HYDROELECTRIC POWER GENERATOR

MIME 1501

Technical Design Report

Hydroelectric Power Generator
Project #SP02

Final Report

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HYDROELECTRIC POWER GENERATOR FOR SMALL VESSELS AND REMOTE STATIONS LOCATED NEAR WATER

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Abstract

The objective of this Northeastern University Capstone Design project is to design a hydroelectric power generator to charge batteries on small water vessels. This product will replace devices using non-renewable fossil fuels by utilizing the Gorlov Helical turbine to capture kinetic energy from moving water.

Power consumption of a sailing vessel could be 250 Watts or higher. Sailing vessels currently use their engines to recharge on-board batteries, which supply the sailing vessel with electrical power. A renewable electrical production device would allow sailing vessels to recharge on board batteries without having to continually restock fuel and burn fossil fuels.

The use of the Gorlov Helical Turbine provides the means to harness the power of moving water with an efficiency of 30 percent or greater. The increased efficiency of the turbine is a direct result of the helical arrangement of the airfoil blades, which eliminates the vibration problems of its predecessor, the Darrieus Turbine. Eliminating vibration increases the life of the turbine by decreasing fatigue and creating a steady flow of electrical current.

The design consists of an electrical generator, a transmission system, a supporting structure and the Gorlov Helical Turbine. An electrical generator will be used to convert the mechanical power generated by the Gorlov Helical Turbine into electrical power to charge the batteries. A transmission system is utilized to properly mate the Helical Turbine to the electrical generator. Lastly a structural frame will support and house all of the design components.

Other applications are also being considered for the hydropower generator. Remote locations cannot gain access to power plants and thus use generators for electrical power production. Locations near moving water can utilize the Gorlov Helical Turbine with the hydropower generator design to produce electricity. This would minimize their dependency on non-renewable fossil fuels.

Testing the hydroelectric power generator in the water demonstrated that the turbine rotated only approximately 100 rpm, which was not enough to turn on the alternator. Using a drill to rotate the shaft at 550 rpm generated 133 watts of power.

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1.0 INTRODUCTION

Waterpower was one of the major sources that helped to change the United States into the most industrialized country. There are many rivers in the US and Alaska that run for long distances and drop hundreds of feet along the way. The diverse landscape in the United States has produced some of the most powerful rivers in the world. Often, man would harness potential energy from these rivers by building dams. Dams such as the Hoover Dam, produce thousands of megawatts of renewable power, provide farms and cities with water, and help to regulate flooding. However, they can be an ecological disruption. Every year in Washington, Pacific salmon are prevented from migrating up the Columbia River because dams such as the Grand Coulee Dam block their way. Even in Massachusetts, the construction of dams and other manmade structures along the Charles River have occupied valuable wetlands needed to absorb floodwaters.

In an effort to gain independence from our nation's dams, we have turned to other power production methods. The burning of fossil fuels and atomic energy are two such methods. Both have drawbacks such as pollution, non-renewable fossil fuel consumption and the use of radioactive materials. However, some of the newest forms of renewable energy have helped us to move away from disruptive energy sources. The Sun beams solar power to the planet much faster than we can consume it. Wind power is another promising source of renewable energy. One example of a wind generator is the Vestas Wind Powered Generator situated in Hull, Massachusetts.

Although dams harnessing waterpower disrupt our environment, the water they rely on for power can still be utilized in other ways. The use of low head turbines in free flowing water has been studied around the world, including at Northeastern University, and implemented successfully in a few locations. In Brazil, rural residence along the banks of the Amazon river have come to rely on the turbine. The turbine is powering six car batteries in a remote area of the rain forest inaccessible to power lines. On an island off the coast of Maine, a turbine is providing the Central Maine Power Company with 5 kilowatts of power. And in Korea, an array of turbines is being constructed to capture the energy of one of the fastest flowing channels in the ocean, the Uldolmok Strait.

With the growing demand for low head, or free flow turbines, the design of the turbine has been reconsidered to increase its efficiency and practicality. Professor A. M. Gorlov, at Northeastern University, previously worked on such projects as the great Nile Aswan Dam in Egypt. He recognized the

need for independence from dams, and as a result has designed and patented the Gorlov Helical Turbine. The helical turbine is based on the Darrieus Turbine, previously one of the world's best choices for harnessing low head free flow hydropower. The helical turbine overcomes many of the Darrieus Turbine's drawbacks.

2.0 PROBLEM STATEMENT AND GOAL

Our task as a Northeastern University MIME Capstone Design Team is to adapt the Gorlov Helical Turbine to applications where an efficient renewable energy device is needed. Our primary focus is sailing vessels. These vessels would normally have to run their engines to charge onboard batteries. The use of engines consumes fuel, a non-renewable energy source that must be replaced during long sailing trips.

There are two goals that we have set for this project are as follows. The first goal is that the device must adequately power a typical ocean vessel, for extended periods of time, by charging on-board batteries. Secondly, it must harness power from the water moving past the sailboat using the Gorlov Helical Turbine. It must also charge the batteries efficiently, safely, and in a practical manner.

3.0 PROJECT DESIGN PATH

By setting goals based on the problem statement, we will further understand our objectives. The problem statement includes the use of one of Professor Gorlov's helical turbines. In order to continue towards a finalized design the turbine performance measures must be determined, allowing the team to compare the turbine to other devices in our selected market. After researching the market, and proving a need for this device, design alternatives can be created and evaluated. Using the turbine performance characteristics, a finalized design including components can be analyzed. Recommendations can then be determined.

4.0 TURBINE PERFORMANCE

4.1 TURBINE BACKGROUND

The helical turbine captures the kinetic energy of flowing water. Until now, the only way to harvest hydraulic energy was with conventional turbines. Conventional turbines rotate due to a fluid's high-pressure head acting on the turbine's blades. Dams are constructed to produce a high-pressure head at the expense of a high potential energy. Although dams are an efficient means of energy conversion, their massive structure and flow-restricting design damages the environment and interferes with fish migration. To alleviate the problems associated with dams, scientists and engineers have tried for years to efficiently utilize conventional turbines alone in free flow, low head applications by reengineering their design. Unfortunately, reengineering the conventional turbine has not resulted in a turbine that is highly efficient and inexpensive.

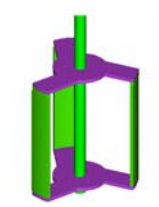


Figure 4.1.1
The Darrieus Turbine

In 1931 the Darrieus Turbine was introduced. The Darrieus Turbine, shown in Figure 4.1.1, is barrel shaped with straight airfoil blades running from the top to the bottom of the barrel along with a shaft that would be perpendicular to the fluid flow. The Darrieus Turbine uses the velocity component (**$V^2/2g$**) of the fluid flow energy as a driving force instead of the fluid's pressure head (**p/g**). This alleviates the need for dams and opens an avenue for new applications of hydropower generation. The Darrieus Turbine rotates at high speed when subjected to low head, low velocity flow. At these high speeds, the turbine is plagued by vibration problems resulting in low efficiency and material fatigue. The concept of the Darrieus turbine is unique but impractical due to its vibration problems.

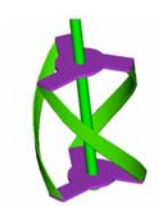


Figure 4.1.2
The Gorlov Helical Turbine

In 1995 Professor Alexander M. Gorlov developed a turbine with all the advantages of the Darrieus turbine and without its disadvantages. Professor Gorlov solved the Darrieus Turbine's vibration problems by designing a turbine with blades that wrap around its circumference, from top to bottom, using a helical geometry. The Gorlov Helical Turbine can be seen in Figure 4.1.2. The helical blade geometry allows the turbine's blades to always be at an optimal angle of attack to the incoming flow. This provides a constant driving torque for the turbine and eliminates vibration. Due to the airfoil cross-section geometry of the turbine blades, the helical turbine rotates in one direction, independent of the fluid flow direction. The

rotational independence of the helical turbine allows for steady power generation in reversible flow applications, such as tidal motion. Also, the helical turbine's blade geometry allows the turbine to be self-starting. This allows for extremely low flow velocity applications. Furthermore, the helical turbine has a maximum efficiency up to 35%, which is 42% more efficient than the typical marine turbine and 33% more efficient that the Darrieus turbine. In summary, the advantages and/or characteristics of the Gorlov Helical Turbine are as follows:

- Turbine harvests velocity head (**$V^2/2g$**), not pressure head (**p/g**)
- Turbine is self-starting
- High speed, vibration free, spinning in low velocity fluid flow
- Low vibration design results in no oscillation of the electric current
- Unidirectional rotation of the turbine in reversible fluid flows
- High efficiency

4.2 TURBINE IMPACT ON DESIGN

The helical turbine is the most efficient choice for use as a hydropower generator. However, to apply the helical turbine to the hydropower generator design, the dynamics of the helical turbine must be fully understood. The dynamic aspects of the turbine that directly impact the hydropower generator design are as follows:

- Power output of the turbine as a function of the fluid velocity
  - $\mathbf{P_{turbine}(V_{flow})}$
  - The power produced by the turbine will give a basis for the amount of energy that can be harnessed and converted to electrical power
- Torque produced by the turbine as a function of flow velocity
  - $\mathbf{T_{turbine}(V_{flow})}$
  - The available torque produced by the turbine will govern the alternator/generator selection
- Drag force of the turbine as a function of flow velocity
  - $\mathbf{D_{turbine}(V_{flow})}$
  - The drag force produced by the turbine will govern the design of the shaft, the mounting assembly, the bearing selection and the frame design

The helical turbine that will be used for the hydropower generator is shown in Figure B.1, Appendix B. It has a diameter of 12" and a height of 18". The turbine incorporates three helical blades each with a 70° angle of twist (φ) with a 60° pitch angle (δ). The blade pitch and angle of twist are the two components that provide the turbine with its helical geometry. A diagram showing the blade contour path described in terms of angle of twist and pitch angle can be seen in Figure B.2 Appendix B. The airfoil profile for each of the turbine blades is NACA-0020 with a 1.6" strait cord length. This specification is shown as Figure B.3, Appendix B.

4.2.1 Turbine Power Production

The power output of the helical turbine is listed in Equation (1) Appendix A: Power Equation Formulation. Unfortunately neither the turbine torque output nor the rotational velocity can be determined explicitly as a function of the fluid flow velocity. From testing however, the efficiency of the turbine was determined and from fluid dynamics, the power of the fluid flow can be determined. This provides us with an alternative way to calculate the turbine power as seen in Equations (2)-(4) in Appendix A: Power Equation Formulation.

4.2.2 Turbine Torque Production

As with the helical turbine power production, the helical turbine torque production is unknown as a function of the fluid flow velocity. It is possible to solve for the torque produced as a function of the fluid flow velocity, for a single turbine blade at an optimal angle of attack. This formulation can be seen in Equations (7)-(9) in Appendix A: Torque Equation Formulation. Equation (9) cannot be used alone to calculate the helical turbine total torque production as a result of the complicated nature of the turbine. At any instant, only one turbine blade is at an optimal angle of attack, while the other two blades contribute to the total torque in different and complex ways. The difficulty of determining the helical turbine total torque requires the use of an alternative method for calculation.

Again, as with the helical turbine power production, the efficiency of the turbine can be used. The torque of the turbine is equal to the turbine power production divided by the rotational velocity, as seen in Equations (5) and (6) in Appendix A: Torque Equation Formulation. Here the rotational velocity of the helical turbine is found as a function of the flow velocity using the experimental data in Figure A.1, Appendix A.

4.2.3 Turbine Drag Formulation

A drag force will be created as fluid flows through the turbine. This drag force is a function of the helical turbine's diameter, height, solidity, the density of the fluid flow, and fluid velocity. The drag force can be calculated using Equation (10) of Appendix A: Drag Force Formulation. However, the drag coefficient in Equation (1) is unknown. The drag coefficient is a function of the turbine solidity and the ratio of linear blade velocity versus fluid flow velocity. The solidity of the helical turbine and velocity ratio are defined respectively in equations (11) and (12), Appendix A: Drag Force Formulation. Once the solidity of the helical turbine and velocity ratio are known, the drag coefficient can be solved for using the drag coefficient chart, Figure A.2, Appendix A. The drag coefficient chart was created using experimental test data provided to the group with the helical turbine. The turbine drag, as a function of fluid flow velocity, is shown in Figure A.3. Appendix A.

5.0 MARKET SELECTION

To develop a feasible device, the market that the device will compete in must be specified. The original problem statement provided to us stated that this device would be used for small vessels. This immediately excludes large ocean ships and barges, all of which would need a larger power production device. There are many types of small water vessels, all which have various components consuming battery power. There are two categories of water vessels, those that use their engines as propulsion and those that use the wind as propulsion. Boats that use their engines for propulsion, otherwise known as powerboats, have on-board battery systems, which are charged using an alternator. The alternator is a device that transforms the mechanical power of an engine into electrical power for a battery. Since a powerboat is constantly using its engine, it is frequently recharging its batteries. It was determined that our focus would not be on powerboats but rather on those that use wind as their power, sailboats.

Sailboats are a strong candidate for a hydropower generator because they propel themselves using the power of the wind. Most sailboats have gasoline or diesel engines onboard for use on short trips or emergencies. However, they do not continually use their engines, thus they do not continually charge the onboard batteries. Sailboats also tend to travel for longer periods of time, creating a large need for a generator, one that does not use consumable fuel.

