overall objective of this project is to design and build a PTO system and prove the design concept. If the project is successful, the designed PTO system will be scaled and be used in a small VIVACE Converter on the order of 1-5 kW that will be implemented in the Detroit River. This system must have the following properties:

1. It must be cost competitive
2. It must require low maintenance
3. It must be environmentally friendly
4. It must be modular
5. It must be scalable
6. It should have as few moving parts as possible
7. It must be able to seal wet and dry components
8. It must be stackable with the need for a large generating capacity, small volume, and long design life

PROJECT REQUIREMENT AND ENGINEERING SPECIFICATIONS

The desired characteristics stated above were determined by taking into consideration the overall environment of the system, the system dimensions themselves, and a desired power density and efficiency in line with other power generation methods such as wind, solar, nuclear, coal, gas, and others. Importance ratings were determined through an analysis of the effects of each attribute to the overall function of the system. The findings were then analyzed by Professor Bernitsas to deliver the final importance ratings dictated below. Different energy generation concepts were generated as discussed in Appendix B, and used in further project requirement and engineering specification analysis.

With a Quality Function Deployment (QFD), shown in Table 1 below, cost is determined to be the most significant factor in weighing the systems. Where many of the other characteristics may be met through more elaborate (albeit complex) systems, one cannot easily move around the issue of cost. Overall, for the benchmarks, the Linear PTO scores out the highest, with the Hydraulic PTO scoring the lowest.

Table 1: Quality Function Deployment (QFD)

Eng. Characteristics / **Customer Attributes**	**Importance**	Generating Capacity	Volume of container	Design Life	Minimum Speed/RPM	Efficiency	**Rotary**	**Linear**	**Hydraulic**	**EPAM**
Easy To Maintain	5	1	3	9	3	3	4	4	3	5
Scalable	4	9	3	3	3	3	3	5	5	5
Cost Competitive	3	9	9	9	3	3	5	5	3	3
Modular	3	3	3	3	1	1	5	5	5	3
Environmentally Compatible	3	9	9	3	1	1	4	4	3	5
Few Moving Parts	5	3	9	3	1	1	3	4	3	5
Stackable	4	9	9	3	1	1	3	5	4	5
Seals Wet and Dry Components	5	3	1	9	1	1	3	3	3	5
Units		W	m^3	Yrs	RPM/ Speed					
Current Unit		60.14	0.01	10	5000	0.22				
Rotary		138	0.015	10	5000	0.55				
Linear		variable	0.01	10/20	1m/s	0.75				
Hydraulic		300	0.003	20	1m/s	0.8				
EPAM		n/a	0.01	20	n/a	n/a				

CONCEPT GENERATION

The immediate function of the PTO system is the conversion of energy, from the kinetic energy of the VIVACE converter to the usable electrical energy. This process begins when the cylinder, acted upon by VIV energy, moves periodically in vertical oscillation. The PTO will capture this energy and convert it into a secondary motion if the generator chosen harnesses energy from a movement not naturally generated by the VIVACE converter . When the generator is activated, it will produce a voltage which will then be carried to a storage or energy transfer system. From this functional decomposition, seen in Figure 3, four major categories for the concepts were determined: (a) motion conversion, (b) energy conversion, (c) energy transmission, and (d) sealing the wet/dry environments. From these four sub-functions brainstorming (both in class and group) was utilized as well as discussions with the sponsor to generate many different concepts. Table 2 below shows all the different concepts for each function generated. In the subsections below, representative concepts are described for each function.

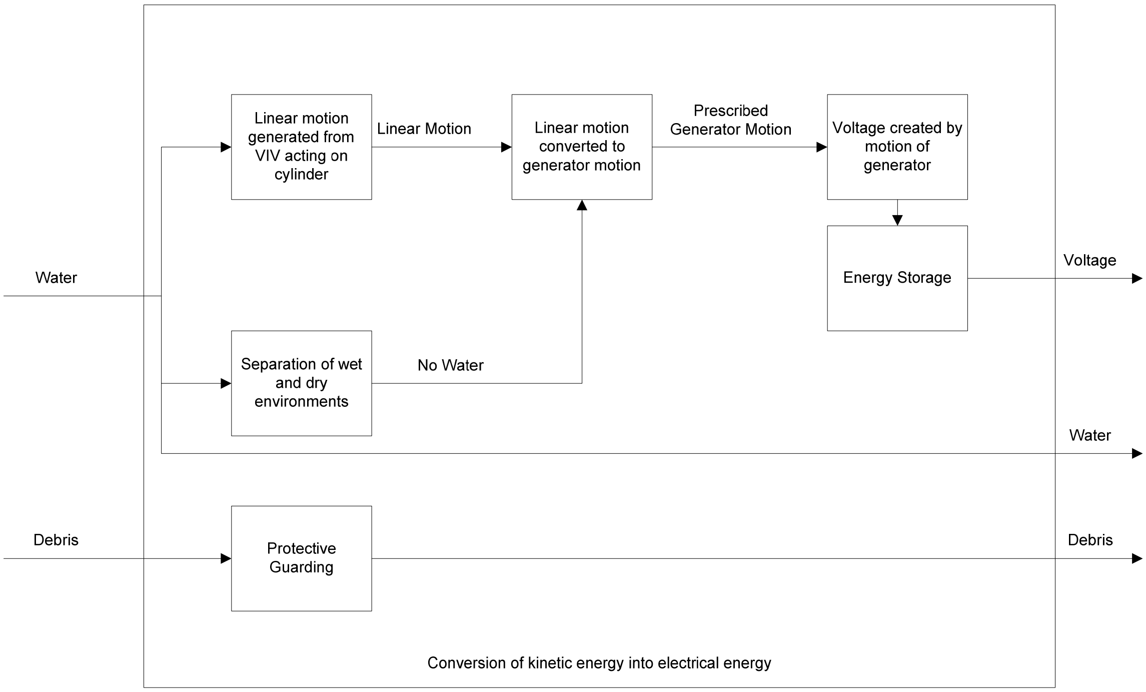


Figure 3: Functional Decomposition

Table 2: Morphological chart: concepts generated for each function

Function	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Convert Motion for Energy Conversion	None (Harness linear motion instead)	Crankshaft	Belt System	Gear System	Winch System	
Convert Energy	Coiled Wire and Magnet	Rotary Generator	Electroactive Polymer Artificial Muscle (EPAM)	Hydraulic System	Magneto Hydro Fluid	Rotary/Linear Combination
Seal dry components from wet components	Accordion shaped material to allow flexibility	Excess material to be used as slack	O-Rings	Elastic materials	Rotary seal	Applied pressure gradient to force out water
Transmit Energy	Alternating Current transmission	Direct Current conversion before transmission	Battery storage before transmission			

Motion Conversion

For certain energy conversion systems, the linear motion of the oscillating cylinder must be converted into other types of motion, which is determined by the type of generator that will be used (Table 2). For a more detailed analysis of energy conversion concepts, see Appendix B. The most straightforward option is to harness the linear motion for the electromagnetic induction based generator or Electroactive Polymer Artificial Muscle (EPAM). If a rotary generator or hydraulic generator is used, however, other methods must be utilized to convert the cylinder's linear oscillation into rotary motion. One such method is a belt system. The end of the cylinder would be attached to a belt which is in turn wrapped around a rotor. The up and down motion could then turn the rotor back and forth (Table 3). Similarly, a straight gear could be fashioned at the end of the rod so when it moved vertically, it would turn a gear on the rotor (Table 3). For both proposals, a transmission mechanism (e.g. gears) could be added in order to change the angular speed to a desired value. Another way is to use a crankshaft. This would convert the linear motion into a constant rotary motion exactly like the piston in your car does. Then the rotary motion is used for a rotary generator, which is shown in Table 4. It would be beneficial because there would be no alternating current from the rotor switching directions. Finally, a winch component could be applied. The moving bar would strike protruding teeth one after another propelling them upward, in turn spinning the gear (Table 3).

Energy Conversion

This component is responsible for taking the converted linear motion and efficiently converting its kinetic energy into electrical energy. The concepts generated for this component are: a linearly moving magnet through a coil of wire producing a current through induction, a rotational generator that would also works through induction, an EPAM that produces a voltage when deformed, a hydraulic system that pressurizes a fluid then passes it through a turbine, a magneto hydro fluid flow system which uses magnetic fluid passing through coils to generate induced current, or a combination of one or more of these. Sketches of concepts are shown in Table 4 and a detailed description of each energy conversion concept is given in Appendix B.

Seal Mechanism

This part of the system accomplishes the task of sealing off the dry environment in the side casing of the module from the wet environment. In order for the power take off system to work effectively, we must be able to keep the electronic components dry. Some possible concepts are o-rings, rotary seals, accordion seals, slacked seals, and elastic materials. The two most basic of these are the o-ring for linear motion and the rotary seal for a spinning shaft. Both of these are readily available and in common use. The elastic seal could work as both seal and spring in the system, working much like a trampoline. The edges would be secured, while rods on either side could act back and forth. The accordion seal and the slack seal are basically the same concept. A seal would be firmly secured on the rod, while loose material (secured at the edges) would allow movement of the rod without the material stretching and being subjected to any fatigue. This is shown below in Figure 4. Finally, one could utilize an applied pressure seal. Here an air compressor would operate to keep a stable air pocket similar to one in an upside-down bowl under water. Sketches of each concept are demonstrated in Table 6 5.

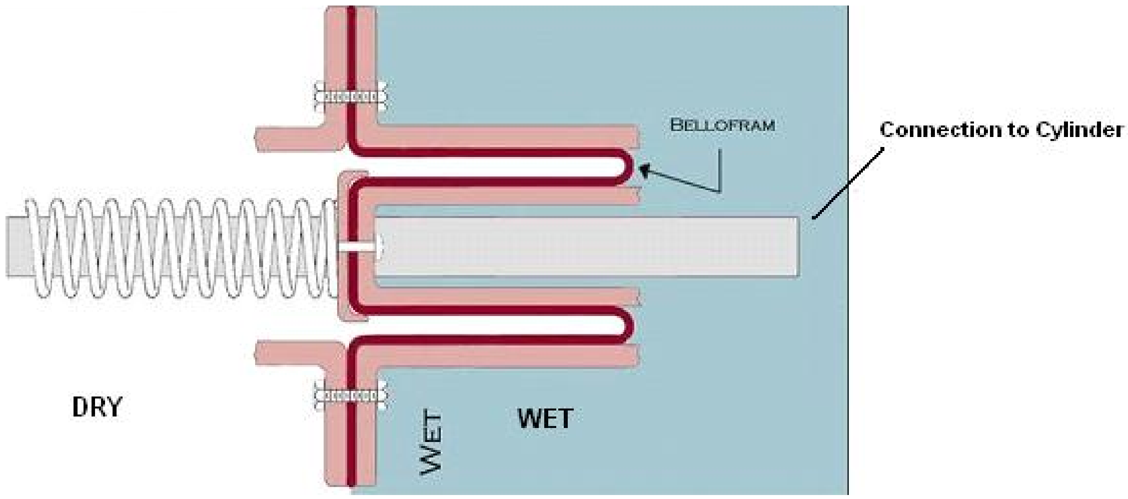


Figure 4: Slack Seal Rendering [6]

Energy Transmission

This component is responsible for either storing or transmitting the electrical current produced by the energy conversion component. There should be a limited amount of energy loss during this transmission. The concepts generated are: transmitting the alternating current through cables, converting the alternating current to direct current, or using the current to charge a battery, as discussed further in Table 6.

CONCEPT SELECTION PROCESS

In choosing the best PTO design, a functional decomposition process was instituted, with the different designs that could meet the requirements of each subfunction weighed against each other. Thus, Pugh Charts (Tables 3-6) were generated for each subcomponent and graded out. This process is summarized in the morphological chart (Table 2).

Seal Mechanism

The applied pressure gradient to force out water concept was deemed too complex, with many possible points of failure. Furthermore, the energy consumption required to create a pressure gradient would reduce the transmitted energy by the PTO system. O-rings and are common seals used widely in machine design because they are easy to make, inexpensive, and reliable. If the sealed joint has relative motion between the part and the o-ring (as is the case with the VIVACE system), however, lubrication is usually required to reduce wear. This is usually accomplished by the fluid sealed. [7] Because water is sealed on the outside and a dry environment is needed inside, there is no place to put lubricant, which would lead to a short design life. Thus, an o-ring should not be used for the seal mechanism. Similarly, elastic materials have relatively short design lives, and are greatly affected by fatigue with constant motion. As such, allowing for slack material would be the best design, as one is not placing great amounts of stress on the seal, and the design is relatively simple to create, requiring little maintenance.

Motion Conversion

Of the concepts considered, the gear system would be the most efficient and simple device to translate motion. Larger scale considerations such as the belt system would be problematic in trying to seal wet and dry components. The winch system is simply less efficient while the crankshaft system and a combination system were deemed to have too many parts (more difficult to maintain) and would take up too much volume (decreasing energy density). Clearly, not having to convert any motion at all would be an immense positive, as noted in the Pugh Charts (Table 6).

Energy Conversion

The Electroactive Polymer Artificial Muscle (EPAM) was the best concept, given that it was a material that would inherently generate energy and could operate in water. As such, the complexity of this device would be drastically reduced, leading to a maintenance free system. The linear and rotary systems were also deemed to be efficient ways of gathering energy without adding numerous points of failure or taking up a lot of volume. The hydraulic and magneto hydro fluid concepts utilize contained fluids, to which such a system would be prone to leakage, to which long term sustainability is questionable. The combination of a rotary and linear system is deemed overly complex. A more detailed discussion of different concepts of energy conversion can be found in Appendix B.

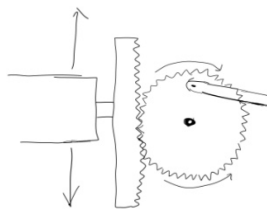
Energy Transmission

Energy transmission concepts were generated and compared as shown in Table 6. Transmitting energy as a direct current versus an alternating current is much less efficient and more prone to loss. Yet given the variable power output of an oscillatory power generation system, rectification is still needed to ensure an output voltage of consistent amplitude. Thus, a current transformer will be necessary to ensure proper power output. The concept of a battery was deemed too bulky, costly, and inefficient when a transformer could do the same job.

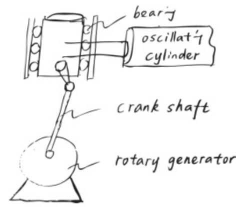
Table 3: Subfunction 1 - Convert Motion for Energy Generation

Sketches

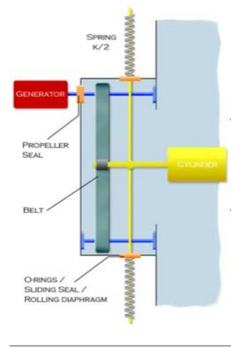
Lab Prototype:



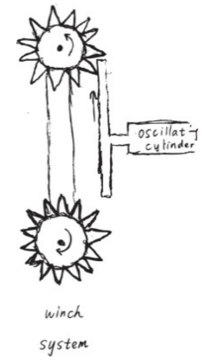
Design 2:



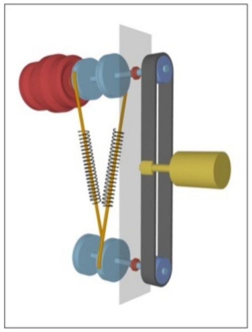
Design 3:



Design 4:



Design 5:



		Lab Prototype	**Design 1**	**Design 2**	**Design 3**	**Design 4**	**Design 5**
Design Criteria	**Weight**	Gear System	None (Harness Linear Motion)	Crankshaft	Belt System	Winch System	Belt and Gear System
Easy to maintain	5		+++	-	0	0	-
Scalable	4	D	0	0	0	0	0
Cost	2	A	-	-	0	0	--
Environmentally Compatible	3	T	+	-	0	0	0
Few Moving Parts	4	U	0	--	0	0	--
Seal wet and dry components	5	M	-	--	--	-	-
Efficient	4		++	--	-	-	-
+		0	23	0	0	0	0
0		0	8	4	18	18	7
-		0	7	36	14	9	26
Total Points		0	16	-36	-14	-9	-26

Table 4: Subfunction 2 - Convert Mechanical Energy to Electrical Energy

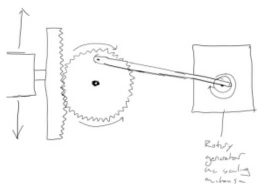
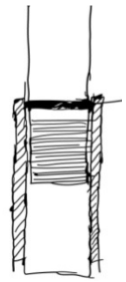
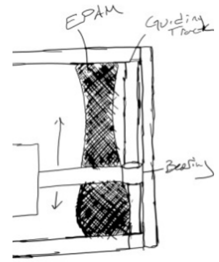
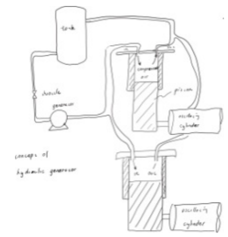
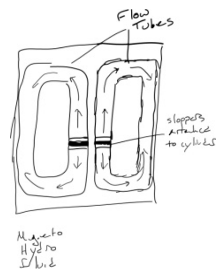
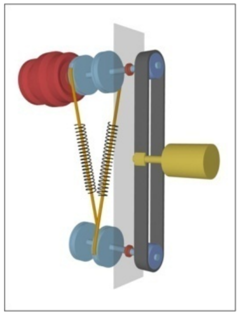
		Lab Prototype	**Design 1**	**Design 2**	**Design 3**	**Design 4**	**Design 5**
	Sketches						
Design Criteria	**Weight**	Rotary	Coiled wire and magnet	EPAM	Hydraulic	Magneto Hydro Fluid	Rotary, Linear Combination
Easy to maintain	5		-	+	---	-	-
Scalable	4	D	++	0	+	+	--
Cost	2	A	-	---	+	--	--
Environmentally Compatible	3	T	+	0	---	0	0
Few Moving Parts	4	U	-	+	-	+	--
Seal wet and dry components	5	M	-	+	0	0	-
Efficient	4		0	-	+	--	-
+		0	11	14	10	8	0
0		0	4	7	5	8	3
-		0	16	10	28	17	34
Total Points		0	-5	4	-18	-9	-34

Table 5: Subfunction 3 - Seal Wet and Dry Components

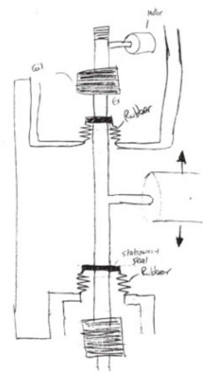
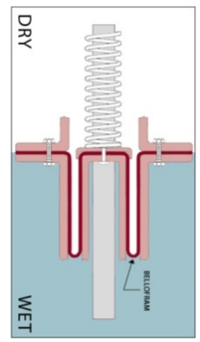
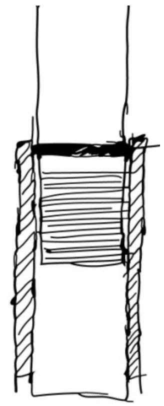
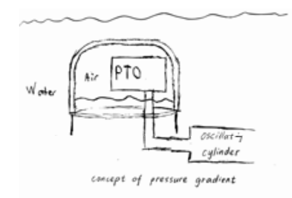
Design Criteria	Weight	Lab Prototype	Design 1	Design 2	Design 3	Design 4	Design 5
	Sketches						
Design Criteria	**Weight**	Rotary Seal	Accordion Shaped Material	Slack Material	O-Ring	Elastic Material	Applied Pressure Gradient
Easy to maintain	5		0	0	-	-	- -
Scalable	4	D	+	+	-	-	-
Cost	2	A	+	+	0	-	---
Environmentally Compatible	3	T	0	0	0	0	0
Few Moving Parts	4	U	0	0	0	0	-
Seal wet and dry components	5	M	0	0	0	0	0
Efficient	4		+	+	0	-	--
+		0	10	10	0	0	
0		0	12	12	18	12	8
-		0	0	0	9	15	32
Total Points		0	10	10	-9	-15	-32

Table 6: Subfunction 4 - Transmit Energy

		Lab Prototype	Design 1	Design 2
Design Criteria	**Weight**	DC Conversion	AC Transmission	Battery
Easy to maintain	5		+	-
Scalable	4	D	0	-
Cost	2	A	+	-
Environmentally Compatible	3	T	0	--
Few Moving Parts	4	U	0	0
Seal wet and dry components	5	M	0	0
Efficient	4		--	-
+		0	7	0
0		0	16	9
-		0	8	21
Total Points		0	-1	-21

In this iterative concept selection process, the process of converting mechanical energy to electrical energy (Subfunction 2) directly impacts the designs considered for sealing the components and converting the motion for energy conversion (Subfunctions 3 and 1). As such, when determining which PTO design would be best, the aggregate sum of Subfunctions 1, 2, and 3 was used to make the ultimate decision, as shown in Table 7. Unfortunately, while the EPAM design offers many benefits and greatly reduces the complexity of the system, the lack of material availability eliminates this option.

