

Ocean Wave Generator using Electromagnetic Induction

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II. Abstract

This project would introduce a design that allows energy to be harnessed from the motion of waves and test to see if it is a feasible form of generation. The feasibility of the “generator” will be determined on several factors including, but not limited to:

- Economic cost
- Power/Energy output
- The ability to scale linearly
- Environmental impact

The current concept is a triangle made of hollow tubes encompassing coils of wire and a magnet that would move through the tube inducing current as it moves with the ocean. The triangle design is used so at least two of the three magnets will always be inducing electricity no matter the orientation of the device as the wave impacts it. The senior project would be to design and build the generator and then to test how much energy is generated over an allotted time. The results would be analyzed and presented with a recommendation regarding the future of the design.

III General Introduction and Background

Since 1975, energy independence has been on the national spotlight. Over \$172 billion (adjusted for inflation in 2005 dollars) has been spent on achieving energy independence^[1]. Senator Voinovich said, “It is critical that we grow more energy independent to increase our competitiveness in the global marketplace and improve our national security. As less of our energy needs are met with our resources, our nation is placed at the mercy of the oil-exporting OPEC nations and vulnerable to geo-political instability and oil market volatility.”^[2]

Our project aims to take steps towards becoming energy independent by introducing new information concerning alternative energies. The problems we hope to address are: the growing need for energy, the need for energy independence, the feasibility of energy harvesting from waves, and the push towards renewable energy.

The solutions that currently exist are mainly solar and wind energy. The advantages that wave energy have over solar is it can be harvested at all times of the day, not just during sunlight. Water is denser than wind and waves and tides are more predictable than wind patterns^[3]. According to Roger Bedard, EPRI advocate, ocean energy potential will cost even less than wind energy^[3]. However, as it stands the development of wave and tidal energy is at an early stage of researching and development^[1]. This project aims to increase the level of information available for others to expand upon.

There are several disadvantages regarding ocean energy. According to Brad Linscott, author of Renewable Energy - A Common Sense Energy Plan, ocean tides aren't feasible because there must be a difference of at least 16 feet between the water level during high and low tides. There exist around 40 locations in the world that meet this criterion. Comparatively, wave energy usually requires the generation device to be located 130ft off the shoreline^[1]; a task easily accomplished on many shorelines. It's difficult to imagine wave energy being the sole energy source for America's energy needs because the distance electricity would have to travel to reach certain places on the continental U.S. However over half of Americans live on the coast and it would be worth it to invest research^[4].

According to Brad Linscott there are two proven methods of energy extraction from waves: The oscillating Water Column (OWC) and the point absorber^[1]. Looking at previous attempts we can compare our design with those two methods.

The oscillating water column is a cylinder that is open at the top and closed at the bottom, secured to the ocean floor by the bottom. A two-way air valve is located at the top of the cylinder allowing air to flow. Air is compressed inside the cylinder and drives an air turbine. An in-depth analysis was performed evaluating several aspects of oscillating column generation including: cost, maintenance, infrastructure, generator performance and efficiency. An example is shown in Figure 1.

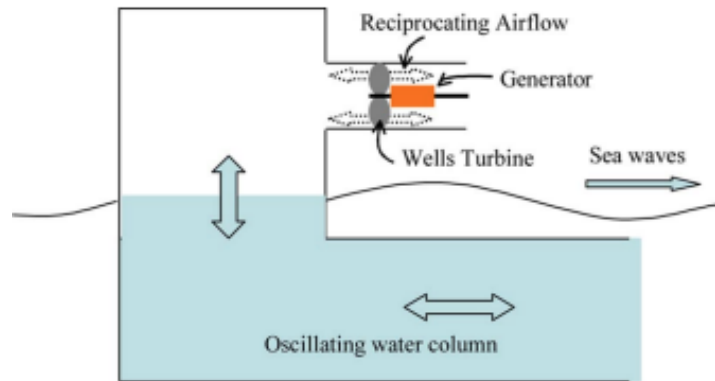


Figure 29: Demonstration of an Oscillating Water Column^[7]

From the analysis performed we are able to make the following comparisons in Table 1:

Area	Oscillating Water Column	Our Design
Maintenance		X
Cost		X
Generated Output	X	
Ability to connect to the grid	X	

Table 11: Comparisons between the concept and OWC

The article highlights how maintenance is a constant worry with the oscillating water column, and since a large portion of the system is underwater and fastened to the ocean floor making it more difficult of a system to maintain. Our design floats on the ocean surface meaning maintenance is much easier. Comparing costs, our design is under 1000USD and using even the best parts place our design hundreds of thousands of dollars cheaper than the OWC. The generated output is much larger from the OWC because it uses professional grade generators and

the OWC used in the analysis is much larger than what we are planning on using. The OWC is easier to connect to the grid because since it's fastened to the ocean floor it can use the floor as a method of transporting energy to the shore.

The point absorber contains a permanent magnet inside a long cylinder fastened to the ocean floor. As the wave moves the cylinder bobs up and down like a buoy generating electricity.

One wave generator that tested this design was the Uppsala Point Absorber^[8]. Similar to the OWC it requires impressive amounts of infrastructure in order to harvest energy. The Uppsala Point Absorber is shown in Figure 2

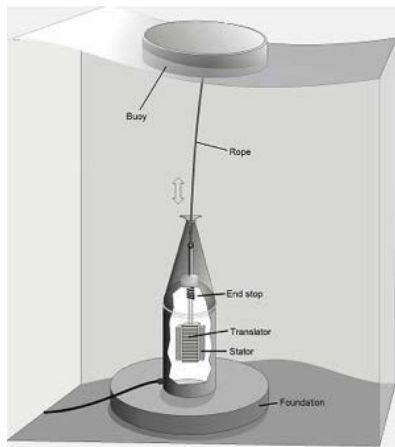


Figure 30: Uppsala Point Absorber [8]

From the analysis performed we are able to make the following comparisons in Table 2:

Area	Point Absorber	Our Design
Maintenance		X
Cost		X
Generated Output	depends	depends
Ability to connect to the grid	X	

Table 12: Comparisons between the concept and the point absorber

Again we're able to compare our design with the design completed by the Uppsala Point Absorber project. The comparisons are almost identical with those made with the OWC, the only difference being that the generated output of a single point absorber and with our design could be comparable depending on the size of the magnets and the length of the cylinder used.

There are several different methods being employed and researched to generate power from ocean waves. Devices have been being created since the early 90's and innovated upon for the last ~20 years. However, there are a few general designs that most devices seem to be based upon. These are point absorber/buoy and surface following/attenuator. Our device borrows elements from both. It would need to be loosely tethered to hold a general position like a point absorber however no underwater components would be needed other than the anchor. It also duplicates the idea of a surface following in that a side of the generator could be oriented parallel to the direction of wave propagation in order for the magnet to slide up and down through the coils. However, our triangle design hopes to produce power more efficiently by having three sides to ensure that no matter the orientation of the device power is being generated by at least two sides.

IV Project Requirements

The generator must be able to use the motion of waves to move magnets through coils of wire, inducing a voltage. This will be done when the wave tilts the design and the magnets fall at an angle. Listed below in Table 3 are the requirements of each item that will be used.

Although the intent of this project is to test and decide on the effectiveness of it being used as a generator, there are certain electrical outputs desired. Since predicting wave amplitudes and frequencies is impossible, specifications of the generator are calculated under ideal circumstances. The ideal circumstance in this case is when a branch is fully vertical and a magnet falls freely due to gravity. EMF is generated by a change of flux through turns of wires given by the following equation:

$$emf = -N \frac{\Delta\phi}{\Delta t}$$

Equation 1: emf calculations

This equation would mean that the strongest magnet should be selected because as it falls through turns of wire it will yield the largest change of flux ($\Delta\phi$). This equation also dictates that the more turns of wire the larger induced voltage. However there are both financial and physical limitations to our selections. Each branch should be able to output a measurable voltage under “normal” ocean conditions and a sizable voltage under ideal conditions.

Component	Description	Requirements
Outer Shell	The outer shell houses everything inside; it is in direct contact with the water.	<p>Buoyancy: The outer shell piping material needs to be buoyant enough to support the weight of the wire, magnets, and data measurement system.</p> <p>Waterproof: The intent of the project is to place it in the ocean while collecting data. The electronics inside need to be free from water.</p> <p>Durability: The material selected and the fastening/joining agents need to be able to withstand the elements and weather.</p>
Inner Shell	The inner shell has the coils of wire wrapped around it, and houses the magnets inside.	<p>Material properties: The material needs to be light, so it doesn't add unnecessary weight to the design. It needs to be sturdy so that it won't bend under the weight of the added wire. It needs to have little friction so the magnets are restricted in their movements.</p>
Wire	Wired in coils so that the magnets will induce voltage through movement.	<p>Gauge: The gauge of the wire needs to be small enough so that there will be enough turns to allow for move voltage, yet large enough to handle currents produced.</p>
Data Logger	Responsible for measuring voltages and storing it	<p>Portability: Since experiments will be conducted away from a laboratory setting the logger needs to be able to store data without being tied to an outlet.</p> <p>Size: Since the design looks to minimize size and volume it must fit within the outer pipe.</p>
Fittings between shells	Connects the outer shells of three legs	<p>Durability: It must be strong and waterproof to keep the legs together while in the water.</p>

Table 13: List of Project Requirements

V Material Selection

Piping material:

A major concern of this project is retaining buoyancy when the design is fully functioning. It will include several thousand feet of wire, 9 relatively large magnets, electronic circuitry as well as inner piping, and materials that will keep parts in place within the outer pipe. This will add to a non-trivial weight that will not exceed the limits of the buoyancy of the material chosen.