Wind propels sailboat through the water. There often exists excess power because the hull of the sailboat will limit velocity of the boat to a certain speed. The excess power captured by the wind can be used to power the generator without a serious impact to the overall speed of the sailboat.

It is advantageous to have an onboard device that will charge the batteries even when the sailboat is not moving. A sailboat that is moored in a harbor will be fixed to an anchor, but will be exposed to tidal and ocean currents. These currents can be utilized to generate power for the sailboat. Commonly, in a bay or harbor, there are ocean currents of 1 knot or more.

6.0 PRODUCT NEED AND POWER CONSUMPTION

The problem description given to our group indicated that small vessels would be the focus of our project. Narrowing of the market led to the decision to create the hydropower generator for sailboats. Battery power is consumed while under sail due to the continual use of navigational, emergency and other equipment. On long sailing trips, this battery power can be reduced rather quickly.

Many sailing vessels have alternators powered by the engines on board. This is the least intrusive method of creating power. There are problems with using the engine to charge the batteries. Engines running while under sail can be noisy and a running engine disrupts a nice sailing trip. Running the engine not only uses a non-renewable energy source in diesel or gasoline, but battery power is necessary to start an onboard engine. Engines use a starter motor to start or “turn over” the engine. If the batteries were to be drained, the starter motor would not have enough power to start the engine. The boat would then have to be brought to shore to charge the batteries.

Many sailboats race competitively in official races all over the world. Long sailing races involve a rule prohibiting engine use and a device is usually fixed to the engine. This device will tell race officials that the engine has been started; hence racers cannot use their engines to charge their batteries. These challenges force sailors to turn to alternative energy sources.

Sailboats use battery power in a number of ways. Typical instruments and devices used on a sustained basis while under sail are listed in Table 6.1. It can be seen that the bilge pump uses 37% of the available power in this case study. Bilge pumps are used to drain water from the hull of the vessel placed there by waves, rain or other ways. The bilge pump is not a continuous draw as the radar system is, but it is commonly used for extended periods of time.

Table 6.1 Power Consumption

Power User	Power (Watts)	Percent of Total
Bilge Pump	100.8	37%
Refrigerator	90	33%
Radar	40	15%
GPS	15	4%
Autopilot	7	3%
Entertainment Equipment	18	7%
Other Navigation Equipment	3.5	1%
Total	274	

The total power consumed by these instruments is shown at the bottom of Table 6.1 as approximately 274W. This does not include the battery power necessary to start the engines using the starter motor. The power consumed by the starter motor is very high and has the potential to drain the battery quickly if used too often or for an extended period of time. There may also be winches on some boats that use power. The following equation, Equation 6.0.1 shows the drain on the batteries based on the calculated typical peak power consumption.

$$I = \frac{250W}{12V} = 20.8A \qquad \text{Equation 6.0.1}$$

Based on 22.8A of current draw, a high-end marine battery supplies 552 minutes of discharge. This translates to 9.2 hours of battery power. Sailing trips commonly last only a day and even in this time period, the batteries could be drained to the point where the sailboat cannot start its engines.

Due to this dramatic current draw from the systems onboard the sailboat, we believe that the sailing market would benefit from a renewable energy source. Our device could serve to either supplement battery power or handle the entire electric current draw.

7.0 MARKET COMPETITION

7.1 COMPETITION RESEARCH

Sources of renewable energy are water, wind and the sun. The Hydropower Generator is not the only product that will provide an alternative method for producing power on sailboats. The primary alternative methods that are currently used to recharge batteries on sailboats are via the use of solar panels and wind generators. Water generators are also used to generate power on sailboats, however they are not as common as solar panels and wind generators.

7.1.1 Solar Panels

There are two types of solar panels currently on the market. There are thin film, amorphous, panels and crystalline, single and multi, panels. In general, crystalline panels are more efficient than thin film panels; i.e. crystalline panels take up less space for the same power output. However, crystalline panels lose more power than thin film panels in high temperature areas. Solar panels can produce power from 5 to 150 Watts. Seimens has a package called the Marine Power Kit 100. This package consists of all the necessary components for generating solar power. The solar panel included in this kit can produce 100 Watts of power at four to five hours of full sunlight and costs approximately $900. The following are some examples of what 100 watts can power:

- 4 15-watt fluorescent lamps for 3 hours
- Small TV and dish for 4 hours
- AM/FM radio for 3 hours
- Water circulation pump for 1 hour

An advantage to using a solar panel is that the sailor does not have to rely on the wind for energy production. Also, little maintenance is required because there are no moving parts. However, since many solar panels have glass, it is relatively easy to break them. Another disadvantage is that solar panels consume a lot space on a sailing vessel. For example, the solar panel that is included in the Seimens Marine Power Kit 100 has dimensions of 59 in. x 24 in. x 2.2 in. It is common to have more than one panel on a sailboat; therefore a sailor must consider the space needed and cost for multiple panels.

Figure 7.1.1.1
Solar Panel in Shadow Cast by the Sail

Another disadvantage to using solar panels is that the power output is dependent upon the amount of available sunlight, the orientation of the panel with respect to the sun and the ambient temperature. Solar panels achieve their advertised power output at full sunlight, which only occurs for five to seven hours a day, depending on the location of the sailboat. The ambient temperature and the power output of solar panels are inversely related. The higher the ambient temperature, the lower the power output. Also, the placement of solar panels on the sailboat is critical because it is undesirable, yet difficult to avoid, having the sail cast a shadow on the solar panel, as shown in Figure 7.1.1.1.

7.1.2 Wind Generators

Another method of generating power on a sailboat is by using the wind. The power output for wind generators ranges from 5 watts to 400 watts. Southwest Windpower makes a product called AIR 403, which can generate 400 watts of power at a 28 mph wind. The AIR 403, shown in Figure 7.1.2.1, is on the market for approximately $1300. It is clearly seen that a benefit of using a wind generator is the high power output. However, it should be noted that a 28 mph wind is an excessive wind for sailboats. Many sailboats do not sail when the wind is greater than 20 mph. The power that is generated from the wind varies as a cube of the wind speed. For example, as mentioned above, the AIR 403 can produce 400 watts of power in a 28 mph wind. A 14 mph wind will not even generate 200 watts but rather only 50 watts of power will be generated.

Figure 7.1.2.1
AIR 403 Wind Generator

One disadvantage to using a wind generator is that the power output is dependent upon a strong wind. Another disadvantage is that wind generators can be noisy due to the wind passing over the blades. The blades spin in a 46-inch (1.15 meter) diameter circle. These relatively large blades pose a safety hazard and they may not be aesthetically pleasing. For example, if the spinning blades were to hit an object, the object or the blades itself could be showered onto the sailboat and the surrounding area. A strong gust of wind could tear off the blades or the whole wind generator, thus putting the crew or anyone in the area in danger. Another disadvantage of using a wind generator is that, because of the spinning blades, it requires maintenance.

7.1.3 Water Generators

Water generators are another method of generating power on a sailboat. Water generators are not as common on sailboats as solar panels and wind generators. Three water generators that are currently on the market are the Aquair UW Submersible Hydro Generator, the Aqua4gen and the Aqua6gen. The Aquair Submersible Generator, shown in Figure 7.1.3.1, was originally designed and used for oil exploration vessels. In a stream flowing at 8 knots, the Aquair Submersible Generator can generate 100 watts of power. The performance of the Aquair Submersible Generator is dependent upon the direction of fluid flow with respect to the propeller. For maximum efficiency, the propeller, 12.5 inches in diameter, must be facing the flow of the stream. The Aquair Submersible Generator requires a stream depth of 13 inches. The cost of the Aquair Submersible Generator is approximately $1200. Accessories for the Aquair Submersible Generator can be purchased separately, such as a spare propeller, a low RPM prop, a shrouded prop, a prop guard, and a vertical mounting leg pole.

Figure 7.1.3.1
Aquair Submersible Generator

The Aquagens, Aqua4gen and Aqua6gen, are water generators whose market is sailboats at all sailing speeds. The power output from the Aquagens ranges from 5 watts to 150 watts. Unlike the Aquair Submersible Generator, which uses a propeller, the Aquagens use a turbine that is towed behind the back of the sailing vessel. The generator is mounted to the sailing vessel. A rope connects the generator to the turbine, as seen in Figure 7.1.3.2. The turbine travels at 1 to 3 meters below the surface of the water. The turbine blades on the Aquagens are available in two different sizes, 90 mm and 115 mm. The Aqua4gen can be

Figure 7.1.3.2
Aquagen Generator and Tow Rope

easily converted to a wind generator. Thus, the water generator can be used when sailing; the wind generator can be used when at anchor or when sailing. See Appendix D for drawings of the Aquagens, the water to wind generator conversion and their power outputs.

One benefit to using a water generator as an alternative method to generate power on a sailboat is that the power output does not depend on the environmental conditions such as the sun or the wind. As mentioned earlier, the power output of solar panels is advertised at full sunlight. The maximum amount of time that solar panels can work at their optimal power generation is only 5 to 7 hours per day. Water generators can potentially operate at their maximum output for 24 hours a day. The water generator is also below the water level, thus it is out of sight and does not take up valuable real estate on the sailboat, unlike solar panels, which consume much space on a sailing vessel. Unlike wind generators, the water generator will silently generate power.

The expected performance of the hydropower generator using the helical turbine will surpass the performance of the water generators currently on the market. In addition to all the benefits listed above for using a water generator on a sailboat, the hydropower generator can generate much more power, its performance is independent of fluid flow, and the drag will be minimal. In an 8-knot stream, the hydropower generator will produce approximately 1200 watts of power, compared to the 100 watts of power that the Aquair Submersible Generator can produce. See Appendix A for the table and equations used to calculate the expected power output for the hydropower generator. Because the hydropower generator uses a turbine whose performance is independent of the direction of the fluid flow, the hydropower generator will operate at maximum efficiency regardless of the direction of fluid flow with respect to the turbine.

7.2 PATENT RESEARCH

7.2.1 Boat Mounted Hydro-Alternator (#6,192,821)

This patent, invented by Robert Luke Morales and Andrew John Kruse, was granted on February 27, 2001. This patent describes a hydro-alternator, which generates electrical power, to recharge the batteries on a bass fishing boat. The design consists of a body that is rigidly mounted to the outboard motor of a boat. A propeller is connected to a rotor and the rotor is connected to the body of the hydro-alternator. An example of this device is shown in Figure 7.2.1.1.

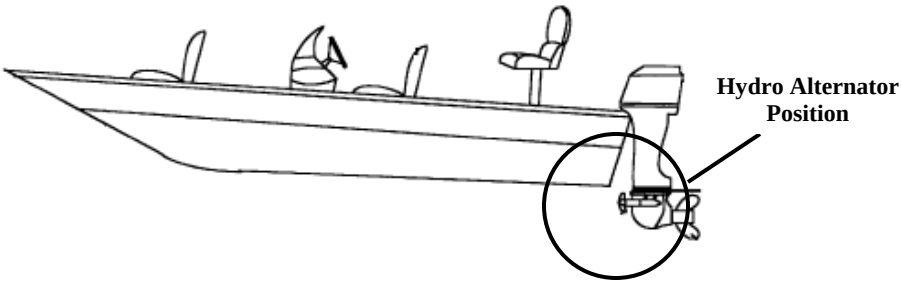


Figure 7.2.1.1 Boat Mounted Hydro Alternator

7.2.2 Portable Wind and Hydro Electric Generating System (#6,246,125)

This patent, invented by Robert C. Axtell, was granted on June 12, 2001. The portable wind and hydroelectric generating system consists of a paddle wheel and a turbine fan assembly. The turbine fan assembly is comprised of a number of impellers. The turbine fan assembly is connected to a generator. See Figure D.1, Appendix D, for a general diagram of this setup.

7.2.3 Helical Turbine Assembly Patents

In addition to the patents mentioned above, there are also a number of patents related to the helical turbine assembly that will be used in the hydropower generator. The following is a list of patents held by Alexander Gorlov, relating to the helical turbine assembly:

- System for providing wind propulsion of a marine vessel using a helical turbine assembly (#6,293,835)
- Method for maintaining flotation using a helical turbine assembly (#6,253,700)
- Helical turbine assembly operable under multidirectional gas and water flow for power and propulsion systems (#6,155,892)
- Helical turbine assembly operable under multidirectional gas and water flow for power and propulsion systems (#6,036,443)
- Helical turbine assembly operable under multidirectional fluid flow for power and propulsion systems (#5,642,984)
- Unidirectional reaction turbine operable under reversible fluid flow (#5,577,882)

8.0 DESIGN ALTERNATIVES

With the market specified and studied, design alternatives can be created. Our first design alternative is to fix the turbine with a generator to the rear of the sailing vessel. The second device is entirely separate from the sailboat, and the third is a combination of design one and design two.

