PROJECT DJO-1203

Design of a Kite-Powered Water Pump and Airborne Wind Turbine

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Abstract

The goal of this project was two-fold, to adapt the existing WPI Kite Power System to pump water, and to develop a new airborne energy system that harvests electricity from the wind using a turbine suspended from a large kite. This project is a continuation of ongoing research at Worcester Polytechnic Institute in the area of using high altitude kites to extract energy from the wind. These high altitude kites can operate at higher altitudes than wind turbines where there is an increase in wind speed and therefore, available power. The main objectives of the water pump project were to retrofit the existing WPI Kite Power System with a low-cost mechanical water pump for use in developing nations, and to build and test a head simulation valve that can simulate deeper well depths for use in system testing. The mechanical pump and head simulation valve were installed on the existing WPI Kite Power System. Lab testing showed that this system is viable for mechanically pumping water out of a well when simulated kite forces are applied to the end of the rocking arm of the system. The main objective of the airborne wind turbine project was to design an airborne wind turbine that could be supported beneath a high altitude kite. The team constructed and installed a support frame for a small vertical-axis wind turbine to be supported beneath an eight meter square sled kite. Wind tunnel testing and field testing of the vertical axis turbine were conducted. More field testing is needed in the future for the kite-powered water pump and a scaled-up airborne wind turbine.

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1. Motivation

The goal of this project is to create two systems that can be powered by wind energy harvested from a kite. The first is a water pump that will be retrofitted onto the existing WPI Kite Power System designed for harvesting wind energy with a kite. This system will utilize the power produced during the power stroke of the kite system to drive a mechanical well water pump. Eventually, we hope this system can be used in developing nations in order to provide water for rural villages. The second independent system will feature an airborne wind turbine that will be suspended just below a high altitude kite. This wind turbine would be able to access the higher wind speeds at altitude and produce a more constant flow of electricity.

The President of the United States, Barack Obama, recently unveiled a new clean energy initiative under the American Jobs Act. This bill sets a goal that 80% of the Nation's electricity would come from clean energy sources by 2035. This standard defines clean energy sources to include renewable resources, nuclear power, efficient natural gas, and coal power with carbon capture and sequestration. The purpose of this initiative is to help the growth of the renewable energy market. Since 2008, the government has added the capacity to produce 20,000 megawatts of electricity from wind, solar, and geothermal. It is expected that by 2012 the renewable market will have doubled its size since 2008. It is estimated that by 2012 the United States will be producing 174 terawatt hours of electricity from renewables annually.[1] The market demands that the sector of renewable must continue to grow. For our project, we will be focusing on developing a new type of wind technology for two different needs and applications.

1.1. Need for Alternative Water Sources

There are still many people in the world who do not have access to clean, potable water. This is particularly true for rural communities in the developing world. In some places there are wells through which water can be pumped out to be used within the community. Most of the time, these wells are susceptible to contamination because they are not sealed. Also, in order to extract water from these wells one must use a mechanical hand pump, which is limited by volume and how quickly a person can pump. The average person in the developing world uses twenty to forty-five liters of water per day for their washing, cooking and drinking. Contrastingly, the average person in North America uses four hundred liters of water per day.[2] The average need for water in the developing world is lower which lends itself to testing the viability of new ways of extracting water. This means that our system needs to produce a smaller volume of water and can be tested on a smaller scale. Using our project as an example, we can use kite power, to drive a pump that pumps water out of the ground. This allows us to design and build a smaller system that will still fulfill the needs of a village in a developing nation because their water needs are much less than in our own country.

1.2. Need for Alternative Wind Energy Sources

The demand for the growth of the renewable resource market provides great opportunities for exploring new and unconventional means for harvesting renewable resources. Our project will be focusing on a new way to harvest wind energy, namely a kite-powered system with a wind turbine. The traditional wind turbine is situated on the top of a large structure so that it can access the higher wind velocities at higher altitudes. These turbines also create a lot of noise pollution as well as sight pollution.

Wind turbines are generally considered to be unsightly by most in whose communities they are built. An alternative to wind turbines are kites. Wind energy can be harvested with kites.

Kites have always been utilized as children's toys or recreational devices. Kites are perfect for generating electricity for three reasons: low cost, access to increased wind velocity at higher altitudes, and ease of operation. A large traditional wind turbine, between one and two megawatts, normally costs upwards of 1.5 million dollars, while kites range in the couple of hundred of dollars. One purpose of this MQP is to develop a turbine system that can be lifted into the air by a kite to capture the wind speeds at high altitudes. This would be beneficial because as the altitude increases, the velocity of wind increases as well. From the equation for power generated by wind ($P = \frac{1}{2}\rho C_p V^3 A$), we can see that if the wind velocity doubles than the power produced increases by a factor of eight. Traditional wind turbines are structurally limited, specifically by the supporting tower and local government height regulations. So, the only practical way for a traditional wind turbine to increase power is to increase its blade swept area. But, large turbines are more expensive and so are more expensive to maintain and operate. Our concept is to lift a small, lightweight wind turbine up to high altitudes with a large kite. This design optimally would produce around one kilowatt of electricity.

1.2.1 Kite advantages over traditional large wind turbines

Kite power has several advantages over traditional wind turbines. First, they can fly at higher altitudes. This allows them to access higher wind velocities and therefore greater power. Figure 1 shows how power and wind speed vary with height above the ground. Secondly, because they are at greater heights they may not produce the same noise pollution as a traditional wind turbine. Another problem with wind turbines is that the larger and taller they become, more ground space and materials are needed for their construction.[3] The footprint for the existing WPI system is about 10 m^2. Although a kite falling to the ground when wind velocity diminishes would make the footprint larger, this area would be determined by the kite tether length where R is the tether length and A is the ground space needed: $A = \pi r^2$.

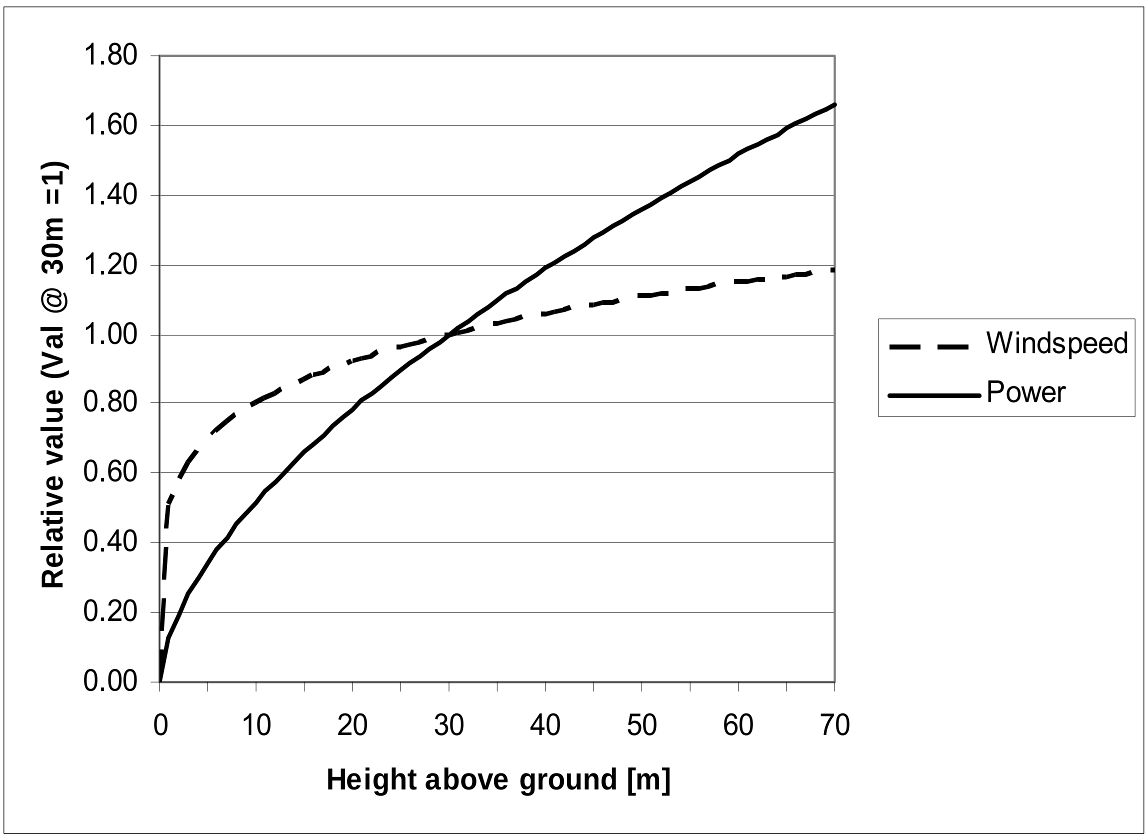

Figure 1: Wind speed and Power vs. Height[4]

2. Background

The goal of the MQP projects at WPI has been to design a kite-powered system that could generate one kilowatt of power.[5] The existing WPI Kite Power demonstrator, shown in Figure 2, consists of a double A-frame supporting a rocking arm, which is attached to the kite. The A-frame itself is made from four-by-four pieces of lumber. The rocking arm is made of metal in order to withstand the fluctuating stresses from the kite. The rocking arm is attached to a kite that raises and lowers with the wind.[6] A sliding weight mechanism on the left end of the rocking arm in Figure 2 is designed to pull on two kite tethers attached to the kite trailing edge. When the left rocking arm end is in the up position, the sliding weight pulls on the trailing edge tethers to increase the angle attack of the kite, thus stalling the kite and reducing the kite lift force on the rocking arm. The rocking arm end then descends to the position shown in Figure 2; the sliding weight now slackens the trailing edge tethers to decrease the kite angle of attack, thus increasing the kite lift force which causes the rocking arm to ascend. This process repeats in a cycle.

Figure 2: Entire WPI Kite Power System

The current system features a sled kite,[7] shown in Figure 3. The sled kite has a very large surface area of 8 meters squared which provides sufficient lift for the system, Sled kites are also extremely stable in flight. For testing purposes, there are two sled kites, one larger and one smaller. The smaller one provides more maneuverability while the larger one affords significantly more power to the system due to its increased surface area.

Figure 3: Sled Kite used in WPI System

The generator for the current WPI system is shown in Figure 4.[8] This generator was chosen as the most efficient type after analyzing several different metrics, including ease of use, cost, power potential, and manufacturability. In more recent years, the generator was modified with a dynamometer.[9] This device applies a mechanical load to the system via friction which reduces the amount of force needed from the normal gear system.

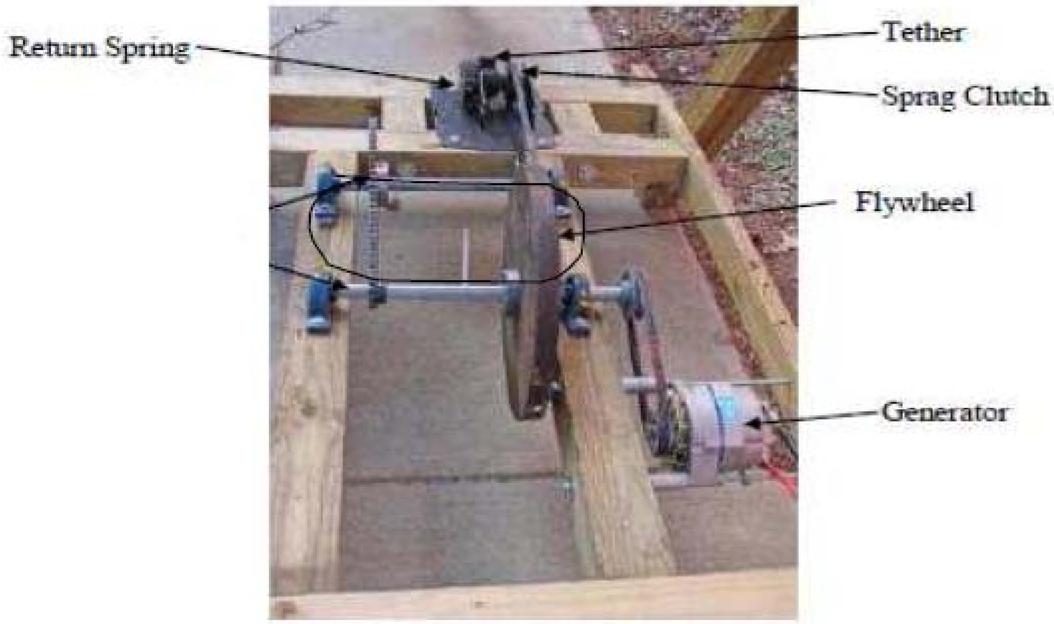

Figure 4: Generator and Flywheel on WPI Kite System

The current system can use a remote control kite system that allows for RC control of the kite from the operator on the ground.[10] To better study the system, a series of sensors were attached,[11] including:

- a force meter to determine how much force the kite is applying, this can be used to calculate lift,
- an inclinometer to determine the angular position of the sway arm,
- a shaft speed sensor to determine the speed at which the system was moving, and
- a torque meter to determine how much torque is being applied.