With this project eventually being placed in water it is vital that it is waterproof to ensure that the circuitry remains safe and functioning properly. The material chosen was acrylic tubing, which is clear allowing us to visually inspect the project while the design is fully enclosed inside. Using acrylic tubing with properly fitting joints should be able to safeguard the circuitry, as it is a material that meets waterproof specifications. The material is extremely resistant to corrosion and very durable which should suit our project well considering the exposure to the elements.

One requirement of this project is to make sure that it is environmentally friendly. This coincides with the goal to make this device scalable (more devices could easily and efficiently be added to the system to produce more power). PVC pipe was chosen as the inner piping material largely because it is one of the world's most sustainable products with an average lifespan of more than 110 years and requiring relatively small amounts of energy and resources to resource while creating virtually no waste^[5]. PVC pipe is very cheap and readily available at most hardware stores and isn't considered a high-risk item.

Magnets:

The magnet chosen was a rare earth magnet because it is the strongest magnet given the operating conditions^[6]. A grade N42 Neodymium magnet with nickel coating was selected for use. The magnet was selected because of its dimensions and relative strength compared to its price. Ideally the strongest magnet would be chosen however the budget of this project largely dictated the magnet selection.

Wire:

The more turns correlates to a higher voltage, so the ability to produce more turns would be desired. The way to meet this requirement is to use a wire with the smallest diameter possible so

that the wire could be wrapped as many times as possible around a pipe. The smallest wire diameter (largest wire gauge) was selected that was readily available at large quantities.

Data Logger:

The data logger was selected largely on price and dimensions. Since price was the largest factor we selected the cheapest data logger that met our dimensions and requirements. Therefore a SparkFun Logomatic v2 data logger was selected that was able write to an 2GB SD card and was able to write fast enough to store enough data points necessary for interpreting data.

Pipe Fittings:

Encasing the inner PVC pipes are acrylic tubes with a diameter of 2 $\frac{3}{4}$ " and a length of 3 ft. At either end there is a bushing with silicone pasted on and a cork is inserted to ensure that no water can enter. For extra buoyancy and resilience another plastic pipe was added that houses both of these inner pipes. This proved to be an effective way of keeping the device connected and safely operating on top of the water.

VI Project Dimensions and Financial Breakdown

Project Dimensions:

Shown below in Table 4 are the physical measurements of one branch for the generator. Excluded from Table 4 are some circuitry necessary for correct operation since their dimension don't have a significant impact on design considerations. The table discusses the parts length and its diameter if applicable, if not the dimensions are noted. It is important to note that all of the dimensions allow for more room than strictly necessary, allowing for margins of error in the design.

Part	Length	Diameter	Dimensions
Outer tubing	5ft	4"	N/A
Exterior Pipe	3 ft	2 ¾"	N/A
Interior Pipe	2.5 ft	¾"	N/A
Magnets	5/8"	1"	N/A
Data logger	4.06"	N/A	4.06" x 0.66" x 1.00"
Wire (AWG 36)	9.4 miles	0.005"	N/A

Table 14: Physical Measurements of one branch of the generator.

Finance and budget:

Shown in Table 5 is the price breakdown for this project. Listed under the "Part" heading is the amount purchased for that item. In the case of the piping the amount purchased is noted in length, otherwise it is just the amount.

Parts:

Part	Price
10' of 2.5" diameter acrylic pipe	\$80
10' of 2" diameter PVC pipe	\$15
20' of 4" diameter plastic tubing	\$7
3 4" diameter plastic tube fittings	\$6.50
6 PVC "caps" 2" diameter	\$7
9 N42 cylindrical magnets	\$75
9 miles of 36 AWG wire	\$100
Glue, foam, miscellaneous supplies	\$25
Logomatic v2 Data Logger	\$67
Total Cost	\$383

Table 15: Parts List and Price

VII Test Plans

The most critical part of the project will test during different stages of the project. Currently those three stages are: Testing for the best design, which the tests are described in detail in Table 6. Then testing the generator after it's built, which the tests are described in Table 7. Then finally testing the generator in the ocean, which the details are described below in this section.

Test 1: Testing for the best design

Test	Description	Additional Notes
Testing evenly wrapped coil	Wire will be evenly wrapped around the length of the pipe wrapped as tightly together as possible. Seen in Figure 4a.	The test will have a PVC pipe placed vertically with the configuration in place. The magnet will be dropped from the top, falling through the coils and landing softly on foam stuffed inside the pipe. The two ends of the coil will be placed on an Oscilloscope that will be running in "Time" mode so that the entire waveform can be seen. The testing configuration is shown in Figure 3 and the coil configurations are shown in Figure 4. The reason for testing these two coil formations is to see if there is any benefit of allowing a magnetic field to completely clear a group of coil before entering the next set
Testing coil wrapped in groups	Wire will be wrapped such that there will be a distance between coils Figure 4b. The distance will be varied to see an entire range of combinations.	
Testing with multiple magnets	Once a wire configuration has been selected magnets will be increased with each other to determine if there's an advantage to using more than one magnet.	While the testing method will be the same as testing the coil, testing conditions will likely change with the selection of the wire configuration, making it difficult to predict.

Table 16: Preliminary testing to find best design

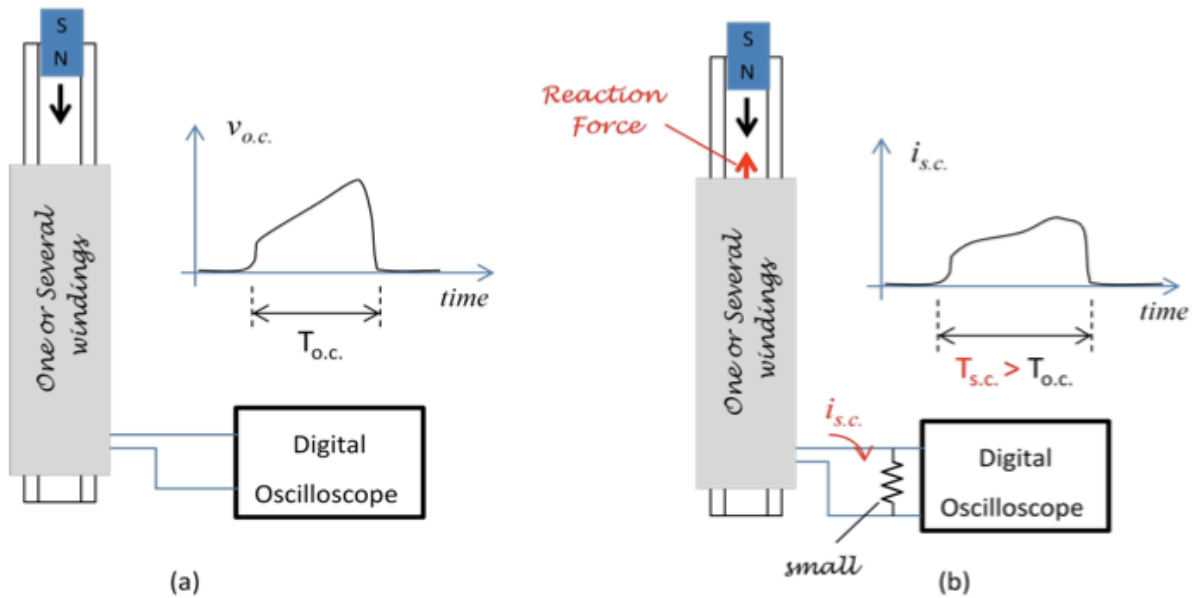


Figure 31: Figure demonstrating how the testing coil will be performed

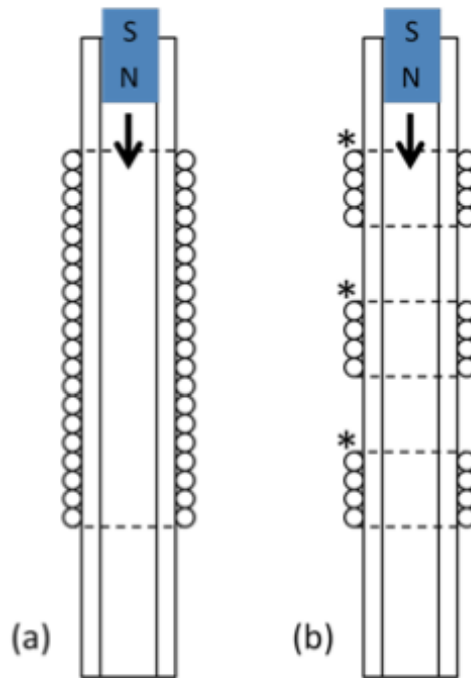


Figure 32: The different configurations of wire that will be tested.