8.1 COMMON COMPONENTS AND OVERALL DESIGN

Each design will consist of common components as shown in Figure 8.1.1. The main components included are the turbine, the generator, a power transmission shaft, a frame and clamping bracket, and multiple high quality, high load bearings. The helical turbine will be provided to the project. Currently, an A/C alternator is being considered for our electrical power device. If the torque of the turbine cannot turn the alternator, a D/C generator could be used. The power transmission shaft should not be complex, but should be designed to meet the force and torque requirements for the device. The use of an alternator may require a large increase in shaft rotational speed. This will require the use of a gearbox to increase the rotational speed of the alternator. The use of a gearbox will also decrease the torque used to power the alternator. A frame will be designed according to the mounting needs and according to the forces of the water on the turbine. Bearings will be specified to meet the needs of the device and to prevent shaft wear.

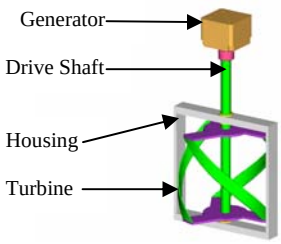


Figure 8.1.1
Overall Design Components

8.2 DESIGN ONE: HULL MOUNTED

The first design consideration places the hydropower generator at the rear of the sailing vessel with the turbine below the surface of the water. This device will include, as part of the frame, a way of connecting it to the hull of the sailing vessel. A method such as that of an elevator or winch and pulley system will be used to raise and lower the turbine into and out of the water. Having an elevation device allows the boater to remove the turbine from the water. A conceptual model is shown as Figure 8.2.1.

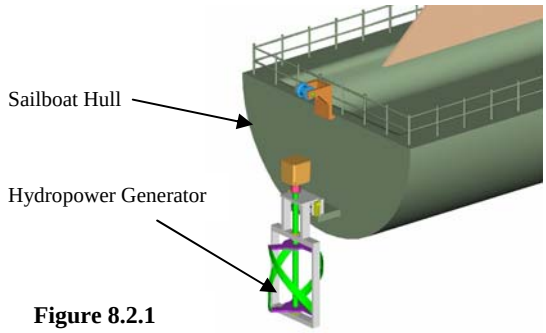


Figure 8.2.1
Conceptual Hull Mounted Device

There are many advantages and disadvantages to using a fixed hull device. It is advantageous to have a device that is permanently mounted allowing for greater ease of use. The device will not need to be transferred or transported to and from the sailing vessel. This will eliminate setup time and increase ease of use. Having the turbine portion of the device located below the surface of the water will minimize the amount of space it will occupy on the sailing vessel.

It will be very difficult however to mount the device to a sailing vessel. To fix this device, it should be mounted to the hull of the sailing vessel. Sailing vessels vary greatly in size and shape. It will be difficult to create a mounting system that is universal with all sailboats' support structures. In addition, sailboats are extremely expensive so this device should be minimally invasive to protect the boats.

8.3 DESIGN TWO: TOW-ALONG DEVICE

The second design considered was a non-hull mounted device. To accomplish this, we created a tow along hydropower generator. Again, this device will incorporate the common components previously listed but additionally it will be integrated with a floating platform. The platform must have a hull to allow for minimal drag resistance from the water. A sample of the device is shown as Figure 8.3.1.

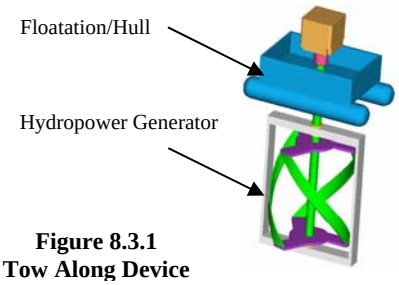


Figure 8.3.1
Tow Along Device

Having the device towed behind the sailing vessel eliminates the negative aspects of the hull-mounted device. The tow-along device is very versatile and can be mated with most sailing vessels simply by extending a towline from the sailboat to the hydropower generator. This puts the device out of the way of the sailboat and sailboat accessories. One drawback to having a tow along device is that most sailboats already tow a dinghy behind them for use in emergencies. Having a tow along device will interfere with

the dinghy and will be difficult to manage. Also, the device would need to be stored onboard during rough weather or other instances where the boater would not want the device in the water. This would occupy a lot of much needed space on the deck of the vessel. Lastly, a main concern for this device is the added engineering and cost associated with the floatation device. The floatation needs to be studied and streamlined to prevent unnecessary drag on the sailing vessel.

8.4 DESIGN THREE: COMBINATION

There are many advantageous features of the previous two design alternatives that our final design alternative will retain. Having the device not mounted to the hull and also having a tow-along device are both desirable. The realization that most sailing vessels tow a dinghy behind them spawned interest in mounting the device to the dinghy. The gas-powered motors used on the dinghies are commonly removed to prevent damage, motor loss, and unnecessary drag. Dinghies are created with standard motor mounting transoms to allow for universal attachment of motors.

Based on these characteristics, the final design alternative is to mount the hydropower generator to the dinghy using a standard motor mount. Not all sailboats will have a dinghy towed behind. Commonly sailors will purchase an outboard motor mount for the sailboat to accommodate either a motor for the sailboat, or for storage of the dinghy motor. The use of a standard motor mounting bracket on the housing of the device will allow for the generator to be mounted to the rear of the sailboat.

The advantages of the combination device are the universal mounting attribute, the minimal size due to the lack of any intricate mounting hardware and the mobility of the device. A conceptual image of how the device will look is included as Figure 8.4.1. The main disadvantages to this design is that the device will be loosely mounted, allowing for it to be dropped during transfer, and the device may need to be stored onboard the sailboat.

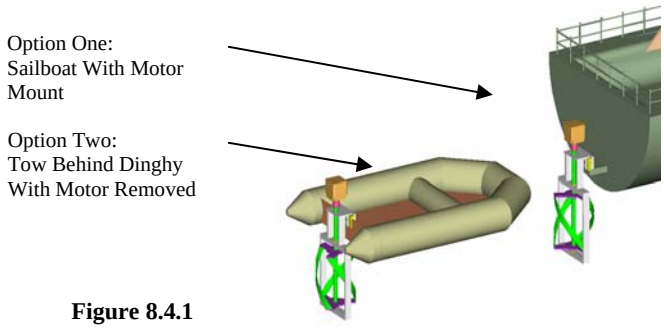


Figure 8.4.1 Conceptual Hull Mounted Device

9.0 FINAL DESIGN

Considering the three design alternatives, the combination design was chosen to allow for maximum design flexibility. The finalized design will consist of the following components:

- Hydropower Generator Frame and Shaft Housing
  - Top Bearing Plate
  - Bottom Bearing Plate
  - Truss Plate (Side Supports)
  - Clamp Plate (Mounting Feature)
- Turbine Shaft
- Tapered Thrust Bearings
- Alternator
- Power transmission system
  - Belt tensioning system
- Electrical Housing

A: Power Transmission
B: Frame
C: Tapered Thrust Bearing
D: Turbine Shaft
E: Alternator
F: Belt Tensioning System/Alternator Mounting Brackets

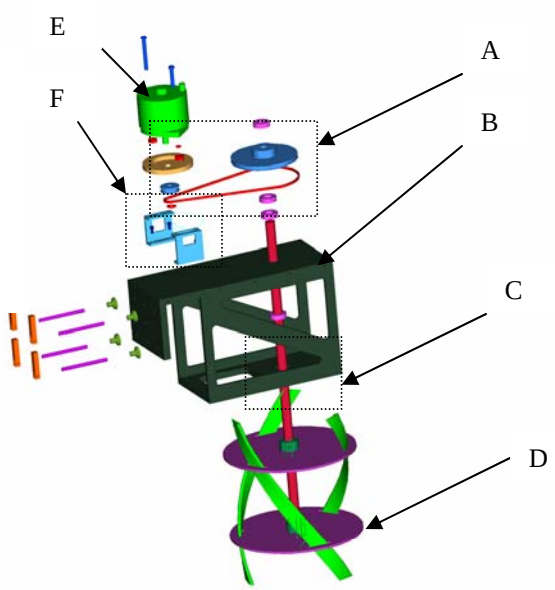


Figure 9.0.1
Exploded Final Design

Each component will be discussed and analyzed independently in the following sections. The prototype design is shown in Figure 9.0.1 with the components listed.

9.1 FRAME

Accounting for the drag forces acting on the turbine, the mass in the water should be minimized, thus minimizing drag. Unfortunately, the three original alternatives included a frame surrounding the turbine to minimize the bending moment on the shaft. This can be seen in Figure 8.1.1. This frame was removed to minimize drag as shown in Figure 9.0.1. Removing the frame from the turbine directly impacts the shaft design. As a result, the shaft has to be designed larger and stronger to accommodate the larger drag forces. The shaft design will be discussed in Section 9.2: Turbine Shaft. The resulting frame housing the shaft and supporting the power transmission system and turbine includes two bearing plates, two truss plates, and one clamping plate as seen in Figure 9.1.1: Frame.

A: Upper Bearing Plate
B: Clamping Plate
C: Truss Plates (2)
D: Lower Bearing Plate
E: Upper Thrust Bearing
F: Lower Thrust Bearing

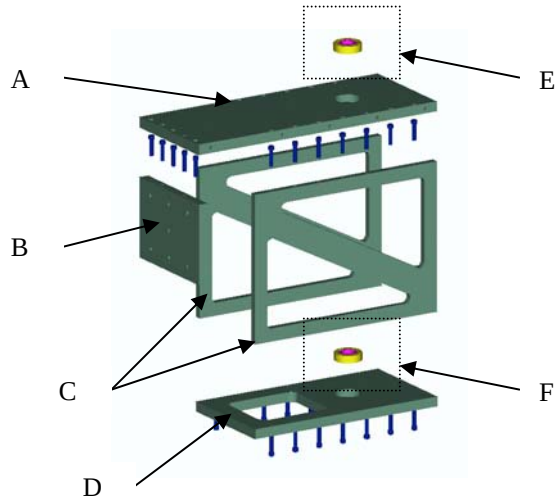


Figure 9.1.1
Frame

9.1.1 Upper and Lower Load-Bearing Surfaces

The upper bearing plate includes a hole housing the upper thrust bearing. The power transmission system and alternator will also be mounted to the upper bearing plate. The plate will be extended past the truss plates to incorporate the clamping plate this can be seen in Figure 9.1.1.

The bottom load-bearing surface will incorporate the same recess for the lower thrust bearing, as did the top load-bearing surface. However, the bottom load bearing surface remains simple to prevent any drag

forces should the water level exceed the height of the lower bearing surface this can be seen in figure 9.1.1.

9.1.2 Side Supports

The two side supports of the frame stiffen the device by increasing the moment of inertia in the direction of the drag force. They will remain strong enough to support the weight of the turbine and shaft, and to support the compression forces of the thrust bearings, described in Section 9.3: Thrust Bearings, and remain light to minimize the weight of the frame. To lighten the weight of the side supports, triangular sections were removed, leaving a supporting truss to brace against the moment caused by the drag force. This force is shown in Figure 9.1.1.

9.1.3 Clamping Plate

To allow for maximum flexibility of the hydropower generator, the mounting feature will resemble that of an outboard motor mount. This allows the hydropower generator to be positioned anywhere that an outboard motor mount would be placed. A study was conducted to determine the typical sizes and dimensions of outboard motor mounts, and of dinghies and mounting brackets where the motor would be placed. This information determines the proper dimensions for the hydropower generator mounting feature.

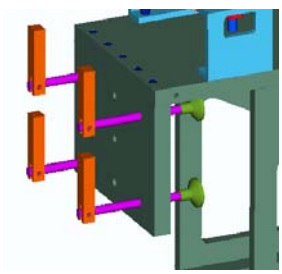


Figure 9.1.3.1
Clamping Bracket

The design incorporates a “U” shaped bracket that rests on the transom of the dinghy. The clamping feature can be seen in Figure 9.1.3.1. To fasten the frame to the transom there are multiple threaded screws with leveling feet to allow the screws to be tightened to the transom. The number of holes in the mounting bracket will exceed the number of compression screws, allowing for multiple configurations to be utilized by the user. This ensures that the device will be firmly mounted to the transom.

9.2 TURBINE SHAFT

The turbine provided to the group is described in detail in Section 4.2: Turbine Impact On Design. A shaft is needed to transfer the power from the turbine to the power transmission system. As previously discussed, the water flow through the turbine creates a drag force. This drag force is applied to the shaft through the turbine’s upper and lower plates. The shaft is subjected to torque applied by the turbine and the alternator, and to radial forces caused by the turbine’s angular velocity. These forces create shaft fatigue and are accounted for in the design of the shaft.

9.2.1 Geometry Selection

There are several factors to consider when selecting the geometry of the shaft. There are two choices for the shaft cross-section, hollow or solid. A hollow shaft saves weight without sacrificing too much strength. However, hollow shafts are not available in as many sizes as solid shafts. Also, a hollow shaft would have to be capped at the lower end to prevent water from entering the alternator housing. A solid shaft provides slightly better strength but is significantly heavier than a hollow shaft. A solid shaft was chosen for the hydropower generator based on the stress analysis in Section 9.2.2: Stress Analysis. This analysis proves that while a hollow shaft could be developed to account for the bending stress, its diameter would be too large.

9.2.2 Stress Analysis

The top of the shaft is attached to a large pulley. The upper thrust bearing supports the shaft at the upper plate. A second thrust bearing, located at the lower portion of the frame, provides additional support to the shaft. The turbine is attached a short distance below the lower bearing. Figure C.1, Appendix C shows the free body diagram (FBD) of the shaft. The shear and moment diagrams can be determined using the FBD. Figure C.3, Appendix C shows the shear diagram of the shaft. The maximum shear force occurs between the upper and lower bearings. Figure C.2, Appendix C shows the moment diagram. The maximum bending moment occurs at the lower bearing. Since both the maximum bending moment and shear force occurs at the lower bearing, this is where the remainder of the analysis will focus.

