Submerged Pressure Differential Wave Energy Converter

A Senior Project

presented to

the Faculty of the Physics Department

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In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science

by

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Abstract

As supplies of fossil fuels are becoming depleted, it is necessary to look for alternative sources of energy. The ocean is a vast, largely untapped source of renewable energy. This project attempts to design a device which can cheaply and reliably convert the energy from ocean waves in to usable electrical energy. Computer simulations and oceanographic knowledge are utilized to develop a working design for an entirely submerged wave energy conversion device.

Introduction

There are a great many efforts being made in the field of alternative energy. Wind and solar power are widely used. Other forms, such as hydroelectric and geothermal power, are less widespread, but equally plausible. Over the next several decades, world energy consumption is estimated to rise considerably[1], and new sources of energy need to be found and developed to the point of commercial viability. The ocean contains a vast amount of energy, very little of which has been constrained for power usage by the Earth's population.

Power based on the motion of ocean water is very renewable. The oceans have existed for thousands of years and continue to behave in much the same way. It is unlikely that ocean based power would significantly impact the behavior of the world's oceans. This is the same reason that ocean based power is environmentally friendly. Solar power and wind power both require large amounts of space on land to function effectively, as well as being visible to the general population. The three dimensional nature of the ocean means that ocean based devices can function as a part of the environment, making less of an impact on native flora and fauna. In addition, the reduced visibility of ocean based devices should make it easier to gain public acceptance for such projects.

1 Clément A et al. 2002. Wave energy in Europe: current status and perspectives. Renewable and Sustainable Energy Reviews 6: 405-431.

Within the greater realm of ocean based energy, there are two areas that bear the most possibility: wave power and tidal power. Both of these rely on the natural movements of the ocean to produce energy, and both have positive and negative aspects.

Wave Power versus Tidal Power

Tidal power can produce a great deal of energy and is very predictable. Tides can be predicted very accurately in time and in some cases have similar changes in water level day after day. However, tidal power requires very specific shoreline geography. Due to this, tidal power is somewhat limited in its application. Despite the predictability of tidal systems, the geological constraints on its usage make it somewhat less desirable.

Wave power can be used anywhere there are waves of a reasonable size, which opens up the available locations significantly. This also means that wave power devices can be deployed en masse, covering a larger area on the ocean's surface or the seafloor. Because of this flexibility, wave power is more desirable for general use.

Types of Wave Energy Converters

According to the European Marine Energy Centre (EMEC), there are six basic types of Wave Energy Converters, or WECs[2], which operate at various points in the water column and shoreline geography. While these six designs do not cover all possible devices, they represent the majority of devices currently being designed and tested. The images included here were found on the EMEC website, and are copyright EMEC 2009..

The first, the attenuator, sits on the surface of the ocean, perpendicular to the waves. As the waves pass, the attenuator moves with the waves, converting their motion to energy. This is the design

2 "Wave Devices." *EMEC Orkney.* n.d. Web. 24 May 2011.

used by Pelamis Wave Power[3], in Portugal.

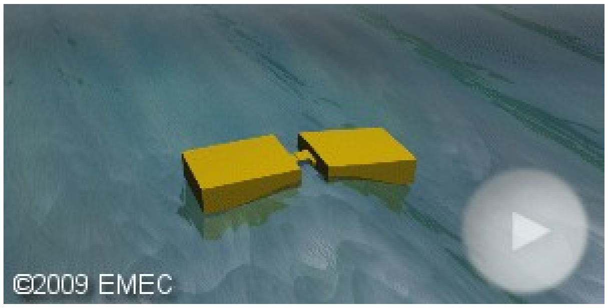

Figure 1 - Attenuator

The second type of WEC is the point absorber. This device rests on the seafloor close to the shoreline, and moves with the waves passing by. It moves in three dimensions to fully take advantage of the wave motion.

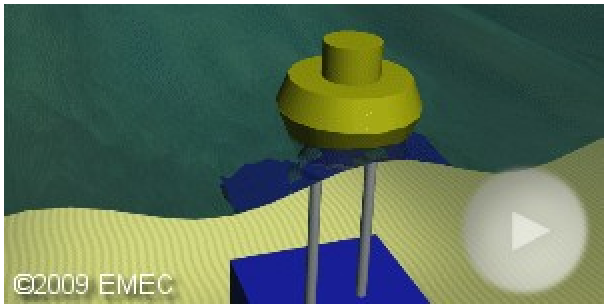

Figure 2 - Point Absorber

The third device is the oscillating wave surge converter. This device rests on the seafloor, and resembles a paddle attached to a pivoted joint. As waves pass overhead, the paddle moves with water particles to capture the wave's energy.