Test 2: Testing the built design

Test	Description	Additional Notes
Testing the data logger	The data logger will need to be tested to ensure that it logs data correctly and if there are any inaccuracies.	The data logger will be connected to a function generator with various waveforms and various frequencies and amplitudes. The data will be collected and read using Excel and plotted against time. The waveforms from the data logger will be compared with the outputs and the accuracy of the data logger will be gauged.
Testing the design with the data logger	The data logger will be tested with the design to ensure that the data logger can give an accurate representation of the waveforms induced by the magnet.	A single PVC pipe will have the magnet(s) inside with caps fitted on the ends. The wire will then be connected to an oscilloscope operating in “Time” mode, while the data logger will be placed in parallel. The pipe’s ends will be moved up and down to move the magnets back and forth. The Oscilloscope and the data logger will record the same data and then compare to see if there is any error, and to ensure the data logger gives an accurate representation of seemingly random data.
Testing Continuity	Testing the magnet wires for continuity and for resistance.	A multimeter will be used connecting the terminals to either ends of the wire. By measuring the resistance of the wire this ensures there are no breaks from one end to the other. It allows the length of the wire to be calculated using AWG tables. From the length of the wire the amount of turns can be calculated, knowing the circumference of the pipe and the length of the wire.

Test	Description	Additional Notes
Finding Maximum Voltage	Finding the maximum voltage able to be induced.	<p>This experiment will be performed by dropping a magnet through the pipe. The pipe will be stood vertically and on either an oscilloscope will be measuring across the wire as seen in Figure 3a.</p> <p>By finding maximum voltage there will be a reference to compare against when analyzing the data returned by ocean trials.</p>
Testing to ensure the design is waterproof	The outer pipes will be tested so to ensure that no water can enter the inside.	Paper towel will be placed inside the pipe and the pipe bushings will be secured with the rubber stopper. Then the entire pipe will be placed underwater and moved rigorously to ensure the bushings and cork will stay in place. If there are any leaks it will be apparent on the paper towel.

Table 17: Tests to be performed on the generator after construction

Test 3: Testing the design in the ocean

Once the design has been proved to demonstrate that it is durable enough and it is waterproof and it logs data correctly, the design will be placed in the ocean water. A rope will be tied to on leg to ensure the device doesn't float away. The data logger will be started and enclosed inside the waterproof pipes. The generator will be guided far enough in the ocean where the waves create motion and the magnets are able to move through the PVC pipe. The first trial will be roughly 10 minutes in order to determine that the data logger is logging data correctly. The second trial will be increased by 5 minutes. No artificial movement will be given to the generator until it is collected.

Safety Concerns:

Because of the strength of the magnets that are likely to be purchased, there will be a significant distance between lab equipment and our testing area. Safety goggles will be worn and no the test will be performed in a lab where there is little distraction and interaction with others.

VIII Test Results Part One

During testing there were a few key variables that we focused on optimizing to obtain the design that would best suit our needs and give favorable results. Early stage testing consisted of purchasing three “shake flashlights” and dismantling them to discern how they operated and then running further tests of our own to determine how the magnets could be used in different situations.

Testing evenly wrapped coil

A coil of wire with length 10.5 cm and 57 turns, without breaks, is wired along a PVC pipe. This experiment is designed to demonstrate whether or not a long coil of wire is an optimal design.

The ensuing waveform that resulted from dropping the magnet is shown in Figure 5.

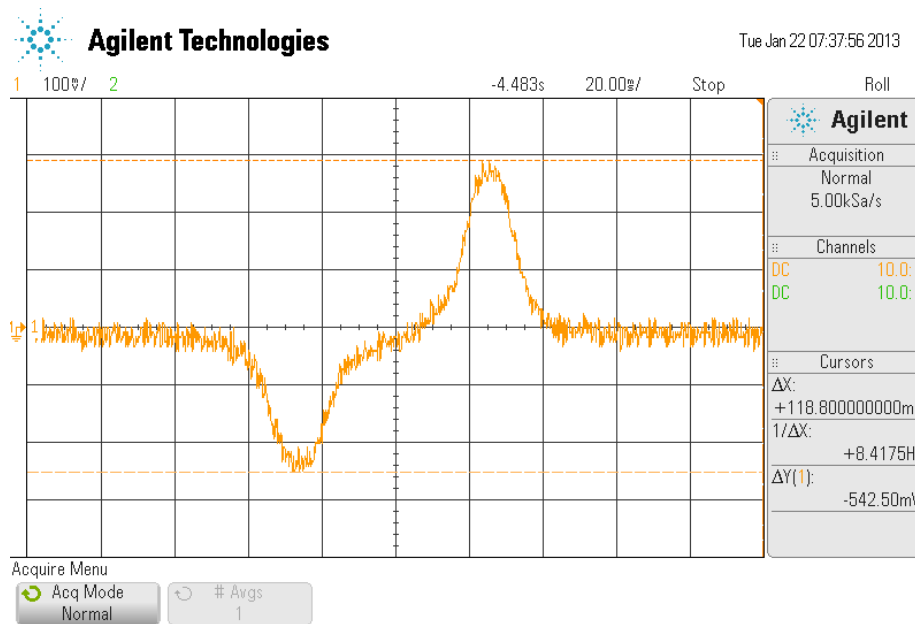


Figure 33: Waveform of a single coil of wire with no breaks

There is a point between the two peaks where the magnet enters and exits the coil where no voltage is being induced. This test determined that the ensuing coils need to be one magnet-length long so the magnetic field will be changing in the coil during the fall.

Testing coil wrapped in groups

Two coils of the same wire are placed at varying distances trying to find the location that allows for most continual generation of voltage.

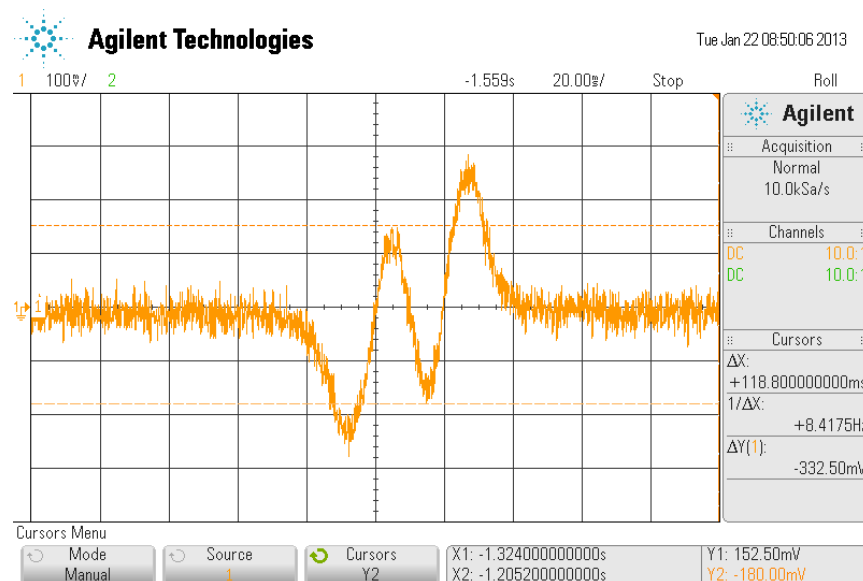


Figure 34: Two coils 1cm apart

In Figure 6 is the waveform for when the two coils are 1cm apart. In the waveform, as the magnet enters the second coil it's also leaving the first, which causes two opposing voltages limiting the peak.

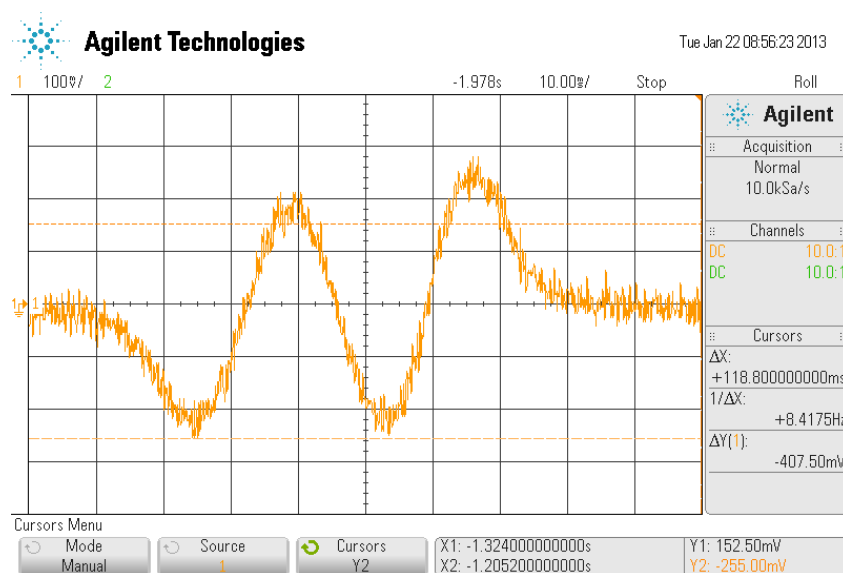


Figure 35: Two coils 5cm apart

Shown in Figure 7 is two coils are placed 5cm apart, the waveforms are almost identical, the magnitudes are bigger as time goes along because the magnet has gained velocity as it fell. The coils are placed such that the voltages aren't interfering with each other. There is also is no lost time where the magnetic field isn't changing.