Fatigue is a major factor in our design since the shaft rotates, causing torsional forces, and is subjected to a bending moment caused by drag forces. Therefore, the shaft is designed to accommodate reverse bending with a static torque. The governing equation is as Equation 9.2.2.1.

$$\left(\sigma K_{fb}\left(\frac{\sigma_{yp}}{\sigma_e}\right)\right)^2 + 3(\tau_{av})^2 \leq \left(\frac{\sigma_{yp}}{F_s}\right)^2 \qquad \text{Equation 9.2.2.1}$$

The governing equation is solved for the factor of safety. The bending stress range for each material studied is shown in Figures C.1 through C.4, Appendix C: Fatigue Analysis, can be calculated using the bending formula, Equation 9.2.2.2.

$$\sigma = \frac{Md}{2I}$$ Equation 9.2.2.2

The stress concentration factor is one because there is no discontinuity in the shaft. The average shear stress is determined by summing the stress obtained from the shear force and the applied torque. The following formulas are used to calculate the shear stress (Equation 9.2.2.4) and the torsional stress (Equation 9.2.2.3). The values for shear and torsional stress are shown in Figures C.1 through C.4, Appendix C: Fatigue Analysis.

$$\tau_{torsion} = \frac{Td}{2J}$$ Equation 9.2.2.3

$$\tau_{shear} = \frac{V}{A}$$ Equation 9.2.2.4

9.2.3 Material Selection

Corrosion resistance is a major consideration since the shaft will be exposed to salt water for extended periods of time. The list of corrosion resistant materials is limited. When cost is also considered, the list becomes even shorter. The two material groups that are corrosion resistant and reasonably priced are aluminum and stainless steel. The aluminum alloy chosen for this analysis is 6061-T6. This alloy is cost effective, readily available, corrosion resistant and available in many sizes.

Two stainless steel alloys were chosen for the analysis: 316 and 17-4PH. Both offer great corrosion resistance as well as a reasonable cost. However, hollow stock is not an option for stainless steel due to its high cost.

There are many goals for the shaft analysis. First, the shaft must be able to withstand the drag force. Since the turbine efficiency is decreased by any flow disturbances resulting from the shaft, minimizing the diameter is an important goal. For the ease of acquiring material for the design, the analysis is limited to sizes available from either McMaster-Carr Co. or MSC Industrial Supply Co. Another goal is to minimize the weight of the shaft. The overall weight of the design, as seen in Section 10.2: Weight Analysis, is less than the weight of a typical outboard engine.

Finally, the deflection of the end of the shaft is analyzed. The goal is to keep the deflection less than .75” to minimize stress on the turbine and to prevent the bearings from binding. The analysis of four different

materials and geometries was conducted. These calculations can be seen in Figures C.1 through C.4, Appendix C: Fatigue Analysis. Both stainless steel alloys were analyzed for a solid shaft. The aluminum alloy was analyzed for both a solid shaft and a hollow shaft.

9.2.4 Final Shaft Design

Based on the above criteria, a .75" O.D. solid shaft made of 17-4PH stainless steel was chosen for the final design. An aluminum shaft was eliminated as a possibility based on the outside diameter required to withstand the drag force effects. Both stainless steel alloys provides similar results for a necessary outside diameter. The 17-4PH alloy was selected because it produces a lighter and stronger shaft.

9.3 THRUST BEARINGS

Thrust bearings will be used to suspend the shaft and turbine inside of the hydropower generator frame and to enable the shaft to spin freely. A thrust bearing is a roller bearing with a tapered diameter creating an angled bearing surface between the outer and inner races of the bearing. A tapered bearing surface will allow for both thrust forces and radial forces to be transferred to one bearing surface. See Figure 9.3.1. In Figure 9.3.1, R is the radial force on the shaft, W is the weight of the shaft and turbine (the thrust force), and F_b is the resultant force on the angled bearing surface.

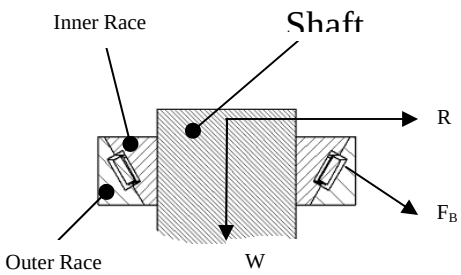


Figure 9.3.1
Forces Acting On The Upper Thrust Bearing

A bearing is placed in both the upper and lower bearing plates, as seen in Figure 9.0.1. Two thrust bearings are needed to secure the axial position of the shaft. The bearings mirror each other, preventing the shaft from rising or falling through the frame. They are corrosion resistant and are sized to fit the turbine shaft diameter.

9.3.1 Bearing Force Analysis

The corrosion-resistant tapered bearing selected for the design must be analyzed to determine if it will fail under the radial load applied by the shaft. Referring to the FBD, Figure 9.3.1.1, the upper bearing will experience a maximum radial force of 183 lbs calculated by Equation 9.3.1.1.

$$P_u = \left(\frac{c}{b} + \frac{d}{2b}\right)F_d \qquad \text{Equation 9.3.1.1}$$

The lower bearing will see a radial force of 358 lbs, calculated by Equation 9.3.1.2.

$$P_l = \left(1 + \frac{c}{b} + \frac{d}{2b}\right)F_d \qquad \text{Equation 9.3.1.2}$$

A summary of this analysis can be seen in the Figure 9.3.1.1.

Figure 9.3.1.1 Table Bearing Analysis		
Upper Bearing Radial Force	183	lb.
Lower Bearing Radial Force	358	lb.
Bearing Radial Force Limit	1,620	lb.
Factor of Safety (Upper)	8.85	
Factor of Safety (Lower)	4.53	

9.4 ALTERNATOR

Searching for the appropriate electrical generator for the hydropower generator consumed much design time. In an effort to save time and cost for the first prototype of the hydropower generator, the electrical generation device chosen was an excited field alternator. This alternator was purchased at a local auto parts store for $51. It was very difficult to acquire the specifications of the device, however it is known that the device will produce a maximum of 63 amps. Typically, the batteries on a sailing vessel supply 12-24 volts. The power of the alternator is equal to the voltage applied times the current output. Using a 12 volt battery, this alternator will be capable of producing 752 watts of power. This is in the range of power production that will be capable of competing with other devices in our chosen market.

Other devices considered for an electrical generation device were permanent magnetic generators and permanent magnetic alternators. These two devices are expensive; $179 for a permanent magnet alternator and nearly $600 for a permanent magnet generator. The torque required to start a permanent magnet device is higher than the torque required to start an excited field alternator. This is because the magnets apply a constant magnetic field to the stator; whereas in an excited field alternator, the magnetic field varies depending on the input voltage. The magnets used in a permanent magnet device are

neodymium, which make a permanent magnet device almost twice the weight of an excited field alternator.

9.5 POWER TRANSMISSION

A two-pulley and belt system is used to transmit power from the turbine shaft to the alternator. This is seen in Figure 9.5.1. A V-belt (C, Figure 9.5.1) was chosen over a timing chain power transmission because it is inexpensive, allows for simple "V-belt" pulleys (A and B, Figure 9.5.1) to be used, and does not need lubrication.

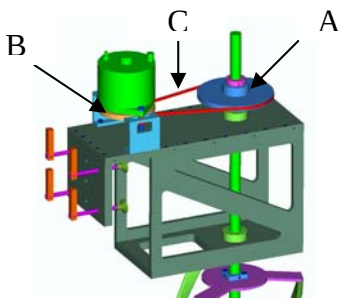


Figure 9.5.1
Power Transmission

The alternator's rotational velocity must be increased to reach operational speed at low turbine rotational velocity. A gearing system is included to accomplish the speed increase. The disadvantage of using a gearing system is that the turbine shaft will not be able to directly attach to the alternator shaft. A direct connection would eliminate the power lost through the V-belt power transmission system. The gearing system will consist of a large V-belt pulley attached to the top of the turbine shaft, and a smaller V-belt pulley attached to the alternator shaft.

Based on the turbine's torque production and rotational speed, and the alternator's input requirements and operational speed, a pulley ratio of 3.5 to 1 is used in the power transmission system. This ratio must be tested in order to verify that it is correct. The torque required by the alternator is directly proportional to the amount of current being drawn from the alternator. If too much current is drawn, and the gearing ratio is too large, the turbine could potentially stall in the fluid flow.

9.5.1 Alternator Mounts

The proper tension must be given to the V-belt to prevent the V-Belt in the power transmission system from slipping. To accomplish this, the brackets supporting the alternator are slotted to provide a method of tensioning the belt. This can be seen in Figure 9.5.1.1. One of the two mounting bolts that hold the alternator will be allowed to move in a groove allowing for the alternator's position to swing. This motion will provide the proper tension in the belt when the proper torque is given to the alternator. The mounting bolt will then

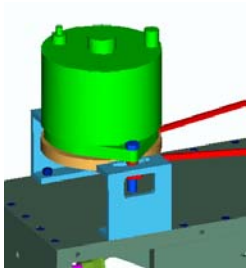


Figure 9.5.1.1
Belt Tensioner

be tightened to prevent the alternator from swinging back towards the turbine shaft.

9.6 ELECTRICAL HOUSING

The power transmission and the electrical generating system are located on top of the frame. These components must be contained in a waterproof housing. The housing will be constructed from 16-gauge (0.051 inches), 6061 aluminum sheet metal. The sheet metal will be bought with dimensions of 30” X 40” and will be machined and formed to create the electrical housing. Holes will be drilled to allow hardware to fasten the housing to the frame. All of the seams will be sealed using a gasket material to eliminate the possibility of water entering the housing. A hole will be drilled on a vertical side of the housing to provide an exit for the electrical wires. A strain relief and a rubber seal will be added to eliminate chafing and to waterproof the electrical housing.

10.0 OVERALL DESIGN ANALYSIS

10.1 COST ANALYSIS

In addition to evaluating the overall design for its functionality and strength, it is also important to evaluate the expected cost of the product. For this project, we are evaluating the cost to make one assembly, the prototype.

Figure E.2, Appendix E: Bill Of Materials contains the detailed bill of materials for the prototype. As seen in the B.O.M., the expected total cost for one prototype is approximately $624. The cost can be divided into two main categories: purchased parts and materials. The cost of the materials accounts for approximately 50% of the total cost for the prototype. An expensive item on our list is the 17-4 PH SS precipitation hardened shaft at $43 dollars. This shaft meets the high strength requirement necessary for our design. We feel that the expense of this shaft is well worth the increased strength and reliability of the product we are developing. The choice to use the ValueCraft alternator at $51 potentially saved the project $150 or more. Even when compared to other ValueCraft alternators, this device is inexpensive.

To aid the students in the Capstone Design course, Northeastern University provides the students with a design studio, tools, a fully equipped machine shop and a machinist. Therefore, we will not take into

account the cost of machining, overhead or labor. Another item that we will not consider in our cost analysis is the cost of the helical turbine. The helical turbine that will be used in the hydropower generator was developed as a prototype. The cost associated with this turbine, it's testing, and its assembly is unknown.

10.2 WEIGHT ANALYSIS

The weight of the hydropower electric generator is critical due to the fact that a person will have to manually transport the device onto and off of the dinghy. Our device must be light enough for manual transport, yet strong enough to withstand high drag forces. The materials and components for the hydropower generator based on our weight and strength requirements. The prototype should weigh not more than an outboard motor, which is also transported manually. A typical 6 horsepower outboard motor weighs 74 lbs.

Figure 10.2.1: Weight Analysis

	Components	**Weight (lbs.)**
1	Frame Assembly	28
2	Shaft	13
3	Bearings	0.5
4	Alternator	11.5
5	Pulleys	0.75
6	Sheet Metal Covers	1
7	Misc. Hardware	5
TOTAL		**59.75**

It can be seen in Table 10.2.1 that our device will weigh approximately 60 lbs. The weight of the helical turbine is not considered in the weight analysis because the density of the turbine, made out of plastic, is less than the density of water. Therefore, the turbine will be weightless with respect to the whole assembly.

11.0 TESTING

Testing of the hydroelectric generator consisted of two experiments. The first experiment involved clamping the device to a dinghy and towing the dinghy behind a sailboat. This experiment was performed to test the theoretical performance of the device using the helical turbine. The second experiment involved attaching a drill to the turbine shaft. This experiment, conducted in the lab, tested the theoretical performance of the device without the turbine. An electrical test circuit was designed for these two experiments

11.1 ELECTRICAL TEST CIRCUIT

In order to test the power transmission and alternator output, a simple test circuit was designed. The circuit was used to provide a load to the alternator and power transmission. Once a load is established, the output of the alternator could be determined as a function of the input into the alternator via the power transmission. The test circuit was designed to draw load in increasing increments with a power draw potential of at least 500 watts. The test circuit consists of the normal alternator charging setup with the addition of 5 motor vehicle headlights each rated at 12 volts and a maximum power of 96 watts wired to the output line of the alternator. The 5 motor vehicle headlights were wired in parallel to the output line of the alternator with each headlight having a separate switch to control current flow. The theory behind the test circuit is as follows:

- Each headlight will provide a load
- Parallel wiring of each light will allow for a greater current draw than a series connection and the voltage across each headlight will be identical.
- Individual switches for each of the 5 headlights will allow each headlight to be turned on separately and thus draw current from the alternator in increasing segments.