Table 7: PTO Aggregate Scores

	Rotary	Coiled Wire and Magnet	Hydraulic	Magneto Hydro Fluid	Rotary/Linear Combination	EPAM
Seal Dry Components From Wet Components	0	10	-1	-9	10	10
Convert Motion for Energy Conversion	0	16	16	16	-26	16
Convert Energy	0	-5	-18	-9	-34	4
Total	0	21	-3	-2	-50	30

SELECTED CONCEPT DESCRIPTION

After meeting with our sponsor, Professor Bernitsas, it was decided that the best design concept weould be a linear induction generator. The rendering in Appendix A shows a cylinder with a 5 inch diameter with one magnet attached to the end. This diameter may be adjusted, however, pending further research. The magnet chosen is ring shaped and encircles a hollow tube containing the coiled wire(s). The height of the coil only needs to be twice the diameter of the cylinder because this is its peak-to-peak amplitude. With this setup, one can fulfill one of the main design requirements and keep the coiled wire(s) out of the wet environment. This leaves the magnet exposed to the elements, however, so either a suitable coating must be found for the magnet, or a magnet made from a corrosion resistant material must be used. Drawings in Appendix A also show close ups of the magnet and coils. In order to induce a voltage, the magnet must oscillate up and down around this tube. This up and down motion, however, will result in friction that could cause significant wear to the tube and/or the magnet. Hence bearings will be used to reduce this unwanted friction, as shown in Appendix A. Given the magnetic properties of metals, the bearings will also have to be non-ferrous as well.

ENGINEERING ANALYSIS

Engineering Fundamentals

The engineering fundamentals focused on for our linear induction generator are as follows. We gained an understanding for electromagnetic induction in order to determine the properties of the magnets and coils that will be used. We gained further understanding of the motion of the VIVACE converter to determine the efficiency of our PTO as well as the maximum weight of the attachment. In addition to this we researched material properties so that our system would not corrode underwater and to insure cost effectiveness.

Equations

Induced emf:
In using a linear generator, the permanent magnets will be mounted with different polarities, allowing for the energy to build up in a flux wave, called the induced electromagnetic flux, or *emf*. ω denotes angular frequency, ψ_{pm} denotes the permanent magnet induced flux per pole, N denotes the total number of coil turns, v denotes speed of the magnet, and w_p denotes the distance between the poles.

$$E = \omega \psi_{pm} N$$ **Equation 1**

$$\omega = 2\pi \frac{v}{w_p}$$ **Equation 2**

$$N = N_{pole} N_{turns}$$ **Equation 3**

Synchronous resistance:
The synchronous resistance, X_s, measures the voltage drop caused by the armature flux created with the motion of the magnet through the coil, with L_s denoting synchronous inductance.

$$X_s = \omega L_s$$ **Equation 4**

Synchronous inductance itself is calculated as shown below, with L_m denoting main inductance, and L_l denoting leakage inductance.

$$L_s = L_m + L_l$$ **Equation 5**

$$L_m \propto N_{coils} N_{turns}^2$$ **Equation 6**

Output Power
The load from the generator can be calculated as a function of resistive load, R_l. Thus, for the linear magnetic generator, one can estimate the output power:

$$P_l = E^2 \left(\frac{R_l}{(R_l + R_g)^2 + (X_s + X_l)^2} \right)$$ **Equation 7**

Cylinder Motion
For a VIVACE converter, the cylinder is placed in the z-direction and oscillates in the y-direction perpendicular to the flow velocity U, which is in the x-direction.

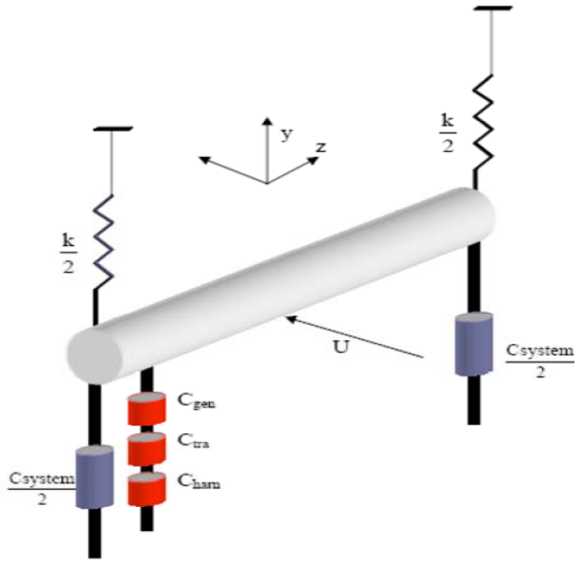


Figure 5: Cylinder Modeling

Using Newton's Second Law, the motion of the cylinder in the y-direction can be modeled as:

$$m_{osc}\ddot{y} + c_{total}\dot{y} + ky = F_{fluid}\vec{y} \qquad \textbf{Equation 8}$$

where y is the direction perpendicular to the flow and the cylinder axis, m_{osc} is the oscillating system mass, which includes one third of the spring mass, k is the spring constant, c_{total} is the total damping coefficient of the system, and F_{fluid} is the force exerted by the fluid on the body in the y-direction. The y-direction fluid flow F_{fluid} has two components: the inviscid part $F_{inviscid}$ and the viscous part $F_{viscous}$. The inviscid force can be expressed as:

$$F_{inviscid} = -m_a\ddot{y} \qquad \textbf{Equation 9}$$

where m_a is the inviscid added mass. Eq.8 is the governing equation describing the cylinder motion, which would be used in computer simulation to determine how the spring stiffness and the damping (mainly due to the electromagnetic induction) affect the Vortex Induced Vibration (VIV) at certain current speed. The results of the computer simulation then give us the guidance of determine the right spring constant, the strength of magnet, and the number of coils.

Energy in Fluid Flow

Total energy in fluid flow can allow for the calculation of extracted energy from a given flow onto the VIVACE system, which when coupled with power take off efficiency, can be used to calculate power generated. Here P denotes pressure, ρ denotes density of water, U denotes velocity, g denotes gravity, z denotes height, and E denotes energy.

$$\frac{P}{\rho} + \frac{U^2}{2} + gz = E \qquad \textbf{Equation 10}$$

Based on that, the power in the flowing fluid over the projected area of the cylinder in the direction perpendicular to the flow direction can be approximated using the following equation:

$$P_{flow} = \frac{1}{2}\rho U^2 \cdot DL = \frac{1}{2}\rho U^3 DL$$ **Equation 11**

where D is the diameter of the cylinder. $1/2\rho U^2$ is the kinetic pressure head in the fluid from Bernoulli's equation, and DL is the projected area of the cylinder in the x-direction.

Energy Density, Efficiency, and Power Extraction
The footprint volume energy density of a VIVACE converter is defined as:

$$\text{Volume Energy Density} = \frac{NP_{harnessed}}{hA}$$ **Equation 12**

where N is the number of cylinders in a VIVACE converter, h is the water depth, and A is the area of the converter footprint. The efficiency of a VIVACE converter can be calculated by:

$$\eta_{VIVACE} = \frac{P_{harnessed}}{P_{flow}}$$ **Equation 13**

where $P_{harnessed}$ is harnessed power by a single VIVACE converter, which can be measured by experiment. The maximum fluid power that can be extracted by a VIVACE converter in synchronization [9] (e.g. at resonance) is calculated as:

$$P_{\text{VIVACE-Fluid}} = \frac{1}{2}\rho\pi C_y U^2 f y_{\max} DL \sin\phi$$ **Equation 14**

where f is the oscillating cylinder frequency, y_{max} is the amplitude of oscillation, ϕ is the phase angle between the fluid force F_{fluid} and the displace of the cylinder (e.g. the displacement lags the forcing by ϕ, and C_y can be calculated using the following equation:

$$-(m_{osc} + m_a)(\frac{1}{2\pi f})^2 y_{\max} + k y_{\max} = \frac{1}{2}\rho C_y U^2 DL \sin(\frac{\pi}{2} + \phi)$$ **Equation 15**

The theoretical upper limit of the efficiency of a VIVACE converter is:

$$\eta_{\text{UL-VIVACE}} = \frac{P_{\text{VIVACE-Fluid}}}{P_{flow}} = \frac{\frac{1}{2}\rho\pi C_y U^2 f y_{\max} DL \sin\phi}{\frac{1}{2}\rho U^3 DL}$$ **Equation 16**

Most of the variables can be measured through experiment and after we get all the variables, we can use the governing equations described above to calculate the theoretical upper limit of the efficiency of a single VIVACE module, its actual efficiency, and the energy density of the final VIVACE converter. The engineering analysis with the help of these equations enables us to test the performance of the designed PTO system quantitatively. In order to test/simulate the performance of the prototype/paper model, the VIVACE modules consisting of a single rigid cylinder mounted on elastic supports in the Marine Renewable Energy Lab is the most important equipment that will be needed.

ENGINEERING DESIGN PARAMETER ANALYSIS

Coil System

Given the variation in amplitude of the cylinder, a series of 5 segmented coils that are 1.99” tall and 0.01” apart will be used to be able to maximize the amount of power generated. Because coils generate an electric current only when a coil completely enters and exits a magnetic field, a singular coil design will either not work in relatively shorter amplitudes or fail to take advantage of the maximum amplitudes. By using several smaller coils, the design can generate power in a few of the coils during relatively smaller amplitudes and generate power in all of the coils during the maximum amplitudes. The segments of coil will also ensure that each coil segment undergoes the maximum change in magnetic flux, maximizing power generation. Given the large amount of time required to wind coils as well as the complexity of voltage rectifiers with additional sources, the number of segments was limited to five.

Iron Core

To increase relative magnetic permeability, an iron core will be inserted at the center of each coil system. While this additional volume will decrease the number of turns (N) in the coil, the added relative permeability will more than compensate for this loss. The equation for the added contributions of the coil and core to the voltage (V) is given below, where Φ denotes the magnetic flux, t denotes time, μ_r denotes the relative magnetic permeability constant, B denotes the magnetic field, R_{total} denotes the outer radius of the coil, and r_{core} denotes the radius of the iron core.

$$V = -\frac{N\Phi}{t}$$ **Equation 17**

$$\Phi = \mu_r B \pi r_{core}^2 + B\pi(R_{total}^2 - r_{core}^2)$$ **Equation 18**

These equations were optimized to determine the specific iron core radius and subsequent coil outer radius that would yield the maximum output voltage. This optimization yielded a core diameter (and resultantly an inner coil diameter) of 1.33” and an outer coil diameter of 1.90”. The outer coil diameter was determined through the constraints of coil housing thickness discussed later in the Engineering Parameter Analysis section. The iron core will need to be insulated from the coils themselves, achieved through the insulated coating on the wires.

Magnet and Bearings

The magnet with the highest magnetic surface field available was chosen with a large enough inner diameter to meet the design specifications. Given the corrosiveness of neodymium magnets, a protective system will need to be constructed in order to protect the material from decay. In the case of the bearings used for the prototype, cost is the main constraint given that the forces of the motion cylinder (that sheds water vortices) can be constrained to yield a small bending moment through the use of bearings. For the final design itself, the main constraint is its ability to work underwater. The inner diameter is also constrained by the dimensions of the magnet.

Springs

As explained in detail in the Engineering Analysis section, the motion of the cylinder can be modeled as follows:

$$m_{osc}\ddot{y} + c_{total}\dot{y} + ky = F_{fluid\,y}$$ **Equation 19**

In introducing an electromagnetic spring, however, an electromagnetic force is also applied to the payload, F_{em}. This additional force, coupled with removing a physical spring, yields a new relationship:

$$m_{osc}\ddot{y} = F_{em} + F_{fluid}y - c_{total}\dot{y} \qquad \textbf{Equation 20}$$

The electric force can be considered a function of the contributions from the magnetic flux (Φ) in the equation below, where L denotes inductance and i denotes current:

$$\Phi_m(t) = L(y)\frac{d}{dt}i(t) \qquad \textbf{Equation 21}$$

Through standard analysis, the expression for magnetic force then becomes:

$$F_{em} = \frac{L}{2}i^2 \qquad \textbf{Equation 22}$$

and the overall modeling equation becomes:

$$m_{osc}\ddot{y} = \frac{L}{2}i^2 + F_{fluid}y - c_{total}\dot{y} \qquad \textbf{Equation 23}$$

Using Kirchhoff's law for electrical circuits, one can model this equation in terms of the electrical power (e) needed to give a specific displacement (y) with a specified capacitor charge (q):

$$[L_0 + Ly]\ddot{q} + [R + L\dot{y}]\dot{q} + \frac{1}{C}q = e \qquad \textbf{Equation 24}$$

Thus, an electrical system is currently being designed based on the modeling constraints of Equations 7 and 8. This system may require a large use of power. As such, the system is designed to have an exceptionally low resistance. As seen in Equation 24, relatively small additions of resistance can have dramatic effects on the output voltage. In this fashion, while there may be large quantities of power required to run the electromagnetic spring, there will be minimal power loss due to a small resistance. Thus, the same power routed through the system can later be used as an output power as well.

Tube

The tube itself is designed to withstand the hydrostatic pressure (p_∞) and stagnation point pressure (p_s) of the water at a depth (h) of 20m, as calculated in the equation below, where ρ denotes water density, V_∞ denotes water current velocity, and g denotes gravity.

$$p_\infty + p_s = \rho g h + \frac{1}{2}\rho V_\infty^2 = \frac{1000kg}{m^3}\cdot\frac{9.81m}{s^2}\cdot 20m + \frac{1}{2}\cdot\frac{1000kg}{m^3}\cdot\left(\frac{1m}{s}\right)^2 = 0.1967MPa \qquad \textbf{Equation 25}$$

Overall stress of the cylinder was determined through a calculation of hoop stress (σ), where r denotes cylinder radius and t denotes thickness:

$$\sigma = \frac{pr}{t} = \frac{0.1967 * .0508}{.0016} = 6.25MPa \qquad \textbf{Equation 26}$$

The effects of the moments caused by the cylinder itself are assumed to be negligible given the use of linear bearings.For material selection of this tube, maximizing yield strength and minimizing tube thickness were the objective functions used. Granta Design Ltd's Cambridge Engineering Selector (CES) was subsequently used to narrow down material options, and PVC selected as the material of choice. For a more detailed analysis, see Appendix H.

FINAL DESIGN DESCRIPTION

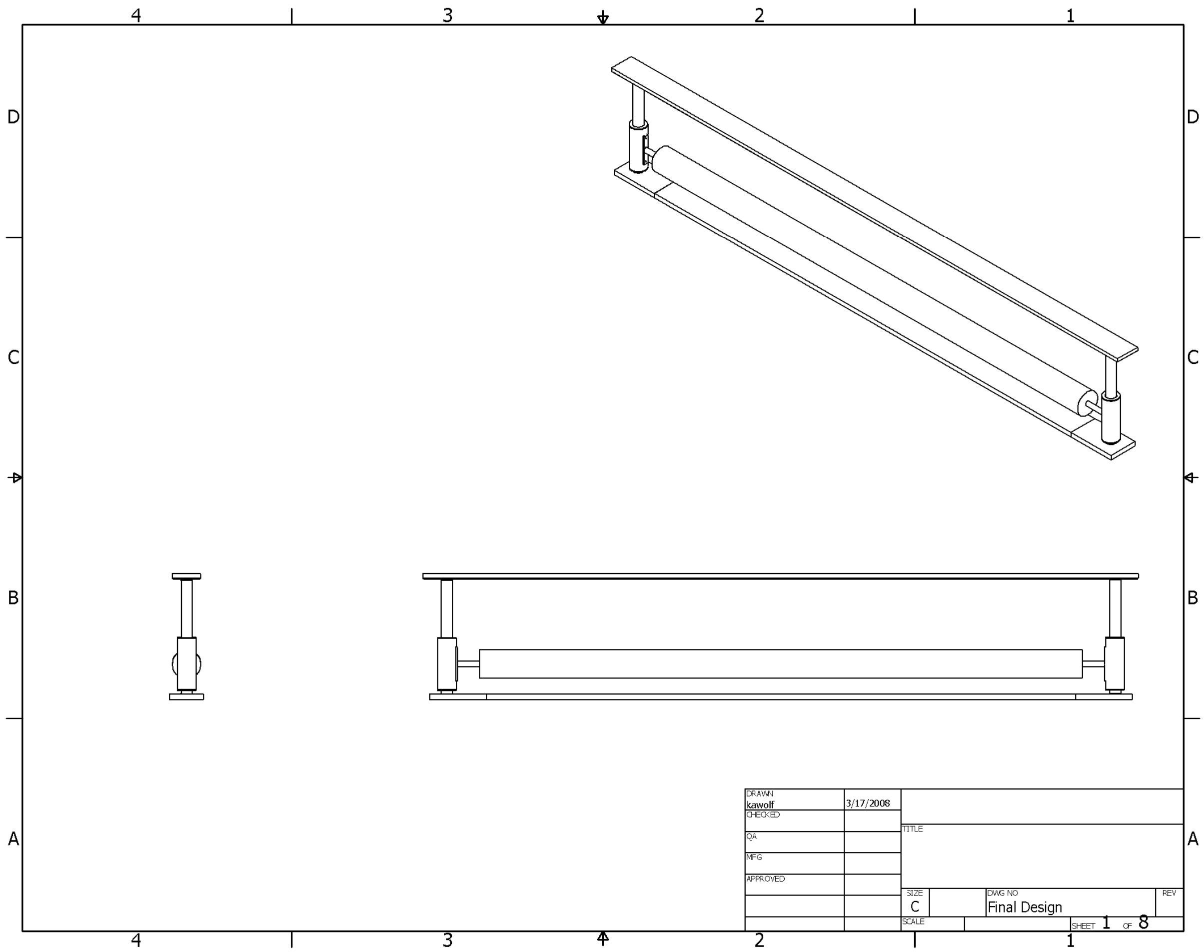


Figure 6: Final Design Engineering Drawing

Our final design is shown above in Figure 6. A cut-away view of the PTO system is shown in Figure A.1 of Appendix A. The basis of our design will be a ring magnet passing over a series of coils which are encased in a watertight PVC housing. This was determined to be the best way to overcome one of the main goals: separate the electric components from the wet environment. The ring magnet moves up and down around the tube, changing the magnetic flux through the coils and generating the power that we need through electromagnetic induction. To reduce friction between the housing and the magnet, linear bearings will be used. The magnet and bearings are also attached to the inner surface of a PVC tube, which will in turn be attached to the VIV cylinder. An engineering drawing showing the setup as a whole is located in Appendix A. A complete list of materials is located in Appendix C.

Magnet and Bearings

When weighed against other types of magnets (Appendix D), the neodymium magnet best met the needs of the PTO system. Neodymium magnets exhibit excellent strength relative to their size. The selected magnet is shown in Figure 7 and is 3" (O.D.) x 2" (I.D.) x 1" (thick), and puts out a 6040 Gauss magnetic field [8] while weighing only 17 oz. In addition, they are highly resistant to demagnetization over time and work well in ambient temperatures (Appendix E). Therefore, they should last the lifetime of the VIVACE module. These magnets are extremely susceptible to corrosion, however, especially in a marine environment. The nickel plating that comes standard will not protect the magnet for long periods of time (Appendix E), in which a waterproof coating must be used for the magnet to last. A waterproof coating found made by Sherwin Williams can be used to protect the magnet (Appendix D). It is designed for metals in a harsh marine environment, including salt water. Thus, it should prevent the magnet from excessive corrosion in the time it will be submerged. Also, in order to reduce the amount of friction between the magnet and the coil housing, bearings must be used. The bearings chosen are linear self-aligning bearings (Appendix D), with a 2" inner diameter and 3" outer diameter. These bearings are designed specifically for underwater use and they should work very well with the final design since they will be exposed in this type of environment.

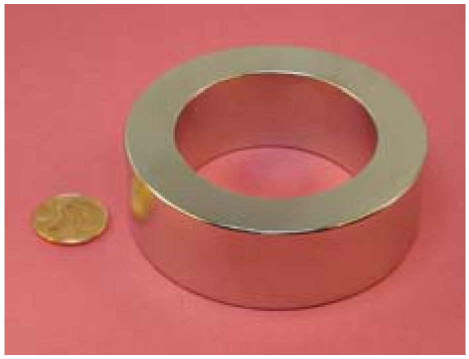


Figure 7: Ring Magnet

Springs

The final design will also incorporate the use of electromagnetic springs, designed so issues such as fatigue life and sealing from the wet environment will not come into play. These springs will be designed with the assistance of Professor Nikos Xiros of Florida Atlantic University; however, this addition is beyond the scope of the project, so will be omitted from the prototype.

Coils

The coil system will consist of 5 separate coils. Each is 1.99" long, has an outer diameter of 1.89", and is separated by 0.05". This separation is accomplished using aluminum spacers (Figure A.2, Appendix A). A 0.006" diameter wire with an insulated coating will be used to prevent unwanted electricity transfer. Several separate coils and not a singular and long one must be used. As mentioned before, this is because of the variable amplitude that VIV generates. Because coils generate an electric current only when a coil completely enters and exits a magnetic field, a singular coil design will either not work in relatively shorter amplitudes or fail to take advantage of the maximum amplitudes. In using several smaller coils, one can generate power in a few of the coils during relatively smaller amplitudes and generate power in all of the coils during the maximum amplitudes. In order to maximize the voltage, as many turns in the coils as possible are desired. This is due to the fact that voltage is directly proportional to the number of turns. The number of coils is dependent on the reach of the magnetic field. The length of the coils should be the same as this distance (as well as the distance between the coils) so that the magnetic field though the coils goes to zero as the magnet moves away from them. The change in magnetic flux is further increased by inserting an iron rod in the coils. This increases the magnetic permittivity of the coils, and generates a greater EMF. This iron core will have a diameter of 1.33" and a length of 10.5".