Measurement	Instrument	Make	Model	Cost	Photo
Force (lbs)	Load Cell	Transducer Techniques	THB-1K	$485	
Inclination (degrees)	Inclinometer	Rieker	N4	$132	
Torque (N*m)	Torquemeter	Cooper Instruments	LXT-971-17.5NM	$1395	
Shaft Speed (RPM)	Magnetic Pick-ups	Concept 2	N/A	Donated	

Figure 5: Sensors Included on WPI Kite System

There are many safety features on the kite system designed to protect the operators. These include guards over any moving or electrical parts to protect sensitive parts while the system is in motion. As well, padding was added to the rocking arm as a safeguard. Also, structural support was added to the base system in order to stabilize the system when experiencing high stresses, as well as to keep the system from tipping while in motion.

2.1 Water Pumps

A pump is a device that raises, transfers, delivers, or compresses fluids or that attenuates gasses especially by suction or pressure or both. One of the first pumps ever invented was known as the shadoof and was used in ancient Egypt. This pump was essentially a bucket on a counterweighted lever and fulcrum in order to ease the lifting of water. To begin the selection process for a pump for our project we first had to research the different types of pumps that are commercially available today. We found there are pumps for everything from moving solids to liquids to gasses. These are the pumps we examined:

- Centrifugal
- Diaphragm
- Gear or Rotary Screw
- Piston
- Flexible Impeller
- Jet
- Vertical Turbine
- Elephant
- Bush

To help classify pumps some definitions that are needed are self-priming, viscosity, and head. Self-priming pumps produce suction even when there is no liquid in the pump and therefore can be used in both gravity fed and suction lift applications. Viscosity refers to a fluids resistance to deformation. For example, water has lower viscosity while honey has higher viscosity. All of the following pumps work with low viscosity fluids, such as water. Finally, head refers to the amount of pressure a pump can operate against at a given volumetric flow rate. Head correlates to the total height a pump can displace water, but further viscous losses due to flow through a pipe are not considered.

Centrifugal pumps are the category of pumps that include one or more impeller. In many centrifugal pumps, “a rotating vanned disk attached to a drive shaft moves fluid without pulsation as it spins.”[12] These pumps can be motor driven or electrically driven, work off of a rotational motion, and have one of the higher flow rates of all pumps. The parts can be changed out for more abrasive conditions and some solids. Centrifugal Pumps work at lower pressures without a pulsating flow and can be self-priming. They have a flow rate range of 5-200,000 gallons per minute and possible head of 10-7,500 feet.[13]

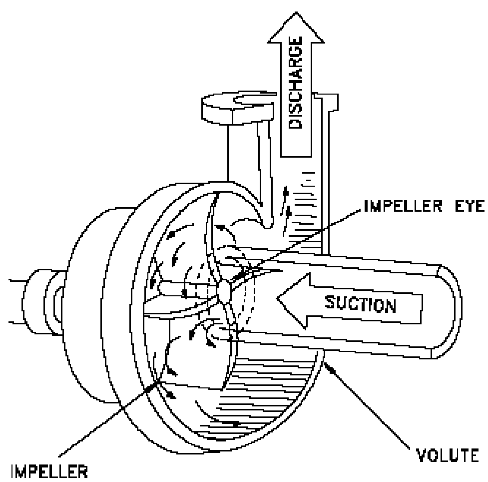

Figure 6: Centrifugal Pump[14]

Diaphragm pumps use one or two diaphragms to displace liquids or solids. These pumps are generally powered by hand or compressed air, but in some cases can be motor driven. For hand powered diaphragm pumps, a lever and fulcrum system is used to open and close the diaphragm while air powered ones use air instead of a lever and fulcrum to produce the same outcome. These pumps have a pulsating flow but are self-priming, have high flow and work at medium pressures. Diaphragm pumps work off of linear motion, have a flow rate range of 1-1,800 gallons per minute and have a total head of 25-15,000 PSI.[15]

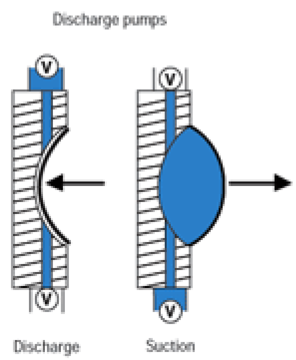

Figure 7: Discharge Pumps[16]

Gear or rotary screw pumps move liquid through two meshing gears and the casing. The moving gears create suction at the inlet port of the pump that draws fluid into the gears. These pumps are designed for high viscosity liquids, are self-priming, and have low flow. They work off of rotational motion, have flow rate ranges from 1-1,500 gallons per minute and have a total head of 10-2,500 PSI.[17]

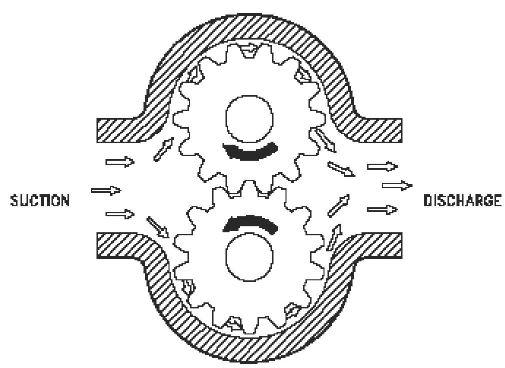

Figure 8: Gear Pump[18]

Piston pumps use double acting pistons of varying length to pump water. These pumps produce a very high pressure with low flow and are not self-priming. Also they have a pulsating flow and can be powered either electrically or hand driven. Piston pumps can either use linear or rotational motion, have flow rate ranges between 5-700 gallons per minute, and total head of 50-5,000 PSI.[19]

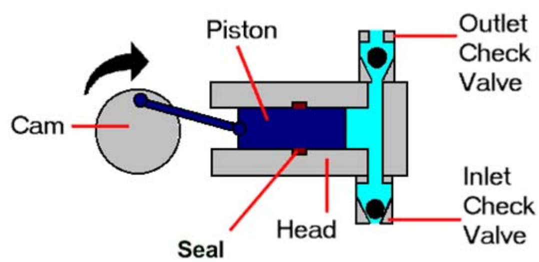

Figure 9: HPLC Pumps[20]

Flexible Impeller pumps work very similarly to centrifugal pumps but have a rotating rubber impeller with vanes that flex as they rotate in order to conform to the pump and pressures. These pumps work at low pressures, are self-priming and have a smooth, continuous flow. They can be both electrically, or motor driven, use rotational motion, have flow rate ranges of 5-150 gallons per minute and total head of 10-60 PSI.[21]

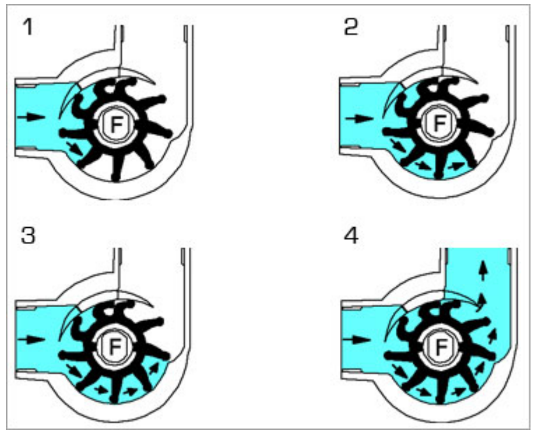

Figure 10: Flexible Impeller Pumps[22]

Jet Pumps are generally used for shallow domestic wells. They are a type of centrifugal pump that generally sit at grade level.[23] Since they are centrifugal, they have a smooth flow, are self-priming and can be motor driven, but are generally driven by an AC motor. They use rotational motion, have flow rate ranges of 1-70 gallons per minute, and a total head of 20-200 ft.

Vertical Turbine pumps are a type of centrifugal pump used for deep underground wells. They have a motor above ground, connected by a long shaft to the impellers at the bottom of the pump. “Vertical turbine pumps are usually driven by an AC electric induction motor or by a diesel engine through a right angle drive.”[24] Since they are a type of centrifugal pump, they have a smooth flow and are self-priming. They also have a high flow rate of 50-150,000 gallons per minute, a total head of 15-2,000 feet and work on a circular motion.

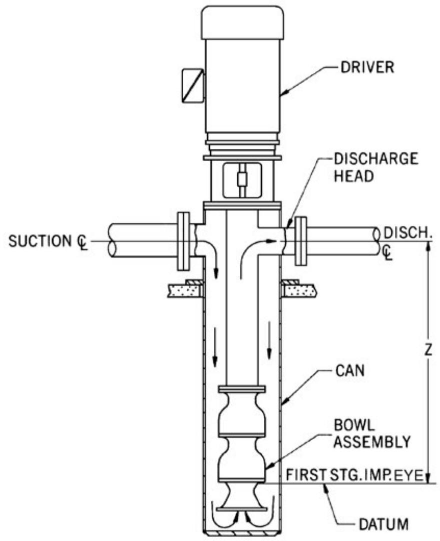

Figure 11: Vertical Turbine Pump[25]

2.2 African Pumps

Pump options in developing nations include piston, diaphragm, rope and washer, and bush pumps. A piston pump is the most widely used type of hand pump in Africa. These pumps draw water up using a cylinder and piston design. It creates a negative pressure which draws the water up out of the ground. A bush pump is a type of piston pump that can be made using local materials. Craftsmen in the area have all of the tools and equipment needed to make one of these pumps which also allows them to easily repair them as well.

A diaphragm pump, which is both commercially available and available in Africa, is best used for deep or crooked wells. The diaphragm pump works similar to the piston pump by creating a change in pressure which draws the water into the diaphragm as the volume is decreased the water is forced out of the pump. A drawback of both piston pumps and diaphragm pumps is that they are not sealed and often can contaminate the water source.

A rope and washer pump, also known as an elephant pump, can be made with recycled materials and can be made by the local craftsmen. This system is designed to be used in a well. It uses a rope with washers that create a seal inside the pipe in order to draw water up the pipe. This system uses a rotational scheme so there would be added cost to our system to implement the gears needed to translate the vertical motion of the kite into rotational motion used to move the rope through the system. A positive about this system is that it seals off the water source so that it cannot be contaminated.

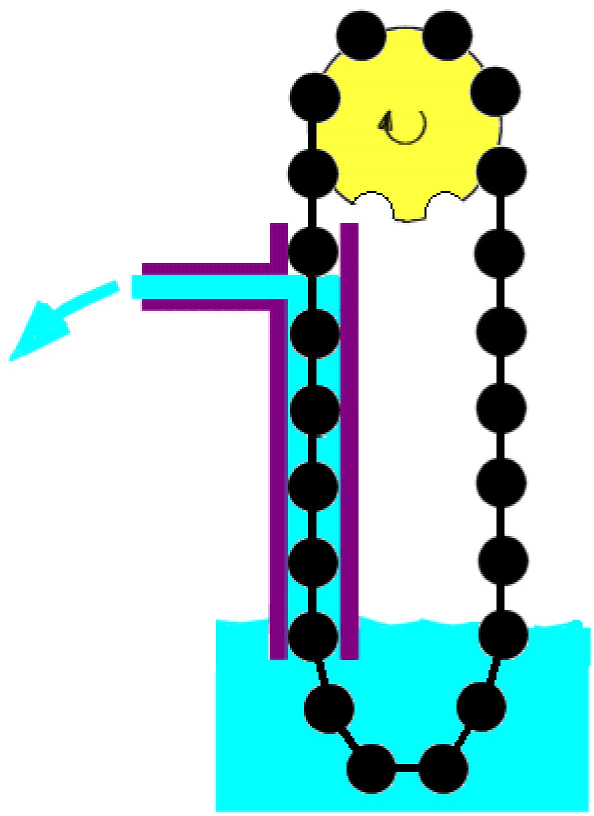

Figure 12: Elephant Pump

The Jooste Cylinder and Pump Company, founded by Christie Jooste in 1967, is a pump company in South Africa dedicated to improving on water pumps commonly used with windmills. They have been awarded for designs with stainless steel to improve both borehole pumps and “Force Cylinder” pumps that all improve upon ones formerly made with brass. All of the pumps are essentially piston pumps that either pump from deep boreholes of up to 200 meters or are surface mounted pumps.[26]

2.3 Current Systems in Africa

Here are a few examples of alternative water pump systems that are currently in use in Africa.