The test circuit can be seen in Appendix F. The associated diagram of the application diagram is also shown in Appendix F. This diagram shows how a battery would be charged under normal application.

11.2 TESTING USING THE TURBINE

11.2.1 Test Setup using the Turbine

This test was conducted on May 25, 2002 in Wickford Harbor, RI. A 38-ft Catalina sailboat was used as the towboat. The hydroelectric generator was attached to a 10-ft Quicksilver inflatable dinghy, which was towed behind the sailboat, as seen in Figure 11.2.1.1 and Appendix G. A person was sitting in the dinghy during testing to work the electronics and to take electrical measurements.

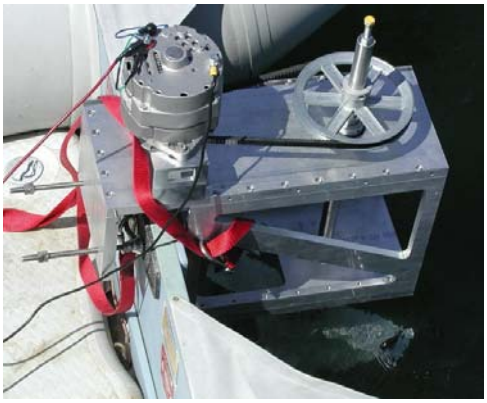


Figure11.2.1.1
Testing using the Turbine in Water

For this test, a four bladed turbine was used in place of a three-bladed turbine by request of Professor A. M. Gorlov. Professor Gorlov felt that the three-bladed turbine would not produce enough torque for our design. This is the reason for the discrepancy between the turbine used for testing and the turbine described previously in this report.

11.2.2 Test Procedure using Turbine

The testing was performed using the test circuit to determine the power output of the alternator as a function of the power input from the turbine. The test was performed as follows:

1. Hydro-generator is positioned and secured at the stern of the dinghy
2. Test begins with all headlight switches in the **Off** position
3. The boat speed is increased in half knot increments until turbine began to rotate
4. Turbine initial rotation speed is recorded
5. The boat speed continues increasing in half knot increments until alternator turn on speed is reached
6. Alternator turn on speed is recorded
7. Once turn on speed is attained boat speed is kept constant
8. A reading of the zero load nodal voltage is taken
9. One headlight is switched **On**
10. Steps 5 and 6 are repeated until all headlights have been turned **On** or alternator shut off
11. Switch all headlights **Off**
12. Increase boat speed by one half knot and repeat steps 2 through 11

11.2.3 Test Results using Turbine

The turbine did not rotate fast enough to turn on the alternator. At a boat speed of 6 knots, the turbine only reached approximately 100 rpm. Also, the turbine did not begin to rotate until the boat speed was 4 knots. A visual inspection and test of the shaft showed that the turbine was spinning freely and easily. The test was repeated without using the power transmission belt to determine if the alternator was placing too much torque on the turbine. The turbine did not spin any faster without the belt. Thus, it was determined that the alternator was not placing too much torque on the turbine.

Due to the last minute change from using a three-bladed turbine to using a four-bladed turbine, there are too many unknowns to suggest an exact reason for the failure. The experimental data provided to our design group regarding the three-bladed turbine design showed that the turbine would rotate at approximately 350 rpm at a flow speed of 3 knots. There is no experimental data available for the four-bladed turbine, thus its theoretical performance is unknown.

11.3 TESTING USING A DRILL

11.3.1 Test Setup using a Drill

To determine if the hydroelectric generator would perform as designed, a Milwaukee ½" drill was used, in place of the turbine, to rotate the shaft. A bolt was screwed into the top end of the shaft and the drill was attached to the bolt. A stroboscope was used to determine the rotational speed of the drill. Figure 11.3.1.1 shows the components used for this test. The same electrical circuit was used for this experiment as was used in the experiment using the turbine.

Figure 11.3.1.1
Test Setup using Drill

11.3.2 Test Procedure using a Drill

The testing was performed using the test circuit to determine the power output of the turbine as a function of the rotational input to the alternator. The test was performed as follows:

1. Test begins with all headlight switches in the **Off** position
2. The alternator was brought to a turn on speed of 1100 rpm's
3. A reading of the zero load nodal voltage is taken
4. The shaft speed is increased to 350 rpm
5. One headlight is switched **On**
6. The shaft speed is increased back to the rpm shown in step 4
7. A reading is taken of the nodal voltage and current draw
8. Repeated steps 5 though 7 until all headlights have been turned **On**
9. The entire test is repeated using values of 400, 450, 500, 550, and 600 in step 4

11.3.3 Test Results using a Drill

Due to the limitations of the drill, the maximum power output of the device was 143 watts. The data obtained from this test is summarized in Appendix H. The maximum power output was obtained at a rotational speed of 550 rpm. This can be seen in Figure H.1, Appendix H.

11.4 TESTING DISCUSSION

Two factors adversely affected the proper operation of this device. The first factor is the turbine supplied did not perform to expectations. The second factor was the original design called for a 1" pulley on the alternator shaft. This caused our design pulley ratio to decrease from 5.4:1 to 3.5:1. Thus the theoretical start up angular velocity of the turbine increased from 204 rpm to 314 rpm. Since the turbine was never able to reach any higher than approximately 100 rpm, the alternator never started.

12.0 RECOMMENDATIONS

By removing the frame surrounding the turbine, drag forces are minimized. However, the result of this was a hydropower generator with a larger shaft, a shaft that is capable of withstanding the large drag forces, and torsional forces of the turbine. The turbine must be supported at its bottom and top plate to increase its rigidity, because the prototype is fragile and has broken under testing. To increase the rigidity of the turbine, the shaft passes through the top of the turbine, through the center of the turbine and mounts rigidly to the bottom surface of the turbine. This can be seen in Figure 9.0.1. Further testing of the turbine may show less drag forces than theoretically determined, allowing the shaft to be reduced in size. Less drag force would also allow for smaller frame members.

The use of an all metal, corrosion resistant turbine will improve the design of the hydropower generator. An all-metal turbine with welded turbine blades may not need support at the bottom plate, as is required for the plastic turbine. The turbine could be fixed to the shaft at the top plate, thus removing the shaft within the turbine from the fluid flow and minimizing drag. A concept for this proposed turbine is shown in Figure 11.0.1. The testing outlined in Section 11.0: Testing shows that the alternator is not being supplied with enough torque to produce enough current to meet power requirements. The amount of torque supplied to the alternator can be increased by using a more powerful turbine and an optimal pulley ratio. However, under the design timeline, we were not able to design another turbine and power transmission, which would maximize power output.

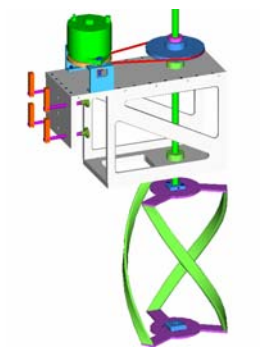


Figure 11.0.1
Proposed Turbine Design

13.0 CONCLUSION

The goal for this project is to create a renewable energy device to be used on small vessels. Considering the market constraints, sailboats were determined to be the focus of this project. Analyzing sailboat power consumption shows that a hydroelectric generator using a helical turbine is capable to supplying adequate power to recharge or supplement batteries. Competition evaluation shows inadequacies in the area of alternative energy devices. Solar panels are fragile and costly. They also take a considerable amount of deck space on a sailboat. Wind generators pose potential safety hazards from spinning propeller blades. Current water generators are inefficient due to the propeller used.

A final design concept has been defined. The design involves a frame assembly, which mounts to either the transom of a dinghy or a motor mount on the stern of a sailboat. This utilizes the advantages of earlier design concepts while eliminating some of the disadvantages. Engineering drawings have been created for all components. The turbine shaft was designed to withstand the fatigue created by the rotation of the

shaft and the bending moment created by the drag force. An alternator was selected, which minimizes cost. The alternator was tested to determine operational characteristics, such as torque required for a desired current.

Based on calculations, the hydroelectric power generator will perform well enough to meet the criteria specified. Testing determined that the turbine did not meet performance expectations. Further testing of the turbine alone would help to determine the path to take to solve this issue. Using an artificial drive method, the device was able to generate power. However, the power generated was not comparable to the expected power output. More power can be generated with the use of a more powerful turbine and an optimized pulley ratio.

References

Boat U.S., Origo 2.2 Cu. Ft. AC/DC Refrigerator/Freezer, www.boatus-store.com/MC_Online/Browse.Asp

Cogdell, J. R. Foundations of Electrical Engineering. 2nd ed. New Jersey: Prentice Hall, 1996.

Dine, Scott, Wind, Water and Sun Sustain Sailors, www.bayweekly.com/year01/issue9_40/lead9_40.html, 2001

Engineering Fundamentals, Alloy Properties 17-4 PH, www.efunda.com/materials/alloys/alloy_home/show_alloy_found.cfm?ID=17-4PH&prop=all&Page_Title=%20Metal%20Alloys%20Keyword%20Search%20Results

Engineering Fundamentals, Alloy Properties AISI Type 316, www.efunda.com/materials/alloys/alloy_home/show_alloy_found.cfm?ID=AISI_Type_316&prop=all&Page_Title=%20Metal%20Alloys%20Keyword%20Search%20Results

e-Marine, Inc, AIR marine wind generator, www.e-marine-inc.com/products/wind_generators/airmarine.html

e-Marine, Inc, KISS High Output Wind Generator, www.e-marine-inc.com/products/wind_generators/kiss.html

e-Marine, Inc, Which is Better – Wind Generator or Solar Panels, www.e-marine-inc.com/articles/art2.html

e-Marine, Inc, Wind Generators, www.e-marine-inc.com/products/wind_generators/wind_generator.html

Ganssle, Jack, Go West! Part IV, www.ganssle.com/jack/ostar4.html, 1993

Gorlov, A.M., 1998, "Turbines with a Twist. In: Kitzinger U and Frankel EG (eds) Macro-Engineering and the Earth: World Projects for the Year 2000 and Beyond, pp. 1-36. Chichester: Horwood Publishing.

Hibbeler, R. C. Mechanics of Materials. 3rd ed. New Jersey: Prentice Hall, 1997.

Macro-Engineering and the Earth (Chapter 1 Turbines With a Twist), Horwood Publishing, Chichester, GB, 2000.

MarineNet, Inc, Alternative Battery-Charging Systems, www.sailnet.com/collections/articles/index.cfm?articleid=woodto022, 2002

Mat Web, Aluminum 6061-T6; 6061-T651, www.matweb.com/SpecificMaterial.asp?bassnum=MA6016

Northern Arizona Wind & Sun, Inc., Solar Electric Modules (Solar Panels), www.windsun.com/PV_Stuff/Solar_electric.htm, February 2, 2002

Oasis Montana Inc., AQUAIR UW Submersible Hydro Generators, www.oasismontana.com/AQUAIR.html, January 1, 2002

Pinney, Tor, The Optimum Electrical Power System for the Cruising Sailboat, www.tor.cc/articles/energy.htm

Seimens Solar Ind., Marine Power Kits – Products, www.solarpv.com/Marine/Products/Products.html, May 11, 2000

Seimens Solar Ind., Marine Power Kit 100, www.e-marine-inc.com/products/solar_panels/marinekit100.html

Spotts, M. F. and T. E. Shoup. Design of Machine Elements. 7th ed. New Jersey: Prentice Hall, 1998.

Ullman, David G. The Mechanical Design Process. 2nd ed. Boston: McGraw-Hill, 1997.

Vandrey, Jobst, Electrical Power Considerations, www.geocities.com/Yosemite/Forest/2727/trailersubweb/trailer_electric.html, September 14, 2000

Western Marine, Aquagens, www.western-marine.com/lvm/aquagen.htm

Young, Hugh D. and Roger A. Freedman. University Physics. 9th ed. New York: Addison-Wesley Publishing Company, Inc., 1996.