Inner Housing

All of these coils are encased in a watertight tube, our inner housing (Figure A.4, Appendix A). To satisfy the need for the thinnest wall possible while being strong enough to withstand the water pressure, it is to be made of PVC with a 2" outer diameter and 1.90" inner diameter. It will be trimmed to a length of 20" to contain the full amplitude of the outer housing when attached to the VIVACE cylinder. The end caps can then be injection molded to be 0.15” thick with an inner diameter of 2” (Figure A.4, Appendix A). One must be able to transport the power as well, however, and thus the wires will exit the tube at the top to a rectifier. The rectifier is to be used so the AC output can be converted to a more useful DC. This process also requires rubber insulation covering the wires, and a watertight seal at the top. The watertight seal can be achieved using 3M Marine Adhesive Sealant Fast Cure 4000 UV (Appendix D), a very versatile product. This accomplishes one of the main goals of separating the wet and dry environments.

Outer Housing

The outer housing (Figure A.5, Appendix A) is to hold the magnet and the bearings, and to attach to the VIV cylinder. Its inner diameter is 3”, its outer diameter is 3.15”, and it is 9” long. The magnet will be adhered to the inner surface of the housing with the two bearings (one on the top and one on the bottom). We found that Extreme Adhesives 300 (Appendix D) would be best suited, as it adheres well to both metal and plastic while being very durable. There is also a mounting bracket (Figure A.6, Appendix A) located on the outer surface which attaches to the VIV cylinder via aluminum bolts. This outer housing will then move up and down with the cylinder around the stationary inner housing.

PROTOTYPE DESCRIPTION

The prototype designed is a simpler, more cost effective design than our final design. To accomplish this, the prototype will not be tested in an underwater environment due to the VIVACE converter at the Marine Renewable Energy Laboratory being broken, and will not have certain components that the final design has due to our time constraint. Though there are some differences between the final design and our prototype, a clear proof of concept will be displayed through the prototype.

Because the prototype will not be tested underwater a cheaper set of bearings were used to align the magnet with inner housing. The bearings used are all-polymer DryLin RJI bearings: closed standard linear bearings. Another difference due to the prototype not being tested underwater is the lack of a corrosive resistant waterproof coating on the magnet. Again this is to reduce the cost and time needed for our prototype.

The manufacturing technique of our prototype is different from our final design’s technique. Our prototype has a different inner housing for the coils and a different outer housing for the magnet and bearings. The inner housing for the coils was a machined PVC pipe with 3M Adhesive/Sealant sealing the ends off with two 2” diameter, 0.15” thick PVC discs. The outer housing for the magnet and bearings is a PVC tube adhered closed with two PVC end caps that have a 3.3” outer diameter and a 2.1” inner diameter. These housings were used because we had no access to an extrusion machine to shape the PVC into a housing. This closes off the end while still allowing the inner housing to move through it. The handle is there so we can demonstrate the oscillatory motion of the VIVACE easily. Also our tolerances were different due to the quality of the machines available. These differences were negligible to the power output.

Certain components of the actual VIVACE PTO were omitted from our design because they were outside of the scope of our project. First there is no voltage rectifier to combine the separate voltages produced by each coil. The circuitry was deemed too advanced to be completed in time. Instead each separate coil was connected to its own light bulb to show the power output visually. A second component not seen in the prototype is the electromagnetic springs. This is because we will not be actually connecting the PTO to the VIVACE, and they are also out of the scope of this project. Finally, only one PTO was made, when in a realistic setting there would be one for each side of the VIVACE cylinder. This is because we are only proving our concept so and extra PTO would be unnecessary.

FABRICATION PLAN

Because of the differences between the final design and prototype, the fabrication plans do not reflect the likely procedures for mass manufacturing; however this is true for most prototypes.

Due to complications within the Marine Renewable Energy Laboratory housing the prototype, it was necessary to forgo testing the PTO on the current prototype VIVACE system. Instead, testing was conducted in dry runs at our convenience. Because of this, the prototype no longer needed to be water tight. To simplify the fabrication further, only a single PTO was produced, rather than the two indicated in the final design.

With these changes in design, the prototype consists of eight components:

- Base
- Coils
- Coil Housing
- Magnet
- Outer Housing
- Bearings
- Coil Spacers
- Iron core

The magnet and the bearings were both manufactured independently by K and J magnets Igus, respectively. Because of this, their shapes and the properties could not be altered, and any changes in the other parts had to accommodate the magnet and bearings.

With this in mind, a 2” (OD) PVC pipe was chosen as the material for the coil housing. The first operation was to cut a 20” length of tube with the band saw. Because the magnet must have a slip-fit with the tube, the PVC was sanded to have an outer diameter of 1.99” ± 0.01”. This also ensured that the tube is straight, minimizing risk of misalignment. The tolerance of this operation was critical because the tube could not obstruct the path of the magnet, yet reducing the diameter too much would render the bearings useless.

The preparation of the outer housing was similar to the fabrication of the coil housing, except that the tolerance was important on the inner diameter. The end caps of the coil housing were made of plastic round stock (PRS) with a diameter of 2”. The outer housing end caps were made out of Plexiglas on the laser cutter and had an outer diameter of 3.5”and an inner diameter of 2.1”.

The coils were wound on a lathe, using a procedure explained to us by a coil manufacturer. It entailed spinning a spool on the lathe at a constant speed while ensuring that the coil is taught as it is wound around the spool. Although this took a significant amount of time, it was quicker than having to order the coils and then waiting for them to be made and shipped.

The spacers placed between each section of coils were made out of aluminum round stock (ARS) which was turned until it had an outer diameter of 1.89”. The tolerance of this dimension was ± 0.001” because a secure fit was required so that there was no risk of the iron core coming loose or moving around. The hole in the spacer for holding the iron core was bored out on a lathe and discs with a thickness of 0.05” were parted off. The iron core did not need any machining as the stock piece was the correct dimension.

The base was made from 1” thick block plastic. It was a simple 6”x10” rectangle, cut with the band saw. A 2” hole was cut out of the base on a drill press using a circle saw.

Table 8: List of Machine Operations

Machine	Operation	Material	Tool Speed	Feed Rate
Coil Housing				
Band Saw	Cutting – 20” length	PVC 2”OD	300 FPM	2 IPM
Outer Housing				
Band Saw	Cutting – 9” length	PVC 3”ID	300 FPM	2 IPM
Lathe	Boring – 3” ± 0.01”	PVC 3”ID	400 RPM	0.5 IPM
Lathe	Turning – 3.5” ± 0.01”	PVC 3”ID	400 RPM	0.5 IPM
Coil Housing End Caps				
Band Saw	Cutting – 0.15” length	PRS 2”OD	300 FPM	2 IPM
Outer Housing End Caps				
Laser Cutter	Design Cutting	Plexiglas	90% power	1.2% speed
Base				
Band Saw	Cutting – 6” length	Plastic Block - t = 1”	300 FPM	3 IPM
Band Saw	Cutting – 10” length	Plastic Block - t = 1”	300 FPM	3 IPM
Drill Press	Circle Saw – 2” dia	Plastic Block - t = 1”	600 RPM	0.25 IPM
Coil Spacers				
Lathe	Turning – 1.89” ± 0.001”	ARS	600 RPM	0.5 IPM
Lathe	Boring – 0.5” ± 0.005”	ARS	600 RPM	0.5 IPM
Band Saw	Cutting – 0.1” length	ARS	100 RPM	0.05 IPM
Coils				
Lathe	Winding	Copper Wire	500 RPM	-

VALIDATION TESTING

The engineering specifications were tested for the customer requirements of power output and efficiency. The basic idea of testing the prototype was to oscillate the magnet around the coils and measure the electromagnetic induced voltage and calculate power. Ideally the prototype was to be attached to a single VIVACE module and tested in the Low Turbulence Free Surface Water Channel in the University of Michigan. The testing channel, however, was under repair, and as such the prototype was tested manually.

To test the efficiency of the PTO system, an input power was applied to the system, with the subsequent output power measured. The input power was applied to the PTO at a frequency and distance equal to that of the VIVACE system (1Hz). The input force (F) was determined through the use of a force gauge, with the subsequent power measured using the following equation, where x denotes distance traveled, and t denotes the time of travel:

$$P_{input} = F \cdot x \cdot t \qquad \textbf{Equation 27}$$

To measure the output power, a multimeter was first used to measure the resistance of a coil, found to be 1600 ohms. An external resistance matching the resistance of the coil was then attached in order to maximize the power output. With the input force acting upon the coils, the output voltage (V) was then measured, with the output power calculated through the equation below:

$$P_{output} = \frac{V^2}{R} \qquad \textbf{Equation 28}$$

With this analysis, the following data was measured, and the efficiency (output power/input power) calculated:

Table 9: Validation Results

Input Data				Output Data		
Distance Traveled (m)	**Applied Force (N)**	**Time Of Applied Force (sec)**	**Power Input (W)**	**Voltage (V)**	**Resistance (Ohms)**	**Power Output (W)**
0.105	4.45	0.167	0.078	8.00	1600	0.04

Efficiency: 0.51

The engineering specifications not validated via testing were the cost and the design life. The cost was calculated by summing the overall cost of the prototype and the additional cost for the final design. The additional cost would result from changing the regular bearing to the waterproof bearing, using coating materials for corrosion prevention, more material need for the scaled up VIVACE module, etc.

DISCUSSION

The main strength of our design was the simplicity. One of the main requirements was that the system be low maintenance, given that it would be located at a depth of forty feet under water; less moving parts correlates to a lesser chance of something breaking. The only thing that moves in the system is the outer housing attached to the VIV cylinder. Everything else is stationary and enclosed in the inner housing. This makes it very easy to isolate the electrical components from the wet environment, which was another very important requirement.

Coil Wire

However, there is some significant room for improvement. We encountered many problems with the wire. It was too thin and was very fragile. We were supposed to have four coils in our prototype, but two of the leads snapped during construction and could not be repaired. The third snapped during set up at the Design Expo. In hindsight, we should have either ordered thicker wire. Then we would not have had this problem. Also, because the wires were so thin, we think they could not carry that much current. This may have contributed to such a low power output. Using thicker wire may have been able to increase this.

Magnet

During project testing, the reach of the magnetic field powered by the magnet may be farther than anticipated, as the manufacturer stated a magnetic field reach of 1.5”, a value beyond the assumptions made. In this scenario, the change in magnetic flux of the coils will be significantly reduced due to the fact that the coil will never completely exit the magnetic field. This in turn will directly lead to a reduction in power, an undesired result. Using a thinner magnet may have been able to help this, because more coils could have been included in the inner housing. A thinner magnet has a shorter reach for its magnetic field. This reach was the basis for the length of the coils (about two inches) because if the magnet can reach across the entire magnet when passing over the coil, it can generate a larger magnetic flux. Consequently, a larger magnetic flux produces a larger emf. So, the thinner magnet decreases the length of the coils and increases the number of them that can be used. K&J Magnetics, the source of our magnet, sells a ring magnet 3"OD x 1 1/2" ID x 1/4" thick that we could have potentially used for this. Two magnets could also be placed close to each other. The interference of magnetic fields will shorten the reach, but its effect on the overall magnetic field strength is unknown.

Iron Core

We also wrapped the coils of wire around iron cores in order to increase the strength of the magnetic field. However, due to time constraints, we were only able to experiment with two different sizes. A larger iron core will increase the magnetic field strength and thus the potential power output. However, it will also increase the magnetic resistance to the motion of the magnet. Given more time and access to a working VIV cylinder in the hydrodynamics lab, we may have been able to find the optimal size core to produce the maximum power without damping the system so much that VIV is suppressed.

Tolerances

The specifications for the manufacturing of the prototype also contain exceptionally tight tolerances. In light of the materials and equipment used, manufacturing methods for these tolerances are quite expensive. An alternative may be to use self-aligning bearings with higher tolerances in place of manufacturing the PTO housings with such tight tolerances. The downside of this scenario is of course an increased cost over relatively cheaper (non-self-aligning bearings).

Damping/electromotive force

Due to the power of the magnet and the use of the iron rod, the additional source of resistance between the metal and magnet are unknown. In cases where the magnetic field never completely leaves the coil, the remaining magnetic field may interfere with the passing magnet itself to generate a resistive force as well. These sources of resistance are direct contributors to damping in the system. If this damping proves too high, the effects of vortices shedding on the cylinder may be mitigated such that the system experiences either reduced amplitude or none at all. To reduce this force, known as counter-electromotive force (counter emf), shortening the reach of the magnetic field as described previously will be the most effective adjustment. In addition, one can reduce the amount of iron used in the system as well. While this reduces the overall magnetic permeability of the system, the motion of the cylinder itself will occur at a higher frequency and amplitude to actually increase the overall performance of the system.

PTO Required Force and VIVACE Cylinder Input Force

The VIVACE Cylinder was experimentally determined to move vertically with a force of approximately 200N. The PTO, however, requires an input force of approximately 5N, in which the system fails to take advantage of the available energy transferred to the cylinder. With this substantially larger force, we can design a system with a larger iron core diameter to increase magnetic permeability, a larger coil outer diameter to increase the number of turns, more magnets to increase the change in magnetic flux, and materials that better conduct current such as laminated steel, which also has a lower resistance. Where all of these changes will add an increased resistance to the motion of the PTO, the overall force exerted by the cylinder will compensate for this change.

From earlier analysis, one can see that the output power of the PTO was less than the desired 1 W. One can also see that the necessary input power in moving the outer housing of the PTO was less than 1 W as well. In drastically increasing the input power of the system with the proposed modifications described above, one can drastically increase the input power to the PTO, with the PTO subsequently harnessing this increased power to give a greater output.

RECOMMENDATIONS

While we are confident in the overall final design and the work we put into it, it is not without fault. Some aspects which could have been significant to our project had to be ignored for the sake of time. First among these omitted components is more consideration of alternative power generators. While it is true that we considered several methods of power generation, it is also true that a bias was given to the linear generator because Professor Bernitsas expressed his desire that the design use that type of power generation. Although our prototype proves that a linear generator does in fact work in this setting, it is strongly advised that further investigation be given to individuals with greater backgrounds in power generation. In particular, we suggest that further investigation into the EPAM material once it becomes financially and commercially available.

In addition, the layout of the PTO should be redesigned, as the current design only includes one PTO on each side of the VIVACE cylinder. There exists the possibility that several PTOs could be attached to the cylinder, depending on the measured force of the cylinder's motion.

There are additional components in the final design which were ignored because they were outside the scope of the design and our ability. These parts are currently being developed by Professor Xiros, but the locations and design of the parts will need to be determined once their concepts have been proven.

The parts of the final design and their characteristics could also be refined from the final design. From our experience with the coils, there is a need to develop some method of both working with the delicate wire and ensuring that the coils are not in danger of being damaged over the expected life cycle of the PTO. Because of the limited resources, we were unable to experiment with varying magnetic field sizes. Changing the magnet's dimensions and materials could affect the PTO's efficiency.

RECTIFIER

Some brief discussion about the rectifier for the final design is as follows. In our final design, we decide to use a full-wave rectifier, which converts both polarities (positive and negative portion) of the input waveform to DC (direct current) and therefore is efficient for power transfer. Figure 8 below shows a schematic diagram of a full-wave rectifier. Here, four diodes are required to achieve the AC to DC conversion and such an electronic device is also called a diode-bridge modulator. The simplest way to estimate the output voltage through the rectifier is to assume the input (voltage U_{in} generated by a single VIVACE module) is pure sinusoidal, e.g. $A\cos(\omega t)$, where A is the amplitude, ω is the frequency of the signal, and t is the time. Then, the output voltage U_{out} can be estimated by performing a Fourier transform as:

$$U_{out} \simeq \frac{A}{2} + \frac{2A}{\pi}(\cos\omega t - \frac{1}{3}\cos 3\omega t + \frac{1}{5}\cos 5\omega t) - \text{loss}$$

Equation 29

where loss represent the loss from the peak input voltage to the peak output voltage of the rectifier. For a full-wave rectifier, the loss is caused by the built-in voltage of the diodes and is about 0.7V for ordinary silicon p-n junction diodes.

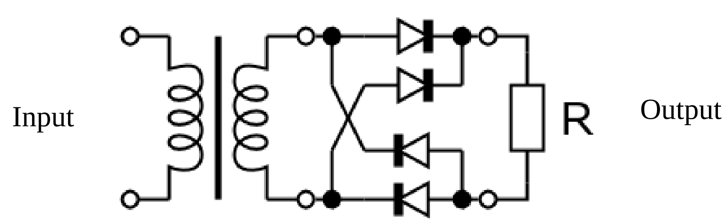


Figure 8: A schematic diagram of a full-wave rectifier

CONCLUSIONS

To convert ocean/river hydrokinetic energy to electricity, Professor Michael Bernitsas of the Marine Renewable Energy Laboratory requested our assistance in designing and fabricating a Power Take Off system for the VIVACE convertor. This system was to generate a power of 1W and be highly efficient. In addition, it was to have as few moving parts as possible, be cost competitive, and be able to seal wet and dry components.

In order to meet customer requirements for the Power Take Off (PTO) system we broke the system into four components. For each of these components we came up with a number of concepts, which were graded through Pugh charts to find which concepts were superior. The final concept developed is a linear induction generator that works by passing a high powered magnet over coiled wire to produce a current through induction. The design features a non-corrosive tube that houses the coils in a dry environment and bearing that will guide the magnet over the coils smoothly. A parameter analysis was performed to improve our understanding of the characteristics of our final design. A stress analysis performed on the tube yielded a minimum safety factor of 2.0 for the material and geometry selected. Moreover, CSE, SimaPro, and DesignSafe software were used to assist material and manufacturing process selection, design for assembly, environmental sustainability, and safety, as seen in Appendix H.

Following these analyses, a fabrication plan was made and a prototype for proof of concept was built. . Through validation testing, the prototype power output was found to be of 0.04 W with a resistance of 1600 ohms. While this result yields an output power substantially less than desired by the customer, the overall efficiency of the PTO will yield a system capable of achieving such goals when scaled up. The results of the prototype fabrication and final design generation prompt further research in the PTO system.

ACKNOWLEDGEMENTS

Much gratitude is expressed to Professor Michael M. Bernitsas and the researchers at the Marine Renewable Energy Laboratory for making this project possible. Further thanks are needed for Professor Gregory M. Hulbert for his close guidance throughout the entire process. Much appreciation is given to Mr. Bob Coury, Mr. Marv Cressey, and Ms. Betty Sweet, who provided invaluable assistance in creating the prototype. Professors Niko Xiros and Stephen Rand provided much needed guidance in electrical issues. Professors Steven Skerlos, Diann Brei, Sridar Kota, Jyoti Mazumder, and Lalit Patil, as well as Graduate Student Instructor Esra Suel are thanked for their participation in the project as well.