3 "The Pelamis." *Pelamis Wave Power.* n.d. Web. 24 May 2011.

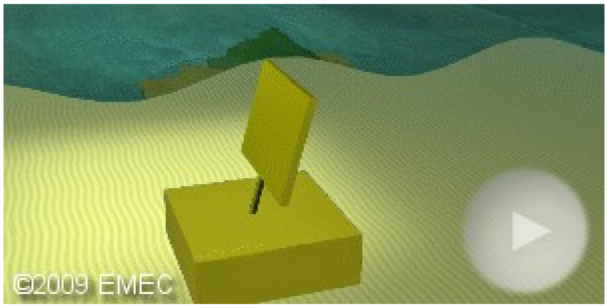

Figure 3 - Oscillating Wave Surge Converter

The fourth type of WEC is the oscillating water column. This is a permanent hollow structure rising above the surface of the ocean close to the shore. As waves come in, the water fills the hollow section of the structure, forcing air past a turbine.

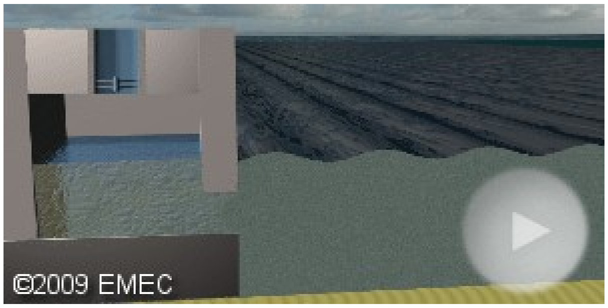

Figure 4 - Oscillating Water Column

The fifth device is the overtopping device. As with the oscillating water column, this is a permanent structure near the shore. As waves come in, they cover a well, and the falling water drives a turbine.

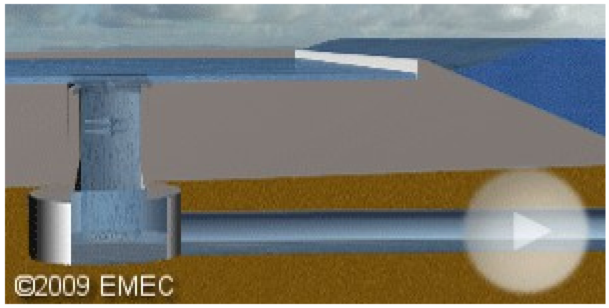

Figure 5 - Overtopping Device

The sixth and final type of WEC is the submerged pressure differential. This sits on the seafloor, typically near shore. The waves passing overhead cause the water level above the device to rise and fall, creating a pressure differential which drives the device. The Archimedes wave swing[4] is one such device. This type of device is what we have chosen to use here.

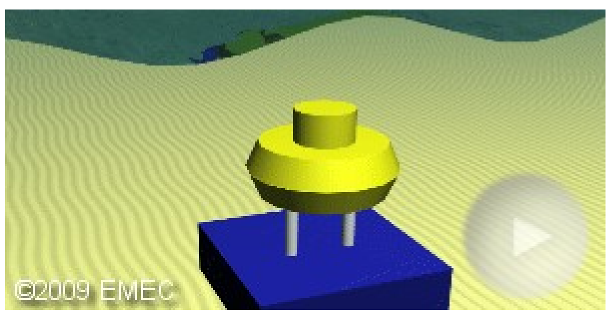

Figure 6 - Submerged Pressure Differential

Design process

The first step in designing a WEC is deciding which of these types of devices is most desirable – how the device will get energy from the waves. One of the selling points of wave power over something like wind power is that it can be installed out of sight of the general population, reducing public outcry over the use of space. This discounts several of the mentioned devices, the attenuator,

4 Damen M et al. 2006. Modelling and Test Results of the Archimedes wave swing. ImechE 220 Part A: 855-856.

oscillating water column, and overtopping devices. The point absorber's range of motion is similar to a ball and socket joint, and the oscillating wave surge converter moves on a hinge joint. The larger range of motion required by these devices is not desirable for a seafloor device, where maintenance and repairs are fairly difficult to do. This leaves the submerged pressure differential, which is the type I have chosen to pursue.