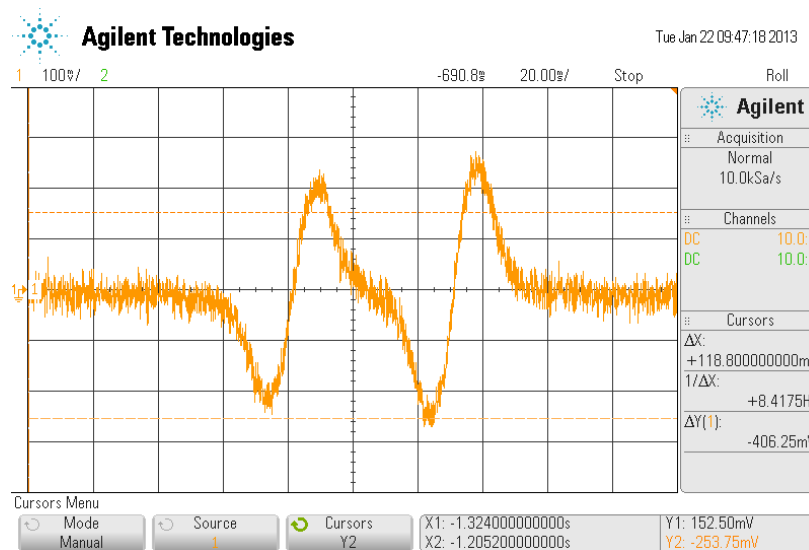


Figure 36: Two coils placed 8.3cm apart

In Figure 8, the coils are placed 8.3cm apart, the results are similar but there is lost time where there is not voltage being generated.

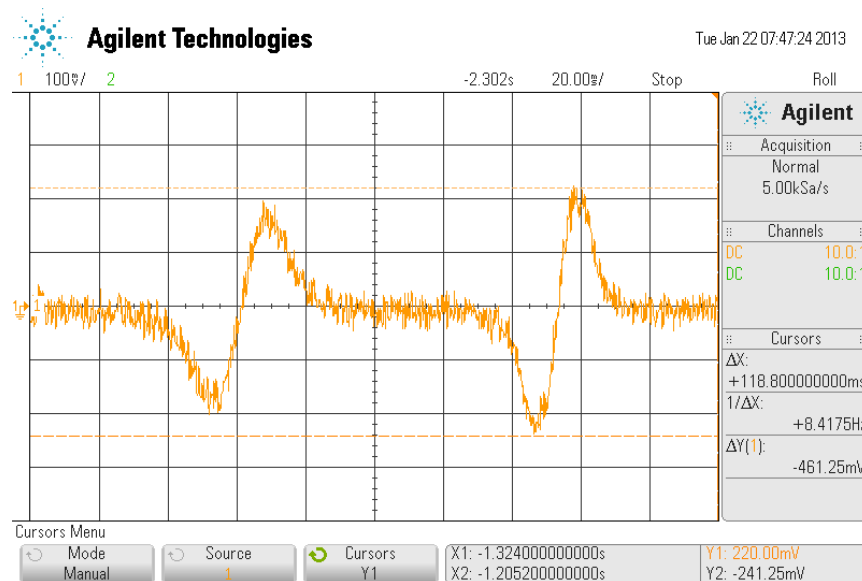


Figure 37: Two coils placed 20cm apart

In Figure 9 the two coils are placed far enough where the magnet falling through the coils and creates two separate peaks not affecting each other.

The tests showed that placing the coils apart yielded better results and placing the coils 5cm from each other would yield the best waveforms without interference. Using that information it was determined that using 3 individual wires with intermittent coils would be best, using either one could or two coils would leave wasted space along the pipe. By using three coils wound adjacent to each other there is enough distance between a single set of coils to not allow for interference, yet all the wire is compact and there is no lost space. A concept of the wire design is shown below in Figure 10 where the different color circles represent different sets of wire 2.7cm long.

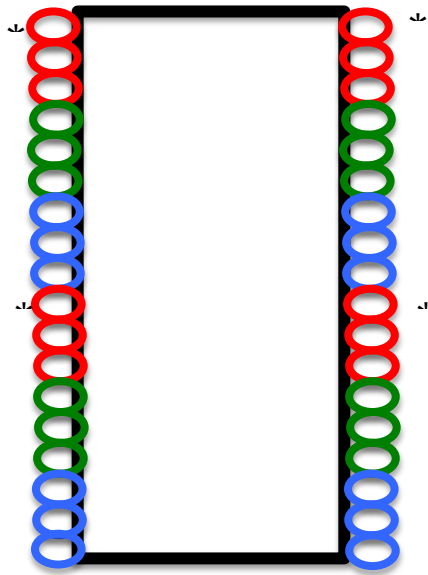


Figure 38: Concept of a three wire design

After the concept of a three-coil winding was devised, the test PVC pipe was wired similarly to the design shown in Figure 10. The test was repeated in similar fashion by dropping a magnet through the coils and displaying the waveform on the oscilloscope. However since the oscilloscope only has two inputs, the waveforms had to be saved and recalled and the test repeated for the missing coils. The resulting waveforms are shown in Figure 11.

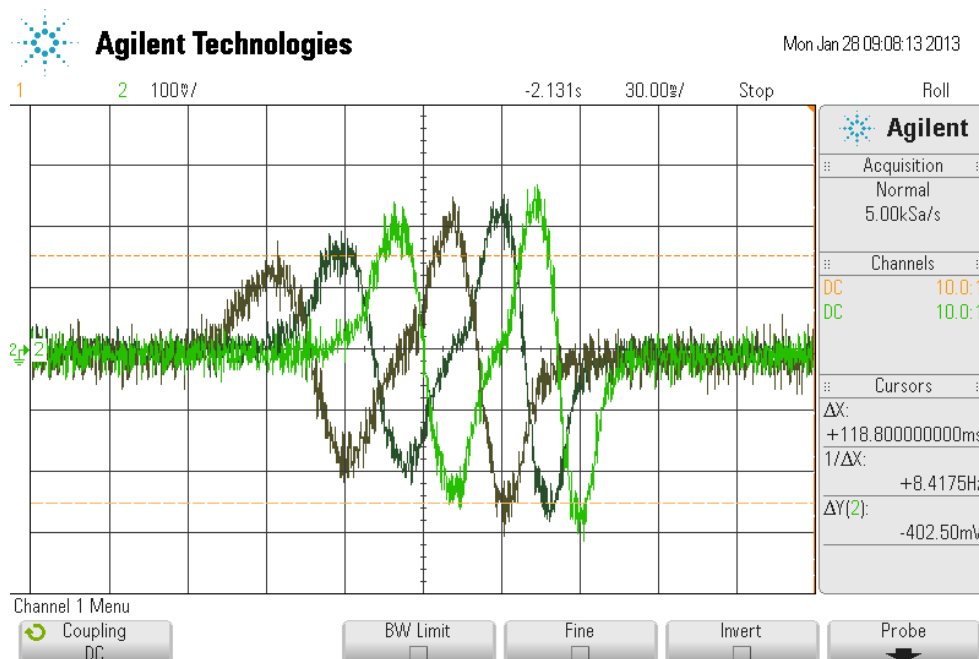


Figure 39: Three wire design waveform output

The results were better than expected, although there is a noticeable “dead-zone” in each, and it progressively gets bigger as the magnet passes through the coils. This is due to us using a 3cm length coil instead of a 2.7cm and each coil adds 0.3cm so the dead zone will only get larger. When the device is built more attention will be put forth to ensure accuracy.

Testing with multiple magnets

In order to test multiple magnets, the three wire concept was connected to an oscilloscope so only one wire of the three was being monitored. A magnet was dropped through the pipes and output of the wire is the green waveform displayed in Figure 12. Then two magnets are dropped through, separated by a wooden dowel cut to a length such that the two magnets enter coils of the same wire simultaneously. This waveform is the yellow waveform shown in Figure 12.

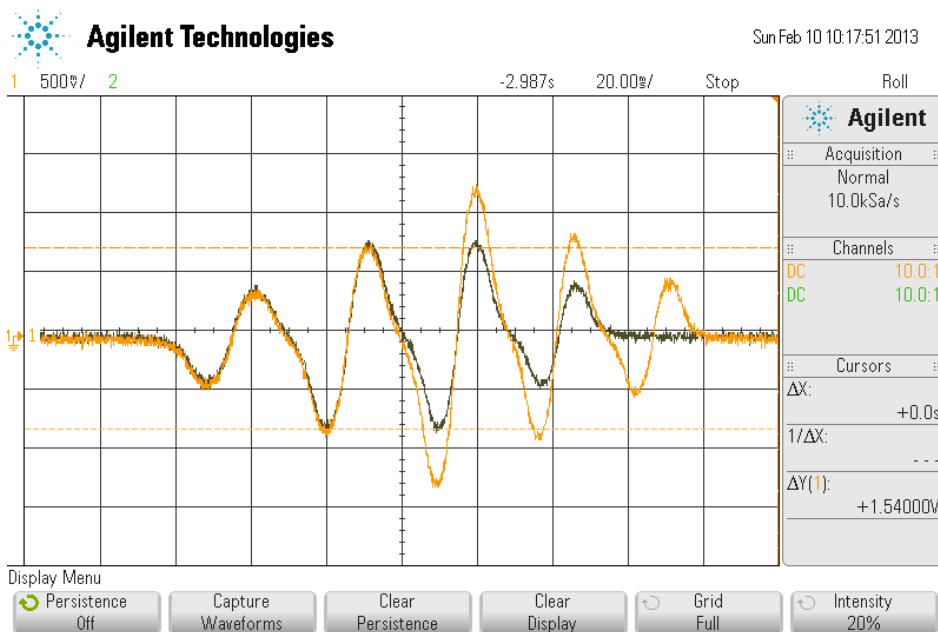


Figure 40: Comparing waveforms induced by one and two magnets

The waveforms in Figure 12 illustrate that with an increase of magnets more voltage is induced. The first graph shows two magnets (green waveform) against three magnets (orange waveform). This peak shows where the third magnet enters the system for the orange waveform, and how its voltage peak is larger compared to the two-magnet waveform (green). Notice that there are more peaks for the yellow waveform because of the third magnet in the system. The number of magnets versus peak voltage is then recorded in Table 8, and represented graphically in Figure 13.