2.3.1 Play Pumps

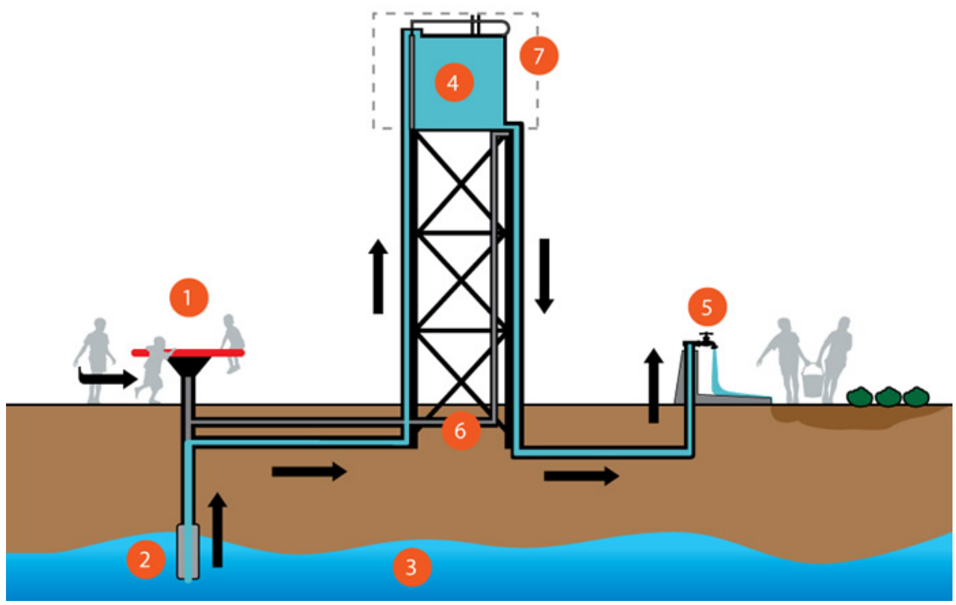

Figure 13: Diagram of Playpump[27]

Water for People is a company dedicated to sustainable drinking water resources, sanitation facilities and hygiene education programs. Water for People helps many developing countries in Africa, Asia, Central America and South America with donations from the general public. One of the systems that they use is called the PlayPump as shown in Figure 13. “While children have fun spinning on the PlayPump merry-go-round (1), clean water is pumped (2) from underground (3) into a 2,500-liter tank (4), standing seven meters above the ground. A simple tap (5) makes it easy for adults and children to draw water. Excess water is diverted from the storage tank back down into the borehole (6).”[28] PlayPump is effective up to a depth of 100 meters but is capable of producing up to 1,400 liters of water per hour at just 16 rpm from a depth of 40 meters. The system is meant to provide enough water for an average sized school in a village in Africa.

There has been some skepticism with the PlayPump system. Barefoot Economics interviewed several school teachers who received the PlayPump a year before the interview. Despite the fact that the PlayPump was installed without the school’s approval, one of the school teachers said, “Since it was installed, they have never filled the tank.”[29] The children only play on it for so long and if they are not playing on it, it is more difficult to use than a hand pump. These difficulties illustrate the need for consultation with users in the local community within developing nations before applying new technologies. An advantage of combining a kite with hand pump to pump water is that when the wind dies, a hand pump could still be pumped easily by a person.

2.3.2 Pump Aid

Pump Aid is another company that is focused on breaking the cycle of poverty through access to clean water. Based out of England, this company focuses mainly on using elephant pumps, as discussed before, in applications such as drinking water, nutrition gardens and toilets. “Communities often provide the stones, bricks or sand for building and most importantly, labour. By involving the community they feel ownership over the pump and/or the toilet and their benefits.”[30] Instead of installing the elephant pump and system for the community, Pump Aid teaches the community how to build it and maintain it which makes the pump easier to use.

2.3.3 Lifewater

Lifewater is a company similar to Pump Aid in goals and approach to the problem of access to clean water, but they use a bush pump, as discussed before, instead of an elephant pump. Also, in addition to working in Africa, they also work in Haiti. Bush pumps are simple, low cost pumps that can be built using materials manufactured in Africa. Lifewater periodically sends skilled professionals overseas to train many of the local workers. “Training includes classroom training and theory on a variety of topics such as: Hydrogeology, Business Planning, Disease Transmission and Equipment Maintenance.”[31] Lifewater is empowering African citizens to be able to maintain their equipment and increase healthy habits.

2.3.4 KickStart

Figure 14: MoneyMaker Pump[32]

KickStart is a company that is dedicated to helping millions of people out of poverty. "We develop and promote technologies that can be used by dynamic entrepreneurs to establish and run profitable small scale enterprises."[33] They are a company the focuses on giving entrepreneurs the tools to become successful. Some of their bigger products include the MoneyMaker line of pumps, a cooking oil press and a stabilized soil block press. The MoneyMaker pumps are designed for use in farms and are hand or foot powered. They are relatively low flow pumps but can be used to irrigate up to 2 acres of land.

2.4 Airborne Wind Turbines

The concept of an airborne wind turbine has been recently developed. Dave Santos was among the first to successfully test this concept. For his company KiteLab, Santos created multiple designs for airborne wind turbines including some more eccentric designs. The following section will outline some of Santos' creations which were useful in providing background information for the design of a new airborne wind turbine produced by WPI's Kite Power MQP.

Kite Motor 1 was the first design Dave Santos created while working for KiteLab. This turbine was an ultra-light soft-turbine which utilized Styrofoam blades to keep expenses and weight to a minimum. The blades, spanning a total of about 1.3 meters, were embedded with wood and bamboo for increased durability. See Figure 15 for images showing the configuration. This motor, along with most of Dave's other designs, used a very basic ground-based generator built around a bicycle. One bicycle pedal is cast in concrete while the other is pulled by the kite. This allows for the generation of power just by the swinging motion of the concrete. On Kite Motor 1's maiden voyage, the whole device, weighing only around 500 grams, was attached to a 14 square foot sled kite. The trial run only produced about 8 watts of power, however, he concluded that with a larger generator and if flown at a higher altitude, the design would be capable of producing up to 200 watts of power.

Figure 15: Kite Motor 1[34]

Dave Santos also produced other designs for airborne wind turbines, including Kite Motor 5. Kite Motor 5 was constructed of fairly common materials such as a cane, a bamboo ski-pole and a fishing rod. The turbine utilized one wing carved from recycled Styrofoam and covered in an old nylon curtain. The entire device weighed around one kilogram and produced two kilowatts of power. Figure 16 shows this system.

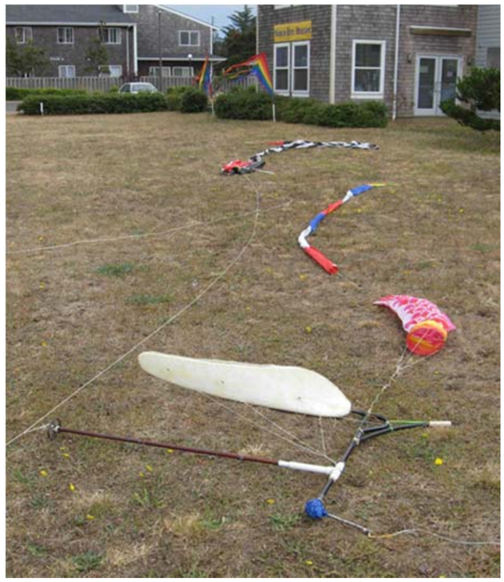

Figure 16: Kite Motor 5[35]

Another design produced by Dave Santos while working with KiteLab was Kite Motor 7. This design utilizes only the tip of a wind turbine. The asymmetric foil is 5 feet long and attached to a kite with a three point bridle. The angle of attack can be controlled to stop or reverse the turbine, which can be very useful when unwinding the connecting tether. Like the other kite motors, Kite Motor 7 also used a ground based generator. An image of Kite Motor 7 can be seen in the Figure 17 below. Researching different existing airborne turbines provided valuable background information for the development of a new design for an airborne turbine which will be discusses in great detail later in the report.[36]

Figure 17: Kite Motor 7[37]

3. Project Goals

From the previous literature review, the following project goals were defined:

Project goals of the water pump system team are to:

- Choose a mechanical water pump,
- Install mechanical water pump on existing WPI Kite Power System,
- Build a head simulation valve to be used in lab and field testing to simulate greater depth wells,
- Perform laboratory testing of the kite water pump system including the use of head simulation valve to verify system is in proper working order,
- Perform off-site testing, first in a barn owned by Professor Olinger then on a beach in Seabrook, NH, of a kite water pump system including use of head simulation valve to obtain the pump curve (head vs. flow rate) for the system,
- Modify an existing Matlab code that models the WPI Kite Power System for electrical power generation to model the water pump system.

Project goals of the wind turbine system team are to:

- Design an airborne wind turbine to be supported beneath a high altitude kite,
- Construct and install a support frame for the airborne wind turbine beneath a high altitude kite,
- Perform wind tunnel tests on the airborne wind turbine, to determine power output as a function of wind speed,
- Perform field testing of the airborne wind turbine,

4. Methodology, Kite Powered Water Pump

4.1 Choosing a Water Pump

Picking a pump is largely dependent on where the pump will be used and what the community requires. It is also important to consider the pump's power for pumping water up into a storage tank. The following table breaks down the different types of pumps discussed in the background section.

Type of Pump	Rotary	Linear	In Africa?	Flow Rate (GPM)	Total Head (ft)
Centrifugal	X			5-200,000	10-7,500
Diaphragm		X	X	1-1,800	60-35,000
Gear or Rotary Screw	X			1-1,500	25-5,500
Piston	X	X	X	5-700	115-11,500
Flexible Impeller	X			5-150	20-140l
Jet	X			1-70	20-200
Vertical Turbine	X			50-150,000	15-2,000
Bush		X	X	5-700	115-11,500
Elephant	X		X		

Table 1: Types of Pumps

In order to properly determine which pump is the best for our application we have to break down the pumps into what we need for our application. Our application refers to fulfilling the needs of a small village of about 200 people and a kite pump operating 24 hours per day or about 45 liters per person per day. Our system needs a volumetric flow rate of 7 liters per minute to fulfill this need.

4.1.1 Linear versus Rotational Motion

The first step in deciding which water pump to use is to choose between a linear or rotational motion pump. The current A-Frame is designed to provide rotational motion to a generator to create electricity. To convert the arcing motion of the A-Frame rocking arm into rotational motion there is a system of wires, belts, pulleys and gears. Also, there is a fly wheel to try and create a more consistent rotational speed. The current system loses much of the energy created by the kite and is dangerous because many of the wires and belts can break while under tension. Also, using all of this gearing creates an added cost to a system that is intended to be low cost.

Therefore, a linear motion pump is the best option for the current set up. With linear motion, there are fewer moving parts so the system is safer, has fewer efficiency losses, and is lower cost. Piston pumps are the best type of pump for our use as there are many already in use in Africa and diaphragm hand pumps tend to be used for low volumes of water.

4.1.2 Borehole versus Force Cylinder

The Bush and Jooste pumps are both linear piston pumps that can be modified for our use. Jooste makes a type of piston pump called a “Force Cylinder” that is designed so that the whole system is above ground. This design is similar to a bilge pump in that it can be transported easily to be used anywhere. Borehole pumps, comparatively, have most of the system, specifically the piston and cylinder, below ground and are fixed in one place.

One of the differences between force cylinders and borehole cylinders is the depths they can pump water from. Force cylinders “pull” water up from below while borehole pumps “push” water up from depth. At a depth of 32.2 feet it takes a perfect vacuum to “pull” water up due to the force of gravity. Since force pumps cannot reduce pressure below to a perfect vacuum, they cannot be used to pump water up from depths greater than 32.2 feet. So, as not to limit the depths we can pump from to less than 32.2 feet, a borehole pump is the best option.

4.1.3 African versus American Manufacturing

While buying American made products and supporting the American economy is important to the group, we are primarily designing the system to be used in developing countries, similar to those in Africa. Also, since developing countries have to deal with low cost water pumps more than advanced countries do, many developing countries have designed low cost pumps that are locally repairable and work very well. Pumps made and designed in developing countries use low cost materials to build a pump that can be easily and cheaply repaired locally. The Elephant Pump, for example, uses rope, pieces of discarded tires and some tubing to create an efficient, low cost pump. Also, the Jooste pumps use stainless steel and a modular design to make a low cost, low friction, easily repairable pump.

4.1.4 Final Considerations and Choice

After considering all of the options we decided to choose the Jooste AS 80 standard borehole cylinder. This is an 80 millimeter interior diameter borehole pump with a maximum stroke length of 370 millimeters. The Jooste Cylinder & Pump Company is based out of Strand, South Africa and has won several awards for South African Design Excellence, Stainless Steel use, and Quality. The design is simple compared to the Bush pump and only one company manufactures these pumps. For Bush pumps, several companies manufacture the pumps in different countries and it was difficult to get in contact with the American companies. The Jooste Cylinder &

Pump Company was very helpful with answering all of our answers, despite the language barrier.

We decided on the 80 millimeter design so that we could pump from greater depths. As the pump diameters get larger, the force needed to pump the water also gets larger. This model is a mid-sized pump from Jooste that allows us to design for varying well depths while being able to pump a greater volume of water.