There are several parameters that need to be determined in order to design the device. I've already determined that a seafloor device is desirable in order to make it more publicly acceptable. From there the next question is one of wave driven or pressure driven devices. As has been previously mentioned, wave driven devices are less desirable due to the difficulty of performing maintenance and repairs. A point absorber moves in all three dimensions, and an oscillating wave surge converter moves in two dimensions. By using a pressure driven device, the available axis are reduced to one: the vertical axis.

Most of the discussion thus far as been of how to get energy from the wave, not how to convert that to usable energy. In order to convert it, there needs to be some sort of generator. Now that this is established, there can be a discussion of types of generator. The two basic types of generator under consideration were linear and turbine generator. A linear generator works through the use of permanent magnets. A number of evenly spaced magnets are attached to a movable shaft, which sits in the center of a solenoid. As the shaft moves, the change in magnetic field as the magnets on the shaft pass the others results in an induced current. On the other hand, a turbine generator is what you will find in most power plants in the world. Something (such as steam or water), drives a turbine, which has a series of magnets which pass by mounted magnets, generated an induced current. In this case, the turbine generator is superior. While it is more difficult to translate the motion of the device into something rotational, a turbine generator is much easier to maintain. With the possibility of leaving the generator

under the surface of the ocean for a protracted length of time, maintenance is a high priority.

The biggest problem with a turbine generator in these circumstances is that it cannot be directly driven by a linear oscillating device, such as a submerged pressure differential WEC. The motion of the float would need to be translated into something rotational. The simplest idea is to build something similar to the pistons in an internal combustion engine. A pair of joints drive a wheel, driving the generator and producing power. However, in order to drive the generator at a high enough speed to produce any significant amount of power, it needs to be moving much more quickly than the frequency of ocean waves allows. To alleviate this, it becomes necessary to add gears, which increases the complexity of the device by quite a bit. This is undesirable for two reasons. First, it makes the device more costly to construct. When one of the primary reasons for choosing wave power over tidal power is the ease with which it can be scaled through the use of fields of devices, cost is an important factor in design, even more so than it generally is. The second reason is the same reason the turbine generator was chosen over the linear generator. When the intent is to leave the device below the ocean's surface, more complexity makes maintenance more difficult.

Another solution to how to drive the generator is inspired by traditional power plants, which use some kind of fuel to heat water, creating steam to drive a turbine. While heating water using wave motion is not feasible, using a liquid to drive the turbine is applicable. If the submerged pressure differential drives a simple pump, water can be forced over the turbine to create the desired electricity. This is not a perfect solution. The frequency of the waves still does not provide enough speed to the turbine to generate significant amounts of energy. Furthermore, there is not a constant flow of water over the turbine, which is desirable for creating a steady voltage. To solve both of these problems, another stage was added between the device and the generator: a tank. Water is pumped into the tank, which has some set pressure. This creates a constant flow of water over the turbine at a higher pressure than the pump alone would achieve. A side benefit of using a pump at the seafloor over a more direct

method to drive the generator is that the generator, one of the more complex pieces involved, does not need to sit on the seafloor, making it easier to maintain. The full loop can be seen below, in Figure 7.