APPENDIX A: Final Design Engineering Drawings (all units in inches)

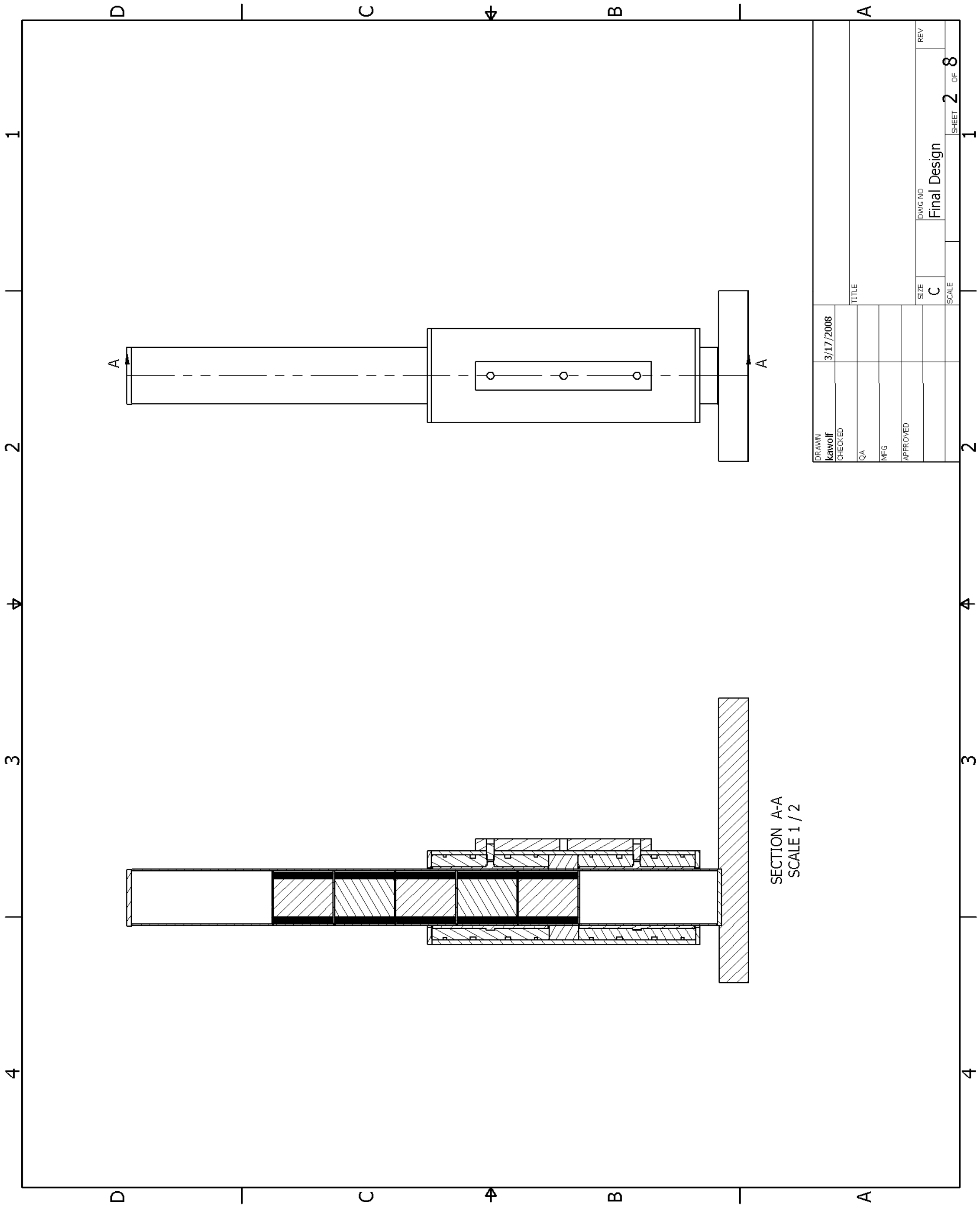


Figure 9: Engineering Drawing of Mounting Bracket

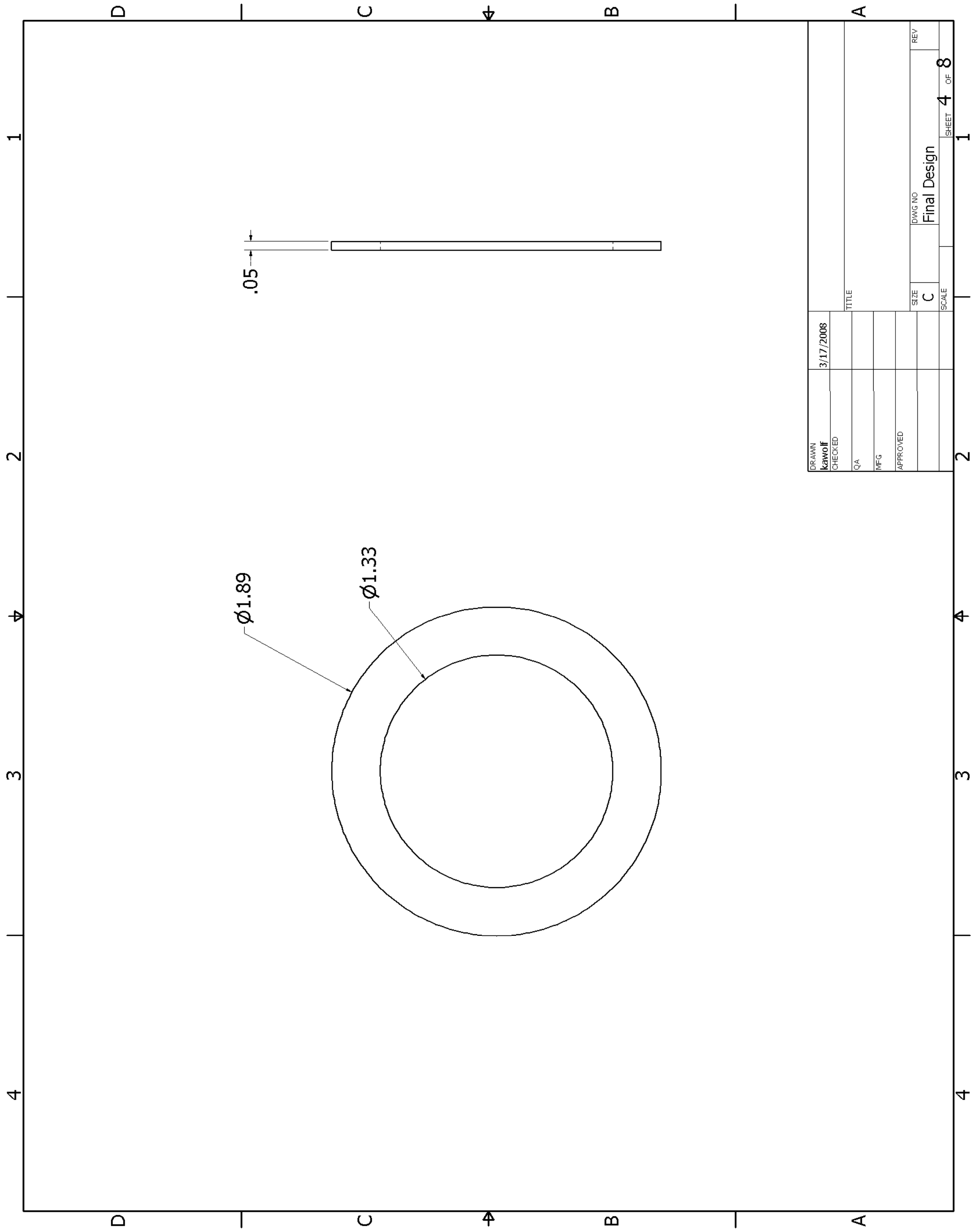


Figure 10: Engineering Drawing of Coil Spacer

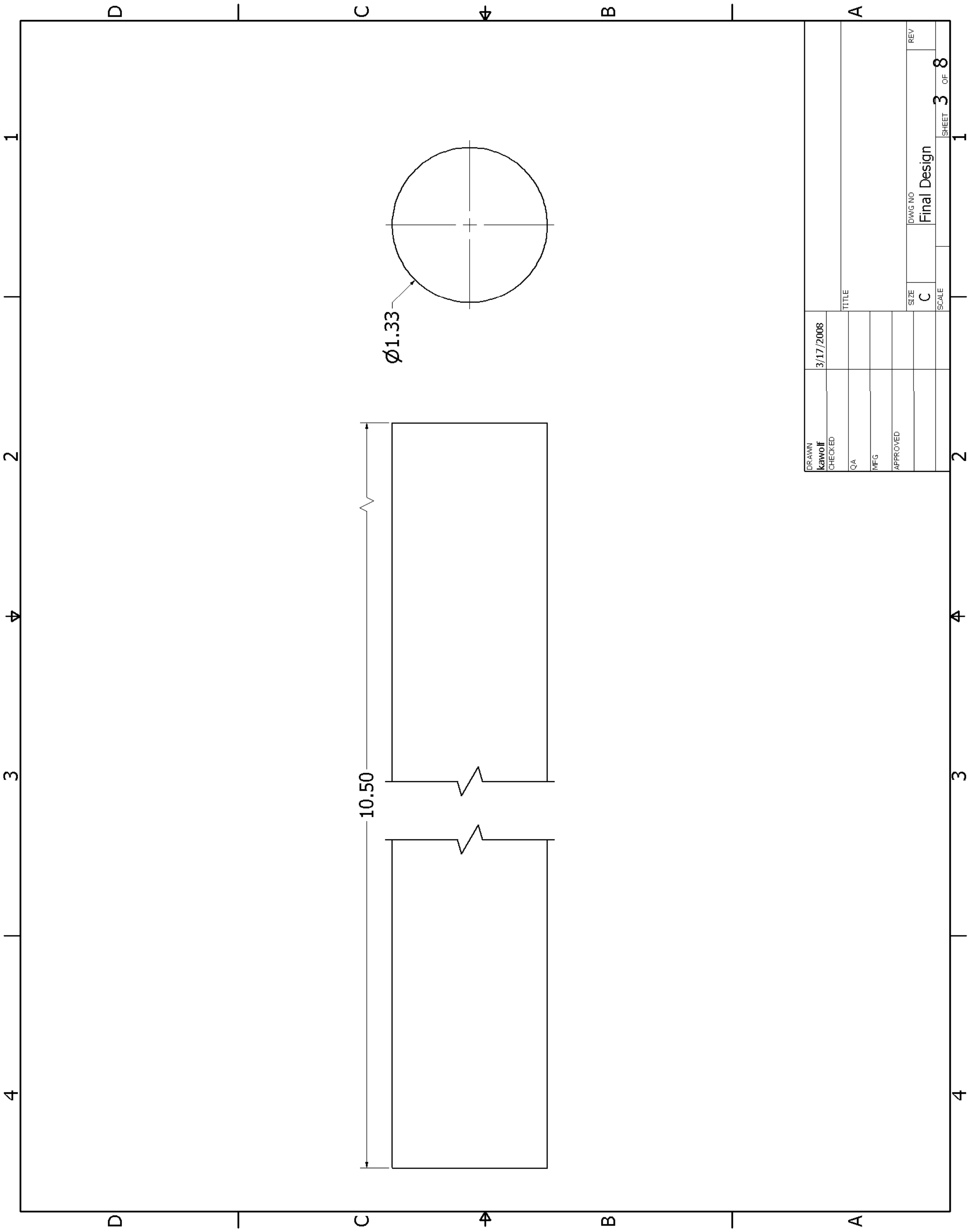


Figure 11: Engineering Drawing of Iron Core

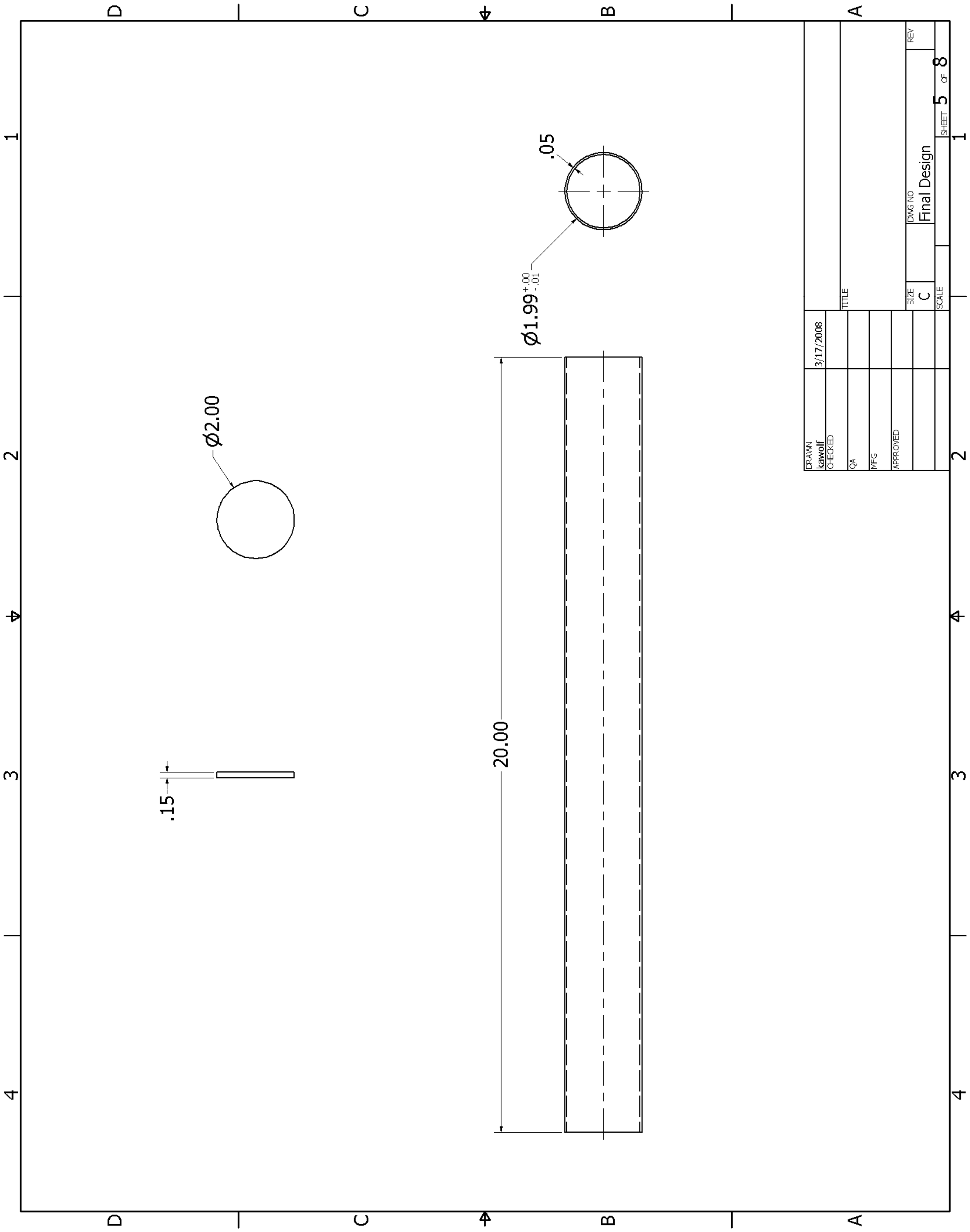


Figure 12: Engineering Drawing of Inner Housing

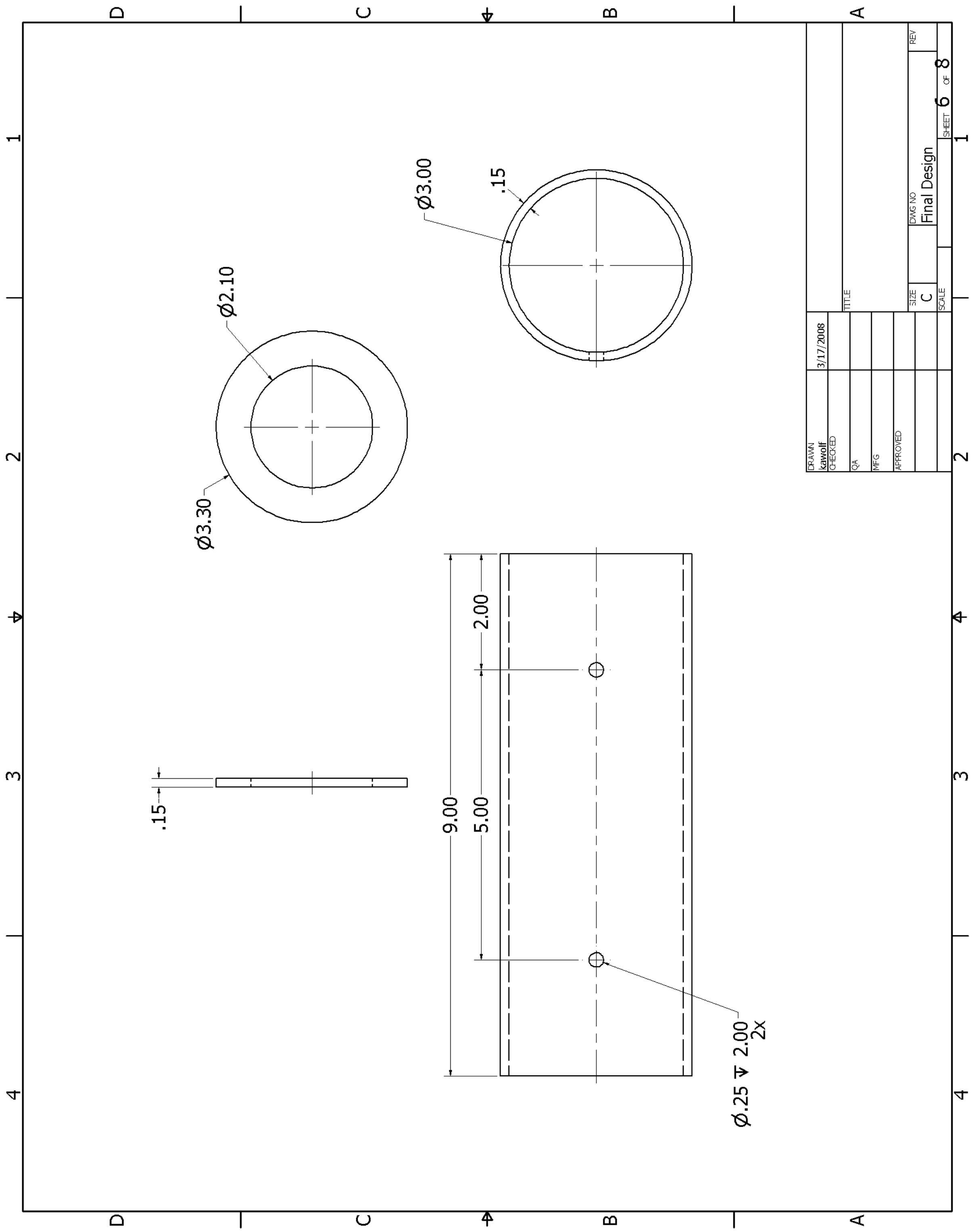


Figure 13: Engineering Drawing of Outer Housing

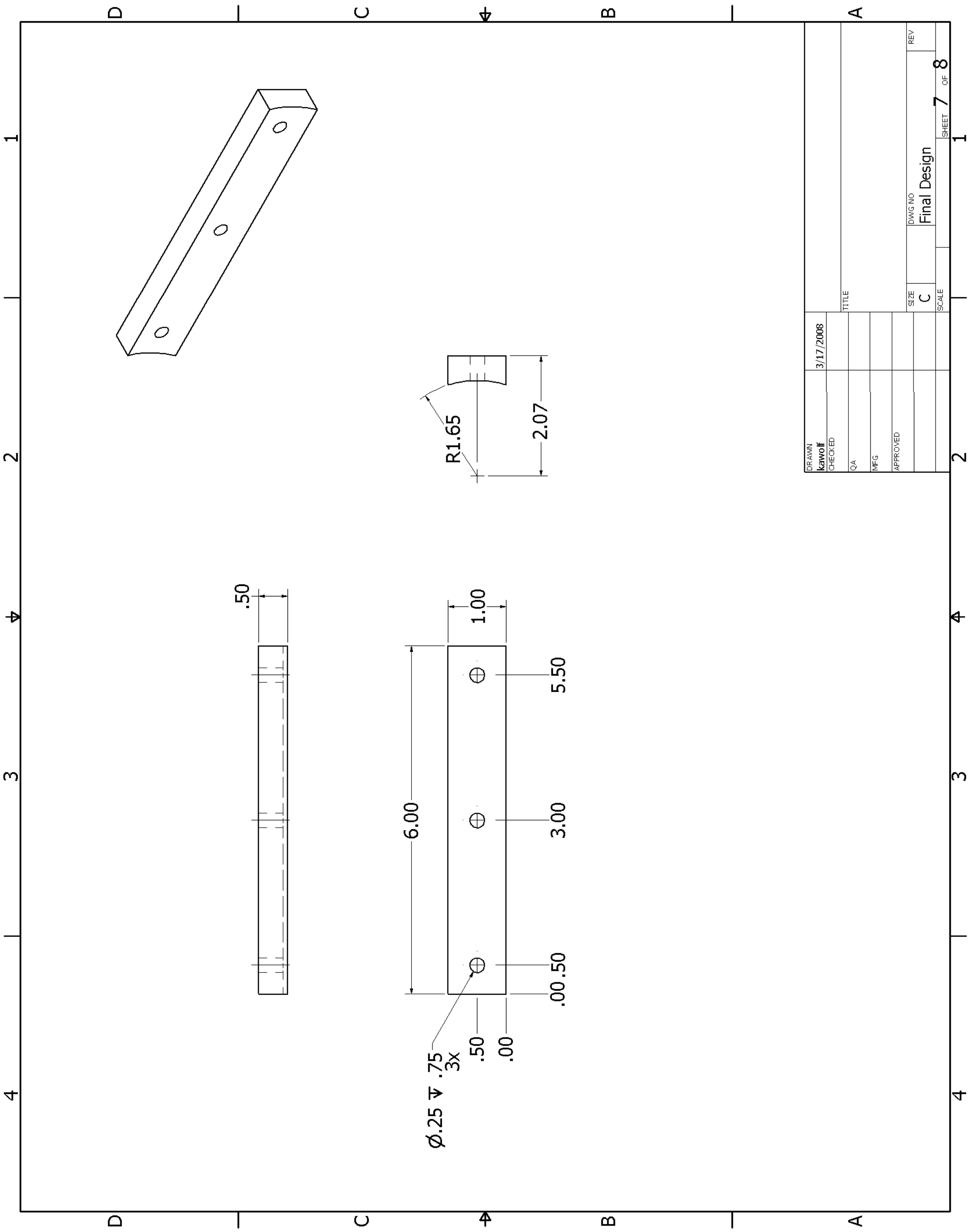


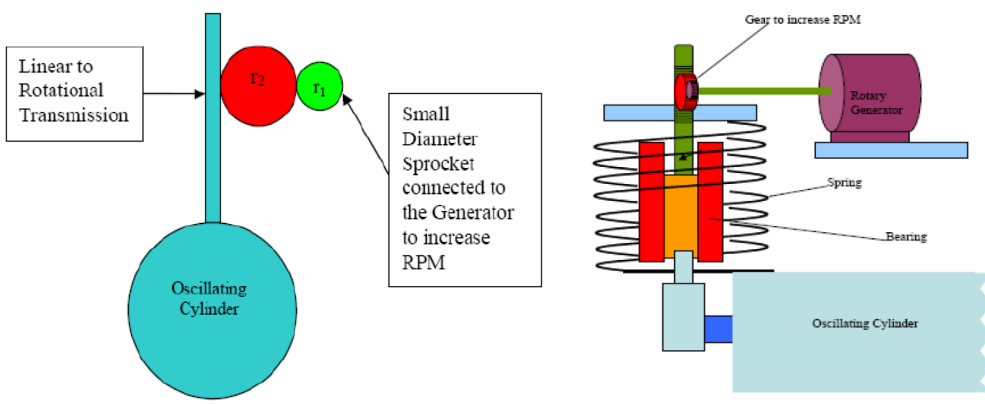
Figure 14: Engineering Drawing of Mounting Bracket

APPENDIX B: Concepts for Energy Conversion

We researched for five basic energy conversion devices that would be possibly used for the PTO system: (a) rotary generator, (b) hydraulic generator, (c) linear generator, (d) Elecroactive Polymer Artificial Muscle (EPAM), and (e) ferrofluid generator.