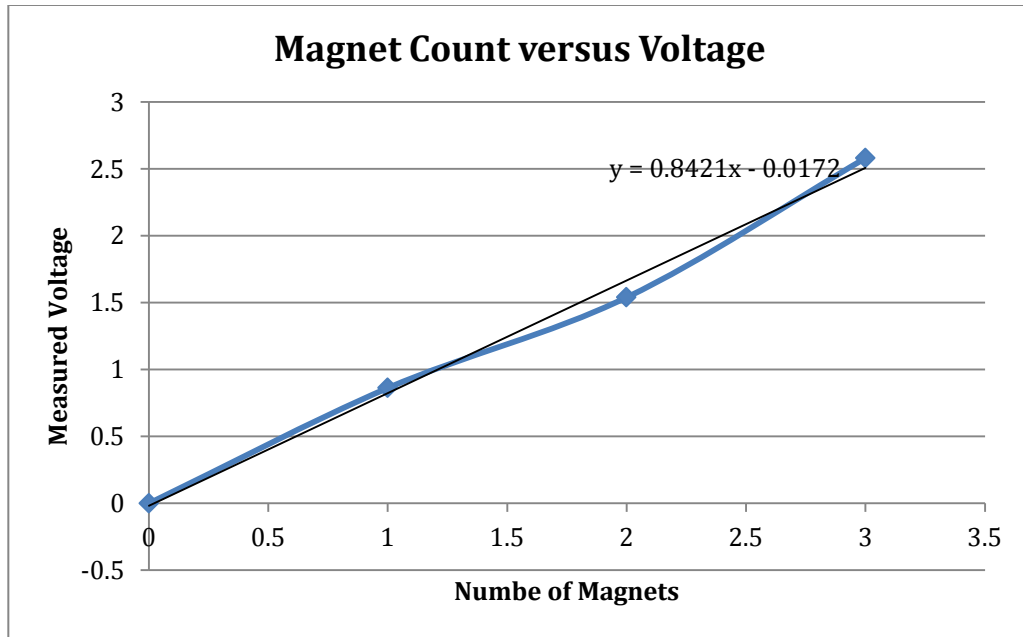


Figure 41: Magnet Count versus Voltage

Magnet Count	Peak Voltage
0	0
1	0.8625
2	1.54
3	2.58125

Table 18: Voltages versus number of magnets

IX Development and Construction

Piping Material:

- The PVC pipe was purchased in 10ft increments and cut into four 2.5ft sections using a ban-saw.
- The Acrylic pipe was purchased in 3ft sections pre-cut.

Wire and PVC pipe:

Experiments found that 5cm between coils yielded the best theoretical output waveforms, and since there is three phases it was determined that 2.5cm per coil would be ideal. The PVC pipe was fixed on one end to a drill with the highest rotational speed of 2000rpm, and on the other end it was hanging loose to a metal screw emanating from the wall. A picture of this set-up can be seen in Figure 14. The idea was that the wire would be stuck to a single point on the PVC pipe and the drill would spin at full speed, spinning the PVC pipe around wrapping the wire around the pipe. The drill was spun at full speed (2000rpm) for 1 minute and 30 seconds, or for 3000 rotations. The circumference of the pipe is:

$$\frac{\frac{3}{4} * 2.54 \frac{cm}{in} * 3.14}{100 \frac{cm}{m}} = 0.0598 m$$

Equation 2: Calculation of length of wire

So with 3000 rotations around a 0.0598m circumference it would equate to **179.4m** of wire used per coil. Since there was roughly 14,484m (9 miles) of wire purchased, 3 pipes and 3 phases per pipe, there would roughly need to be 9 coils per phase per pipe.



Figure 42: Mechanism for wiring pipe

Acrylic Pipe Fittings:

The bushing was fitted into the acrylic pipe as seen in Figures 15 using silicone glue. It took three hours for the glue to dry and for the seal to be watertight. Once the glue was dried, the bushing was fitted with a rubber cork that was large enough to be fit securely in the bushing, yet allow enough space to be pulled out by hand. That is it didn't lie flush with the bushing, which can be seen in Figure 15.



Figure 43: Bushing and cork used to make pipe watertight

The data logger was larger than the inner circumference of the bushing, and as a result the bushing had to be filed down to allow for the data logger to be entered. This can be seen in Figure 16 as marked by the red circles.



Figure 44: Bushing filed down

Shown in Figure 17 is the data logger system inside the Acrylic pipe. The acrylic pipe was intentionally selected long enough to allow for this space for the data logger to fit. The data logger needed a 9V battery, which is shown in Figure 17.

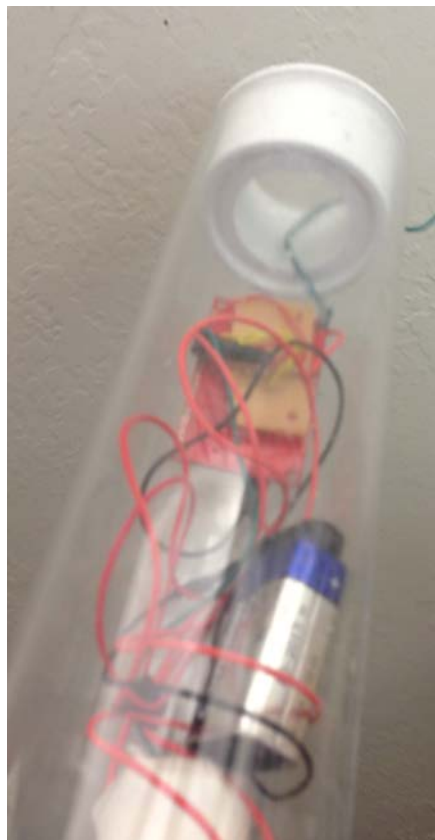


Figure 45: Data logger and circuitry inside acrylic pipe

In order to view the data logger functioning properly (signified by two flashing LEDs on the data logger) a hole was cut into the outer piping so it can be observed through the acrylic pipe. As shown in Figure 18.



Figure 46: Hole cut into outer piping

The complete design fitted together can be seen in Figure 18



Figure 47: Ocean generator

X Test Results Part Two

Testing Continuity

After the three legs of the generator were built the wires was checked for continuity, by measuring the resistance of each wire for each phase. Using the American Wire Gauge standard, the resistance of the wire was converted to feet. The results are displayed below in Table 9. The names of the branches are named Antigua, Bermuda, Cyprus.

Phase	Antigua [Ω]	Bermuda [Ω]	Cyprus [Ω]
A	671	2332	DNE
B	2208	2035	DNE
C	1700	DNE	DNE
	Antigua [ft]	Bermuda [ft]	Cyprus [ft]
A	1617.66	5621.99	DNE
B	5323.05	4905.98	DNE
C	4098.36	DNE	DNE

Table 19: Values of resistance and length for all coils of wire

Complications arose in all branches, most notably with both Antigua and Cyprus. Both branches had significant breaks in wire. Antigua was soldered and mostly recovered. There were some losses in Phases A and C. With Bermuda there was a single break in Phase B that was easily soldered to complete the phase, however Phase C was lost completely when other coils covered the break between two wires in that Phase. There were several complications in Cyprus where several breaks were lost and were not able to be recovered to be soldered.

Finding Maximum Voltage

It was determined that Bermuda would be the best Branch moving forward since it had the most complete branches, and the data logger purchased was only logging a single branch at a time. In lab to two working Phases (Phase A and B) were tested by dropping all three Magnets vertically through the pipe, with its leads connected to the two inputs of an oscilloscope. Seen in Figure 13 is the result of this experiment. The green waveform is Phase A and the orange is Phase B. It can be seen that the waveforms don't match exactly, due to the uneven amounts of length in the Phases. The maximum amount of voltage was found in Phase A where it was 81.62V peak-to-peak. Comparing the peaks individually, the difference arises from inaccurate spinning method. Using a drill and stopwatch to count turns isn't very accurate, and shows that it doesn't yield consistent results.