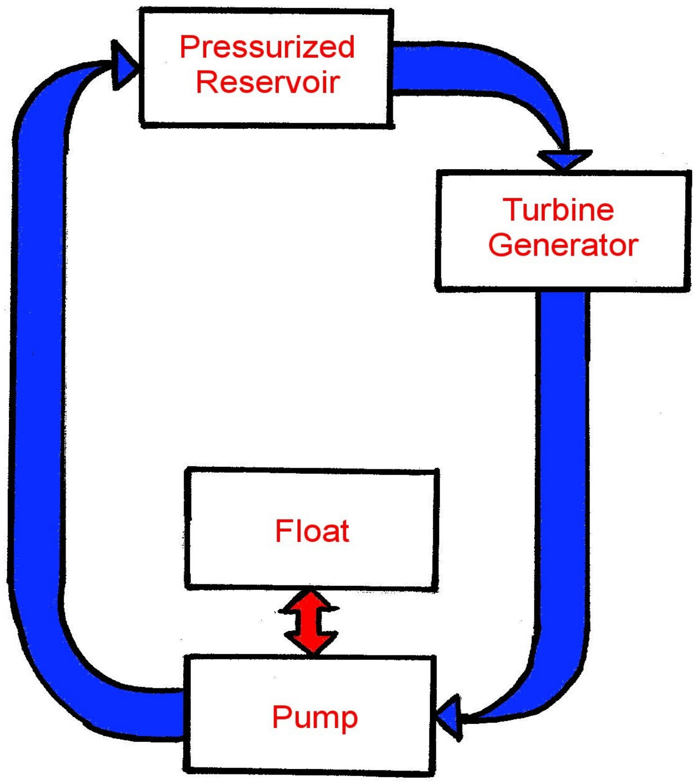

Figure 7 - Seafloor Device with Turbine Generator

The seafloor pump works through the use of pressure differentials. A contained shaft slides along a larger, hollow shaft. When the inner shaft goes out, the lower pressure created draws water in through a one-way valve at the end. When the shaft goes back in, the higher pressure forces the water out through a second one way valve. With the continuous motion of the waves, this provides a steady stream of water into the pressurized reservoir.

One of the problems encountered with a submerged pressure differential comes from the ocean's tides. Due to the mechanical nature of the device, the float being used to drive the pump needs to be

centered at approximately the same height from the ocean floor at all times in order to produce the most energy. If the ocean stayed at a constant depth this would not be a problem, but tides are a fact of life and must be accounted for. In order to keep the float at an even height at all times, we propose to actively control its buoyancy. The float can be made rigid, then partially filled with water. Because density is a function of mass and volume, described as such

$$\rho = M / V \qquad \textit{Equ. 1}$$

this is a simple way to adjust the density.

The other problem that comes along with tides is that the float needs to actively respond to the changing sea level at different points during the day – when the tide comes in, the float needs a lower density and vice-verse. Furthermore, seawater is more complex to deal with than fresh water. Because of salinity and particulate matter in the water, the equation of state for seawater has 26 terms[5] describing the density of seawater as a function of temperature, pressure (or depth), and salinity. However, due to the relatively small changes in depth occurring in this situation, temperature and salinity can be assumed to be relative constant, leaving just depth as a variable.

In order to control the density of the float, there needs to be some kind of control system. The simplest way to do this is to measure the density of the surrounding water using the modified equation of state, compare it to the desired density, and pump water into or out of the float as required. In order to remove the waves from consideration, a low pass filter was used. This keeps the float from constantly trying to adjust to each passing wave. The final circuit is below, in Figure 8.

5 Bleck, R., Brydon, D., Sun, S. 1998. A New Approximation of the Equation of State for Sea Water, Suitable for Numerical Ocean Models. Journal of Geophysical Research. 1-10.