Appendix A: Equations

Power Formulation

The power produced by the helical turbine is as follows:

$$P_{Turbine} = T_{Total}\ \omega \qquad (1)$$

Where:

T_{Total} = **Total Torque produced by the turbine (***Unknown/Experimental***),**
ω **= Angular velocity of turbine. (***Unknown/Experimental***)**

**Since* T_{Total} *and* ω *cannot be calculated numerically the power produced by the turbine cannot be calculated using equation (1). Therefore, power produced must be formulated using the known efficiency of the turbine and the available flow power as follows:*

$$P_{fluid} = 0.5\ \rho\ AV^3_{fluid} \qquad (2)$$

Where:

ρ = **Fluid density,**
A= **Turbine frontal area**
V_{fluid} = **Fluid flow velocity,**

The efficiency of the turbine is 32% (η = 0.32**).** (3)

From equations **(2)** and **(3)**:

$$\mathbf{P_{Turbine} = \eta\ P_{fluid}} \qquad (4)$$

Torque Formulation

$$\mathbf{T_{Total} = P_{Turbine} / \omega} \qquad (5)$$

$$\mathbf{\omega = 7.2\ V_{fluid}} \qquad (6)$$

(*From Exerimental Data*)

Figure A.1

	Fluid		Turbine		
Water Vel.	Avail. Power	ω	Torque	Power	Blade Vel.
(ft/sec)	(watts)		(lb-in)	(watts)	(ft/sec)
0	0	0.00	0	0	0
0.1	0.002	0.72	0.008	0.001	0.360
0.2	0.016	1.44	0.031	0.005	0.719
0.3	0.053	2.16	0.070	0.017	1.079
0.4	0.126	2.88	0.124	0.040	1.439
0.5	0.247	3.60	0.194	0.079	1.799
0.6	0.426	4.32	0.280	0.136	2.158
0.7	0.677	5.04	0.381	0.217	2.518
0.8	1.010	5.76	0.497	0.323	2.878
0.9	1.438	6.48	0.629	0.460	3.238
1	1.973	7.19	0.777	0.631	3.597
1.1	2.626	7.91	0.940	0.840	3.957
1.2	3.409	8.63	1.119	1.091	4.317
1.3	4.335	9.35	1.313	1.387	4.676

Force from a single blade torque solution is as follows:

$$\mathbf{F = k_o\, A\, V^2_{fluid}} \qquad (7)$$

Where:

$\mathbf{k_o}$ = constant = **1.2** ρ,
A = projection of the frontal area of the blade on the plane perpendicular to the fluid flow =
3/3.14 x **{ d + sin(d) + $3^{0.5}$** x **cos(d-1) }**
*Where d = ½ Cord Length***,**
V_{fluid} = **Velocity of fluid flow.**

Once the force on the blade has been determined, the torque produced by a single blade can be calculated from the following:

$$\mathbf{T = FR\sin(\varphi)} \qquad (8)$$

Where:

F = **The force on the blade,**
R = **Radius of the turbine,**
φ = **Blade twist angle.**

Combining Equations **(5)** and **(6)** gives the Torque equation for a single blade:

$$T = k_o\ A\ R\ V^2_{fluid} \sin(\varphi) \qquad (9)$$

APPENDIX A (cont.)

Drag Formulation

The drag force (**F_{Drag}**) can be calculated using the following:

$$F_{Drag} = 0.5\ Cp\ \sigma\rho\ V^2_{fluid}\ D\ H \qquad (10)$$

Where:

Cp = **constant = Drag Coefficient,**
σ = **Solidity,**
ρ = **Fluid density,**
V_{fluid} = **Fluid flow velocity,**
D = **Diameter of turbine,**
H = **Height of turbine.**

Drag force found in equation 10 is based on a stationary turbine in fluid flow. In order to account for blade motion, the drag force calculated is increased by 30% based on experimental results conducted by Professor Gorlov. Also, the dynamic (turbulence) effect must be accounted. This is accomplished by adding 25% to the drag force.

The drag coefficient (Cp**) is a function the turbine solidity and the ratio of linear blade velocity vs. fluid flow velocity. Once the Solidity (σ) and Velocity Ratio (**Un**) are known,** Cp **can be solved for using the** Drag Chart**, which has been provided on the next page.**

σ = **{Total blade surface area} / {Total frontal area of the turbine}** (11)

$$= \frac{n}{\pi}\left(d + \sum_{k=1}^{n}\left(\sin\left(\frac{k\pi}{n} - d\right) - \sin\frac{k\pi}{n}\right)\right)$$

Un = **{Linear Velocity of Blades} / {Fluid Flow Velocity}**
= **{**ω R **} / {** V_{flow} **}** (12)

APPENDIX A (cont.)

Figure A.2

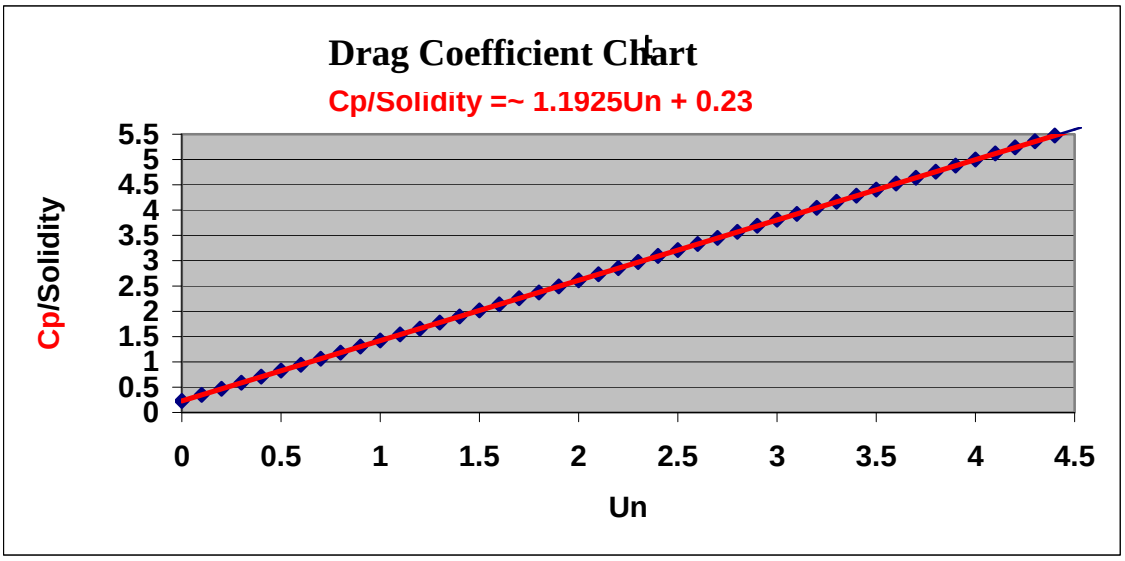
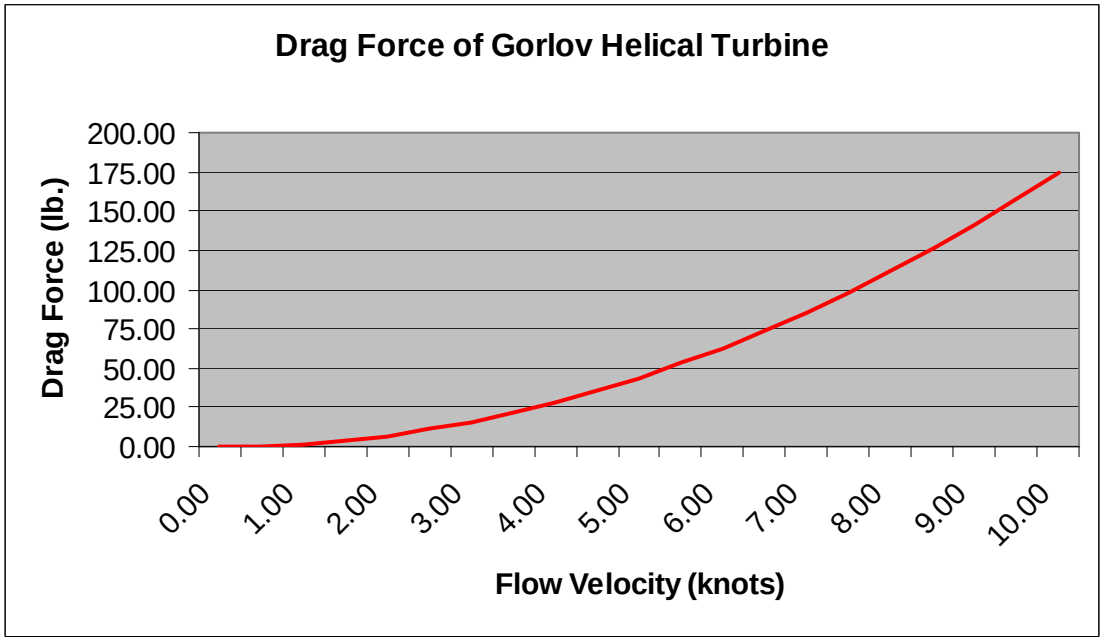


Figure A.3



Appendix B: Turbine Characteristics

Figure B.1: The Helical Geometry Of The Turbine Donated To This Project

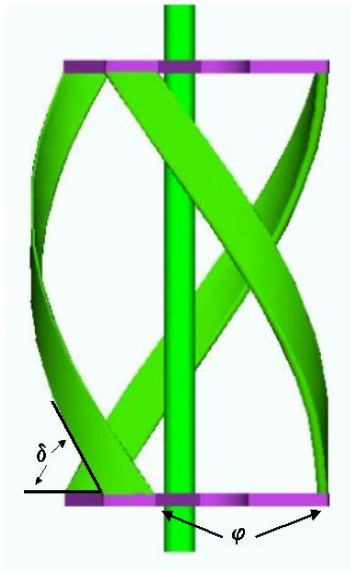
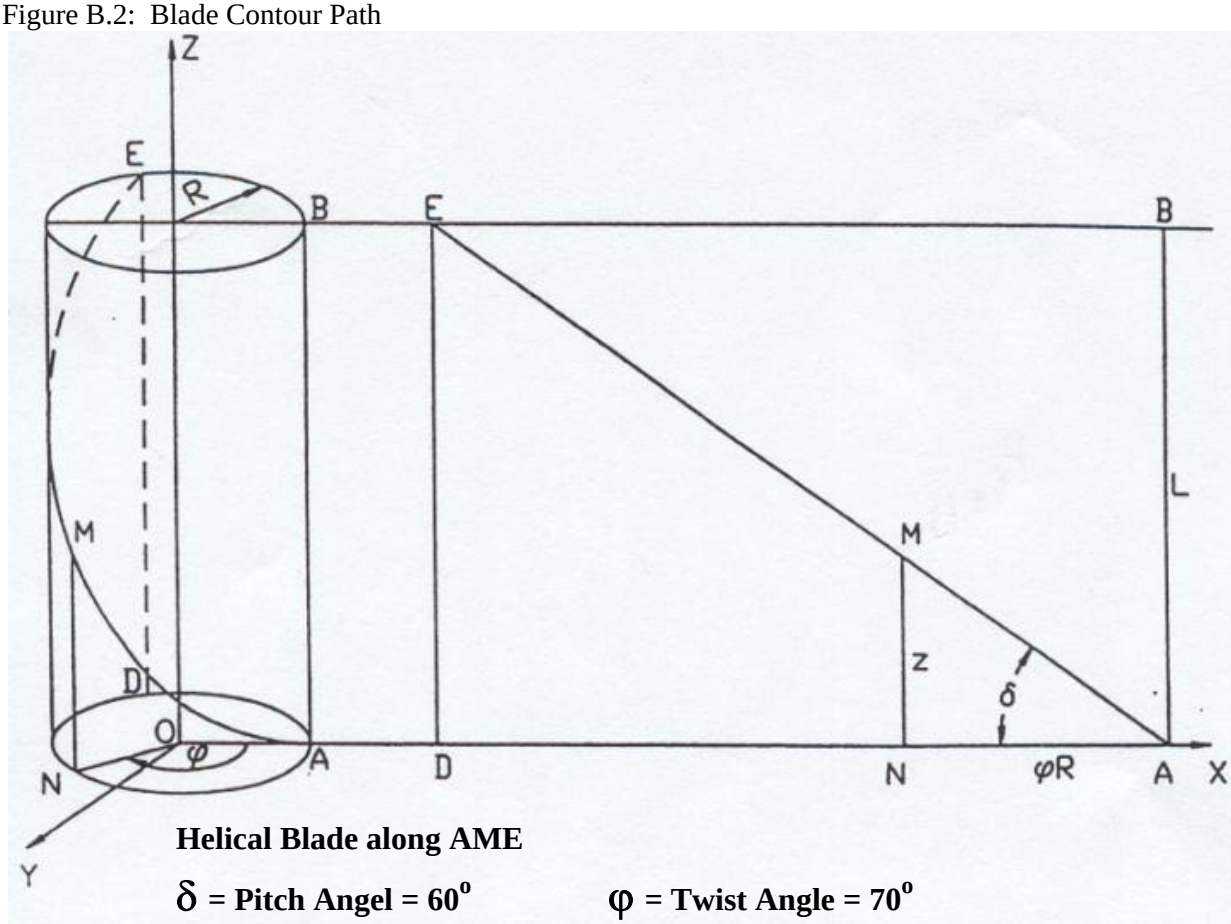
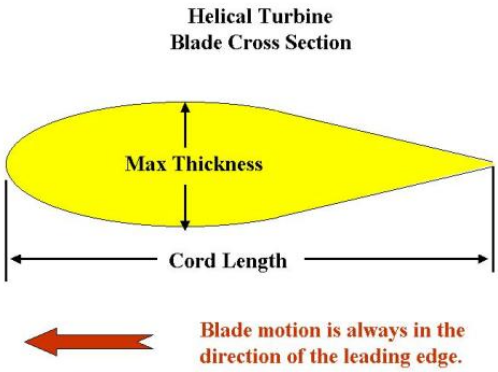


Figure B.2: Blade Contour Path



Appendix B: Turbine Characteristics Continued

Figure B.3: Blade Cross Section (drawing is not to scale)



NACA-0020 defines the ratio between an airfoil's Cord Length and Maximum Thickness.