Rotary Generator One of the currently existing PTO systems for the VIVACE Converter uses a rotary generator. A rotary generator is a rotating electromagnetic generator consisting of a rotor and a stator. In order to use a rotary generator, the linear oscillatory mechanical motion of the VIVACE cylinder must be converted to a rotational oscillatory motion of the generator shaft. While most rotary generators require a relatively high shaft RPM to generate sufficient electrical output (e.g. a shaft RPM of 250 gives an output voltage of 10V [10]), the VIVACE converter generates a relatively low RPM (e.g. the oscillation frequency of the cylinder is about 1Hz [9]). Therefore, a two-gear transmission system would be required to increase the generator shaft's RPM (see Figure 3). For the same reason, a low RPM rotary generator is desired. In initial testing of a rotary generator with the VIVACE prototype, a maximum peak efficiency of 0.308 and a maximum power of about 10 W were reported. The corresponding integrated power efficiency for the tested VIVACE module was 0.22 at a water flow velocity of 0.840 m/sec [9].

Rotary generators are typically inexpensive and readily available [10-12]. They have high efficiency, especially when the size of the VIVACE Converter System is small (i.e. only a few VIVACE modules are used in the system). Some of the rotary generators are designed to be built into wind turbines, which can sustain a higher torque and thus have a lower RPM requirement [5]. These products are the first choice when a rotary PTO system is designed. In making this system compatible with an aquatic system, however, there are mitigating factors. For example, the design of a seal system is a big challenge, which separates the wet environment (e.g. the oscillating cylinder) and the dry environment (e.g. the rotary generator). Also, if several VIVACE modules are used in the electricity generation system (thus, there are several AC outputs), it is not easy to combine multiple AC outputs into a single power output.



(a) (b)

Figure 15: Front view (a) and side view (b) of the two-gear transmission mechanism [9].

Hydraulic Generator A hydraulic generator is another option to be used in our PTO system. Ross Henderson designed a wave energy conversion system known as Pelamis using this type of PTO. He described the Pelamis PTO as consisting of sets of hydraulic cylinders that pump fluid, via control manifolds, into high-pressure accumulators for short-term energy storage. Hydraulic motors use the smooth supply of high-pressure fluid from the accumulator to drive grid-connected electric generator [13]. A simplified hydraulic circuit is shown in Figure 4 below.

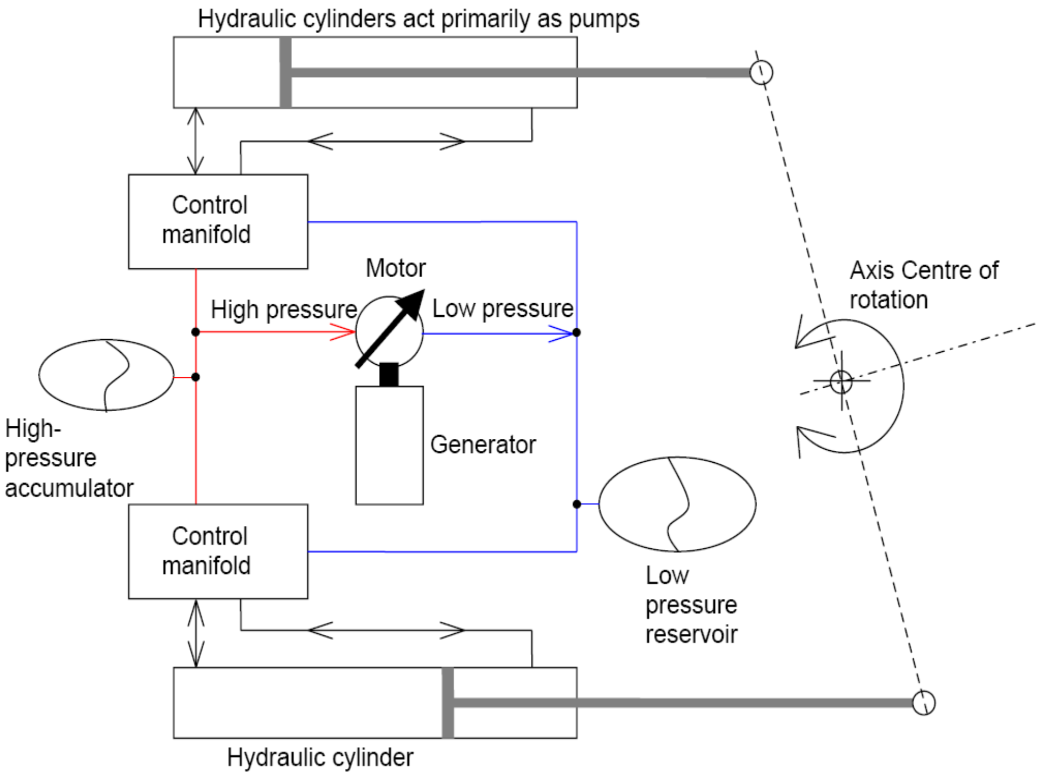


Figure 16: Simplified hydraulic circuit of the Pelamis wave energy converter [13]

The design of a single high-pressure accumulator in the PTO system makes it much easier to combine multiple power generation outputs. Thus, when the size of the VIVACE power generation is large (i.e. many VIVACE modules are used), a hydraulic generator is preferred regardless of its low efficiency. Moreover, with the generation and development of Digital Displacement™ [13] machines, a novel digital hydraulic pump capable of offering a much higher efficiency than conventional hydraulic transmission is possible [9]. The abovementioned seal mechanism and many valves involved in the PTO systems, however, are still challenges for this design.

Linear Generator A linear generator is another PTO option. A linear generator is simply a device which passes a coil or coils of wire through a magnetic field to produce an electromotive force (emf), or simply a voltage. The cause of this emf is the phenomenon known as electromagnetic induction [14]. If you are familiar with the Faraday flashlight on TV, it works using this same principle. This device allows for a simple and effective way of creating electricity. There are relatively few moving parts so maintenance costs would be low. In addition, it works at low RPMs, and is very efficient [6]. One of the main challenges is again sealing off the wet and dry environments. A seal would need to be devised to account for the in-and-out motion of the magnet through the coils (or the coil through magnet). In addition, some kind of external restoring force is needed to perpetuate the motion of the cylinder. Most coiled springs do not have the fatigue life to withstand the number of cycles this device will undergo [6]. Price is also an issue. The neodymium iron boron (or equivalent rare Earth) magnets needed in this design are expensive, about ten times the cost of ferrite magnets [6]. Finally, because each cylinder would be moving at a different frequency and outputting a different voltage, it would prove very difficult converting all of the AC outputs to DC at a common voltage [6].

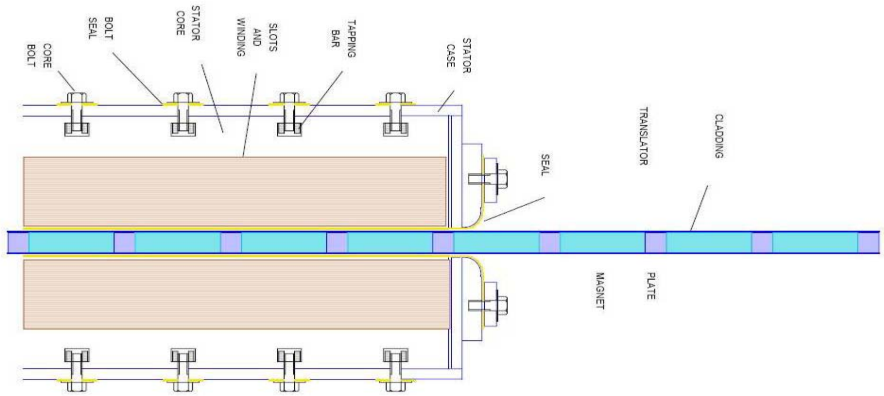


Figure 17: Linear Generator Technical Drawing [6]

EPAM Another possible option is a technology known as Electroactive Polymer Artificial Muscle (EPAM) developed by Artificial Muscle INC. The electroactive polymer is a conductive polymer [15] which, when an electric field is applied across it, deforms. It can also be used in the opposite sense: to convert kinetic energy into electricity as a generator. In this generator mode, EPAM can be seen as a device that varies its capacitance. When mechanical stresses are applied on the polymer and it is stretched, electrical charge is placed on the material (it has high capacitance). When the polymer contracts (it has low capacitance), the elastic stresses work against the electric field pressure and increase electric energy [16]. These polymers have shown high coupling efficiency and high energy density [17], as well as exhibiting good performance when submerged in water [15]. In addition, the system is extremely simple with only one moving part, so maintenance would be infrequent. Also, sealing wouldn't be much of an issue since all moving parts could be left in the wet environment. The fatigue life, however, is unknown and would need to be able to withstand tens of millions of cycles. Finally, the biggest problem with implementing this technology is that it is relatively new and is not yet commercially available.

Figure 18: EPAM Proof of Concept [13]

Ferrofluid Generator A ferrofluid is composed of nano-scale ferromagnetic particles suspended stably in a carrier fluid. The basic idea of a ferrofluid generator is to use devices like a pump to drive the magnetic fluid and then the fluid passes through a high density of coil to generate the time varying magnetic flux and induced current. One thing to mention is that though ferrofluids can become strongly polarized in the presence of a magnetic field; they do not retain magnetization in the absence of an externally applied field. Thus, permanently magnetized fluids are difficult to create at present. [18] Also, the price of ferrofluids is relatively expansive: about 130 dollars for one liter. [19]

Figure 19: Ferrofluid magnetic liquid [19]

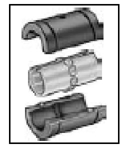
APPENDIX C: Part List

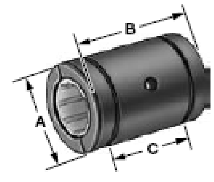
Part #	Price	Part Name	Qty	Material	Color/Finish	Size	Mass	Manuf. Process	Function
RZ0Y0X0	$95.00 + S&H	Neodymium Magnet	1	Neodymium-iron-boride		3" od x 2" id x 1" thick (inches)	481.941893 (gms)	None	
8639T57	$190.82 +S&H	Self- Aligning Linear Bearing	2	Plastic insert/Aluminum Shell		2" id x 3" od		None	
		Inner Coil Housing	1	PVC		1.90" id x 2" od x 20" long		Injection Molding	Isolate electric components from water
		Outer Housing	1	PVC		3" id x 3.15" od x 9" long		Injection Molding	Hold magnet/bearings and attach to VIV cylinder
		Iron Core	5	Iron		1.51" diameter; 2.04 " long		Extruded	Increase relative magnetic permeability
60980042885	$10.56 + S&H	3M™ Marine Adhesive/Sealant 5200 White	1	polyurethane	white	3 oz Tube		n/a	seal inner housing
		Spacer	4	Aluminum		1.33id 1.89"od 0.05" thick		Stamped	Separate coils/iron cores
Ext-300		Methyl Methacrylate Adhesive	1	Methyl Methacrylate				n/a	Adhere magnet and bearings to outer housing

APPENDIX D: Parts

Bearings for Final Design:

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.	For Housing Bore Max.	O'all Lg. (B)	Fixed-Alignment Bearings (C)	Fixed-Alignment Bearings	Fixed-Alignment Bearings Each	Self-Aligning Bearings (C)	Self-Aligning Bearings	Self-Aligning Bearings Each	Replacement Inserts	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

Magnet Coating Information Sheets

Industrial & Marine Coatings

SHERWIN WILLIAMS.

4.67
DURA-PLATE® 235
MULTI-PURPOSE EPOXY

PART A	B67-235	SERIES COLORS
PART B	B67V235	HARDENER

PRODUCT INFORMATION

Revised 1/06

PRODUCT DESCRIPTION

Dura-Plate 235 Multi-Purpose Epoxy is a modified epoxy phenalkamine, formulated specifically for immersion and atmospheric service in marine and industrial environments. Dura-Plate 235 provides exceptional performance in corrosive environment, and can be applied at temperatures as low as 0°F.

- Self-priming
- Low temperature application
- Surface tolerant - damp surfaces
- Provides salt water and fresh water immersion resistance
- Cures at temperatures as low as 0°F
- Approved as a primer under MIL-P-23236, Type IV, Class 2, Grade B

RECOMMENDED USES

For use over prepared steel and masonry surfaces.

- Salt water and fresh water immersion resistance
- Ballast tanks, offshore and marine structures
- Bilges and wet void areas
- Above- and below- water hull areas
- Decks and superstructures
- Water and waste water tanks
- Acceptable for use with cathodic protection systems.
- Dura-Plate 235 Black meets or exceeds the performance criteria of C-200; SSPC Paint 16; and Mil-P-23236B(SH) Type I or IV Class 2
- Suitable for use in USDA inspected facilities

Note: Not for immersion service when tinted.

PRODUCT CHARACTERISTICS

Finish: Semi-Gloss

Color: Wide range of colors available

Volume Solids: 68% ± 2%, mixed

Weight Solids: 79% ± 2%, mixed

VOC (EPA Method 24): Unreduced: <280 g/L; 2.33 lb/gal
Reduced 10%: <327 g/L; 2.72 lb/gal

Mix Ratio: 4:1 by volume

Recommended Spreading Rate per coat:

Wet mils:	6.0 - 12.0
Dry mils:	4.0 - 8.0
Coverage:	136 - 272 sq ft/gal approximate

NOTE: Brush or roll application may require multiple coats to achieve maximum film thickness and uniformity of appearance.

Drying Schedule @ 6.0 mils wet @ 50% RH:

	@ 0°F	@ 40°F	@ 77°F	@ 120°F
To touch:	18 hours	3½ hours	2 hours	20 mins
To handle:	36 hours	12 hours	3½ hours	40 mins
To recoat:				
minimum:	36 hours	12 hours	3½ hours	40 mins
maximum	6 months	6 months	6 months	6 months
Cure to service:	30 days	14 days	7 days	3 days
Pot Life:	16 hours	8 hours	4 hours	1 hour
Sweat-in-time:	1 hour	30 mins	15 mins	5 mins

If maximum recoat time is exceeded, abrade surface before recoating. Drying time is temperature, humidity and film thickness dependent.

Shelf Life: 36 months, unopened
Store indoors at 40°F to 100°F

Flash Point: 116°F PMCC, mixed

Reducer/Clean Up: Reducer R7K104

PERFORMANCE CHARACTERISTICS

System Tested: (unless otherwise indicated)
Substrate: Steel
Surface Preparation: SSPC-SP10
2 cts. Dura-Plate 235 @ 5.0 mils dft/ct

Abrasion Resistance:
Method: ASTM D4060, CS17 wheel, 1000 cycles, 1 kg load
Result: 65 mg loss

Adhesion:
Method: ASTM D4541
Result: 850 psi

Direct Impact Resistance:
Method: ASTM D2794
Result: 10 in lb

Dry Heat Resistance:
Method: ASTM D2485
Result: 250°F

Moisture Condensation Resistance:
Method: ASTM D4585, 100°F, 2000 hours
Result: Rating 10 per ASTM D610 for rusting
Rating 10 per ASTM D714 for blistering

Pencil Hardness:
Method: ASTM D3363
Result: H

IMMERSION
(Ambient temperature)

- Salt Water .... Recommended
- Fresh Water .... Recommended
- Ballast Tank Mix .... Recommended

Epoxy coatings may darken or yellow following application and curing.

continued on back

Industrial & Marine Coatings

4.67
DURA-PLATE® 235
MULTI-PURPOSE EPOXY

PART A	B67-235	SERIES COLORS
PART B	B67V235	HARDENER

PRODUCT INFORMATION

RECOMMENDED SYSTEMS

Steel, immersion or atmospheric service:
2 cts. Dura-Plate 235 @ 4.0 - 8.0 mils dft/ct

Steel, immersion service:
1 ct. Dura-Plate 235 @ 4.0 - 8.0 mils dft
1-2 cts. Dura-Plate UHS @ 10.0 - 12.0 mils dft/ct

Steel, immersion service:
1 ct. Dura-Plate 235 @ 4.0 - 8.0 mils dft
1-2 cts. TarGuard Coal Tar Epoxy @ 8.0 - 16.0 mils dft/ct

Steel, immersion service:
2 cts. Dura-Plate 235 @ 4.0 - 8.0 mils dft
2 cts. SeaGuard Anti-Foulant
(refer to respective data pages for coverage)

Steel, atmospheric service:
1 ct. Dura-Plate 235 @ 4.0 - 8.0 mils dft
1-2 cts. Macropoxy 646 @5.0 - 10.0 mils dft/ct

Steel, atmospheric service:
1 ct. Zinc-Clad II Plus @ 3.0 - 5.0 mils dft
1-2 cts. Dura-Plate 235 @ 4.0 - 8.0 mils dft/ct

Steel, atmospheric service:
1 ct. Zinc-Clad IV @ 3.0 - 5.0 mils dft
1-2 cts. Dura-Plate 235 @ 4.0 - 8.0 mils dft/ct

Steel, atmospheric service:
1 ct. Corothane I GalvaPac Zinc Primer @ 3.0 - 4.0 mils dft
1-2 cts. Dura-Plate 235 @ 4.0 - 8.0 mils dft/ct

Steel, atmospheric service:
1 ct. Dura-Plate 235 @ 4.0 - 8.0 mils dft
1-2 cts. Acrolon 218 HS @ 3.0 - 6.0 mils dft/ct
or Hi-Solids Polyurethane @ 3.0 - 5.0 mils dft/ct

Concrete/Masonry, immersion service:
1 ct. Kem Cati-Coat HS Epoxy Filler/Sealer @ 10 - 20 mils dft/ct, as required to fill voids and provide a continuous substrate
2 cts. Dura-Plate 235 @ 4.0 - 8.0 mils dft/ct

Galvanized, atmospheric service:
1 ct. Dura-Plate 235 @ 4.0 - 8.0 mils dft

The systems listed above are representative of the product's use. Other systems may be appropriate.

SURFACE PREPARATION

Surface must be clean, dry, and in sound condition. Remove all oil, dust, grease, dirt, loose rust, and other foreign material to ensure good adhesion.
Refer to product Application Bulletin for detailed surface preparation information.
Minimum recommended surface preparation:

Iron & Steel:	
Atmospheric:	SSPC-SP2 or SSPC-SP12/NACE 5, WJ-4
Immersion:	SSPC-SP10, 2 mil profile or SSPC-SP-12/NACE 5, WJ-2
Concrete & Masonry:	
Atmospheric:	SSPC-SP13/NACE 6, or ICRI 03732, CSP 1-3
Immersion:	SSPC-SP13/NACE 6-4.3.1 or 4.3.2, or ICRI 03732, CSP1-3
Galvanized, atmospheric:	SSPC-SP1

TINTING

Tint Part A with 844 Colorants only. Mill White tints at 150%. Ultradeep Base tints at 100%. Five minutes minimum mixing on a mechanical shaker is required for complete mixing of color.

Note: Not for immersion service when tinted.

APPLICATION CONDITIONS

Temperature: 0°F minimum, 120°F maximum (air and surface)
At least 5°F above dew point
Material should be at least 40°F for optimal performance.

Relative humidity: 85% maximum

Refer to product Application Bulletin for detailed application information.

ORDERING INFORMATION

Packaging:
Part A: 1 gallon and 4 gallons in a 5 gallon container
Part B: 1 quart and 1 gallon
Weight per gallon: 11.3 ± 0.2 lb, mixed, may vary with color

SAFETY PRECAUTIONS

Refer to the MSDS sheet before use.

Published technical data and instructions are subject to change without notice. Contact your Sherwin-Williams representative for additional technical data and instructions.