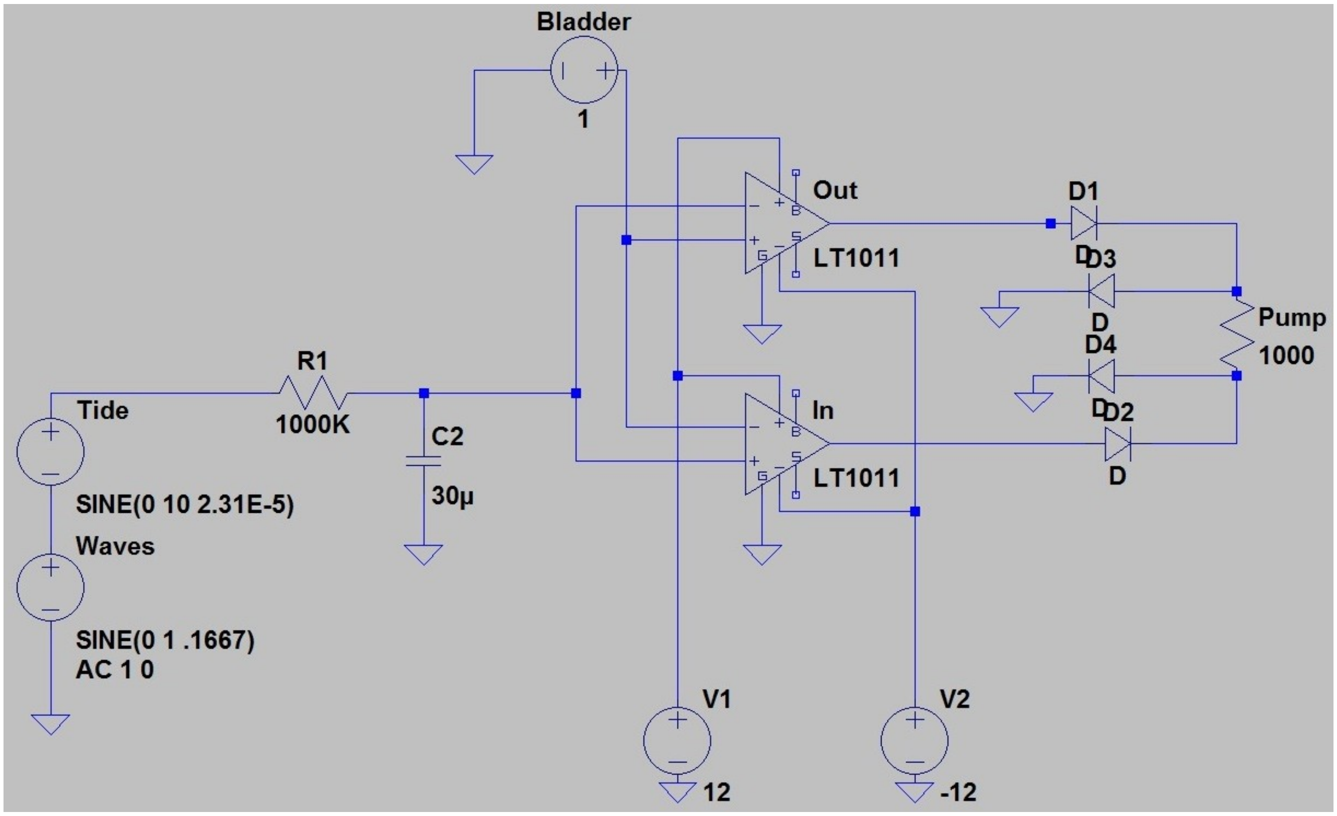

Figure 8 - Float Control Circuit

The basic design of the float can be seen below in Figure 9, though not to scale and not accurately shaped. Because the density differential is the reason the float moves, the surface area and shape of the float are unimportant. The float construction is dictated by what it needs to hold, how it behaves in the water, and what is attached to it. Inside the float, there is a bladder, which can be filled with or drained of a fluid. By keeping this a closed system, we control the exact density of the float at all times. This liquid is stored in an external reservoir at the seafloor with the device. The fluid chosen here is fresh water, due to easy availability and low viscosity. In order to promote stability and keep costs down, the float drives four simple pumps with each passing wave. By increasing the number of simple pumps, each pump can have a smaller diameter without a losing pumping power. Supporting the float at four points makes it more resistant to things that could otherwise knock it away from the vertical, such as strong currents or ocean fauna. The float housing needs to contain either a two-way

pump or two one-way pumps, the bladder used for density control, the control circuit, air, and possibly additional ballast material. The pumps serve as the main form of ballast material in addition to controlling the water in the bladder. Further research is necessary to determine the optimal size and shape of the float, but an oblate spheroid with a major axis diameter of about one meter and a minor axis diameter of about one half of a meter seems to be a reasonable starting point.