4.1.5 Pump Connection

One of the problems with using a linear pump is that the rocking arm of the A-Frame does not move in a perfectly linear motion. Figure 18 shows that as the arm moves up and down there is an arcing motion that can cause binding in pump linkages if it is not accounted for.

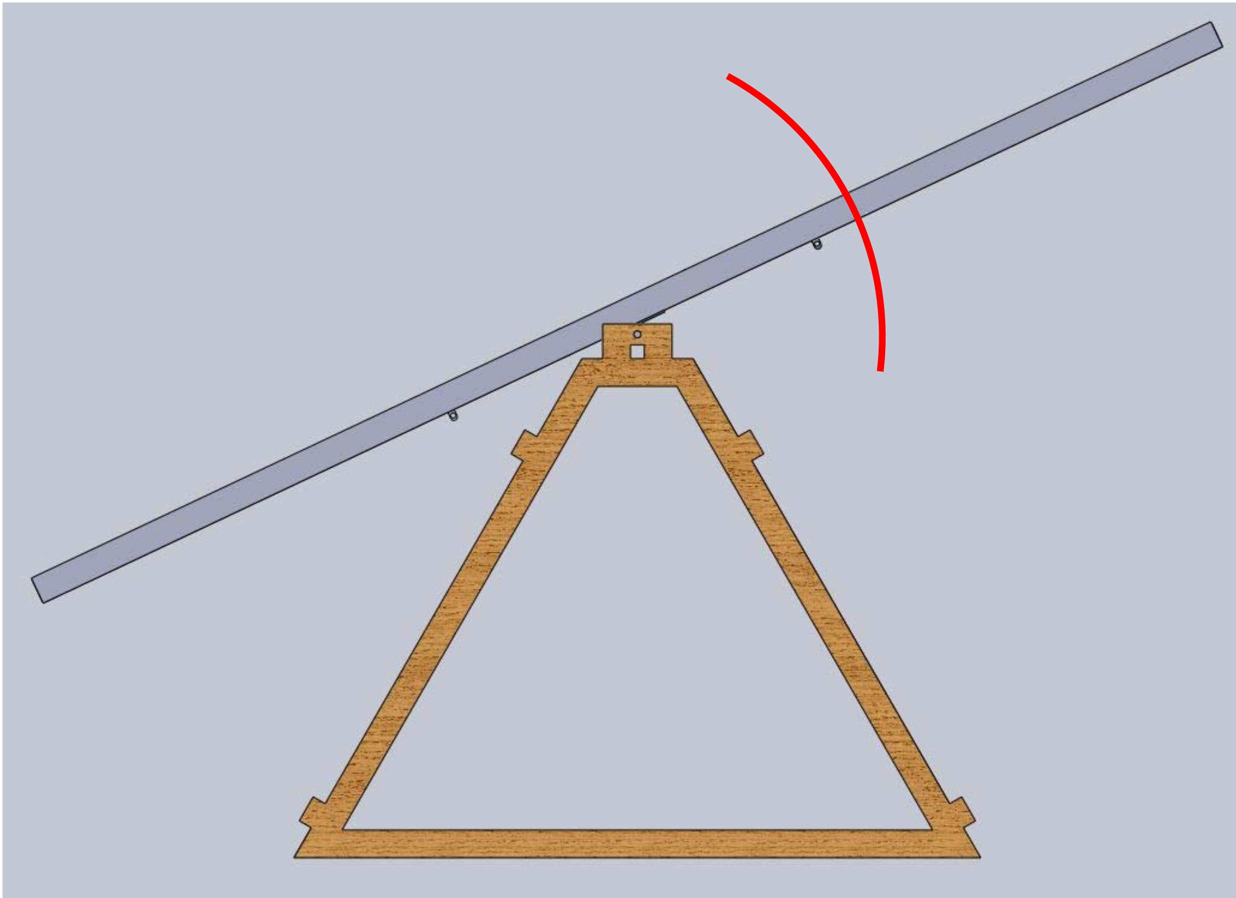

Figure 18: SolidWorks Model showing A-Frame Rocking Arm Arcing Motion

The red line shows the arcing motion. After deciding on using a borehole pump, we came up with two ideas for modifying the system to work well with the linear motion of the pump; a design similar to a pump jack and a design that features a two bar linkage to drive the water pump.

4.1.6 Pump Jack

A pump jack is a pump used for mechanically lifting liquid (usually oil) out of wells that no longer have enough bottom pressure for the liquid to flow all the way to the surface. Figure 19 shows the basic design and set up of a pump jack.

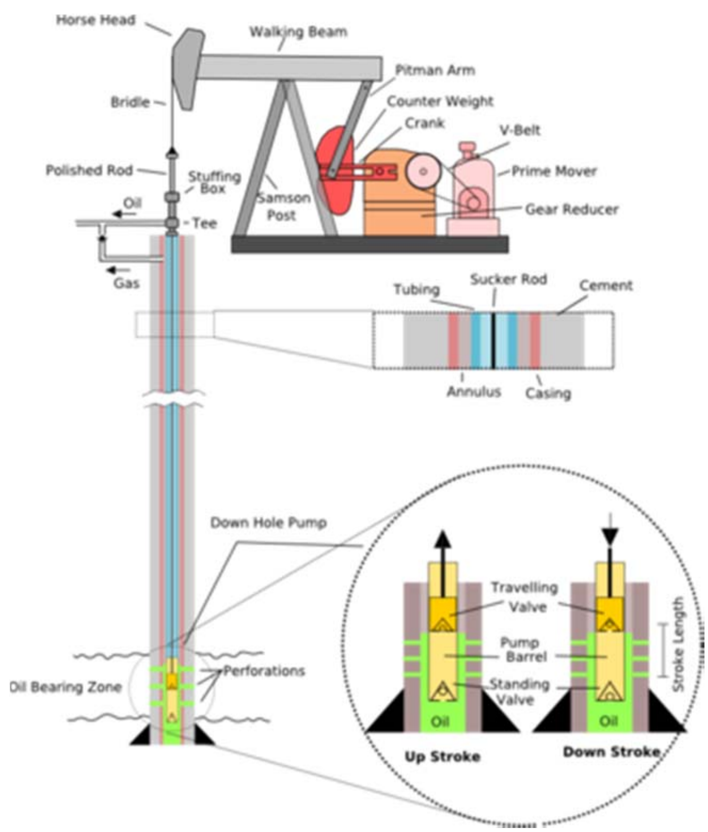

Figure 19: Diagram of Typical Pump Jack used in Commercial Wells[38]

A pump jack consists of five main components: motor, A-Frame assembly, Horse head, bridle and a borehole pump. The motor is generally electrically powered but can be gas powered in remote locations. The A-Frame assembly, which consists of a walking beam (analogous to our rocking arm) and a Samson post (analogous to our A-Frame), is driven by the motor to produce the up and down rocking motion. The horse head is a rounded part that the bridle, or thick metal wires, wraps around. This is the main part that converts the arcing motion to linear motion. As the horse head goes up the bridle wraps around it in order to keep the motion of the pump rod vertical. When the horse head goes down the bridle unwraps and is stiff enough to translate the force down as if it were a solid rod.

While the pump jack design works for large scale oil wells, there are some issues in modifying it for use in our system. First, we would have to manufacture the horse head and find a way to attach it to the rocking arm. Manufacturing the horse head would be expensive and time consuming as we would have to calculate the arc and build several different horse heads for different positions along the length of the rocking arm.

Second, the metal wires used to wrap around the horse head would have to be bought. We would also have to calculate the stiffness of the wires to properly fit our system. We did not attempt to calculate the stiffness because we were not sure if it would even work at this small of a scale.

Also, most pump jacks have a lubrication system that keeps the system from binding. Even with the lubrication there is still rubbing that causes the replacement of several parts annually. This would be another aspect of the pump jack that we would have to manufacture or buy. Also, the replacement of parts annually would not fit our goal of a low cost, low maintenance system.

Finally, using a pump jack design concept, we would have to change it for different types of pumps as well as different depths of wells. Also, the pump jack concept cannot be modified for other hand pumps easily because it can only be used for borehole pumps without a hand pump attachment.

4.1.7 Our Design

The concept that we used is shown in Figure 20.

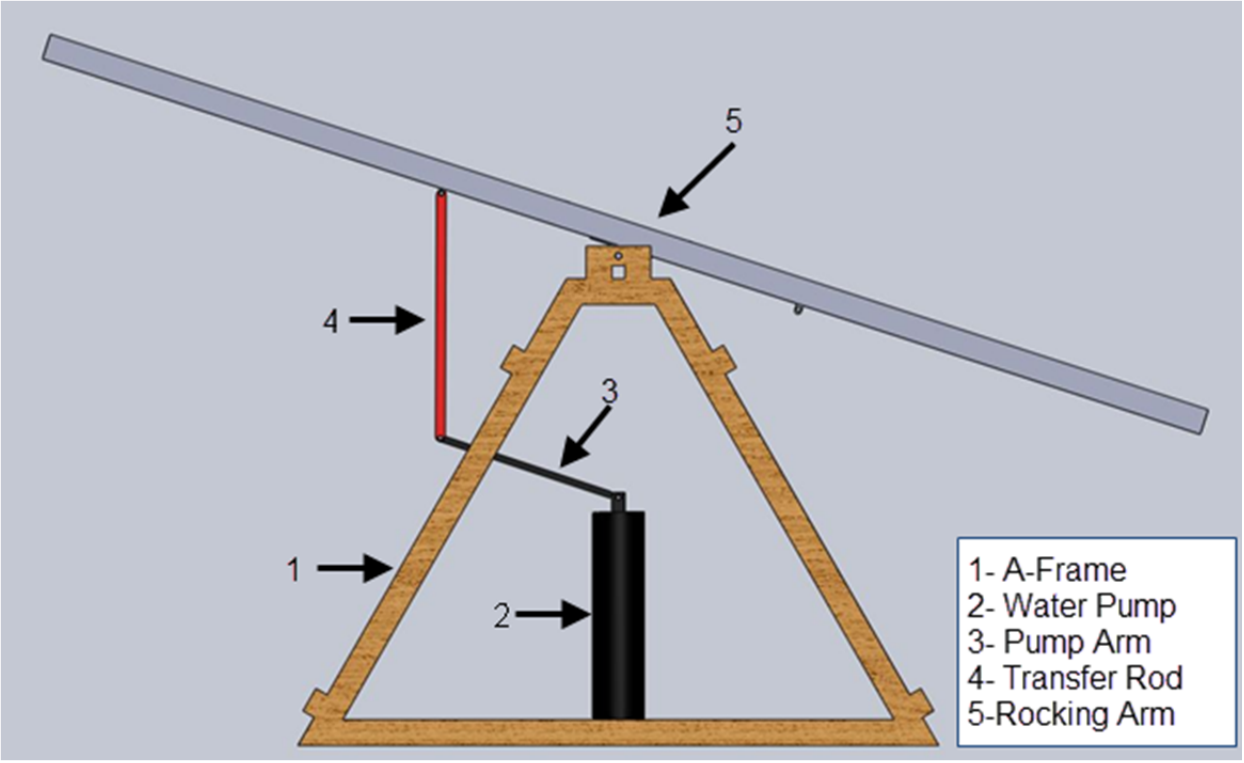

Figure 20: SolidWorks Model of Linkage Design

The transfer rod (4) connects the pump arm to the rocking arm. At either end of the transfer rod there is a swivel point that allows the transfer rod to stay nearly vertical and never bind. The length and attachment point (to 5) of the transfer rod can be adjusted for stroke length and to optimize pumping performance at different wind conditions.

Our design is simpler than the pump jack concept for several reasons. It is cheaper and easier to manufacture than the pump jack because all that needs to be manufactured are the transfer rod and swivel points. Also, our design can be easily modified for any hand pump that is already in use in any village. Also for testing purposes, this design can be adjustable with several different swivel points on the rocking arm and pumping arm in order to maximize the volume of water pumped for different well depths or wind conditions. With this design, along with the Jooste Pump we need to buy the hand pump attachment, since the standard Jooste borehole cylinder does not include the pump arm.

4.2 Installing the Pump

The Jooste Hand Pump and Cylinder were delivered with an additional part, called a base flange or toe plate, in order to hold the hand pump up while allowing the piping to go through, shown in Figure 21. The Base Flange allowed for very easy installation of the pump.