NACA-0020, defines the Maximum Thickness of the airfoil to be 20% of Cord Length.

Appendix C: Shaft Analysis

Figure C.1: Shaft Free Body Diagram

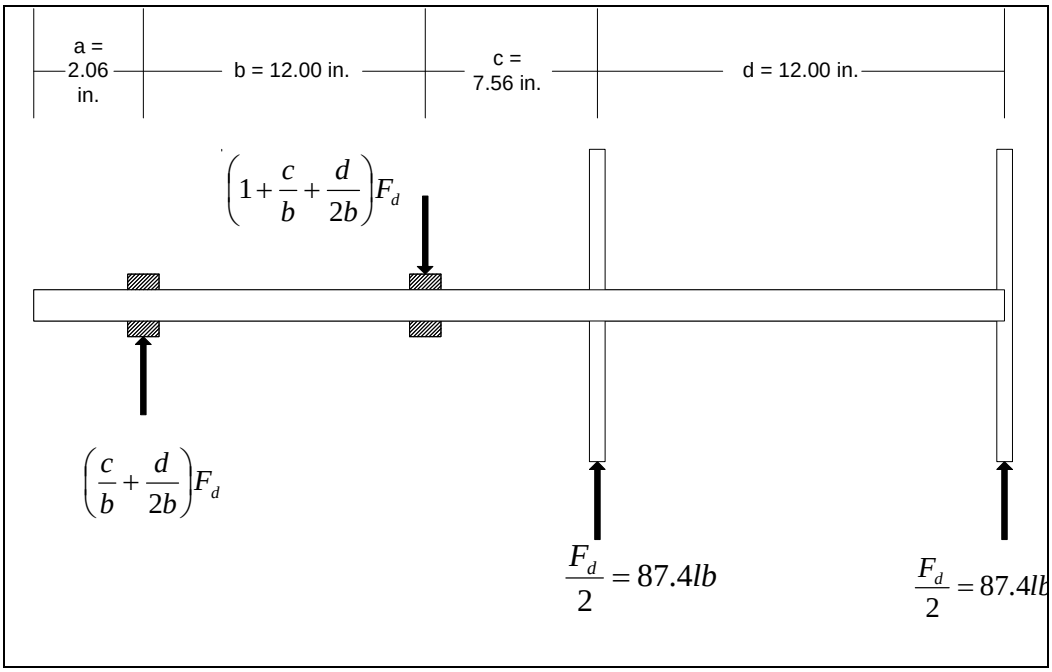


Figure C.2: Shaft Moment Diagram

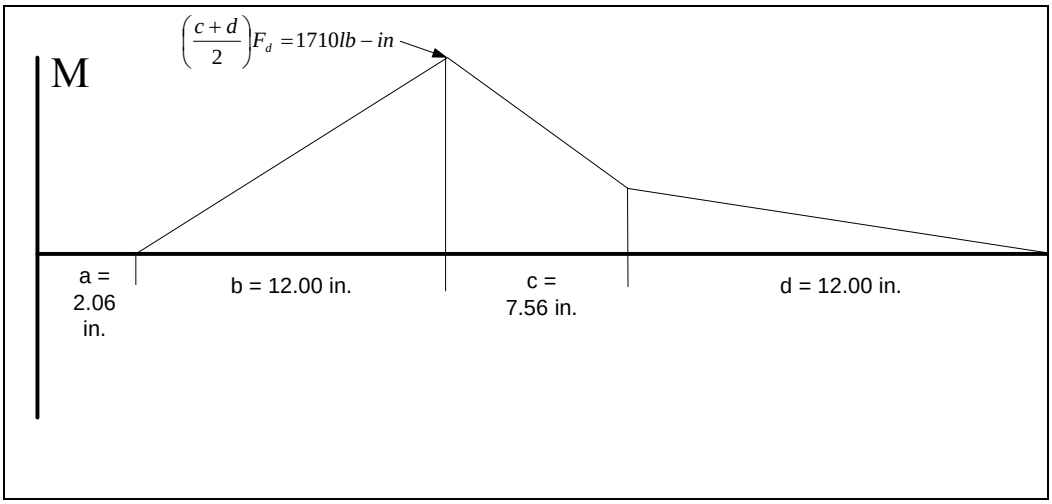
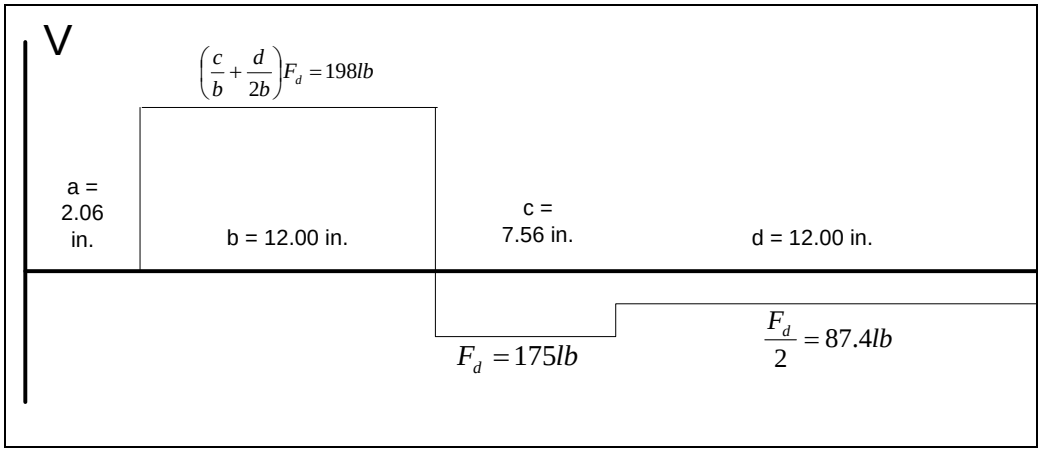


Figure C.3: Shaft Shear Diagram



Inputs	Solid SS 17-4	Solid SS 316	Solid Al 6061	Hollow Al 6061	Notes:
σ_{ult} (psi) =	155,200	75,000	45,000	45,000	Ultimate Strength
σ_{yp} (psi) =	145,000	30,000	39,900	39,900	Yield Point
σ_e (psi) =	96,133	59,375	36,875	36,875	Endurance Limit
E (psi) =	28,430,000	28,000,000	10,000,000	10,000,000	Elastic Modulus
υ =	0.27	0.27	0.33	0.33	Poison's Ratio
G (psi) =	11,175,314	11,023,622	3,759,398	3,759,398	Torsional Modulus
K_{fb} =	1.00	1.00	1.00	1.00	Fatigue Bending Stress Concentration Factor
ρ (lb/in^3) =	0.28	0.30	0.10	0.10	Density

Design Properties					Notes:
a (in) =	2.06	2.06	2.06	2.06	Shaft Length from Alternator to Upper Bearing
b (in) =	12.00	12.00	12.00	12.00	Shaft Length between Bearings
c (in) =	7.56	7.56	7.56	7.56	Shaft Length from Lower Bearing to Turbine
d (in) =	12.00	12.00	12.00	12.00	Shaft Length Inside Turbine
TL (in) =	21.63	21.62	21.62	21.62	Length of Shaft Subject to Torque
L (in) =	33.63	33.62	33.62	33.62	Overall Length of Shaft
D (in) =	**1.00**	**1.00**	**1.00**	**1.50**	Diameter of Shaft
t (in) =	n/a	n/a	n/a	0.25	Shaft Wall Thickness
A (in^2) =	0.79	0.79	0.79	0.98	Cross Sectional Area of Shaft
V (in^3) =	26.41	26.41	26.41	33.01	Volume of Shaft
W (lb) =	**7.34**	**7.87**	**2.57**	**3.22**	Weight of Shaft
J (in^4) =	0.0982	0.0982	0.0982	0.3988	Polar Moment of Inertia of the Shaft
I (in^4) =	0.0491	0.0491	0.0491	0.1994	Area Moment of Inertia of the Shaft

Applied Forces					Notes:
T_{max} (lb-in) =	221.28	221.28	221.28	221.28	Maximum Torque Produced
F_{max} (lb) =	174.79	174.79	174.79	174.79	Maximum Drag Force Produced at 10 knots

Fatigue Analysis					Notes:
M_{max} (lb-in) =	1,710	1,709	1,709	1,709	Maximum Bending Moment

V_{max} (lb) =	198	198	198	198	Maximum Shear Force
$\tau_{tor,max}$ (psi) =	1,127	1,127	1,127	416	Average Shear Stress Produced by Torque
$\tau_{shear,max}$ (psi) =	252	251	251	201	Average Shear Stress Produced by Shear Force
τ_{ave} (psi) =	1,378	1,378	1,378	617	Total Average Shear Stress
σ_{bend} (psi) =	17,415	17,412	17,412	6,429	Maximum Bending Stress
N_{fs}=	**5.50**	**3.29**	**2.10**	**5.67**	Fatigue Factor of Safety
x (in) =	0.2239	0.1896	0.5308	0.1307	Deflection of Shaft at Bottom of Turbine

Figure C.4: Shaft Design Comparison for Various Materials

APPENDIX D: Market Competition Schematics

Figure D.1: Portable Wind and Hydro Electric Generating System

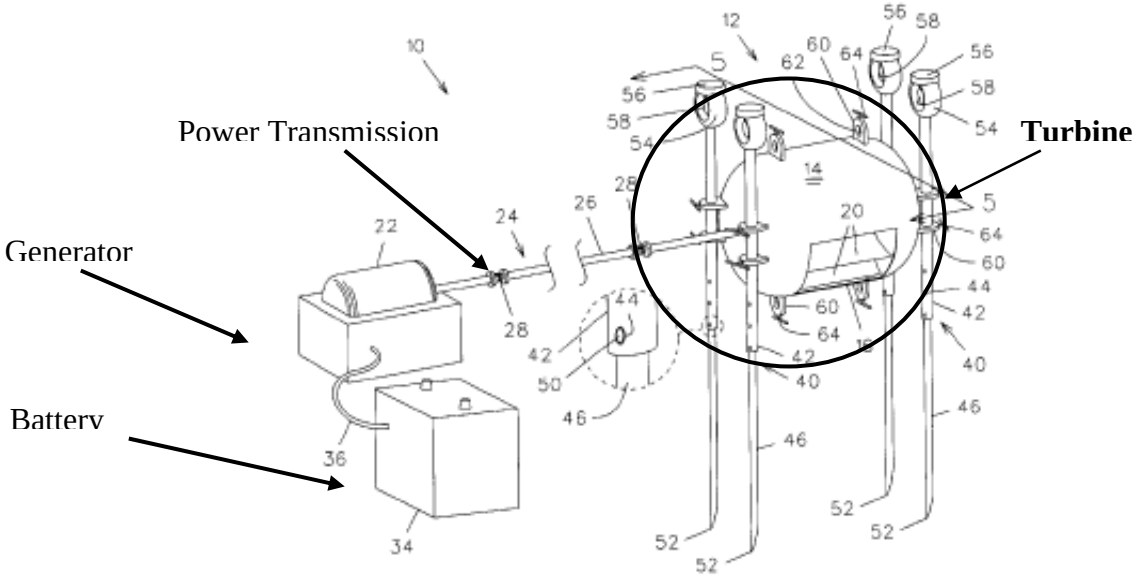


Figure D.2: Aquagens Device

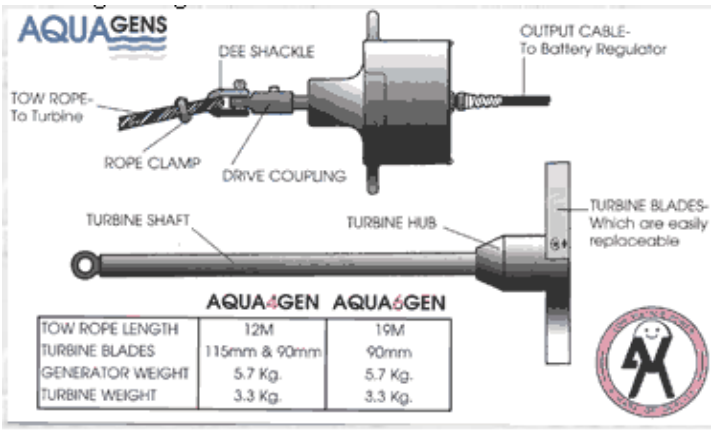
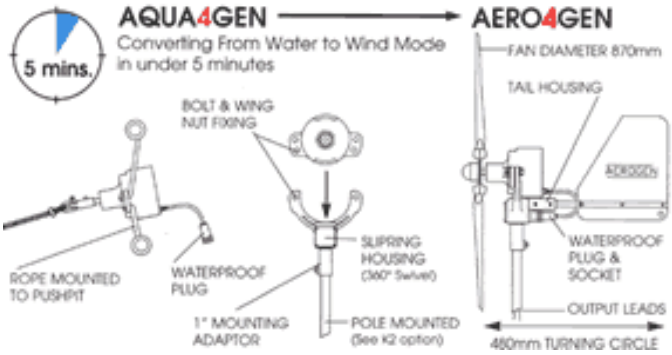