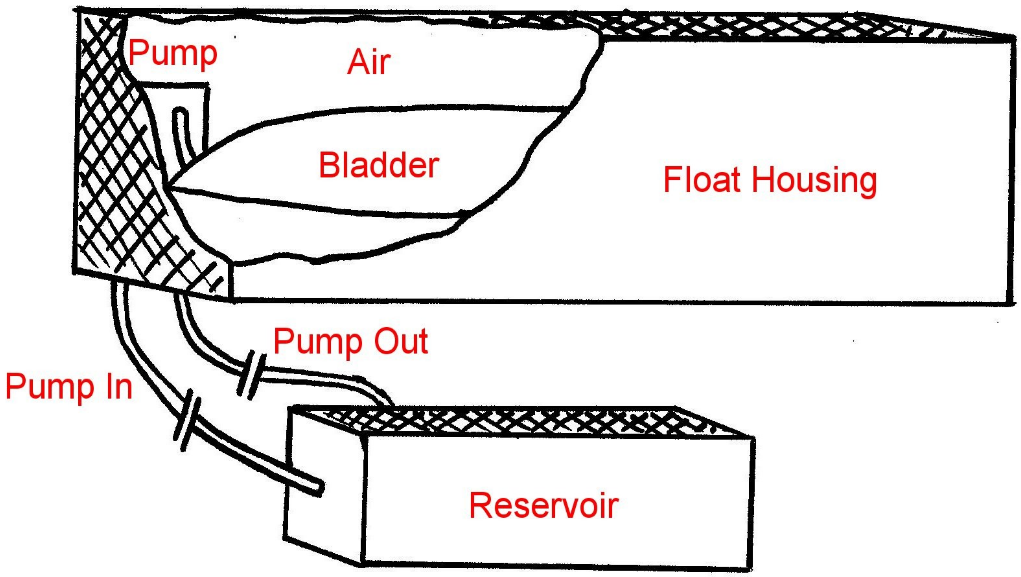

Figure 9 - Float Design

The pumps attached to the float are a very simple design. An internal shaft is attached to the float, and moves up and down with the float as waves pass overhead. There is a seal between the pump shaft and the inner diameter of the pump housing, as indicated by the O-rings below in Figure 10. The one way valves and pump housing are anchored to the seafloor.

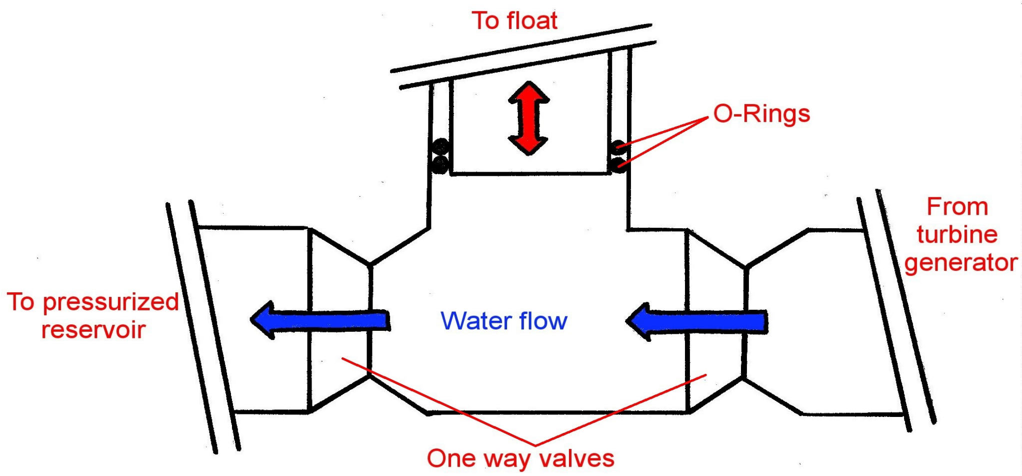

Figure 10 - Pump Design

In order to keep seawater and other natural contaminants from interfering with the pump function, some kind of flexible, nonreactive covering is necessary between the float and the pump casing.

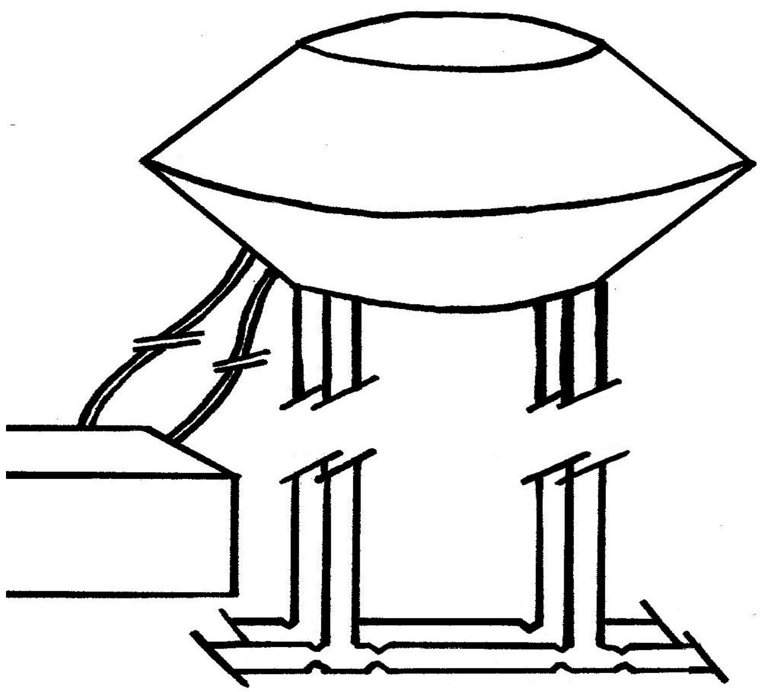
Figure 11 - Entire Device

Construction and Cost

Due to the harsh nature of the environment the WEC was designed for, the materials need to be sturdy to withstand dynamic loads. Metal parts need to be either entirely sealed off from the environment or not used, and any moving part also needs to be protected. In addition, cost should be kept low to promote the modular nature of the device. Because of these factors, the majority of the device is made from PVC plastic. PVC is non-reactive and handles a range of temperatures much greater than the device should experience in the ocean. It is pressure rated to much higher pressures than are expected to be found at the depths the WEC is designed for, and is easily and cheaply available at virtually any hardware store. The range of diameters means that a simple pump can be easily constructed.