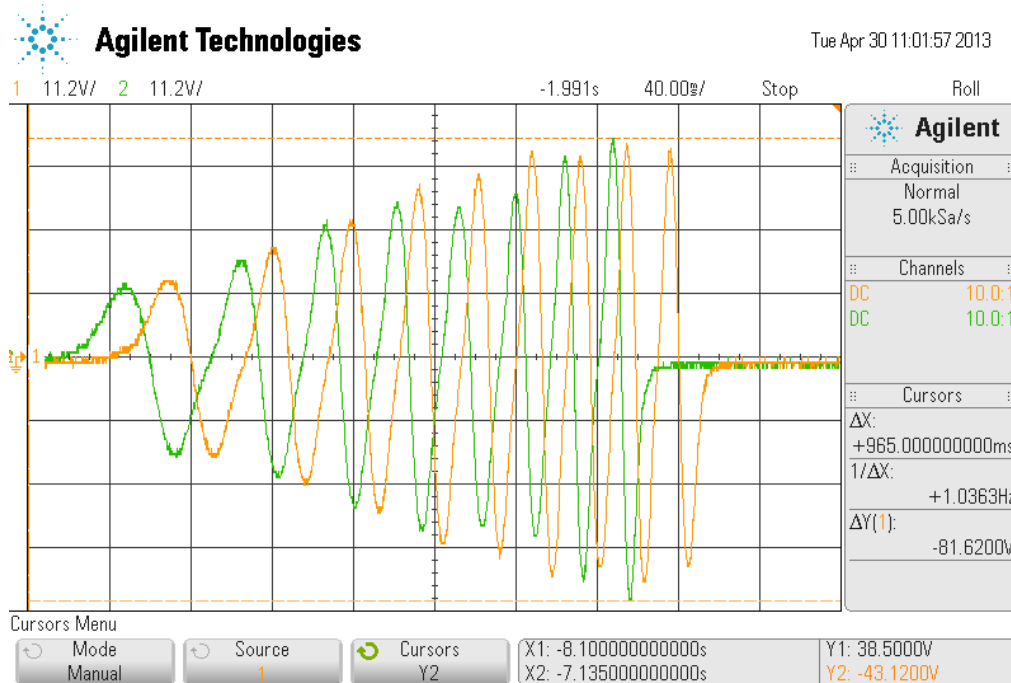


Figure 48: Waveforms of the Phases A and B of Bermuda

Testing to ensure the design is waterproof

The acrylic pipe was layered with silicone glue and bushings were placed on the end. Inside the pipes paper towel was placed and corks were fitted into the holes of the bushings, so that the device was watertight. A bucket was filled with water and each acrylic pipe was submerged and moved around to simulate ocean movement. Each branch was checked for leaks by examining the paper towel. No leaks were found.

Testing the data logger

The raw data was stored on an SD card via the data logger in *.txt* files. However, the data when opened in Notepad was largely gibberish when binary values were expected. However, when opened with the hex reader freeware “HxD” data was observable and then converted and graphed thru a macro on Excel. This process, although, a bit cumbersome allowed for what looked like gibberish in a notepad file to be converted to graphs that matched very closely to what was expected based off the inputted waveforms.

After the data could be read in excel, accuracy was then tested. Using a DC power supply the data logger's inputs were placed across the power supply's terminals and the power supply's DC output was increased in 0.1V increments from 0V to 5V. It was soon discovered that the data logger could not log data below 0V and above its reference voltage of 3.3V.

The challenge became to have the inputs voltage be no lower than 0V and no higher than 3.3V. The solution was to implement a voltage diving circuit that not only reduced the voltage onto the appropriate scale but that allows positive shifting of the voltage. Shown in Figure 14 is the circuit that allows this solution. The resistors R1 and R2 will combine in parallel and form a voltage divider across them with R3. The circuit would then use half the data logger voltage which would shift it 1.65V.

$$V_{OUT} = V_{IN} \frac{R1||R2}{(R1||R2) + R3}$$

Equation 3: Voltage Divider Calculation

Knowing the results from the maximum voltage experiment, resistors were chosen that would scale the peaks (38.5V and -43.12V) into the usable range. A voltage divider ratio of 0.04 was selected to place the maximum peaks within range. To achieve this ratio the resistors shown in Figure 14 were selected. The measured values of the resistors gave a ratio of 0.0477.

In Figure X the output of the circuit is now the input into the data logger.

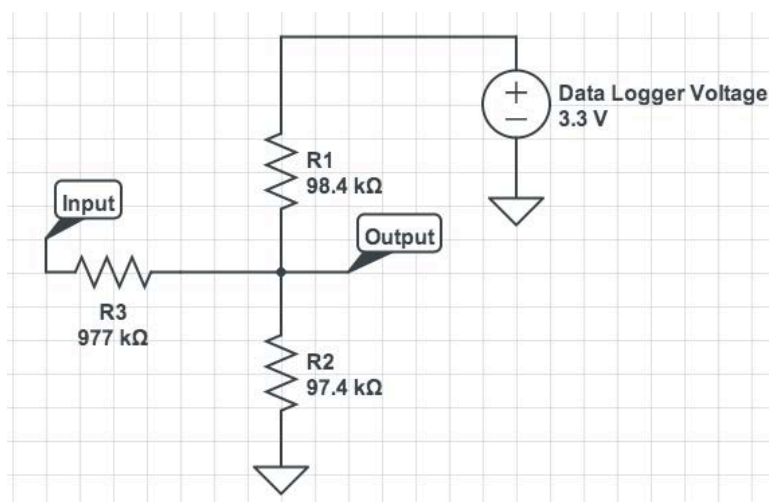


Figure 49: Voltage Divider Circuit

Testing the design with the data logger

After the voltage divider circuit was built and connected to the data logger, Phase A from Bermuda was connected to an oscilloscope input and data logger input and randomly tilted back and forth to produce a waveform. This waveform was induced by one magnet and is seen in Figure 15 and the waveform produced by the data logger is seen Figure 16.

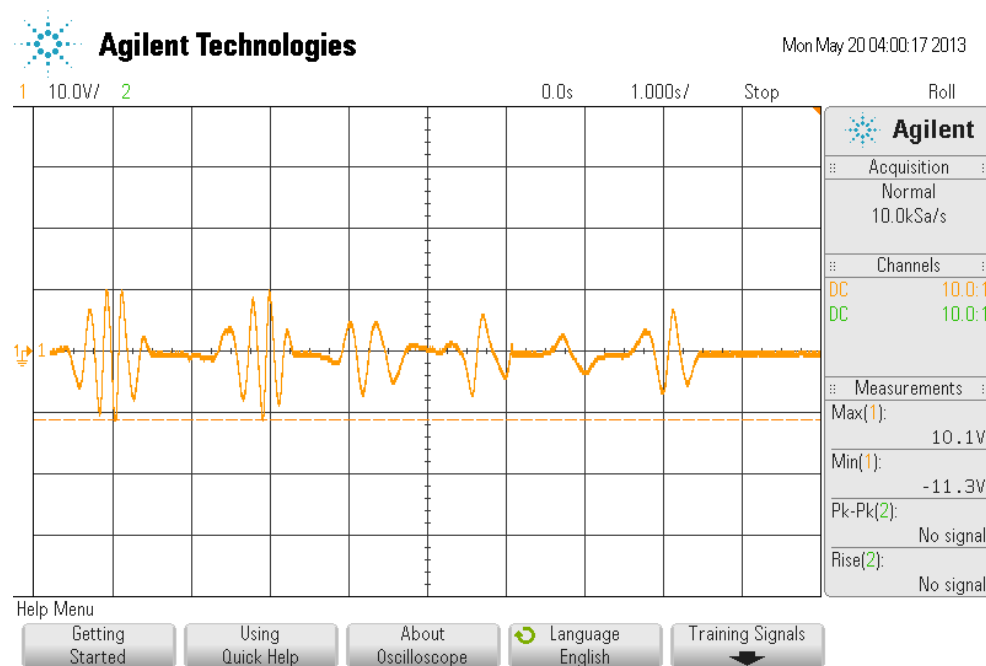


Figure 50: Oscilloscope capture of a random waveform

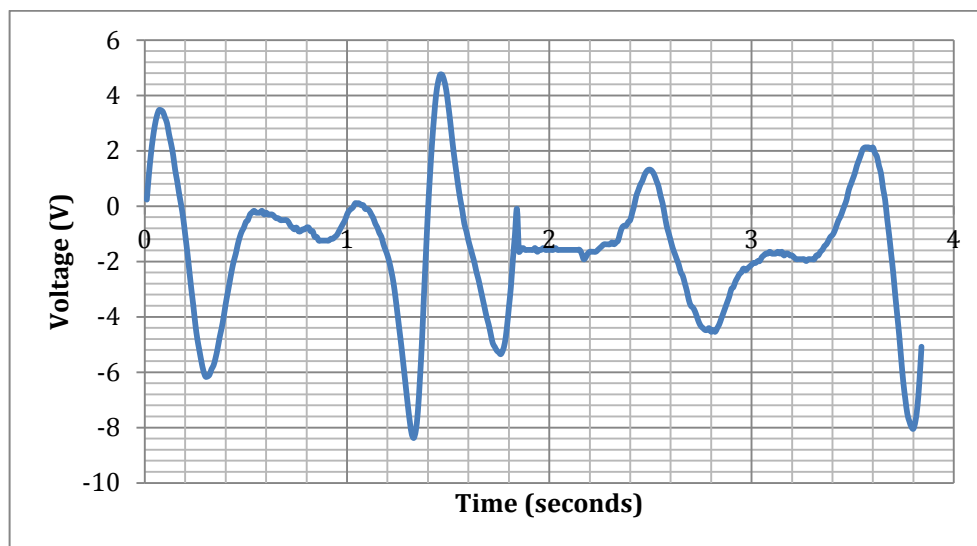


Figure 51: Data logger output of a random waveform

The section that the data logger recorded is shown blown up in Figure 17 and is superimposed onto the data logger's readings and is shown in Figure 18.