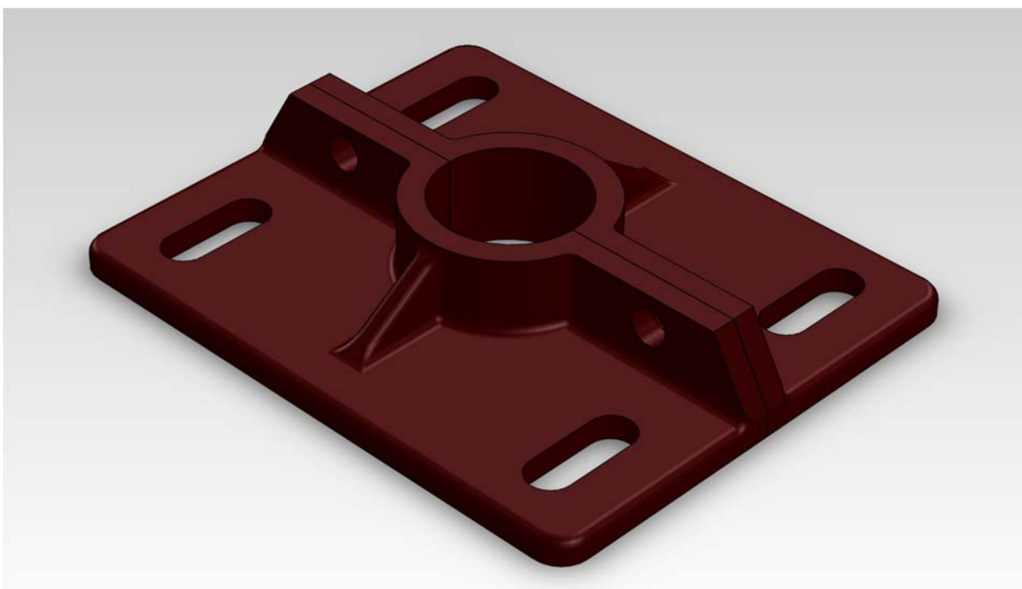

Figure 21: Solidworks Model of Base Flange from Jooste

First, however, all the necessary parts to connect the hand pump to the cylinder had to be obtained. The hand pump could accept a 1 ½ inch pipe, while the cylinder accepted a 2 inch pipe. In order to be able to adapt to several different test scenarios, four 2 foot sections and one 1 foot section of 2 inch pipe were obtained along with several adaptors to convert 2 inch piping to 1 ½ inch piping where necessary. All of the materials can be found in table XXX. Also, in order to move the plunger through the cylinder, a threaded rod must go through the piping between the hand pump and cylinder. The hand pump had a threaded rod of size 7/16-14 while the cylinder had a threaded rod of size M16x2.0. Because M16x2.0 threaded rod was not readily available we obtained two 3 foot sections of 7/16-14 threaded rod and several couplers to attach the rods to each other. When it came to attaching the 7/16-14 threaded rod to the M16x2.0 threaded rod we could not find a coupler readily available so we had to manufacture one out of aluminum stock.

Material	Amount
PIPING	
2inx2ft pipe	4
2inx1ft pipe	1
2in pipe coupler	3
2in-1.5 in coupler	1
1inx3in nipple	1
2inx3in nipple	1
THREADED RODS	
7/16-14x3ft	2
7/16-14 Coupler	1
7/14-14 x M16x2.0 Coupler	1

Table 2: Bill of Materials for Pump Installation

Next, the pump had to be connected to the A-Frame. Through previous Kite Power MQP's, a framework was developed near the base of the A-Frame to hold the equipment necessary for power generation. First, all of those components were removed so as not to damage them with water. Next the framework had to be modified slightly. Figure 22 shows a basic sketch of how the framework was before it was modified and after the modification. The 4inx4in beam (highlighted in red) was added so that the pump would be centered under the swing arm. There is about 3 inches of space in between the two 4inx4in beams to allow for plenty of space for the 2 inch pipe to fit through. Also, the Plexiglas attached to one side of the A- frame was removed to allow for the pump arm to move freely outside of the interior frame of the A-frame.

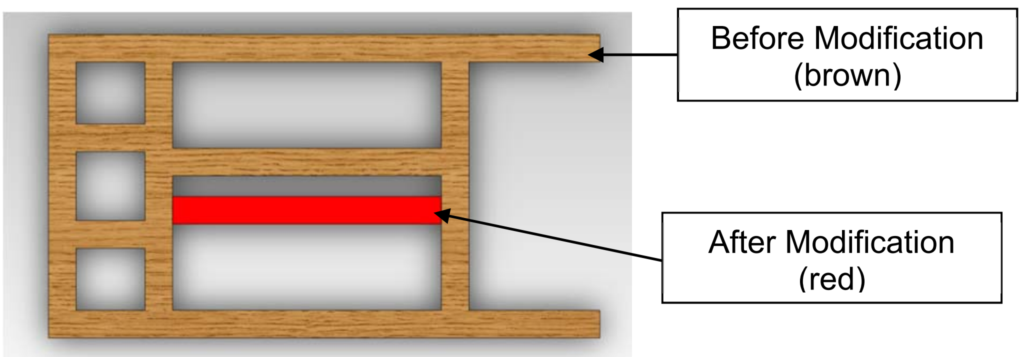

Figure 22: Structural Changes to A-Frame of Existing WPI Kite System

After the frame was modified, the pump was attached to the A-Frame. This was done by bolting one half of the base flange to each 4inx4in beam such that the swivel point of the pump was approximately centered under the swivel point of the A-Frame. Since there was a cement floor underneath the A-frame while the pump was being installed on the A-frame, the cylinder could not be connected. It is a simple process to add the cylinder, though; simply attach the proper amount of piping and threaded rods to the bottom of the pump and attach the cylinder to the bottom of that. Initially, the pump was set up with a spigot, instead of the head simulation valve, as an output so that water could easily be diverted using a water hose. Figures 23-24 show the pump after being attached to the A-Frame.

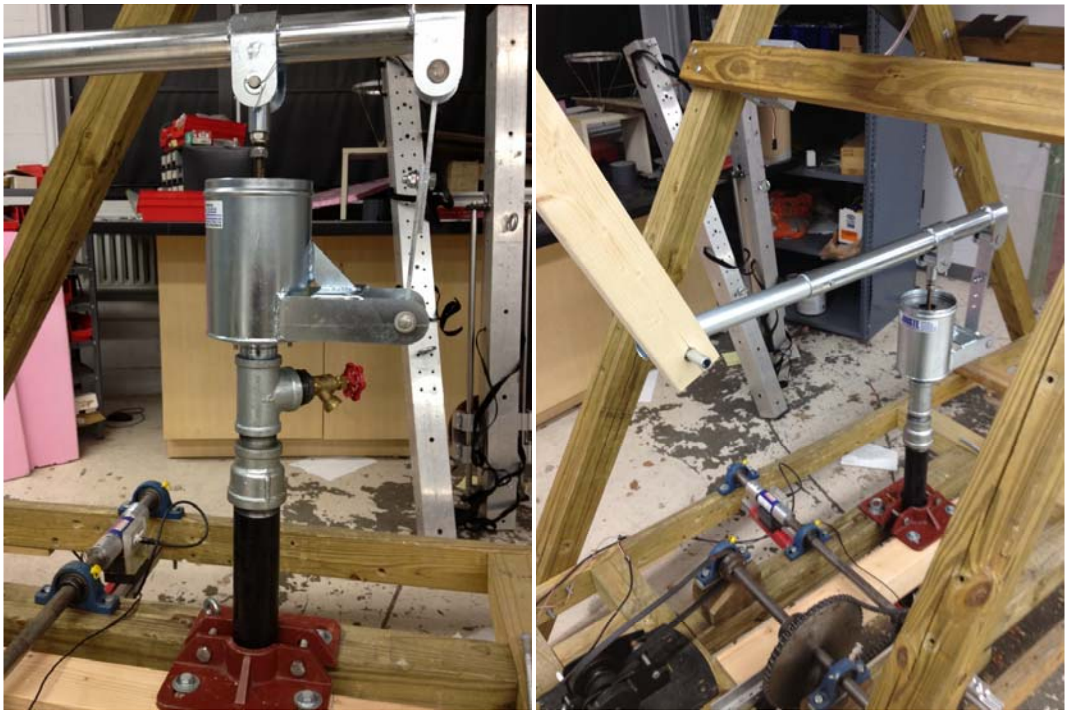

Figure 23: Pump Attached to A-Frame (Left) and Attached to Swing Arm (Right)

Note: electrical generation equipment seen in photos was removed to accommodate pump system.

Figure 24: Pump Installed on A-Frame and Connected to Swing Arm

Finally, in order to transfer power from the swing arm to the pump arm two 2x4's were used as a simple and quick way for attachment. Holes were drilled in order for the 2x4 to slide over the handle of the pump and in order for the other end of the 2x4 to be bolted to the swing arm. In future projects, a more durable transfer rod should be designed.

4.3 Head Simulation Valve

Due to the space constraints in the WPI Fluid Dynamics Lab (Higgins Lab 016), we needed to find a way to simulate a deep well. The Fluid Dynamics Lab has a sub-basement with a vertical depth of approximately 5 feet, thus without adding additional devices to simulate a deeper well, we would be restricted this very low depth. To achieve a deeper well we decided to build a head simulation valve. The design we used is based on work by students at Messiah College.[39] The head simulation valve is a series of piping that attaches to the pump cylinder. Inside of this piping, there is an adjustable valve that allows an opening to be restricted to different amounts. In this way, we are able to restrict the flow of water through the pump, and increase the pressure, simulating the necessary head that we need in our tests.

Simpler devices are possible to add an additional pressure head to the system to simulate a deeper well, for example a simple length of pipe or garden hose attached to the pump exit. However, these simple devices add a pressure head which is dependent on volume flow rate of water through the device. The head simulation valve is essentially a spring-loaded valve that applies a fixed pressure head at varying flow rates. The applied pressure head can also be easily adjusted by changing the spring force in the valve.

Figure 25: Completed Head Simulation

We chose the dimensions of the valve so that it will fit the pump cylinder. The port attaching the simulation valve to the cylinder is two inches in diameter, matching that of the pump cylinder. It is important that these are the same to reduce losses that would occur when changing sizes of the cylinders.

We made some modifications to their design to better fit the team's needs. For example we changed the way the spring is attached to the valve inside the cylinder, and also made the hole where the threaded rod passes through the cap threaded to help prevent leaking and maintain pressure. For more detail on the modifications, see Appendix.

A full list of parts and assembly instructions from Messiah College are detailed in Appendix A. Appendix B is our method for building the head simulation valve with our improvements to the system, based heavily off of the Messiah College device.

4.4 Simulation

A simulation of the kite powered water pump system was developed in Matlab by modifying code from previous research at WPI.[40]

4.4.1 Previous Work

Several governing equations were developed in a previous study by David J. Olinger and Jitendra. S. Goela to find the performance characteristics of a small scale kite-powered system.[41]

This study focused on generating electricity using the kite power system and was adapted for this MQP to be able to simulate pumping water with the kite power system.

First, the governing equations for the kite dynamics were derived. Taking moments of the kite drag, lift, and weight about point A (point at the end of the rocking arm), and dividing by the tether length yield:

$$\frac{W_K}{g}\frac{dV_{2A}}{dt} - \frac{2W_K V_{1A} V_{2A}}{gL_t} = F_{DK}\sin(\theta+\phi) - F_{LK}\cos(\theta+\phi) + W_K\cos\theta \quad (1)$$

Where W_K is the weight of the kite, the kite moves with a velocity V_K at angle β with respect to the ground, and the relative or local velocity V_R at an angle of φ with respect to the ground results from a combination of the kite motion and the horizontal wind velocity. The kite tether is oriented at angle θ with respect to the ground. The lift and drag forces, F_{LK} and F_{DK} respectively, are oriented perpendicular and parallel to the V_R vector, respectively. The force on the tether, F_t, is considered constant along the tether length since tether transmission losses due to tether profile are being neglected. The velocities V_1 and V_{1A} represent the kite velocities along the kite tether direction with respect to the stationary ground and point A (end of rocking arm) respectively. Also, the velocities V_2 and V_{2A} represent the kite velocities normal to the kite tether with respect to the stationary ground and point A, respectively. Figure 26 shows a diagram defining all of the variables.