DISCLAIMER

WARRANTY

Sherwin Williams

Industrial & Marine Coatings

4.67A
DURA-PLATE® 235
MULTI-PURPOSE EPOXY

PART A	B67-235	SERIES COLORS
PART B	B67V235	HARDENER

APPLICATION BULLETIN

Revised1/06

SURFACE PREPARATION

General Surface Preparation
Surface must be clean, dry, and in sound condition. Remove all oil, dust, grease, dirt, loose rust, and other foreign material to ensure good adhesion.

Iron & Steel, Immersion Service:
Remove all oil and grease from surface by Solvent Cleaning per SSPC-SP1. Minimum surface preparation is Near White Metal Blast Cleaning per SSPC-SP10/NACE 2 or SSPC-SP12/NACE 5. For SSPC-SP10/NACE 2, blast clean all surfaces using a sharp, angular abrasive for optimum surface profile (2 mils). For SSPC-SP12/NACE No. 5, all surfaces to be coated shall be cleaned in accordance with WJ-2. Pre-existing profile should be approximately 2 mils. Light rust bloom is allowed. Remove all weld spatter and round all sharp edges by grinding. Prime any bare steel the same day as it is cleaned.

Iron & Steel, Atmospheric Service:
Minimum surface preparation is Hand Tool Clean per SSPC-SP2 or SSPC-SP12/NACE 5. For surfaces prepared by SSPC-SP2, first remove all oil and grease from surface by Solvent Cleaning per SSPC-SP1. For better performance, use Commercial Blast Cleaning per SSPC-SP6/NACE 3, blast clean all surfaces using a sharp, angular abrasive for optimum surface profile (2 mils). For surfaces prepared by SSPC-SP12/NACE No. 5, all surfaces shall be cleaned in accordance with WJ-4. Pre-existing profile should be approximately 2 mils. Prime any bare steel the same day as it is cleaned.

Galvanized Steel
Allow to weather a minimum of six months prior to coating. Solvent Clean per SSPC-SP1 (recommended solvent is VM&P Naphtha). When weathering is not possible, or the surface has been treated with chromates or silicates, first Solvent Clean per SSPC-SP1 and apply a test patch. Allow paint to dry at least one week before testing adhesion. If adhesion is poor, brush blasting per SSPC-SP7 is necessary to remove these treatments. Rusty galvanizing requires a minimum of Hand Tool Cleaning per SSPC-SP2, prime the area the same day as cleaned.

Concrete/Masonry, Atmospheric Service:
New
For surface preparation, refer to SSPC-SP13/NACE 6, or ICRI 03732, CSP 1-3. Surface must be clean, dry, sound, and offer sufficient profile to achieve adequate adhesion. Minimum substrate cure is 28 days at 75°F. Remove all form release agents, curing compounds, salts, efflorescence, laitance, and other foreign matter by sandblasting, shotblasting, mechanical scarification, or suitable chemical means. Refer to ASTM D4260. Rinse thoroughly to achieve a final pH between 8.0 and 10.0. Allow to dry thoroughly prior to coating.
Old
Surface preparation is done in much the same manner as new concrete; however, if the concrete is contaminated with oils, grease, chemicals, etc., they must be removed by cleaning with a strong detergent. Refer to ASTM D4258. Form release agents, hardeners, etc. must be removed by sandblasting, shotblasting, mechanical scarification, or suitable chemical means. If surface deterioration presents an unacceptably rough surface, Kem Cati-Coat HS Epoxy Filler/Sealer is recommended to patch and resurface damaged concrete.

Concrete/Masonry, Immersion Service:
For surface preparation, refer to SSPC-SP13/NACE 6, Section 4.3.1 or 4.3.2, or ICRI 03732, CSP 1-3.

Always follow the industry standards listed below:
ASTM D4258 Standard Practice for Cleaning Concrete.
ASTM D4259 Standard Practice for Abrading Concrete.
ASTM D4260 Standard Practice for Etching Concrete.
ASTM F1869 Standard Test Method for Measuring Moisture Vapor Emission Rate of Concrete.
SSPC-SP13/NACE 6 Surface Preparation of Concrete
ICRI 03732

APPLICATION CONDITIONS

Temperature:	0°F minimum, 120°F maximum (air and surface) At least 5°F above dew point

Material should be at least 40°F for optimal performance.

Relative humidity:	85% maximum

APPLICATION EQUIPMENT

The following is a guide. Changes in pressures and tip sizes may be needed for proper spray characteristics. Always purge spray equipment before use with listed reducer. Any reduction must be compliant with existing VOC regulations and compatible with the existing environmental and application conditions.

Reducer/Clean Up .... Reducer R7K104

Airless Spray
- Unit .... 30:1 Pump
- Pressure .... 2400 - 2800 psi
- Hose .... 1/4" - 3/8" ID
- Tip .... .015" - .019"
- Filter .... 60 mesh
- Reduction .... As needed, up to 10% by volume

Conventional Spray
- Gun .... DeVilbiss MBC-510
- Fluid Tip .... E
- Air Nozzle 704
- Atomization Pressure .. 60-65 psi
- Fluid Pressure .... 5-15 psi
- Reduction .... As needed, up to 10% by volume

Brush
- Brush .... Natural Bristle
- Reduction .... Not recommended

Roller
- Cover .... 3/8" woven with phenolic core
- Reduction .... Not recommended

If specific application equipment is not listed above, equivalent equipment may be substituted.

continued on back

SHERWIN WILLIAMS.

Industrial & Marine Coatings

4.67A
DURA-PLATE® 235
MULTI-PURPOSE EPOXY

PART A	B67-235	SERIES COLORS
PART B	B67V235	HARDENER

APPLICATION BULLETIN

APPLICATION PROCEDURES

Surface preparation must be completed as indicated.

Mix contents of each component thoroughly using power agitation. Make certain no pigment remains on the bottom of the can. Then combine 4 parts by volume of Part A with 1 part by volume of Part B. Thoroughly agitate the mixture with power agitation. Allow the material to sweat-in as indicated prior to application. Re-stir before using.

If reducer solvent is used, add only after both components have been thoroughly mixed, after sweat-in.

Apply paint to the recommended film thickness and spreading rate as indicated below:

Recommended Spreading Rate per coat:

Wet mils:	6.0 - 12.0
Dry mils:	4.0 - 8.0
Coverage:	136 - 272 sq ft/gal approximate

NOTE: Brush or roll application may require multiple coats to achieve maximum film thickness and uniformity of appearance.

Drying Schedule @ 6.0 mils wet @ 50% RH:

	@ 0°F	**@ 40°F**	**@ 77°F**	**@ 120°F**
To touch:	18 hours	3½ hours	2 hours	20 minutes
To handle:	36 hours	12 hours	3½ hours	40 minutes
To recoat:				
minimum:	36 hours	12 hours	3½ hours	40 minutes
maximum	6 months	6 months	6 months	6 months
Cure to service:	30 days	14 days	7 days	3 days
Pot Life:	16 hours	8 hours	4 hours	1 hour
Sweat-in-time:	1 hour	30 mins	15 minutes	5 minutes

If maximum recoat time is exceeded, abrade surface before recoating.
Drying time is temperature, humidity and film thickness dependent.

Application of coating above maximum or below minimum recommended spreading rate may adversely affect coating performance.

PERFORMANCE TIPS

Stripe coat crevices, welds, and sharp angles to prevent early failure in these areas.

When using spray application, use a 50% overlap with each pass of the gun to avoid holidays, bare areas, and pinholes. If necessary, cross spray at a right angle

Spreading rates are calculated on volume solids and do not include an application loss factor due to surface profile, roughness or porosity of the surface, skill and technique of the applicator, method of application, various surface irregularities, material lost during mixing, spillage, overthinning, climatic conditions, and excessive film build.

Excessive reduction of material can affect film build, appearance, and adhesion.

Do not mix previously catalyzed material with new.

Do not apply the material beyond recommended pot life.

In order to avoid blockage of spray equipment, clean equipment before use or before periods of extended downtime with Reducer R7K104.

Prior to immersion service, test coating with appropriate holiday detection equipment. Set charge in accordance with manufacturer's recommendation.

Not recommended for immersion service when tinted.

Refer to Product Information sheet for additional performance characteristics and properties.

CLEAN UP INSTRUCTIONS

Clean spills and spatters immediately with Reducer R7K104. Clean tools immediately after use with Reducer R7K104. Follow manufacturer's safety recommendations when using any solvent.

SAFETY PRECAUTIONS

Refer to the MSDS sheet before use.

Published technical data and instructions are subject to change without notice. Contact your Sherwin-Williams representative for additional technical data and instructions.

DISCLAIMER

The information and recommendations set forth in this Product Data Sheet are based upon tests conducted by or on behalf of The Sherwin-Williams Company. Such information and recommendations set forth herein are subject to change and pertain to the product offered at the time of publication. Consult your Sherwin-Williams representative to obtain the most recent Product Data Information and Application Bulletin.

WARRANTY

The Sherwin-Williams Company warrants our products to be free of manufacturing defects in accord with applicable Sherwin-Williams quality control procedures. Liability for products proven defective, if any, is limited to replacement of the defective product or the refund of the purchase price paid for the defective product as determined by Sherwin-Williams. NO OTHER WARRANTY OR GUARANTEE OF ANY KIND IS MADE BY SHERWIN-WILLIAMS, EXPRESSED OR IMPLIED, STATUTORY, BY OPERATION OF LAW OR OTHERWISE, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE.

Magnet Information:
NEODYMIUM

- Attributes of Neodymium Material [20]

- Very high resistance to demagnetization
- High energy for size
- Good in ambient temperature
- Moderately priced
- Material is corrosive and should be coated for long term maximum energy output
- Low working temperature for heat applications, but higher levels of heat resistance materials are being introduced periodically

- If left exposed to the elements, the iron in the magnet will rust. To protect the magnet from corrosion and to strengthen the brittle magnet material, it is usually preferable for the magnet to be coated. Coatings include Nickel (most common/preferred), zinc, tin, copper, epoxy, silver and gold. [21]

- Neodymium material is brittle and prone to chipping and cracking, so it does not machine well by conventional methods. [21]

- Rare Earth magnets have a high resistance to demagnetization. They will not lose their magnetization around other magnets or if dropped. They will however, begin to lose strength if they are heated above their maximum operating temperature, which is 176°F (80°C). They will completely lose their magnetization if heated above their Curie temperature, which is 590°F (310°C). [21]

- Neodymium magnets are over 10x stronger than the strongest ceramic magnets. [21]

Positive	***Negative***
Very High Energy Product	Higher Cost (Except from us!)
High Coercive Force	Low Mechanical Strength - Brittle
	Moderate Temperature Stability
	Low Corrosion Resistance (When uncoated)

[21]

CERAMIC

- Attributes of Ceramic Material [20]

- High intrinsic coercive force
- Tooling is expensive
- Least expensive material compared to alnico and rare earth magnets
- Limited to simple shapes due to manufacturing process
- Lower service temperature than alnico, greater than rare earth
- Finishing requires diamond cutting or grinding wheel
- Lower energy product than alnico and rare earth magnets
- Most common grades of ceramic are 1, 5 and 8 (1-8 possible)

- These materials are readily available and at a lower cost than other types of materials used in permanent magnets. [22]

- Anisotropic magnets are magnetized in the direction of pressing. The anisotropic method delivers the highest energy product among ceramic magnets at values up to 3.5 MGOe (Mega Gauss Oersted). Ceramic magnets have a good balance of magnetic strength, resistance to demagnetizing and economy. [22].

Positive	***Negative***
Low Cost	Low Energy Product
High Coercive Force	Low Mechanical Strength - Brittle
High Resistance to Corrosion	

[21]

SAMARIUM COMBALT

- Attributes of Samarium Cobalt Material [20]

* High resistance to demagnetization
* High energy (magnetic strength is strong for its size)
* Good temperature stability
* Expensive material (cobalt is market price sensitive)

- Samarium cobalt is a type of rare earth magnet material that is highly resistant to oxidation, has a higher magnetic strength and temperature resistance than Alnico or Ceramic material. [22]
- These magnets offer the best temperature characteristics of all rare earth magnets and can withstand temperatures up to 300° C. [22]
- Sintered samarium cobalt magnets are brittle and prone to chipping and cracking and may fracture when exposed to thermal shock. Due to the high cost of the material samarium, samarium cobalt magnets are used for applications where high temperature and corrosion resistance is critical. [22]

Positive	***Negative***
High Corrosion Resistance	High Cost
High Energy Product	Low Mechanical Strength - Brittle
High Temperature Stability	
High Coercive Force	

[22]

- SAMARIUM COBALT MAGNETS… offer the designer a tremendous combination of extremely high magnetic properties, outstanding thermal stability and excellent corrosion resistance. [23]
- Other advantages of SmCo over NdFeB include better corrosion resistance and greater magnetic output at temperatures above about 150°C. [23]

- Sensor applications requiring a stable magnetic field benefit from SmCo's low reversible temperature coefficient of induction: -0.030%/°C for Sm_2Co_{17}. The best NdFeB varies twice as much. The only common material with a lower coefficient than this is alnico, but with significantly lower magnetic output and resistance to de-magnetization. [23]

ALNICO

- Attributes of Cast Alnico Material [20]

• Size parameters range from 1 ounce to about 70 pounds
• Will cast to a variety of shapes and sizes

- Attributes of Sintered Alnico Material

• Size parameters range from about one ounce of material up to one cubic inch
• Pressed to close tolerance/minimal grinding to finish
• Mechanically strongest of alnico

- Attributes of Both Cast and Sintered Alnico [20]

• Very temperature stable, great for high heat applications
• Maximum working temperature 975° - 1020° F
  May be ground to size
• Does not lend itself to conventional machining (hard and brittle)
• High residual induction and energy product compared to ceramic material * Low coercive force compared to ceramic and rare earth materials (more subject to demagnetization)
• Most common grades of alnico are 5 and 8

- Alnico magnets are made up of a composite of aluminum, nickel and cobalt with small amounts of other elements added to enhance the properties of the magnet. [22]
- Alnico magnets have good temperature stability, good resistance to demagnetization due to shock but they are easily demagnetized.[22]
- Alnico magnets are produced by two typical methods, casting or sintering. Sintering offers superior mechanical characteristics, whereas casting delivers higher energy products (up to 5.5 MGOe) and allows for the design of intricate shapes. Two very common grades of Alnico magnets are 5 and 8. These are anisotropic grades and provide for a preferred direction of magnetic orientation. Alnico magnets have been replaced in many applications by ceramic and rare earth magnets. [22]

Positive	***Negative***
High Corrosion Resistance	High Cost
High Mechanical Strength	Low Coercive Force
High Temperature Stability	Low Energy Product

[22]

Magnet Waterproof Coating Information

Document Library
Technical Data Sheet

Rev: 2
Effective: 12/1/2004

Status: Active
Supersedes: 07/06/2000

3M™ Marine Adhesive/Sealant 5200

3M Part No.(s)	3M Part Descriptor(s)
06500	10 fl. oz. cartridge (295 ml) - White
05203	3 fl. oz. tube (90 ml) - White
05206	1fl. oz. tube (30 ml) - White
21463	5 gal. pail (18.93 L) – White
06504	10 fl. oz. cartridge (295 ml) - Black
05205	3 fl. oz. tube (90 ml) – Black
06502	10 fl. oz. cartridge (295 ml) - Mahogany

Description

3M™ Marine Adhesive/Sealant 5200 is a one-part polyurethane that chemically reacts with moisture to deliver strong, flexible bonds. It has excellent adhesion to wood, gelcoat and fiberglass. It forms a watertight, weather-resistant seal on joints and boat hardware, above and below the waterline. In addition, its flexibility allows for dissipation of stress caused by shock, vibration, swelling or shrinking.

Features

- Tough/flexible polyurethane polymer
- Non-shrinking
- One-part moisture cure
- Long working time

Typical Physical Properties

Base	Polyurethane
Density lbs/Gallon (Approx.)	11.3 lbs/gallon
Color	White
Solids Content (Approx.)	97%
Consistency	Medium paste
Service Temperature - °F	-40°F (-40°C) to 190°F (88°C)
Shore A Hardness (cured)	68
Specific Gravity	1.36
Coverage (10 oz.)	1/8 inch (0.3175 cm) bead = 120 lineal feet (36.6 m)

Performance Properties

Tensile, Elongation, and effect of water submersion:

A 1/8-inch (0.3175 cm) dumbbell specimen with a 1/8-inch (0.3175 cm) square cross section was tested at 2.0 inches/minute (5.08 cm/minute). All samples tested at 50% Relative Humidity and 70°F (21°C).

Environmental Conditions	Time	Tensile Strength psi (kg/cm^2)	Elongation (%)
50% R.H./ 70°F (21°C)	*52 days*	*705 (49.6)*	*762*
Fresh Water	*52 days*	*634 (44.6)*	*805*
Salt Water	*52 days*	*638 (44.9)*	*802*

Overlap Shear Strength
One inch (2.54 cm) overlap specimens (0.093 inch (0.2362 cm thickness). Samples cured at 70°F (21°C), 50% Relative Humidity.

Substrate	psi	kg/cm^2
Wood(s):		
Teak	502	35.3
Pine	680	47.8
Oak	549	38.6
Maple	656	46.1
Fir	700	49.2
Mahogany	564	39.7
Metal(s):		
Steel	538	37.8
Stainless Steel	352	24.7
Aluminum	393	27.6
Brass	474	33.3
Bronze	252	17.7
Copper	198	13.9
Lead	107	7.5
Zinc (Galvanized)	484	34.0
Plastics/Polymers:		
Fiberglass	362	25.5
Gelcoat	519	36.5
Polycarbonate	381	26.8
Acrylic	217	15.3
Nylon	175	12.3
ABS	231	16.2
Polypropylene	55	3.9
Polyethylene	48	3.4

Note: Because actual use conditions can vary for each application, each user must determine the suitability of 3M Marine Adhesive/Sealant 5200 for the intended use.

Application Information

Directions for Use

Surface Preparation:

There are waxes, coatings, sealants, grease, oil and other contaminants used in the marine industry, making it very important to clean all surfaces to be bonded before applying 3M™ Marine Adhesive/ Sealant 5200. Recommended procedures include cleaning with 3M™ General Purpose Adhesive Cleaner*, P. N. 08984.

Application of Adhesive Sealant:

Abrading the surfaces with a 180 grit to 220 grit abrasive, and subsequently wiping off residue, will enhance the bond strength. Cut tip of the nozzle to desired bead size. Puncture seal inside the threaded nozzle end and screw on nozzle. If using a 10 fl. oz. cartridge, knock out the bottom seal with a hammer and place the cartridge in a caulk gun. Apply 3M™ Marine Adhesive/Sealant 5200 to the seam or part to be bonded. Position parts. Tool material to desired appearance. Remove excess material with 3M™ General Purpose Adhesive Cleaner*, P. N. 08984.

Cure:

	Relative Humidity	Temperature	Time	Cure Depth
Open Time	50%	70°F (21°C)	30 hours	N/A
Open Time	90%	90°F (32°C)	4 hours	N/A
Full Cure	50%	70°F (21°C)	5 days	1/8 inch (0.3175 cm)

Cleanup:

For cleaning 3M™ Marine Adhesive/Sealant 5200 before it is cured, use a dry cloth to remove the majority of sealant, followed by a cloth damp with General Purpose Adhesive Cleaner*, P. N. 08984, toluene or acetone. Cured 5200 can be removed mechanically with a knife, razor blade, or sanding.

Limitations -

- Alcohol should not be used in preparation for bonding as it will stop the curing process, causing the adhesive to fail..

- Heat resistance - Due to the decreased value in bond strength at elevated temperatures, we do not recommend use of this product above 190°F (88°C).

- Do not apply at temperatures below 40°F (4°C) or on frost covered surfaces. Do not apply at surface temperatures above 100°F (38°C).

- 3M™ Marine Adhesive/Sealant 5200 is not recommended for use as a teak deck seam sealer. Extended exposure to chemicals (teak cleaners, oxalic acid, gasoline, strong solvents and other harsh chemicals) may cause permanent softening of the sealant.

- 3M™ Marine Adhesive/Sealant 5200 is not recommended for the installation of glass, polycarbonate or acrylic windows that are not also mechanically fastened with a system designed by the manufacturer. Inconsistent adhesion of these unprimed substrates, specific design of the window, and movement due to thermal expansion and flexing, may cause application failure. It is strongly recommended that the customer contact the window/port light/hatch manufacturer for recommendations on proper sealing procedures.

- When using 3M™ Marine Adhesive/Sealant 5200 with metals, it may be necessary to prime the surface to achieve adequate adhesion and durability of the bond. Scotch-Weld™ Structural Adhesive Primer EC-1945 B/A may be used for priming of most metals.

Applications:

Typical bonding and sealing applications include:

- Fiberglass deck to fiberglass hull
- Wood to fiberglass
- Porthole frames
- Deck fittings
- Moldings
- Trunk joints
- Between struts and planking
- Stern joints and hull planking

Structural bonding and sealing of:

- Wood
- Fiberglass
- Gelcoat
- Primed metal

Sealing of:

- Some plastics (test before assembly)
- Glass
- Metals

Storage and Handling:
Recommended Storage Temperature Range: 60°F (16°C) to 80°F (26°C)
Expected Shelf Life at Recommended Storage Temperature: 24 Months

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Precautionary Information
Refer to Product Label and Material Safety Data Sheet for Health and Safety Information before using this product.