Each seafloor pump consists of two one way valves, available at approximately $8 USD, several PVC fittings, with a total cost of about $14 USD, two long PVC pipe segments, at a cost of approximately $5 USD each, a pair of O-rings at approximately $1 USD apiece[6], and a plug for the pipe used as the pump shaft, the Oatey 33400 gripper, costing approximately $2.50 each[7], leaving the total cost of each pump at approximately $41 USD from a major retailer.

The float housing is a custom extruded PVC piece, cost unknown, containing the control circuit, which is priced below, two one way pumps, costing approximately $40 USD[8] each, and a bladder. The total cost of the pump is approximately $80 USD plus the cost of the float housing.

The tubing running from the float's reservoir to the float's bladder and from the seafloor to the pressurized reservoir at the surface is 1/2” ID surgical tubing, which can be purchased for approximately $4 USD per foot[9]. Assuming a depth of 30 feet, with the generator situated 15' above sea

6 *Home Depot.* n.d. Web. 24 May 2011.
7 *KSC Direct.* “1 1/2” Gripper OAT 33400.” n.d. Web. 8 June 2011.
8 “Cal Pump.” *Just Water Pumps.* n.d. Web. 24 May 2011.
9 *Amazon.* n.d. Web. 24 May 2011.

level at low tide, approximately 105 feet, leading to a cost of approximately $420 USD.

The reservoir holding water before the turbine generator can be made of any material, as long as it can be sealed completely. Because it can be placed above sea level, maintenance and dimensions are not major issues. Once again, more research needs to be done to determine the optimum size and material, but something as simple as a 5 gallon bucket from Home Depot, costing only $7 USD, could be easily modified to suit this purpose.

The control circuit is also inexpensive. The two integrated chips used, the LT1011s, cost only $3.50 USD each[10], and the remaining components consist of a single resistor, a single capacitor, several batteries, and several diodes, all of which can be purchased for a total of around $6 USD. The pressure sensor is the MPX5999, which costs $5.75 USD[11]. All of these prices are for individual parts, neglecting any possible discount for a bulk purchase.

The total cost of the device then comes to approximately $575 USD plus the cost of the float housing. With bulk pricing and improvements to the materials used, it is reasonable to assume that the total cost per device could be substantially reduced.

Results

The simulated input to the control circuit to waves and tides is shown below in Figure 12. The voltages corresponding to the pressure sensor are shown in green, and the data after passing through the low pass filter are shown in blue.

10 "LT 1011." *Linear Technologies.* n.d. Web. 24 May 2011.
11 "MPX5999: Integrated Pressure Sensor." *Freescale Semiconductor.* n.d. Web. 24 May 2011.