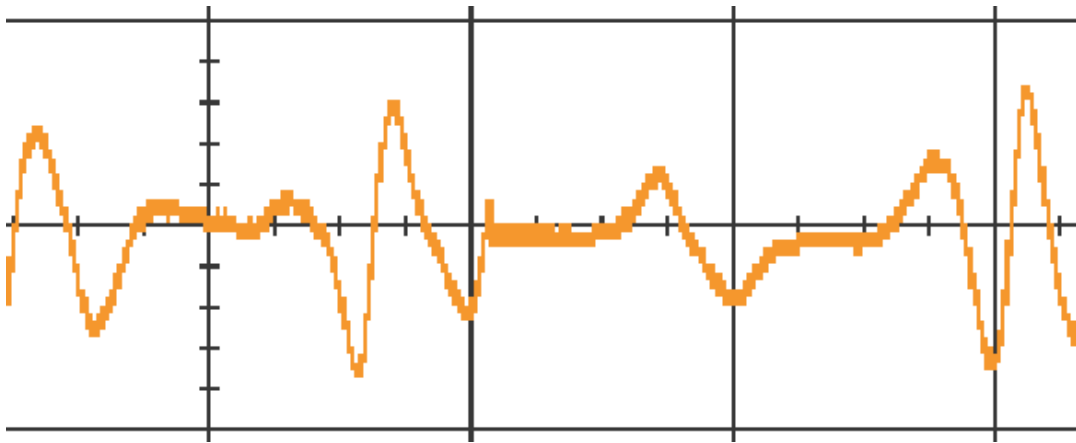


Figure 52: Enlarged section of the oscilloscope output

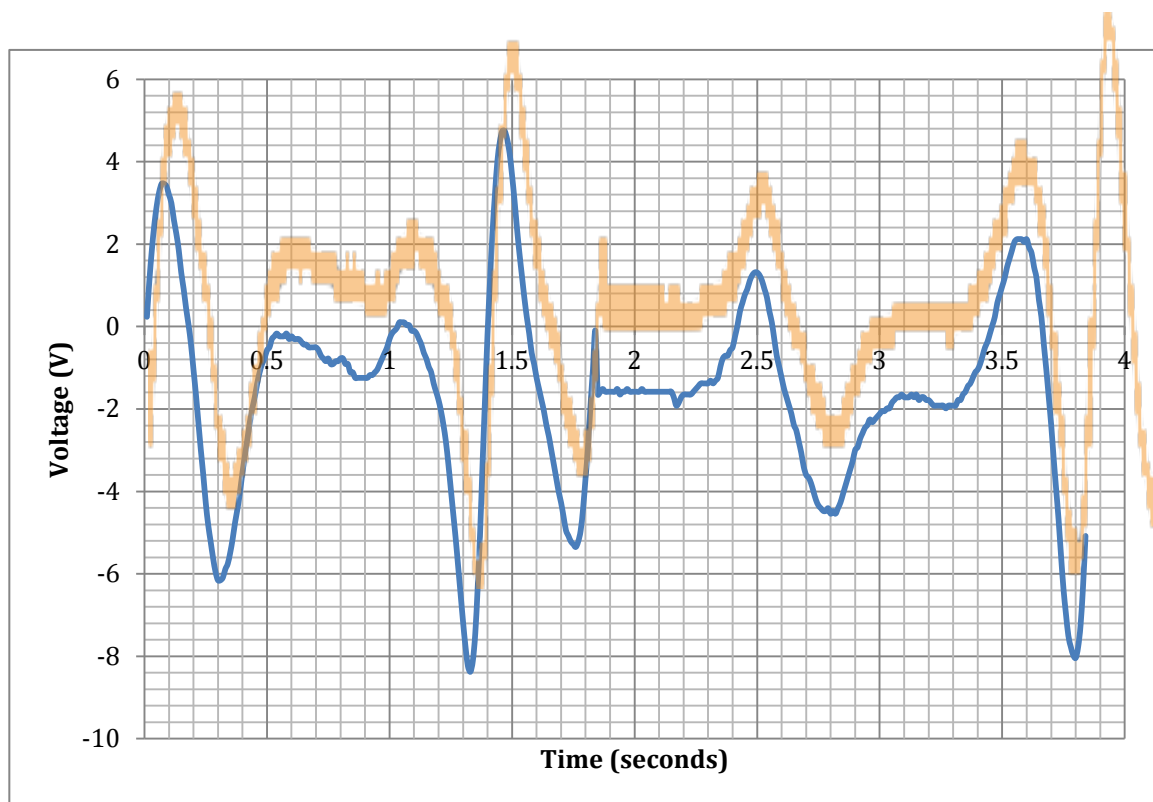


Figure 53: Superimposed images of the data logger and oscilloscope

It can be seen that there is an offset with the data logger's displayed data. In order to verify this, a point on the data logger was selected that the oscilloscope waveform showed to be 0V. This was then added to the entire data set given by the data logger and is shown in Figure 19.

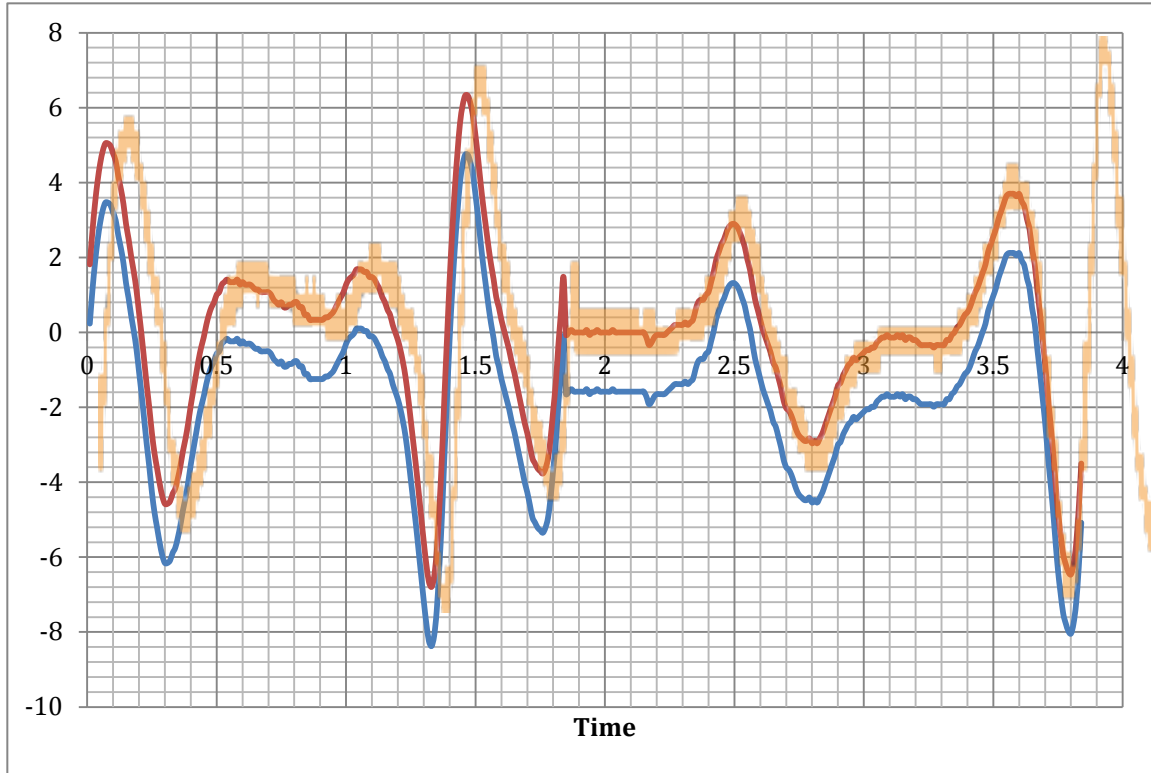


Figure 54: Super imposed images of the original data logger output, the oscilloscope image, and the fixed data logger output.

XI Test Results Part Three

The above graph shows a full ocean trial in which the datalogger was turned on and the device was carried down to the water from the beach and pulled out into the deeper water. This accounts for the first two minutes and all of the relatively small fluctuations. Then the next 500 seconds (120 to 620 seconds) show waves causing the magnets to propagate thru the pipe and induce emf. In the conception of this design one of the strengths of using wave technology was that unlike solar or wind it would generate all day regardless of sun or wind exposure. However, this generalization is not entirely true because as the graph shows there are periods of up to 40 seconds where there were not any waves of significant magnitude to tilt the design to a sufficient angle to cause the magnets to slide.