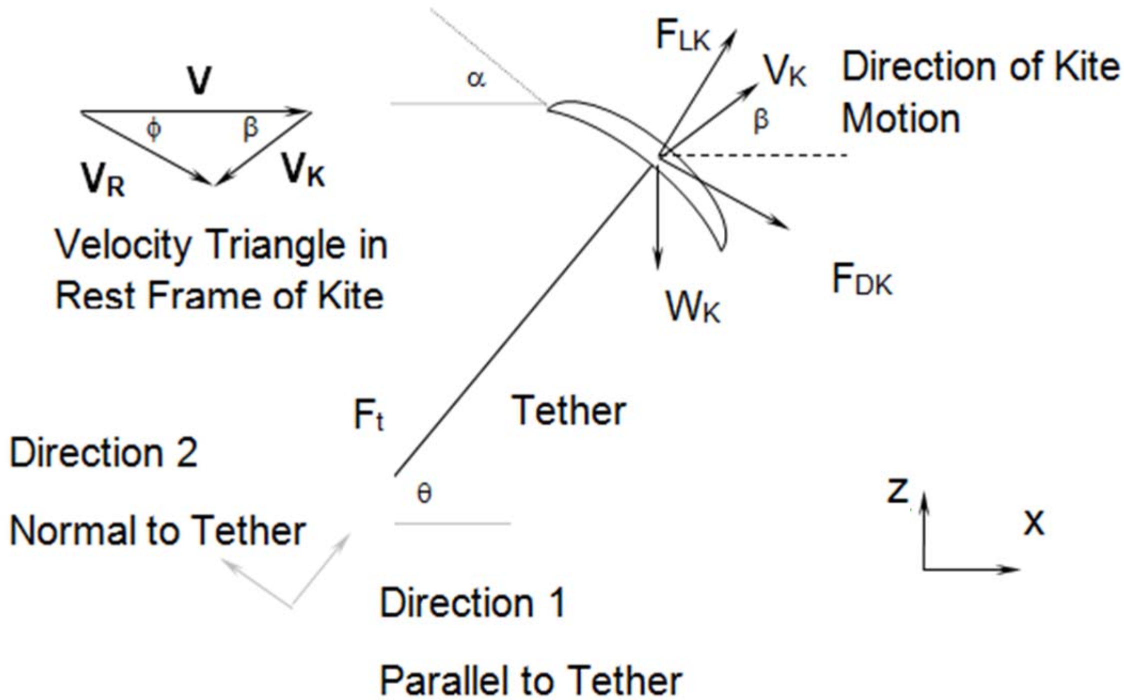

Figure 26: Parameter Definitions for the Kite and Tether

Then taking a force balance along the tether yields:

$$\frac{W_K}{g}\frac{dV_{1A}}{dt} = F_{DK}\cos(\theta+\phi) + F_{LK}\sin(\theta+\phi) - W_K\sin\theta + \frac{W_K V_{2A}^2}{gL_t} - F_t \tag{2}$$

In Equation 2, the tether's moment of inertia, lift and drag are neglected. The coriolis term in equation 1 and inertia term in equation 2 drops out since the tether length L_t is constant so that V_{1A}=0. Therefore, equation 2 simplifies to:

$$F_t = F_{DK}\cos(\theta+\phi) + F_{LK}\sin(\theta+\phi) - W_K\sin\theta + \frac{W_K V_{2A}^2}{gL_t} \tag{3}$$

The kite lift and drag forces, F_{LK}, F_{DK} are calculated assuming that the kite is modeled as a finite length wing (in the span wise direction) with a thin airfoil section.

Assuming a linear lift coefficient curve (below airfoil stall angle), the lift coefficient is given by

$$C_L = \frac{a_0}{1 + \frac{a_0}{\pi (AR)}} (\alpha_{eff} - \alpha_{L=0}) \tag{4}$$

Where $\alpha_{L=0}$ is the angle of attack at which zero lift occurs on the kite.

The kite drag coefficient is calculated using:

$$C_D = C_{D0} + \frac{C_L^2}{\pi (AR) e_0} \tag{5}$$

From finite wing theory, where C_{D0} is a parasitic drag coefficient that introduces viscous effects into the drag calculation, and e_0 is an Oswald efficiency factor that accounts for drag-due-to-lift effects and wing tip vortex effects from non-elliptic shaped wings. The lift-to-drag ratio, L/D, which also varies with time during the kite motion is given by C_L/C_D.

The time-varying lift and drag on the kite are then given by

$$F_{LK} = \frac{1}{2} \rho V_R^2 C_L A_K \tag{6}$$

And

$$F_{DK} = \frac{1}{2} \rho V_R^2 C_D A_K \tag{7}$$

In addition, the differential equation below is required to find the kite tether angle

$$\frac{d\theta}{dt} = -\frac{V_{2A}}{L_t} \tag{8}$$

To model the motion of the rocking arm, a moment balance about the pivot point is applied:

$$I_{AD}\frac{d\omega}{dt} = \sum M_B = F_t R_A \cos(\gamma - \theta + \pi/2) - F_C R_C - K\Delta x R_C - W_{BA}\frac{R_A}{2}\cos(\gamma) + W_{DB}\frac{R_D}{2}\cos(\gamma) - W_{CTR}R_{CTR}\cos(\gamma) \tag{9}$$

This is adjusted for the water pump case to:

$$I_{AD}R_A\frac{dV_A}{dt} = F_t R_A \cos\left(\gamma - \theta + \frac{\pi}{2}\right) - F_C R_C - W_{BA}\frac{R_A}{2}\cos(\gamma) + W_{DB}\frac{R_D}{2}\cos(\gamma) - W_{CTR}R_{CTR}\cos(\gamma) \tag{10}$$

Where V_A is the velocity of the rocking arm end, I_{AD} is the moment of inertia of the rocking arm, R_A is the half-length of the rocking arm, γ is the angle of the rocking arm, W_{BA} is the weight of the rocking arm from pivot to point A, W_{DB} is the weight of the rocking arm from pivot to point D (opposite end of point A), and W_{CTR} and R_{CTR} are the weight and radius of the counterweight respectively.

In addition, the following kinematic equation is required:

$$\frac{d\gamma}{dt} = -\frac{V_A}{R_A} \tag{11}$$

Equations 1, 8, 10 and 11 are the four first-order differential equations describing the motion of the kite, tether and rocking arm.

The initial conditions for the three first-order differential equations at t=0 are VA=0, V2A=0, and γ=-15 deg. The differential equations are solved for VA, V2A, γ, and θ as functions of time using a Runge-Kutta scheme in a MATLAB algorithm. Once the four primary variables are determined at each time step (with Δt=0.002 s) the other important system parameters could be calculated, such as the parameters dealing with the motion of the kite.

4.4.2 Modifications to Simulation

During this MQP new equations were developed in order to change the previous simulation to model a water pump. After the initial design was complete, angles had to be calculated in order to find the resultant angle of the pump arm and the linkage with respect to horizontal from the swing arm angle. The problem was simplified to a quadrilateral, where the lengths of all four sides were known and one angle was known as shown in the figure below.

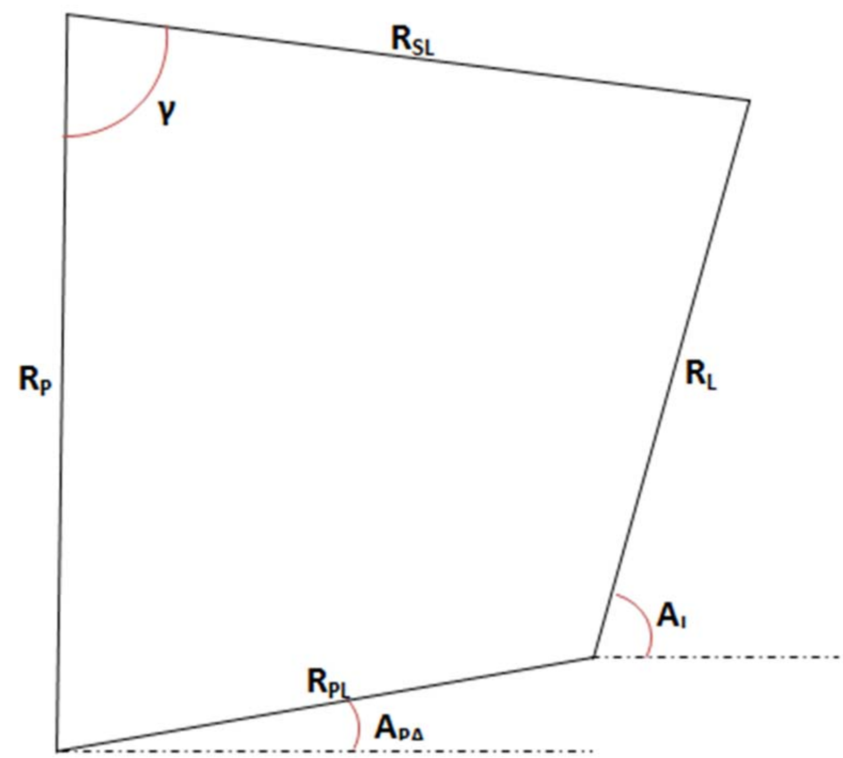

Figure 27: Simplified Quadrilateral to find Pump Arm and Linkage Angles

Here R_{SL} is the length from the swing arm pivot to the linkage (along the swing arm), R_L is the length of the linkage, R_{PL} is the length from the pump arm pivot to the linkage (along the pump arm), R_P is the vertical distance between the pivots of the pump arm and swing arm. A_{PA} and A_L are the pump arm angle with respect to the horizontal, and the linkage angle with respect to horizontal, respectively. A_{PA} and A_L are both unknowns, however, breaking the quadrilateral into two triangles and using the law of sines and law of cosines they can be found. First the law of sines and law of cosines (shown below) were used to calculate all interior angles:

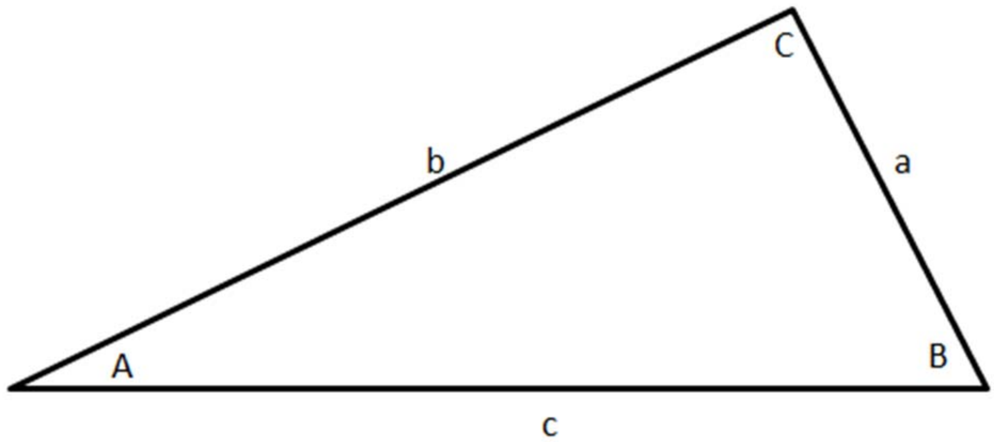

Figure 28: Labeled Triangle for Law of Sines and Cosines

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C} \tag{12}$$

$$a^2 = b^2 + c^2 - 2bc\cos A \tag{13}$$

After all of the interior angles were found, A_{PA} and A_L can be found using simple trigonometry to be:

$$A_{PA} = 90° - \left[\sin^{-1}\left(\frac{R_{SL}}{C}\right)\sin(\gamma + 90°) + \sin^{-1}\left(\frac{R_L}{C}\right)\sin\alpha\right] \tag{14}$$

$$A_L = 180° - \alpha + \gamma \tag{15}$$

where

$$C = \sqrt{R_p^2 + R_c^2 - 2(R_p R_c)\cos(\gamma + 90°)} \quad (16)$$

$$\alpha = \cos^{-1}\left(\frac{R_{PL}^2 + R_L^2 - C^2}{2R_{PL}R_L}\right) \quad (17)$$

Next the force and the velocity at the pump rod (translating to the pump cylinder) and at the linkage were calculated to help verify the strength of materials needed at those locations and the amount of water being pumped. The normal kite force, F_{KN}, on the swing arm was already calculated in the previous MATLAB simulation. Therefore, the following equations could be derived using basic physics to calculate the forces throughout the Kite Water Pump System:

$$F_L = \frac{R_{SL} F_{KN}}{R_A \sin(A_L - \gamma)} \quad (18)$$

where F_L is the force through the linkage and R_A is the half-length of the rocking arm, as defined in previous work.

Next, the Pump Rod force, F_{PR}, was calculated:

$$F_{PR} = \frac{R_{PR} F_{PLN}}{R_{PL}\cos(A_{PA})} \quad (19)$$

where R_{PL} is the distance from the pivot of the pump arm to the pump rod along the pump arm, and F_{PLN} is the normal force of the linkage with respect to the pump arm and is defined as:

$$F_{PLN} = F_L \cos(\gamma - A_L + 90°) \quad (20)$$

Next, the velocities were calculated using very similar equations, however slightly modified for velocities to find the velocity of the pump rod, V_{PR}:

$$V_{PR} = \frac{R_{PR}}{R_{PL}} V_L \cos(A_{PA} - A_L + 90°) \quad (21)$$

And V_L is the velocity along the linkage, defined as:

$$V_L = \frac{R_{SL}\omega}{\sin(A_L - \gamma)} \tag{22}$$

where ω is the angular velocity of the rocking arm as defined in the previous work.