Country
US

Important Notice to Purchaser
Technical Data: All physical properties, statements and recommendations are either based on tests we believe to be reliable or our experience, but they are not guaranteed. Because actual use conditions can vary for each application, each user must determine the suitability of 3M Marine Adhesive/Sealant 5200 for the intended use

* If 'Directions for Use' reference P.N.'s 08984, 08986, or 08987, please read. Federal and local air quality regulations may regulate or prohibit the use of surface preparation and cleanup solvents based on VOC content. Consult your local and Federal air quality regulations for information. When using solvents, use in a well ventilated area. Extinguish all sources of ignition in the work area and observe precautionary measures for handling these materials. Refer to product label and MSDS for P.N. 8984, 8986, or 8987 for detailed precautionary information.

Warranty and Limited Remedy: 3M warrants this product will be free from defects in materials and manufacture. **3M MAKES NO OTHER WARRANTIES, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO, ANY IMPLIED WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE**. If the product is proved to be defective your exclusive remedy and 3M's and seller's sole obligation will be, at 3M's option, to replace the product or refund the purchase price.

Limitation of Liability: 3M and seller will not be liable for any loss or damage arising from this product, whether direct, indirect, special, incidental or consequential, regardless of the legal theory asserted, including warranty, contract, negligence or strict liability.

For Additional Health and Safety Information
3M Marine
3M Center, Building 223-1N-13
Saint Paul, MN 55144-1000
1-877-366-2746 (1-877-3M MARINE)
http://www.3m.com/marine

EXTREME ADHESIVES®

15 Batchelder Road, Seabrook, NH 03874
Phone: 603-474-3070 Fax: 603-474-2750
800-888-GLUE (4583)
www.extremeadhesives.com

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 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
- Moderate 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.

APPENDIX E: E-mail to K & J Magnetics

Hi Kevin,

Thank you for contacting us. I'm afraid you won't like any of the answers:

1) How wear resistant is the nickel plating on them, and does it come standard? I need these magnets to be able to withstand the wear from being rubbed against a shaft.

A: The nickel plating will not hold up to constant wear. It should not be relied upon this way. You would have to insert a bushing of brass or nylon to use the magnets this way.

2) How corrosion resistant is the nickel plating? These magnets will need to last about 10 years under water.

A: The nickel-plating is corrosion-resistant, but not corrosion-proof. It will definitely not last 10 years (or even 1) underwater.

3) Can these magnets be welded at all? If not do you have any suggestions for permanently attaching them to other objects?

A: They definitely cannot be welded. We recommend that they be fastened by a mechanical method like a screw, but they can be attached using adhesives. If you have any other questions, please do not hesitate to ask.

Best Regards,
Kevin Stayer
K&J Magnetics, Inc.
www.kjmagnetics.com

APPENDIX F: Prototype Bill of Materials Outside of Machine Shop

Item	Qty	Source	Catalog Number	Cost	Contact	Notes
Hard-Wall Rigid Clear PVC Tubing, 1-7/8” ID, 2” OD, 1/16” Wall Thickness	3 Feet	McMaster-Carr	53945K223	$20.98	mcmaster.com	
Gray PVC Round Tube, 4” OD x 3” ID	1Foot	McMaster-Carr	8749K25	$25.72	mcmaster.com	
Magnet Wire, 36 Awg, Copper, 12300’ Length	3 Spools	McMaster-Carr	7588K85	$24.93	mcmaster.com	
3" OD x 2" ID x 1" thick Magnet	1	K&J Magnetics	RZ0Y0X0	$95.00	kjmagnetics.com	
Bearings	2	Igus, Inc.	RJI-01-32	$71.68	igus.com	

APPENDIX G: Description of Engineering Changes Since Design Review #3

There have been numerous changes to our prototype since Design Review #3. When assembling the outer housing we found we did not need to attach end caps or apply adhesive to the bearings and magnet because the bearings had a tight enough fit within the housing that further constraints were not required to hold them in. Normally the end caps and adhesive would be needed to hold the magnet and bearings in place, but in our case they could be omitted.

The inner housing had a few changes as well. Through testing our system we found that the separate coils required extra space between them in order to produce the largest output voltage possible. This was due to the spacing allowing for a maximum change in magnetic flux. To achieve this we included more spacers. The spacers we made of ¾” PVC tubing and cut to 2” in length and placed in between each coil. Two 5” spacers were used at either end of the coils to fill the remaining tube space of the inner housing in order to keep the coils centered in the inner housing. As a result of this new spacing technique we were limited having only 3 coils in our 10” stroke instead of the original 5 coil system.

We also changed the diameter, length, and material of the inner core of the coils. We used 3 separate ½” diameter steel rods of length 2.5”. The reason for this change is because the magnet was becoming too heavily attracted to the ends of the iron rod and the outer housing would be difficult to move by hand. With a smaller less magnetically attractive rod we reduced the counter emf to a reasonable level in order to demonstrate the efficacy of the design. With this new diameter and material we were able to increase the number of turns of each coil in order to help compensate for the losses in magnetic permeability. The reason we used three separate rods was because with one rod we found that the entire rod magnetized increasing the size of the magnetic field and therefore decreasing the magnetic flux. With three rods the magnetic flux was increased and therefore a larger voltage was produced.

APPENDIX H: Design Analysis

Material Selection

The tube itself is designed to withstand the hydrostatic pressure (p_∞) and stagnation point pressure (p_s) of the water at a depth (h) of 20m, as calculated in the equation below, where ρ denotes water density, V_∞ denotes water current velocity, and g denotes gravity.

$$p_\infty + p_s = \rho g h + \frac{1}{2}\rho V_\infty^2 = \frac{1000kg}{m^3} \cdot \frac{9.81m}{s^2} \cdot 20m + \frac{1}{2} \cdot \frac{1000kg}{m^3} \cdot \left(\frac{1m}{s}\right)^2 = 0.1967MPa \quad \textbf{Equation 30}$$

The effects of the moments caused by the cylinder itself are assumed to be negligible given the use of linear bearings.

As such, the first objective function (M_1) yielded the maximization of yield strength (σ_Y) and a minimization of cost (C):

$$M_1 = \frac{\sigma_Y^{\frac{1}{2}}}{C\rho} \quad \textbf{Equation 31}$$

With the first objective function and the minimum yield stress, Granta Design Ltd's Cambridge Engineering Selector (CES) was subsequently used to narrow down material options, as shown below:

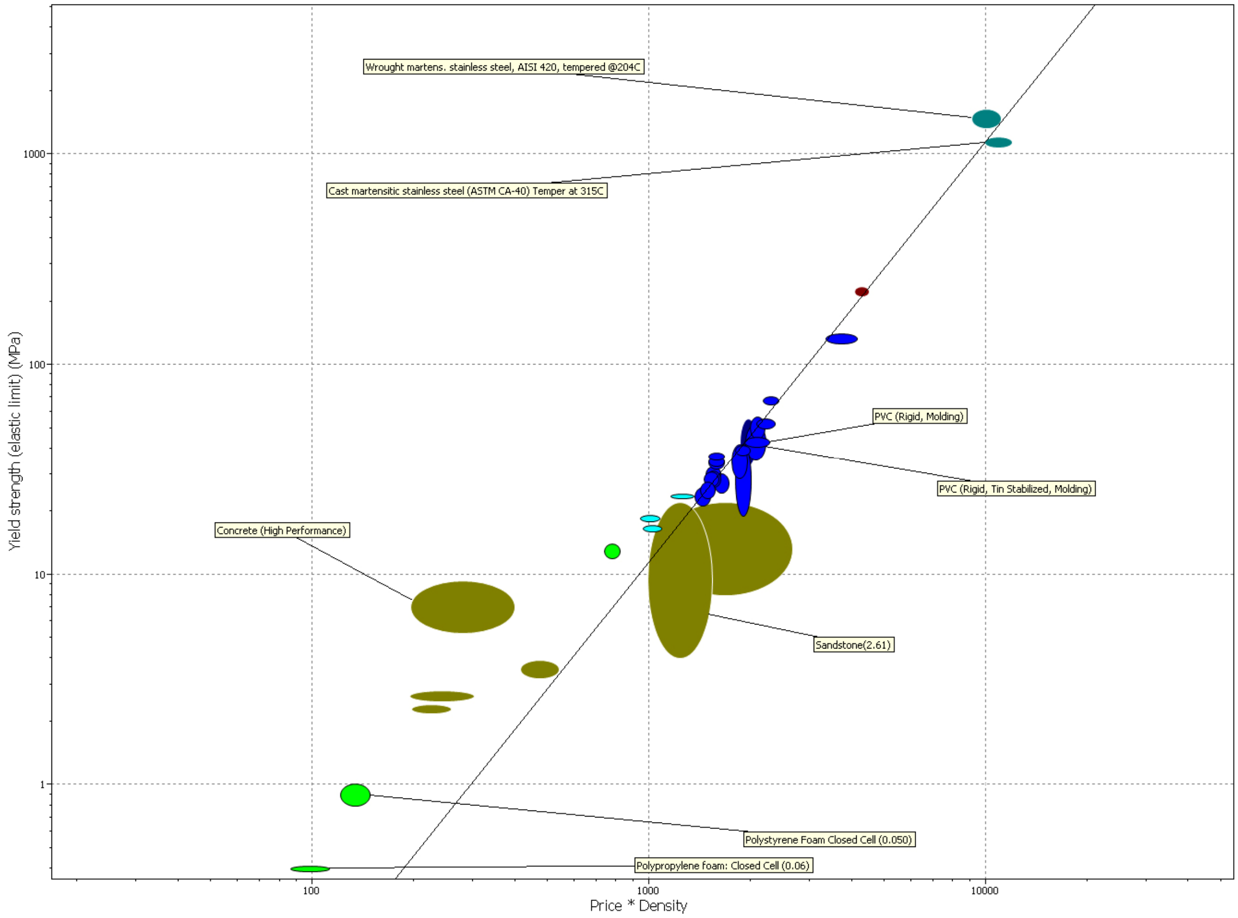

Figure 20: Yield Stress to Cost Ratio Criteria Used To Reduce Material Consideration

With a hollow tube, the thinner the wall thickness, the greater the amount of turns one can have per coil, and thus a greater power output. In order to have a thinner wall, however, one must maximize the stiffness (Young's Modulus or E) of the material with respect to the density. This yielded the second objective function (M_2), as shown below.

$$M_2 = \frac{E^{1/3}}{\rho}$$ **Equation 32**

This objective function was plotted with the materials already reduced by the previous objective function in CES. The additional constraint that it must be able to function in salt water was also added to generate the final material list of which to choose from.

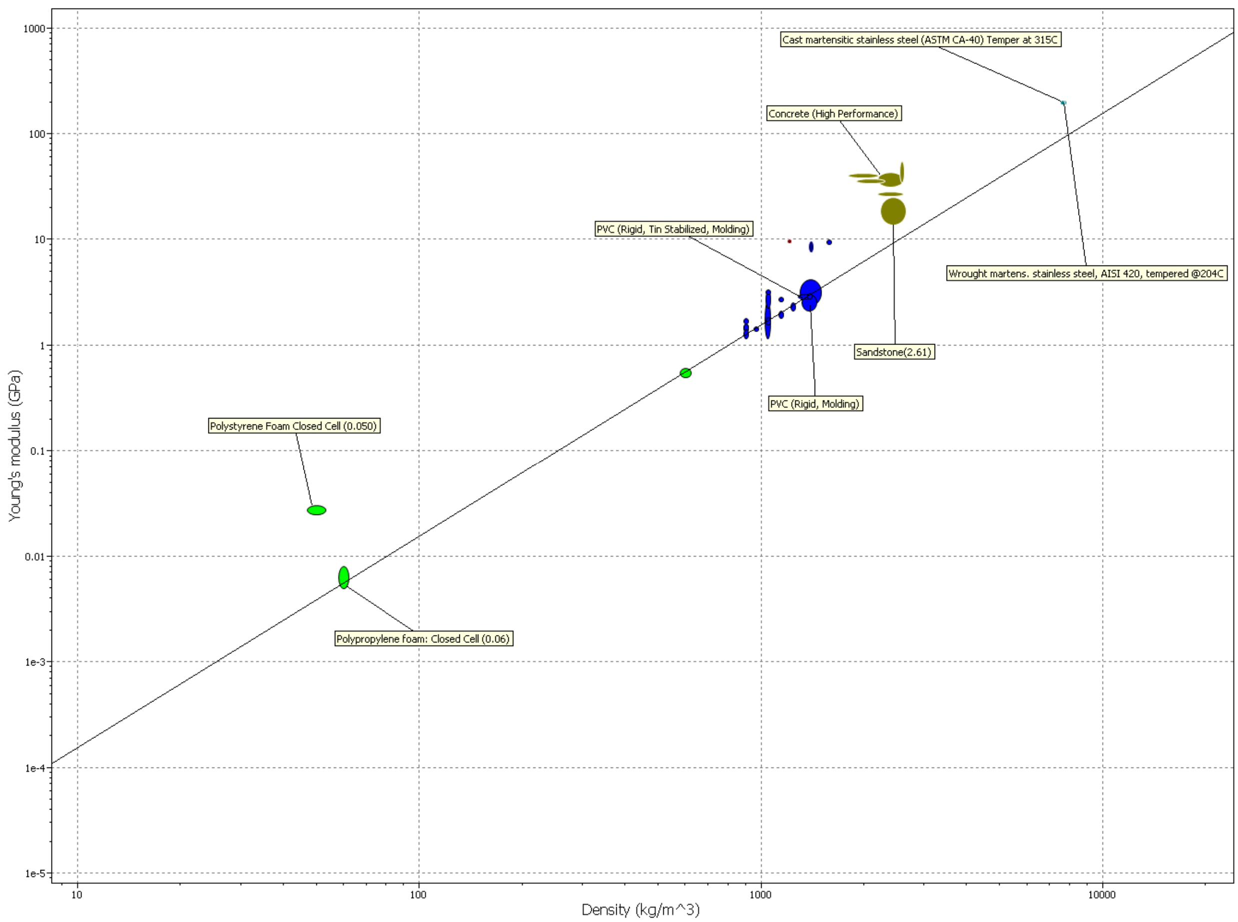

Figure 21: Final Materials Matching Criteria Given

Immediately, materials on the lower bound such as polystyrene foam (in green) were reduced because the yield strength only calculated to a safety factor of 2. Materials like cement and sandstone in beige were also removed due to their relative coarseness a source of excess friction, which could interfere with the movement of a linear system. While stainless steel (in teal) provides optimal rigidity, it also provides a magnetic resistance. As such, polyvinylchloride (PVC) was determined to be the optimal material selected, with a high stiffness allowing a thin tube and a high safety factor for yield strength as well.

Design for Assembly

An assembly efficiency of 8.24% was found for our final design by performing a design for assembly (DFA) analysis. Our design would take 4 minutes and 15 seconds to assemble and cost $101.92. Aside from the coils bolts and the mounting bracket the parts involved in our design are all very easy to handle because they are all symmetric cylinders. Therefore the problem was insertion. The primary reason for such a low efficiency was the fact that each coil needed to be attached to its own iron rod and then spaced seperately inside of the inner housing. This calls for 16 separate parts to be combined into one through assembly. The coils, iron cores, and spacers accounted for 173.88 seconds of the 254.79 total seconds of assembly. Below is the original DFA table formulated for our design.

Table 10: Original Design For Assembly Chart

1	2	3	4	5	6	7	8	9	Name of Assembly
Part ID	# of operations	handling code	handle time	insertion code	insertion time	operation time	operation cost	minimum parts	Linear power take off system for a VIVACE hydroelectric generator
1	1	00	1.33	00	1.5	2.83	1.132	1	inner housing
2	2	00	1.33	97	12	26.66	10.664	1	end cap
3	5	15	2.25	97	12	71.25	28.5	1	coils
4	5	00	1.33	16	8	46.65	18.66	1	iron core
5	4	00	1.33	16	8	37.32	14.928	0	spacer
6	2	00	1.33	16	8	18.66	7.464	0	end spacer
7	1	00	1.33	00	1.5	2.83	1.132	1	outer housing
8	1	00	1.33	10	4	5.33	2.132	1	magnet
9	2	00	1.33	17	9	20.66	8.264	1	bearing
10	1	10	1.5	06	5.5	7	2.8	0	mounting bracket
11	2	11	1.8	38	6	15.6	6.24	0	mounting bolt
						254.79	101.916	7	0.082420817
						TM	CM	NM	Design efficiency = 3*NM/TM

After performing a test for minimum number of parts and ease of assembly, we were able to redesign our system to be much more cost effective. Changing the inner housing to be closed on one side allows us to need only one end cap to seal the housing instead of two. Wrapping all the coils around one pre-spaced 20 inch aluminum tube instead of separate spacers turns 11 parts into one that is easily inserted into the 20 inch inner housing, dramatically reducing the assembly time. A 20 inch iron rod is then slid into the aluminum spacer instead of 5 separate rods being attached to each coil. The outer housing could be injection molded with a mounting bracket already on it reducing the number of parts. Finally instead of press fitting the bearings into the outer housing we could seal them in the housing using an end cap. After making these changes the efficiency improves to 61.97%; taking 39 seconds to assemble at a cost of $15.49. Below is the new DFA table for the improved design

Table 11: Improved Design For Assembly Chart

1	2	3	4	5	6	7	8	9	Name of Assembly
Part ID	# of operations	handling code	handle time	insertion code	insertion time	operation time	operation cost	minimum parts	Linear power take off system for a VIVACE hydroelectric generator
1	1	10	1.5	00	1.5	3	1.2	1	inner housing
2	1	00	1.33	97	12	13.33	5.332	1	end cap
3	1	15	2.25	01	2.5	4.75	1.9	1	spaced coils
4	1	00	1.33	00	1.5	2.83	1.132	1	iron core
6	1	00	1.33	00	1.5	2.83	1.132	1	outer housing
7	1	00	1.33	00	1.5	2.83	1.132	1	magnet
8	2	00	1.33	00	1.5	5.66	2.264	1	bearing
9	1	10	1.5	30	2	3.5	1.4	1	outer housing end cap
						38.73	15.492	8	0.619674671
						TM	CM	NM	Design efficiency = 3*NM/TM

Design for environmental sustainability

In the material selection assignment, we determined the five top material choices for the tube. Here we choose two of them: polyvinylchloride (PVC) and high-performance concrete to perform an environmental sustainability analysis using SimaPro software and eco-indicator.

The mass of the materials that we need in our final design is determined to be 15kg for PVC and 25.6kg for concrete. PVC (s) I and concrete (reinforced) I are selected as the closest materials available in SimaPro. Figure H.3 below shows the calculated total mass of use of raw materials, air emission, water emissions, and solid waste. It is obvious that use of concrete for the tube in our final design requires much more raw materials than PVC. However, use of concrete results in less air emission, water emission and solid waste.

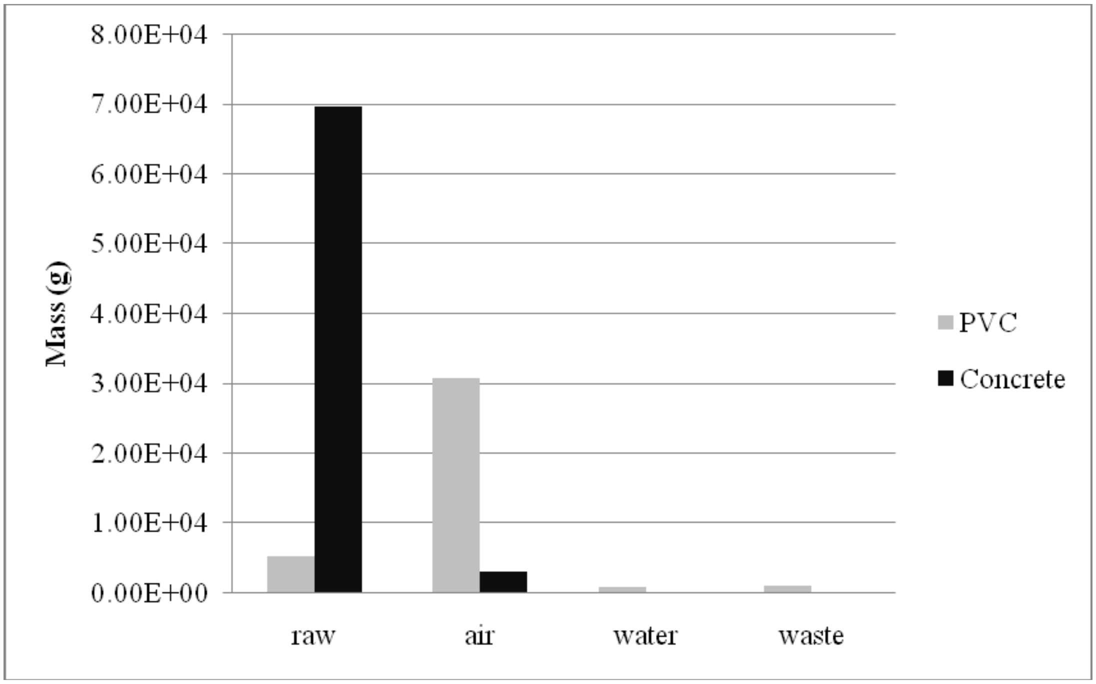

Figure 22: Total mass of use of raw materials, air emission, water emissions, and solid waste

Figures H.3 to H.6 shows the relative impacts in disaggregated damage categories, normalization plot, and single score comparison in points, respectively. PVC has a larger environmental impact than concrete on carcinogens, organics, climate change, eutrophication, and land use while concrete has a bigger environmental impact on inorganics, ozone layer, ecotoxicity and minerals. Based on the normalization plot, the biggest environmental impact of the two materials are on respiratory diseases from inorganic outputs, climate change, and minerals. In addition, both of the materials have much larger effects on human health than ecotoxicity and resources. Overall, concrete has a higher Eco-Indicator 99 point value (about 1.7) than PVC (about 1.1). When the life cycle is taken into consideration, concrete still has a larger environmental impact than PVC.