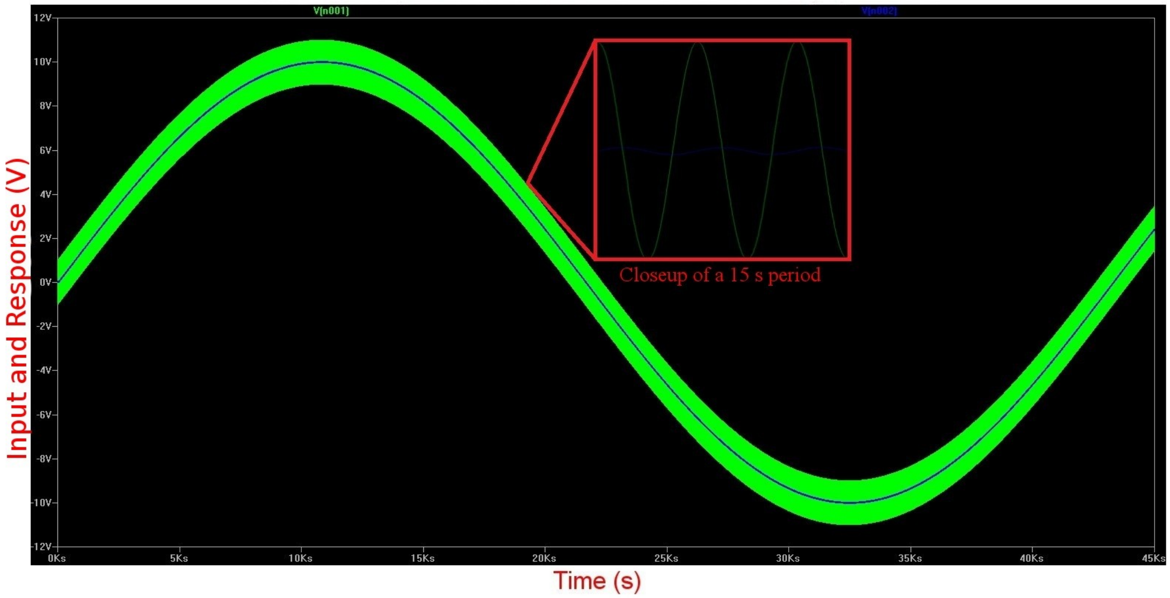

Figure 12 - Sample input and filter response

The simulated response to the this input is shown below in Figure 13. The blue line shows the Out pump's response, which is to be on while the tide goes out.

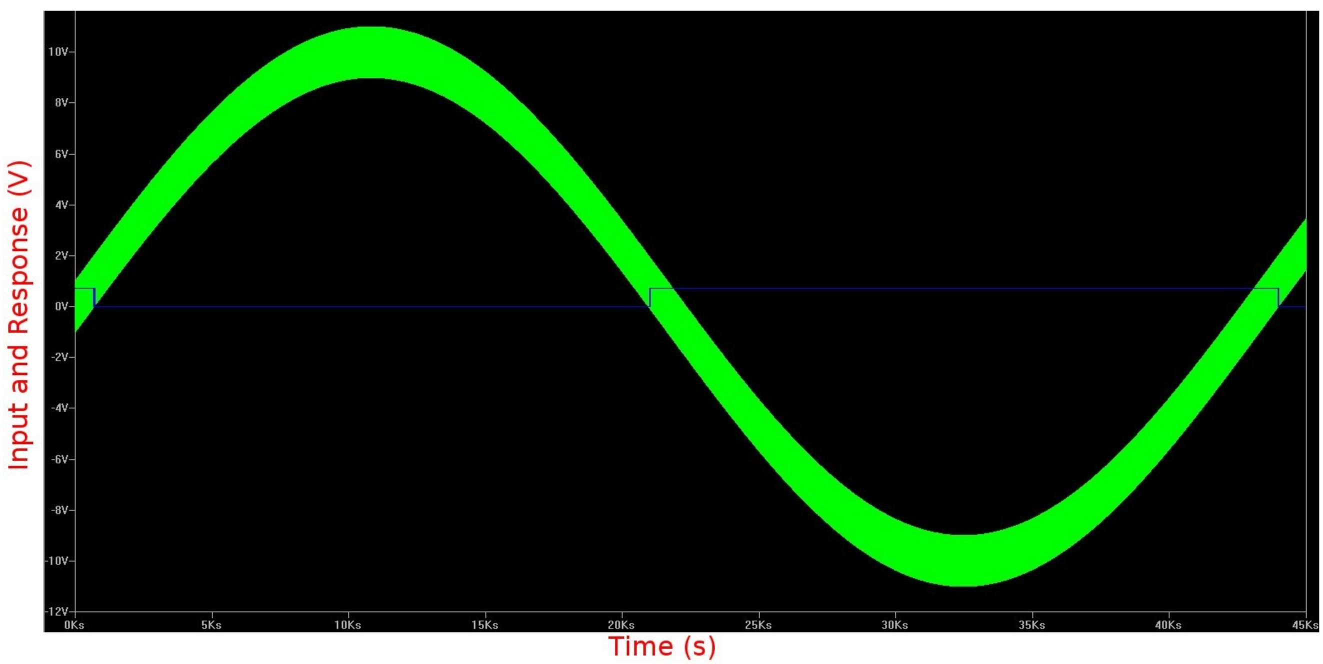

Figure 13 - Sample Input and Circuit Response

Conclusion

There can still be significant inquiry made into several aspects of this design, such as the power produced, the optimum shape of the float and other pieces, the electronics used and design of the control system, and the environmental impacts of such a design. Despite this, an inexpensive and easily constructed wave energy converter appears to be a viable method of power generation, and is worth further consideration and testing.