Finally, the load on the system from the action of pumping water was analyzed. The load when the plunger of the pump is being pulled up, W_{UP}, and down, W_{DOWN}, are defined as:

$$W_{UP} = \rho_{H_20} g H \frac{\pi}{4} D_{Well}^2 + P_{static} \tag{23}$$

$$W_{DOWN} = -P_{static} \tag{24}$$

where ρ_{H2O} is the density of water, g is gravity, H is the depth of the well and P_{static} is the static pump force, or the force produced with no water. The normal force of the linkage on the rocking arm is given by;

$$F_C = F_{PLN} \sin(A_L - \gamma) \tag{25}$$

where FC is the normal force on the rocking arm applied by the linkage. The FC force is used in equation (10) above to couple the pump analysis into the solution of the four differential equations (1), (8), (10), and (11).

5. Design of Airborne Wind Turbine

It was important to consider many factors when selecting the airborne turbine design. The first consideration was the style of the turbine. Basic designs were reviewed for use of both horizontal and vertical axis wind turbines. The final decision was that a vertical axis wind turbine would be more practical to attach to a support frame suspended from the kite. With the vertical axis style wind turbine that was selected, the actual axis of rotation could be rotated to better fit different designs. This design would also be more efficient for capturing wind from any direction.

5.1 Design Concepts

The designing of the structure to secure the turbine onto the kite went through multiple stages of development before the final design was chosen. This was largely because of the need to adapt the design to the type of turbine. There was little research available to serve as guidance because this type of idea is unique to the project and not constructed for commercial purposes. Because this type of attachment is not being produced elsewhere we went through many iterations before finalizing this design.

5.1.1 Alternative Design 1: Pinwheel

Our first design we considered was to adapt the turbine to act like a pinwheel kite. The idea was to fit a turbine, see Figure 29, directly in front of the kite so that the air passing through the turbine will still hit the kite. We did not want extra drag on the system from a bulky support frame. One factor that made this idea attractive was the direction of the wind would always be perpendicular to the horizontal axis wind turbine

(HAWT) and that we would not need to change its angle or direction to achieve full power.

Figure 29: The Honeywell Turbine that Would be Placed in Front our Sled Kite[42]

The difficulties we ran into were how to fit the turbine in front of the kite in such a way that it would be structurally stable, and whether or not the drag and the turbulence created behind the blades would cause the kite to malfunction and lose lift, even in strong winds. The turbulence is the reason why wind farms have such distance between turbines, because there is a loss of energy that the turbine behind needs to operate at optimal efficiency, see Figure 34. Although this design is great with recreational kites, there were too many negative issues associated with it, causing us to scrap the plan altogether.[43]

Figure 30: Turbulence Behind HAWT Horns Rev 1 Offshore Wind Turbines

5.1.2 Alternative Designs 2 & 3: L-Shaped HAWT and VAWT

The second and third designs considered were to suspend the turbine below the kite tether. The plan was to attach the turbine to a fixed point on the kite tether with nylon string, and further down the tether use another fixed point to attach a retractable arm. The reason for the retractable arm is to allow the user to control the angle of the turbine to the direction of the wind. For optimal efficiency, the turbine has to be facing perpendicular to the direction of the wind. If we were to use a HAWT, this would provide extra difficulties because of the need to attach a generator on the same axis as the retractable arm. This problem lead us to use replace the HAWT, with a vertical axis wind turbine (VAWT) but with the same retractable arm idea (Figure 31).

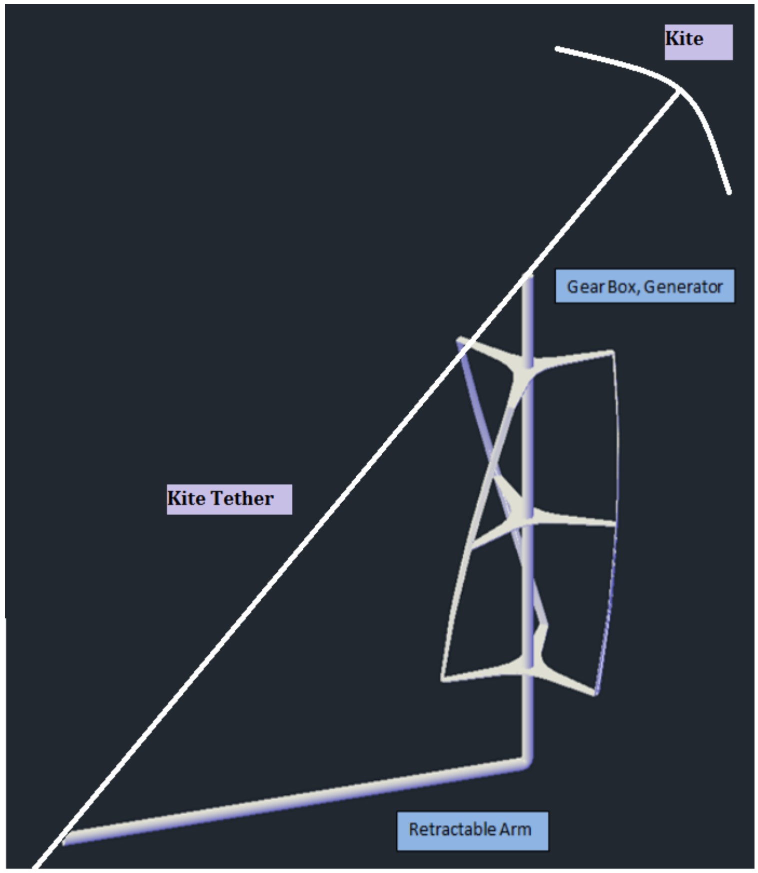

Figure 31: L-Shaped Concept with VAWT and Retractable Arm

The VAWT has a generator at its base easily attachable to the retractable arm or the top of the turbine. This plan, however, had many shortcomings, the first one being the plan for two fixed points along the tether. If we take this to be the hypotenuse of a right triangle, then the arm will be the shortest the higher the kite flies. This becomes a problem as the kite loses sufficient lift and descents to a smaller angle (with respect to the ground). As this occurs, the arm has to extend further and further to keep the turbine at a 90 degree angle to the wind, but since it is at a fixed point to the tether, the arm ends up interfering with flow of air in front of the turbine. Not only that, but because of these angle changes, the turbine would have to hang far enough out so that the upper portion of the blades do not hit the tether, and the retractable arm has to be placed far enough below so that the bottom portion of the blades do not hit it as well. Not only are we now adding more electrical components to a turbine that is supposed to generate electricity, but now the mechanism is becoming too large and the drag forces and weight might become too much for the kite to handle, thus we moved on to Design 4.

5.1.3 Design 4: The Closed-U Frame

As we abandoned the L-Shaped designs, we wanted to keep the VAWT because it would be easier to adapt to our needs. Since VAWTs are omni-directional, they can capture wind in any direction perpendicular to it, we came up with the idea of turning the turbine on its side. This is not typically done because VAWTs have their gearbox placed at the base of the turbine, allowing for easier maintenance. By placing the turbine on its side, it would not only capture the optimal amount of wind, but would allow us to build a structure around it with no electronic control parts, and that can be easily modifiable if the turbine is ever changed. The design chosen is shown in Figure 32. We came up with a box because it is simple and easy to construct. PVC pipe was chosen for most of the support frame because of its tensile strength, flexibility, low cost, and light weight. Since the turbine itself was only going to weight around 5 lbs, the support frame was designed to be as light weight as possible while still providing structural stability.

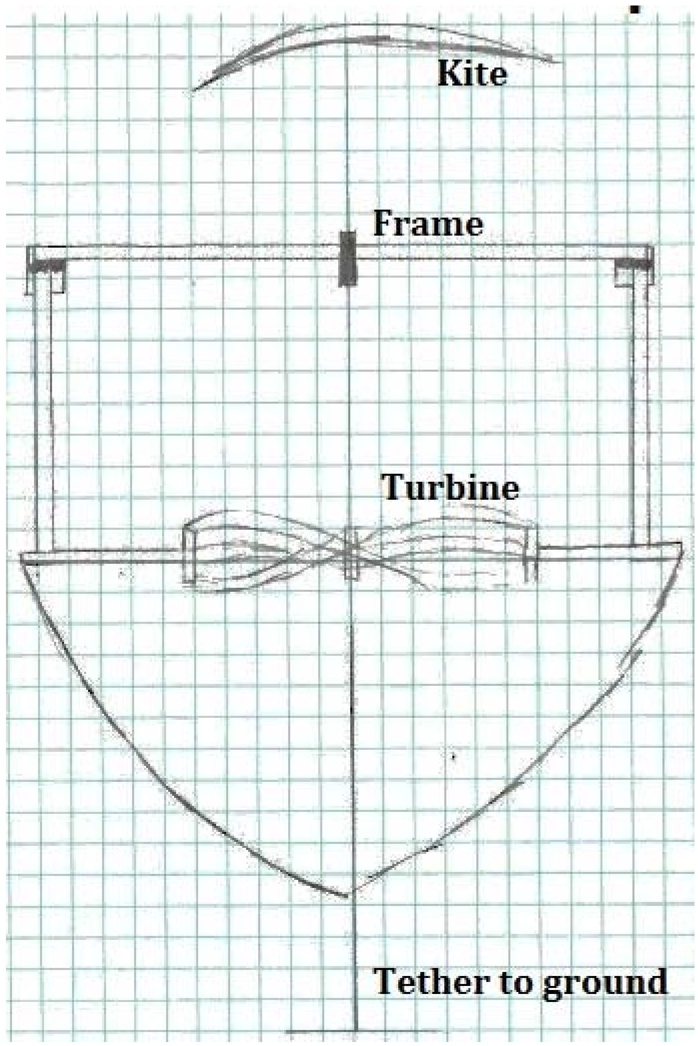

Figure 32: Closed U-Frame Design

The trouble that we ran into was how to attach it to the tether to provide enough strength to hold the turbine. The concept that we developed that would provide enough strength to the system is two metal plates would sandwich the kite tether and be tightened by wing nut bolts both above and below the string. This would ensure that the system will not fall in the middle of flight, and the friction between the plates and the sting would ensure that it would not slide up or down the string. Now that the unit is secure to the tether, and to keep with the box design, a hole would be drilled in the metal plates to allow the top horizontal bar of the box to be placed. For added strength and to ensure that the bar would not slide or rotate, on each sides of the plate two PVC bars would be placed perpendicular with a bolt running through both them and the horizontal top bar. With all of these factors in place, the last issue that needed addressing is the angle of the kite and how that would affect the turbine hanging. As the angle changed, we needed a way to have the turbine still hang down (to a certain degree). Thaw we came up with is attaching simple door hinges to the ends. This would allow the turbine to be able to not only hang down due to gravity as the angle of the kite to the ground changed, but since the turbine is omnidirectional, the wind can push the turbine back and it would still capture the same amount of wind as if it were hanging completely down. To prevent it from blowing back too much and thus creating a swinging motion if the wind was sporadic, we attached two kite strings to the ends and attached the other end to the kite string, shown in Figure 33.

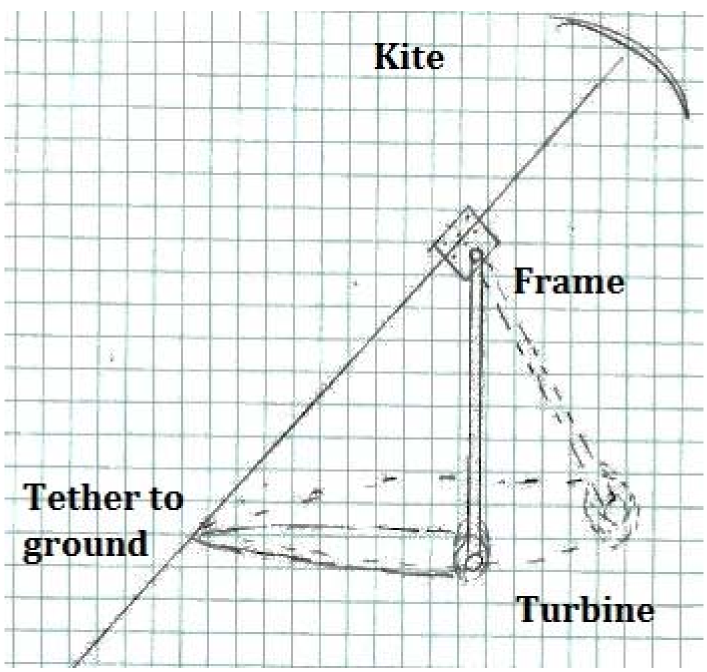

Figure 33: Closed-U Design Side View

5.1.4 Final Design 5: The Yoke

Progressing further, we saw that if we kept this box design, there might be too many torque forces on the long horizontal bars, causing not only the unit to sway and possibly unstable, but could affect the kites performance. As a result, a modification was needed to decrease these possible torque factors. The design we came up with is shown in Figure 34.