Testing the device out in the ocean generated a maximum voltage of ~68 Vp-p, however this quantity on its own is nearly useless because it is entirely dependent on the resistance it is across. In this case, with the resistance per leg per phase known a more useful metric of power [W] can be calculated. A matched load with a complex conjugate (an opposite reactive load) allows for the greatest power transfer and knowing that there will be a voltage divider across the winding resistance and the load allows the following equation to be derived:

$$P_{max} = \frac{\left(\frac{V}{2}\right)^2}{R} = \frac{1}{4} \frac{V^2}{R}$$

Equation 4: Finding Max Power

Inserting values from the peak voltage generated yields

$$P_{max} = (0.25) * \frac{(35.4)^2}{2332} = 134.34 \text{ mW}$$

Equation 5: Inserting values to find Max Power

However, this metric again is not extremely useful because this is just a measure of max instantaneous power transfer on one phase of one leg. To give a more accurate illustration of the power generated, the average voltage generated over an entire trial can be used in place of the max power. Extrapolating this data the following table was generated:

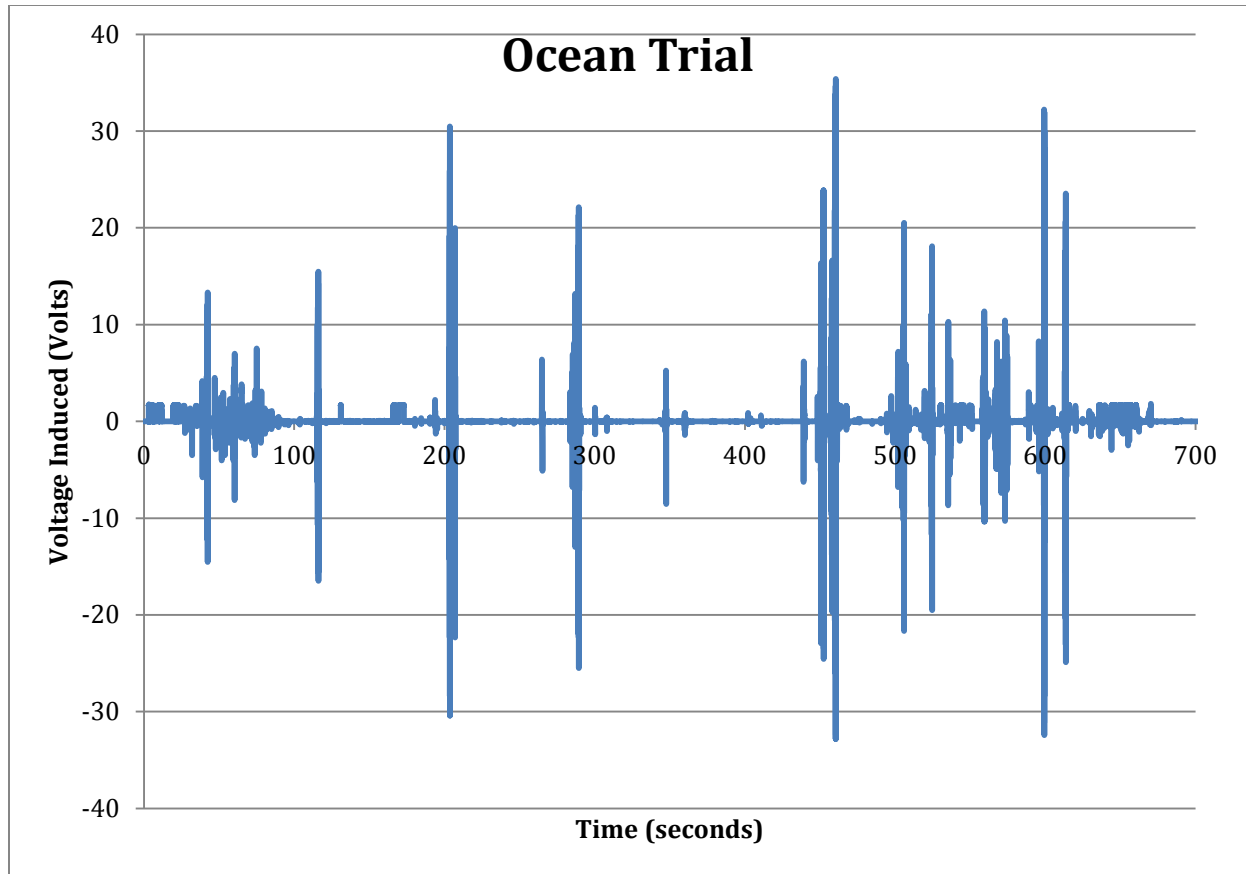


Figure 55: Data logger values from best Ocean Trial

	Single Phase	Three Phase	Three Legs
AVG Power	7.084E-08	6.376E-07	5.738E-06
Wh	1.832E-06	1.649E-05	1.484E-04
mWh/day	1.056	9.50	85.50
Wh/week	0.05172	0.4655	4.189
Wh/mo	0.950	8.550	76.95
kWh/yr	0.1406	1.266	11.39

Table 20: Energies available over different time periods

The graph below depicts what occurs when the device encounters a large, slow rolling wave. The wave hits the device at the ~203 second mark and causes the magnets to slide down the length of the PVC pipe over the course of 1 second. At 206.25 seconds the device begins to tilt back the other way as it slides down the back side of the wave. The *emf* generated is slightly smaller because sliding down the backside of the wave does not occur at as steep of an angle as the front side of the wave.

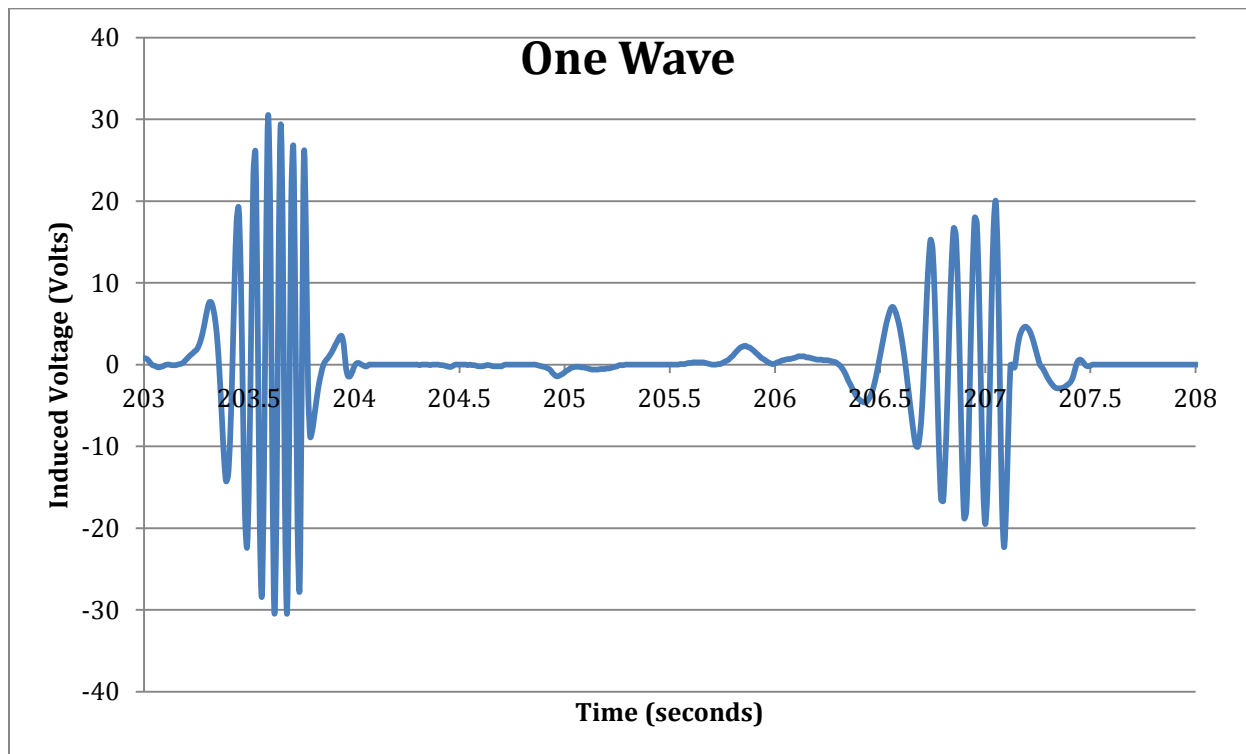


Figure 56: One wave passing through generator

From 203.39 seconds to 203.79 seconds there are approximately 6 periods. This yields a period of:

$$\frac{6 \text{ periods}}{0.4 \text{ seconds}} = 15 \text{ Hz}$$

Equation 6: Nyquist Criterion calculation

As there is a sampling rate of 100 Hz this easily satisfies the Nyquist criterion of having double the frequency as a sampling rate to ensure accuracy. The graph above builds in magnitude with

each peak and trough due to the magnets picking up speed as they move down the pipe and then ending with a slight jarring as it bumps into the other end of the pipe which causes the non-sinusoidal bumps at the end of each sinusoid.

XII Conclusion

The overall concept idea of the project was a resounding success in that it operated exactly as expected. However, the efficacy of the project is questionable at this scale especially considering the resources necessary for the device. One of the major goals was to be sustainable and while the transfer of energy is very sustainable because it is coming from ocean waves due to gravity, the production of the devices must be taken into account as well. In the current design, 9 N42 Magnets are being used as well as over 9 miles of magnet wire. If one were to scale up this project in order to obtain more power, it would have to be taken into consideration whether or not using rare earth magnets and a great quantity of copper in the wire is worth the power generated.

Based off the data on a yearly basis each device can generate approximately 11.4 kWh per year which is a mere fraction of what is used by individual people in most developed countries around the world. If the project were to be scaled up by adding more devices in the future things that should be taken under consideration include finding a more effective way of winding the pipes, how to store or transmit the power, and how to minimize the ecological footprint of producing the device.

XIII Bibliography

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