Figure D.3: Water to Wind Mode Conversion for Aqua4gen



APPENDIX D: Market Competition Schematics Continued

Figure D.4: Power Output Data for Aquagens

Boat Speed [Knots]	Aqua4gen				Aqua6gen	
	Large turbine blades [115mm]		Small turbine blades [90mm]		Turbine blades [90mm]	
	Amps 12-14V	Drag lbs.	Amps 12-14V	Drag lbs.	Amps 12-14V	Drag lbs.
2.5	0.1	-	0.1	-	-	-
3	1	10	0.3	-	-	-
3.5	1.5	12	0.7	14	0.1	-
4	2	15	1	17	1	4
5	4	20	2	23	2	8
6	8	30	4.5	30	3	16
7	10	40	7	35	4.5	18
8	11	50	8	40	6	27
9			9	45	10	40
10			10	50	12	45
11					14	53
12					16	60
14						

Table E.1: Bill Of Materials

Item No	Part No	Drawing Name	DESCRIPTION & MATERIAL REQUIRED	SUPPLIER	MFG PART NO.	QTY PER ASSEM	UNIT PRICE	PRICE EXT
1	**1700**	**ASSY, FRAME**	**ASSEMBLY DRAWING**	**N/A**	**N/A**	**1**	**N/A**	**N/A**
2	1701	PLATE, BEARING, TOP	3/4" T1-6061 Al. Plate Stock	Metal Source	N/A	1	$40.00	$40.00
3	1702	PLATE, BEARING, BOT	3/4" T1-6061 Al. Plate Stock	Metal Source	N/A	1	$40.00	$40.00
4	1703	PLATE, CLAMP	3/4" T1-6061 Al. Plate Stock	Metal Source	N/A	1	$9.00	$9.00
5	1704	PLATE, TRUSS	1/2" T1-6061 Al. Plate Stock	Metal Source	N/A	2	$20.00	$40.00
6	1705	BEARING, TAPERED	Corrosion-Resistant Steel Bearings	McMaster-Carr	6678K11	2	$25.15	$50.30
7	1706	1/4-20 SHCS X 1.25"	1/4-20 SHCS X 1.25", 18-8 SS, box of 100	McMaster-Carr	92196A544	1	$14.50	$14.50
8	**1800**	**ASSY, POWER GENERATOR**	**ASSEMBLY DRAWING**	**N/A**	**N/A**	**1**	**N/A**	**N/A**
9	1801	SHAFT	Shaft, 17-4 PH SS, 1" Dia., Hardened	McMaster-Carr	88855K16	1	$43.37	$43.37
10	1804	SHAFT, PULLEY	Diecast Vbelt Pulley, 7" OD, 1" Bore	McMaster-Carr	6245K74	1	$8.67	$8.67
11	1805	ALTERNATOR, PULLEY	Diecast Vbelt Pulley, 1.50" OD, .5" Bore	McMaster-Carr	6245K6	1	$2.21	$2.21
12	1806	BELT	Ax23 25" Vbelt	McMaster-Carr	6054K102	1	$5.99	$5.99
13	1807	BRKT, ALTERNATOR, RH	3" X 3" X 1" T1-6061 Al. BLOCK	Metal Source	N/A	1	$2.50	$2.50
14	1808	BRKT, ALTERNATOR, LH	3" X 3" X 1" T1-6061 Al. BLOCK	Metal Source	N/A	1	$2.50	$2.50
15	1809	COLLAR, SHAFT	Collar, Aluminum, 1" ID	McMaster-Carr	6436K72	6	$4.48	$26.88
16	1810	ALTERNATOR	Alternator- Valuecraft, 63A (1986 Chevy Chevette)	AutoZone	7274M	1	$50.00	$50.00
17	1811	ROD, THREADED	Threaded Rod, 3/8-16"	McMaster-Carr	93250A145	1	$5.76	$5.76
18	1812	FEET, LEVELING	Swiveling Leveling Mounts, 300 Series SS	McMaster-Carr	6103K61	4	$10.52	42.08
19	1813	HANDLE	3" X .5" X .75" T1-6061 Al. BLOCK	Metal Source	N/A	4	$1.00	$4.00
20	1814	BOLT, ALTERNATOR	Bolt, 3/8-16 x 2", SS	Home Depot	n/a	2	$1.00	$2.00
21	1815	BEARING, COVER	RUBBER/METAL SEAL	N/A	N/A	4	$5.00	$20.00
22	1816	ALTERNATOR, COVER	Aluminum Sheet Metal Stock, 4' x 4' x .05"	Metal Source	N/A	1	$10.00	$10.00
23	1817	**ASSY, TURBINE**	**ASSEMBLY DRAWING**	N/A	N/A	1	N/A	N/A
25	1817	PLATE, TURBINE	Aluminum Sheet Metal Stock 14” x14” x 0.25”	McMaster-Carr	8915K27	2	$58.36	$116.72
26	1818	CLAMP COLLAR, LARGE	Aluminum Round Stock 2” O.D.	McMaster-Carr	8974K711	2	$5.00	$10.00
27	1819	CLAMP COLLAR, SMALL	Aluminum Round Stock 2” O.D.	McMaster-Carr	8974K711	4	$2.50	$10.00
28	1820	8-32 SHCS X 1.5”	8-32 SHCS X 1.5”, 18-8 S-S, box of 100	McMaster-Carr	92196A201	1	$7.66	$7.66
29	1821	BLADE, TURBINE	Formed Plastic	Prof. Gorlov	N/A	3	$20.00	$60.00
			TOTAL					$624.11

APPENDIX F: Test Circuit

Figure F.1 Application Circuit

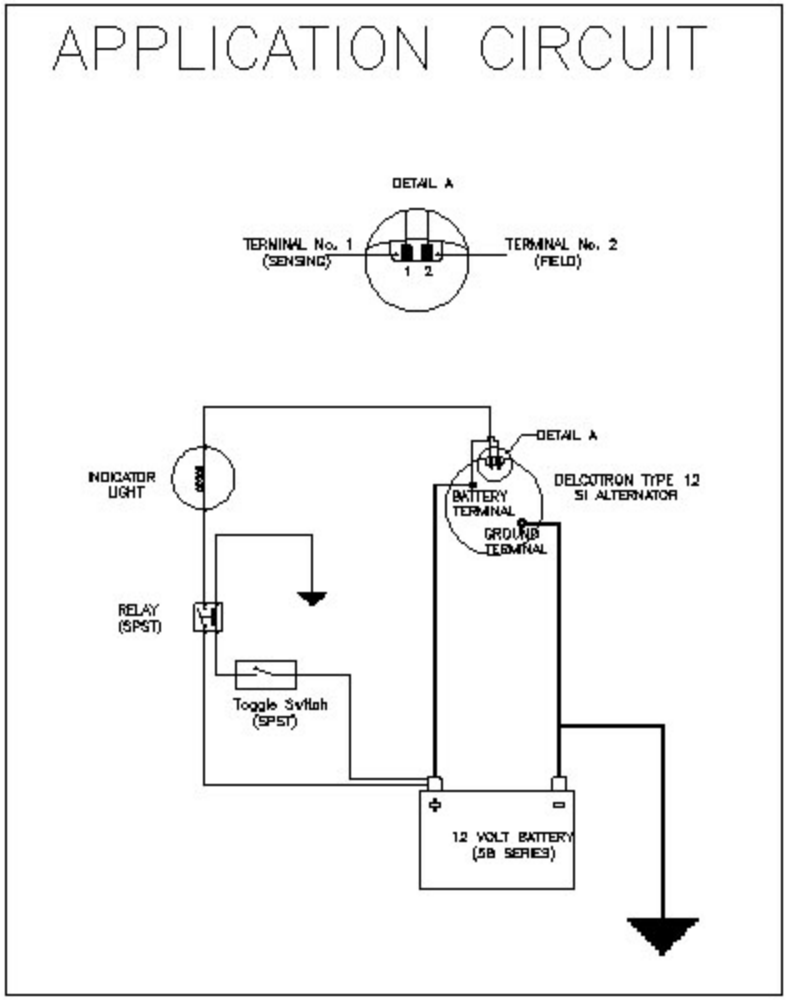
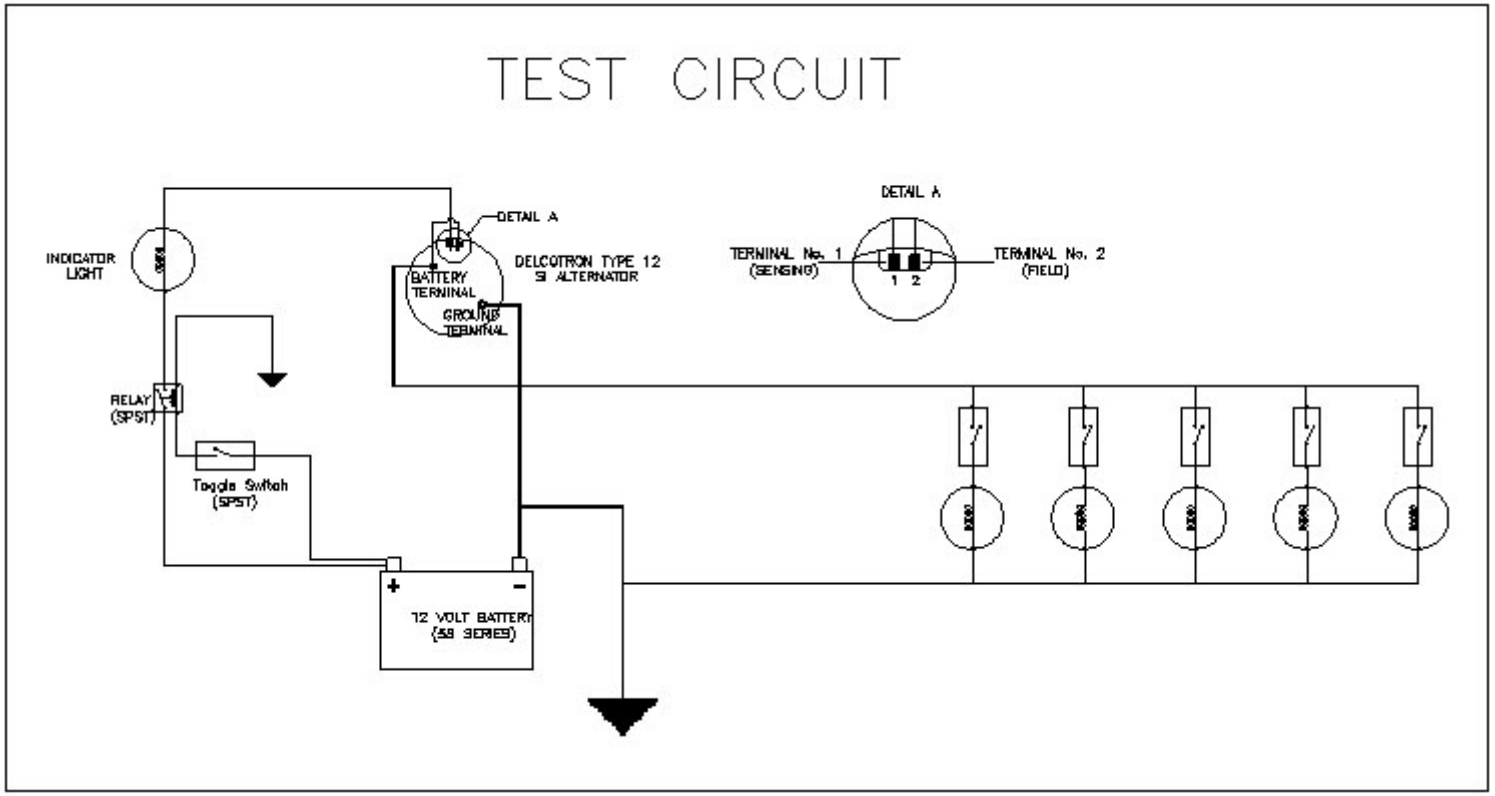


Figure F.2 Bulb Side Circuit Diagram



APPENDIX G: Pictures from Testing using Turbine

Figure G.1: Attaching Hydroelectric Power Generator to Dinghy

Figure G.2: Hydroelectric Power Generator Attached to Dinghy

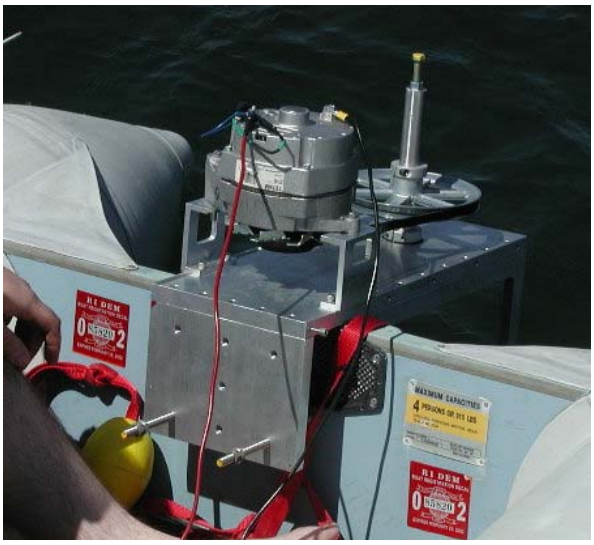


Figure G.3: Testing of Hydroelectric Power Generator

APPENDIX H: Test Results Using A Drill

Figure H.1: Turbine Shaft Speed Versus Power Output