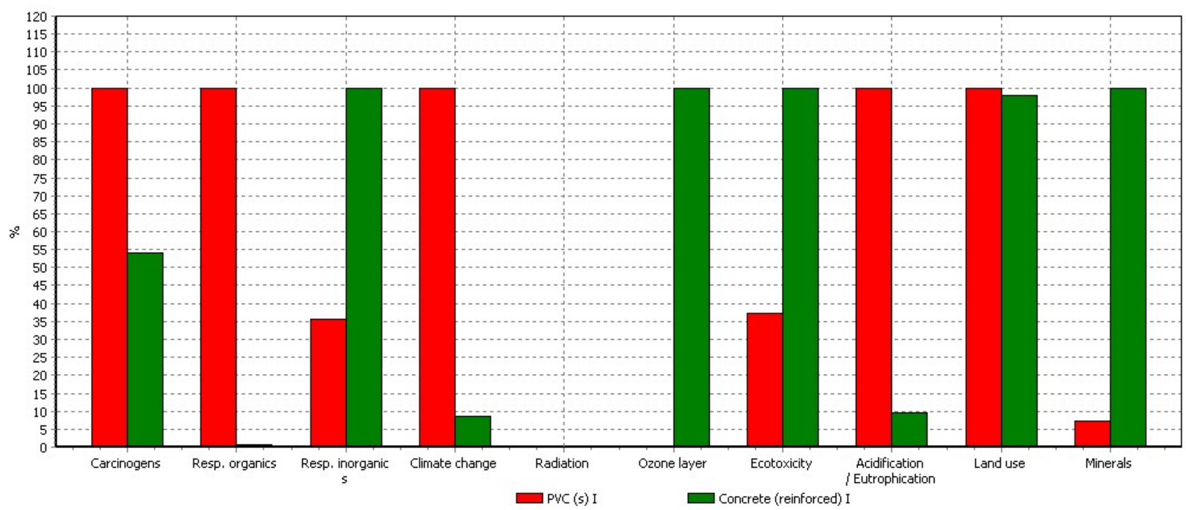

Figure 23: Comparing 15 kg 'PVC (s) I' with 25.6 kg 'Concrete (reinforced) I' Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / characterization

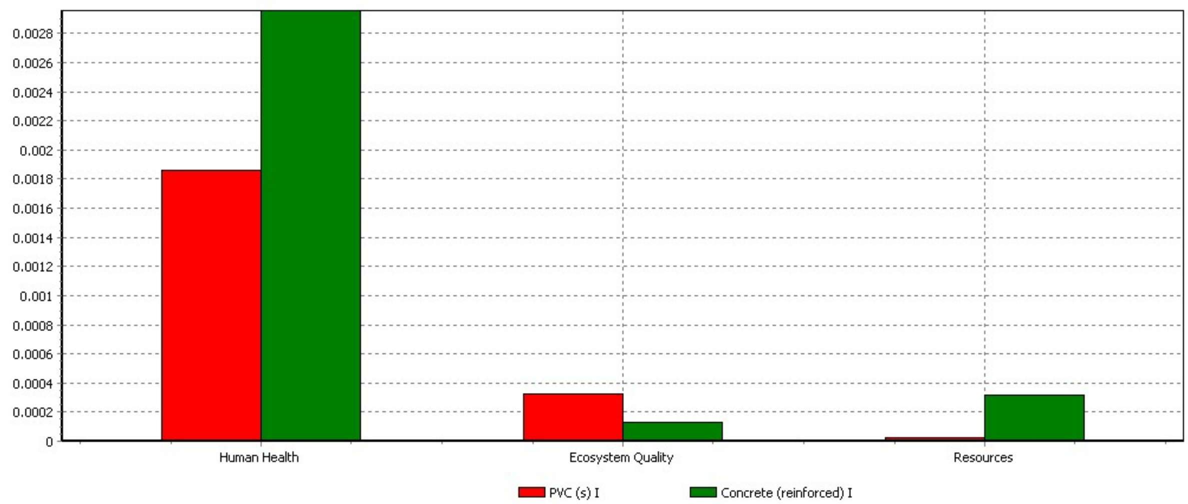

Figure 24: Comparing 15 kg ‘PVC (s) I’ with 25.6 kg ‘Concrete (reinforced) I’ Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / normalization

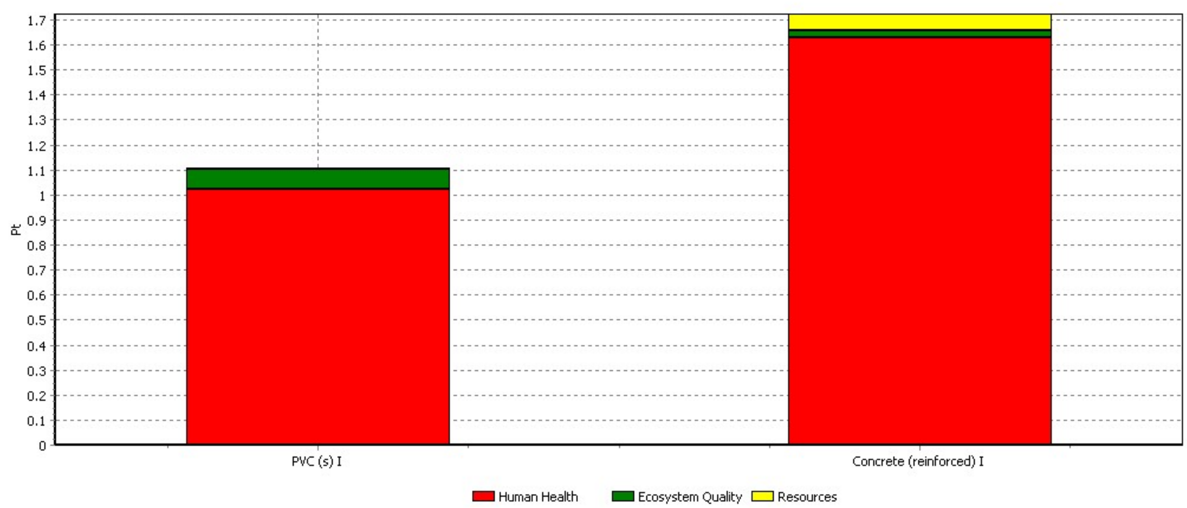

Figure 25: Comparing 15 kg ‘PVC (s) I’ with 25.6 kg ‘Concrete (reinforced) I’ Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / single score

Design for Safety

To perform a risk assessment, we must first specify some of the hazards in our power take off system. For our prototype, we only generated a 5mA current so the risk of deadly electrocution is essentially none, but the current my cause a painful sensation. The other hazard our prototype possessed was pinching someone’s hand. The outer housing moved up and down and required somewhat of a large force to move it past the coils, so if your hand was on the base close to the inner housing, you might pinch your hand. The final design is slightly more complicated, but the risks to people should be few since the system will be in a remote location at the bottom of a river. The biggest one is probably electrocution. The power that VIVACE generates has to be transferred to the shore via transmission lines. These could present a hazard to people venturing near them. However, as long as the area is labeled with warning signs, kept fenced off, and the lines are kept well insulated, the general public should be fine. Maintenance crews, however, should exhibit caution if they are making repairs. The VIVACE modules themselves only become a hazard if they are placed in water that is too shallow. Then they present a collision risk to boats. This can be easily solved by making sure they are away from frequented areas and in deep enough water. One of the requirements of this system is that it be low maintenance given its remote location. But, if repairs are needed, a few things need to be considered for a diver's safety. There is only one moving part to the VIVACE system: the outer housing that is attached to the VIV cylinder. Like in our prototype, this could pinch one's hand. A repair diver should use a locking mechanism to immobilize the cylinder before proceeding. In addition, strong magnets will be used in the PTO system. This could attract any metal the diver has on him. The magnets are not strong enough to keep the diver trapped underwater, but it would save them a lot of trouble keeping their tank, or any other metal objects far enough away.

The two most unexpected risks encountered through the DesignSafe analysis were entanglement and material handling. We have to take into account any kind of fishing lines or nets that may be cast off by fishermen. If they get caught on a VIVACE module it could pull someone overboard. This could be prevented simply by setting up warning buys around the modules. However, the risk of this happening is very small since a fishing line would break before pulling someone in. the other, much bigger hazard occurs when placing the modules in the water. They would have to b lifted via crane and could potentially crush someone or knock them into the water. But, with proper procedures, warnings, and safety equipment this risk can be drastically reduced.

Risk assessment is a strategy for analyzing how safe a product is. FMEA is another risk measuring method and stands for Failure Modes and Effects analysis. The main difference between the two is the methodology. Risk assessment incorporates three main steps: identify hazards, assess risk, and reduce risk. Identifying hazards involves brainstorming based on the users and the tasks that the product is meant to accomplish. Assessing risk can be done qualitatively or quantitatively via a scoring system. After this is done, one can work to eliminate any risk that is unacceptably high through design, guards, warnings, training, or protective equipment. The methodology for FMEA is a little different. The first step is to identify any possible failures a system could encounter and the effects this would have. This must be done for every part of the system. Next is to assess the failures to determine anything that could reduce the chance of anything failing.

No matter how many precautions are taken, risk can never be reduced to zero. Therefore, a safety analysis should be undertaken to reduce it to a level as low as reasonably practical. Just how low of a level is a judgment call. For instance, in our project the final resting place of the VIVACE modules can present a navigation hazard if placed in shallow water, but this can be easily avoided by simply keeping it in deep water. But the risk of electrocution is not so low because the power must get to shore, and will not be as isolated. But, with proper precautions the risk can be reduced to an acceptable level.

designsafe Report

Application:	VIV PTO	Analyst Name(s):	Crimmins
Description:		Company:	
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:	Professor Michael Bernitsas - Power Point Presentations		

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 : drawing-in / trapping / entanglement Fishing lines, nets, etc could become entangled on the VIV module and pull someone overboard.	Slight Occasional Unlikely	Moderate	warning sign(s)	Slight Remote Negligible	Low	
All Users All Tasks	mechanical : pinch point Cylinder moving up and down, could pich hands/limbs of maintenance worker.	Slight Remote Unlikely	Low	adjustable enclosures / barriers, warning label(s)	Slight Remote Negligible	Low	
All Users All Tasks	mechanical : magnetic attraction / movement High power magnet used for electromagnetic induction and could attract metal objects (air tank of diver repairing the module, diving belts, etc) that get too close.	Minimal Remote Negligible	Low	adjustable enclosures / barriers, warning label(s), maintain a minimum distance fro magnet	Minimal Remote Negligible	Low	
All Users All Tasks	mechanical : impact If placed in water that is too shallow, there is a risk of a boat hitting it.	Serious Occasional Possible	High	Make sure the modules are placed in deep enough water away from frequented routes on the water, warning sign(s)	Serious None Negligible	Low	
All Users All Tasks	electrical / electronic : energized equipment / live parts A current runs from the PTO to the shore via transmission line and if handled improperly could electrocute someone.	Serious Occasional Unlikely	Moderate	warning sign(s), standard procedures, gloves	Serious Remote Negligible	Low	
All Users All Tasks	electrical / electronic : water / wet locations If waterproofing fails, it could ruin the coils' ability to generate power. Also shoreline transmission line exposes maintenance crews to water and electricity.	Serious Frequent Unlikely	High	separate hazard / people in time or space, good insulation, warning sign(s), , restricted users	Serious Remote Negligible	Low	
All Users All Tasks	material handling : placement under water The heavy module must be placed underwater, and doing so involves lifting it off a boat's deck and lowering it to the bottom of the river/bay/ocean. This could knock someone overboard or crush them if handled improperly.	Serious Occasional Unlikely	Moderate	audible alarm or sounds, visible alarm or signal, keep personel away from crane as it moves module, head protection, life vests	Serious Occasional Negligible	Moderate	

Figure 26: DesignSafe Analysis

Manufacturing Process Selection

The overall design of the VIVACE PTO requires exceptionally tight tolerances. Tight tolerances are needed due to the necessity of keeping a fluid linear motion while at the same time ensuring the minimum distance between the magnet and the coils as well as the maximum number of turns per coil. As such, a maximum tolerance of 0.01” was specified for most materials used (with the exception of the iron core). Other factors considered were production rate and cost.

Neodymium Iron Boron Magnet

The combination of neodymium, iron, and boron into a magnet creates a substance that is exceptionally hard and brittle. As such, machining with any reasonable tolerance is quite difficult at best. Even if using tools such as diamonds, the heat generated during the process may demagnetize the material and even serve to ignite the powdery residue created from the machining process as well. As such, the only available option is pressure molding a powdered mixture of the substance, sintering the resultant product, and then slicing this into its desired shape. A coating can subsequently be applied.

Polyvinyl Chloride Tube

In addition to the maximum tolerances already discussed, a maximum roughness of 0.02mil was specified in order to ensure a smooth linear motion between the magnets and bearings and the tube itself. Process selections were also limited by its hollow shape. The remaining processes were weighed according to the production rate and cost, as shown below:

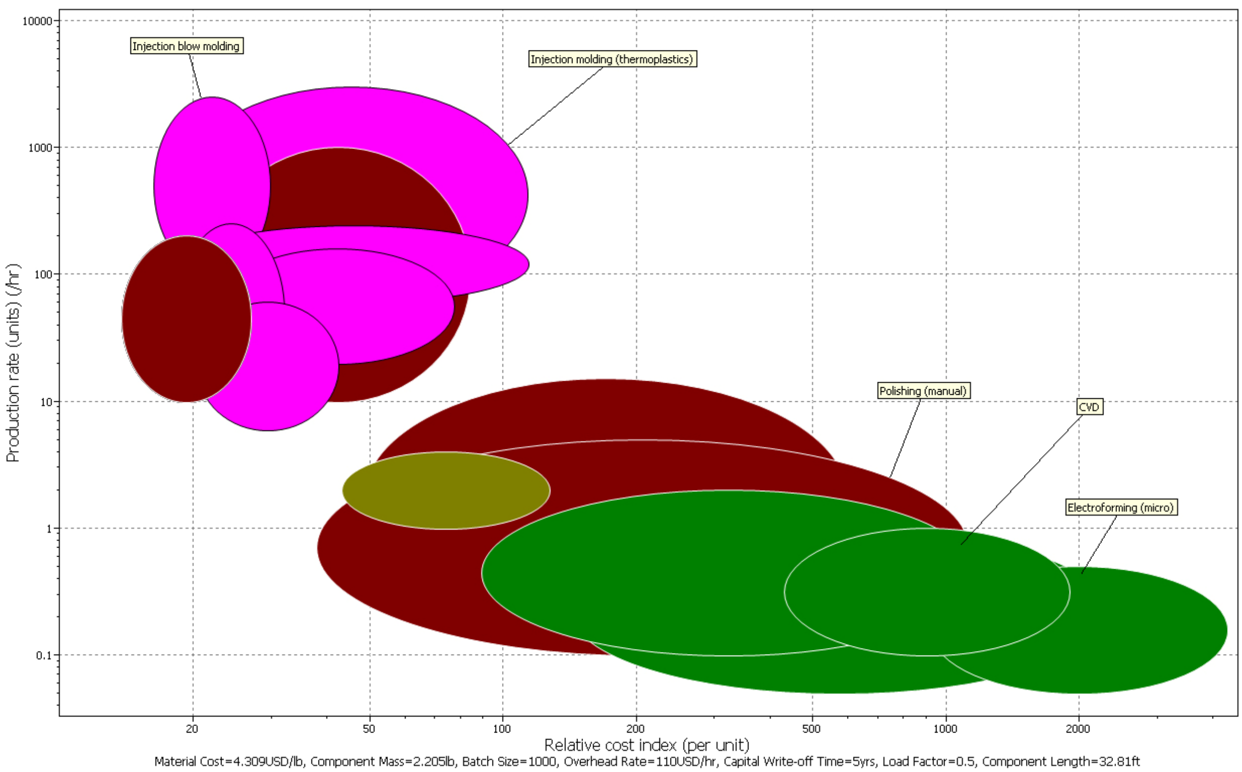

Figure 27: PVC Tube Process Selection

From the figure, processes such as electroforming and chemical vapor deposition (in green) were deemed to be too expensive, with a low production rate. Of the available processes, injection blow molding (pink) was the process determined to maximize the production rate to relative cost index ratio. Injection blow molding consists of a hollow perform injection molded over a mandrel, which provides the hollow shape. The mandrel functions as the blow nozzle, where air is injected under pressure through this mandrel to blow the desired polymer against the mold wall to form the desired shape. After the polymer cools, the mold is opened and the part ejected.

Aluminum Spacer:

In addition to the maximum tolerances already discussed, the aluminum spacer was weighed according to the production rate and cost, as shown below:

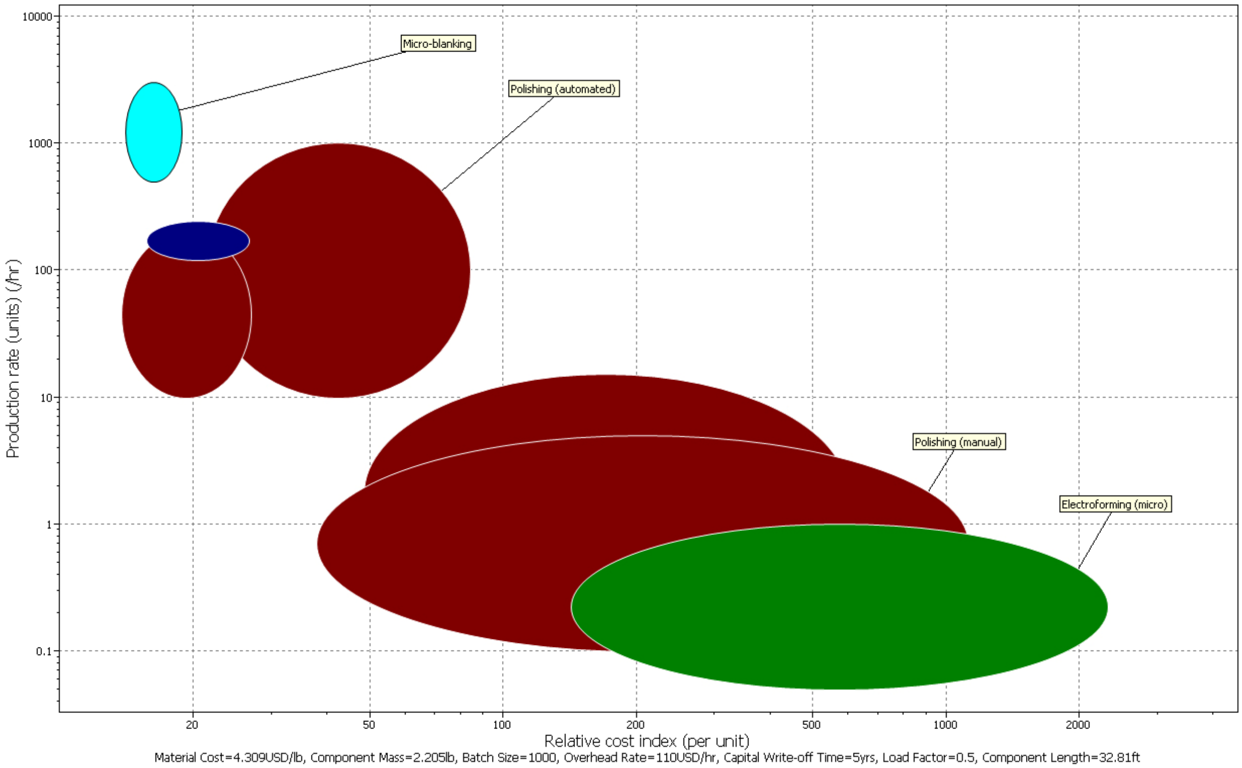

Figure 28: Aluminum Spacer Process Selection

From the figure, processes such as polishing (maroon) and electroforming (green) were deemed to be too expensive, with a low production rate. Of the available processes, micro-blanking (light blue) was the process determined to maximize the production rate to relative cost index ratio. Micro-blanking is a small scale form of blanking, in which metal sheets are cut using punch and die sets. Micro-blanking as opposed to blanking is used given its high level of precision between the punch and the die.

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