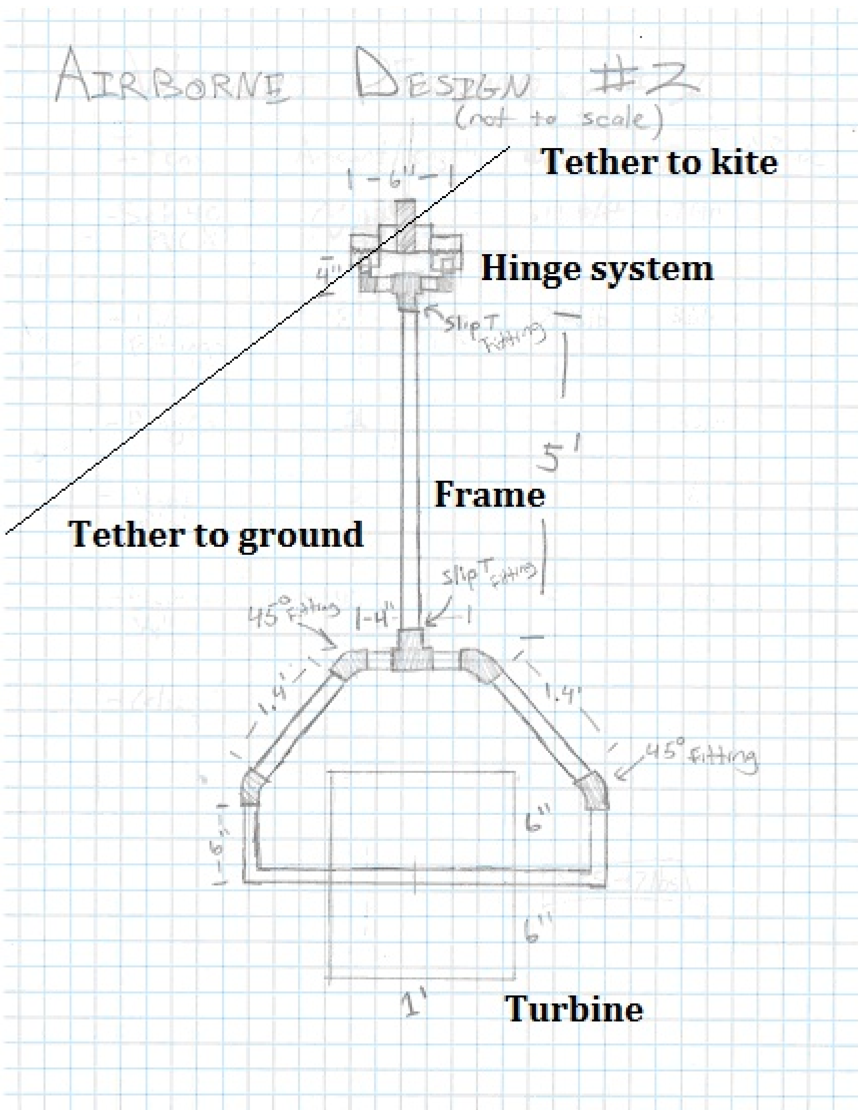

Figure 34: Yoke Design

By decreasing the box size considerably, we can still keep the same principles as our previous design, but now made its profile to the wind smaller, thus decreasing drag as well. Since the box size is smaller, the turbine must be contained in another fashion. The simplest and most aerodynamic idea is to use a yoke concept; a straightforward upside-down "Y" design where the turbine would be contained within the "Y" and still hang down. If the turbine size ever changes, it makes modifying it even easier when a bigger turbine is introduced, because the only part needed to be lengthened is the triple point connection at the bottom of the "Y".

Construction progression of this design is shown below in Figure 35 and 36.

Figure 35: Yoke Design in Lab

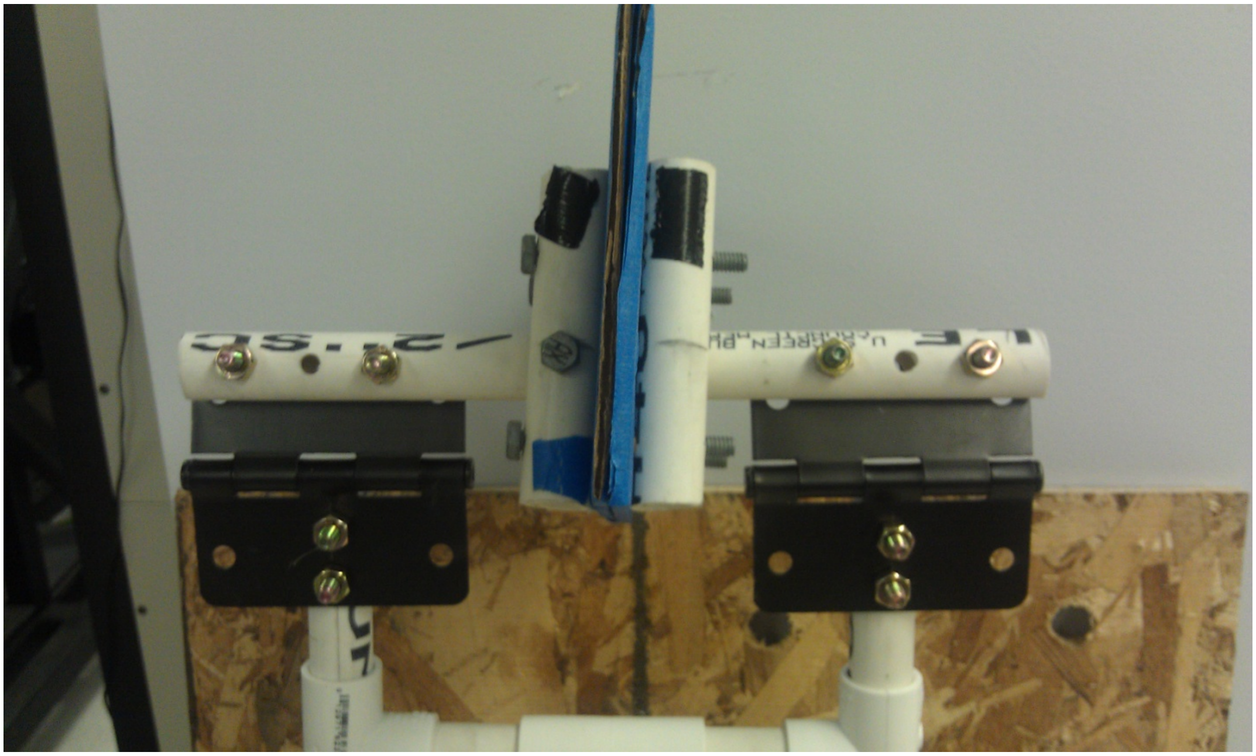

Figure 36: Hinge Design that Allows Turbine to Hang Vertically

5.2 Airborne Wind Turbine Selection

Wind Turbines that were initially researched include:

- Micro 10W Turbine by Four Seasons Wind Power, a Darrieus type turbine
- EDDY by Stranwind, a helical turbine
- UGE by Stranwind, a helical turbine
- Hivawt300 by Hivawt, a combination Darrieus and Savonius type turbine

Once the style of the turbine was decided on, we focused on the ultimate goal of the project which is to produce 1kW. Other considerations that affect the final design were weight, dimensions, material, cost, and the ability to modify the system using available resources.

The Hivawt300 by Hivawt was considered an efficient design due its use of two different turbine designs. Being rated at 300W, sized at just over one square meter, and weighing twenty-five and a half kilograms, the turbine fit within the parameters of the project. The design, however, was complex enough to prevent major modifications without having to require external manufacturing of major parts.

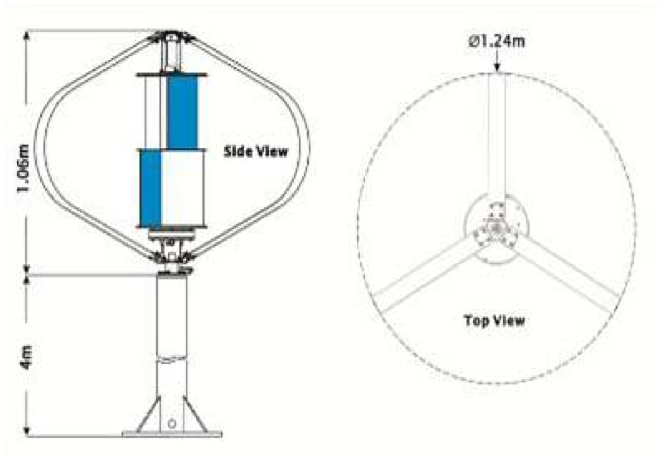

Figure 37: HIVAWT Wind Turbine Design[44]

The helical design turbines, the EDDY and UGE, both by Stranwind, were serious candidates. The helical design provided advantages aerodynamically. The power output for these two models, being rated at 600W and 1kw respectively, would reach our goal and their sizes, approximately one and a half square meters and two square meters, were still within the parameters of the project. Unfortunately, the weights of the turbines, weighing 179.9 lbs and 385.8 lbs respectively, were exceeding the lift force generated by our sled kite. These figures were found using the lift force equation:

$$L = C_L \frac{1}{2} \rho V^2 A$$

For 10 MPH:

$$6.05lbf = 0.02 * \frac{1}{2}\left(0.0023769 \,{}^{slugs}\!/\!_{ft^3}\right)\left(14.67 \,{}^{ft}\!/\!_{s}\right)^2\left(81ft^2\right)$$

And 20 MPH:

$$24.19lbf = 0.02 * \frac{1}{2}\left(0.0023769 \,{}^{slugs}\!/\!_{ft^3}\right)\left(29.34 \,{}^{ft}\!/\!_{s}\right)^2\left(81ft^2\right)$$

The above two equations show the lift force calculated for the sled kite flying in 10 mph and 20 mph winds. The lift coefficient was found from the work on the previous MQP groups' testing. The turbine and system designed by this project group weighed less than 10 lbs which is well within the capabilities of the sled kite.

Also, a major factor was that the helical design of the turbines would make it impossible to make modifications to the turbine without relying on external manufacturers.

Figure 38: Stranwind EDDY Design[45] (Left) and Stranwind UGE Design[46] (Right)

The Micro 10W Turbine by Four Seasons Wind Power was initially dismissed due to its low power output of 10W. After reviewing the other turbine options, this turbine was given further consideration. Being approximately $0.3m^2$, and weighing 2.27kg, the turbine would be advantageous for our design. Priced at $200, it was much more affordable than the other turbines considered which were all priced between $2000-$3000. Also, most importantly, the design was simple enough to allow major modification in-house. The straight Darrieus design and modular pieces of the turbine would be possible to extend or recreate in larger sizes in order to produce a larger power output. The Micro 10W Turbine was selected for use in the project.

Figure 39: The Micro 10W Turbine[47]

Although the Micro 10W Turbine has a power output of only 10 Watts, it can be used for initial testing of our concept with a very low weight turbine. Once this initial testing confirms/validates our overall design, we plan to scale-up the system by designing a considerably larger turbine with longer span turbine blades and larger rotor area which will both produce a greater power output.

5.3 Turbine Support Frame

While designing the support frame, we considered the details of how the turbine was going to be physically attached below the kite. Once we purchased and received the turbine, we were able to analyze the existing base mount, a flanged pipe. We found that the existing base mount was easily attached to the support frame. But, the base mount was a large portion of the total weight of the system. So we decided that the base mount should be reproduced out of ABS plastic using a 3-D printer. The part was modeled and reproduced.

The top of the turbine has a threaded rod which forms the central axis and is welded into the generator. The thread size was measured and a corresponding sized female-to-female threaded connector, threaded rod, flanged roller type bearing, washers, and locknuts were purchased. By connecting the rod to the existing rod and locking the bearing in place with the lock washers, the rod would not slide, but could be adjusted to any length.

5.4 Construction of the Support Frame

After selecting the yoke design, alternative design 5, construction began. PVC piping was selected for the material to be used for the support frame because of its weight and stiffness. The support frame was assembled according to the original design. Bolts were added to the critical joints to ensure that the frame would stay together. The support frame was designed to connect to the tether by two metal plates that would bolt together on either side of the tether and hold it in place using friction. A benefit of this design was the plates would partially restrict any yawing that might occur because the plates were parallel to the tether. The plates were located above a set of hinges which would allow the support frame to remain vertical with the changing angle of the tether. After assessing this design, it was decided that it was not the best option to connect the support frame to the tether.

A redesign of the connection aspect, a working design was produced which used the hinge system implemented by the plate design but replaced the plates with a “double V” of rope. This was accomplished by attaching two eye bolts into the main horizontal member which had previously held the plates. These eye bolts were inserted vertically and extended down so that they had the added purpose of restricting the movement of the hinges so the support frame and turbine would not be able to pitch too far and hit the tether. A piece of rope was then attached to the eyelets on either side forming a “V” on either side. The tip of each “V” had a loop tied in it and attached a bow style shackle to each loop in order to make attachment to the tether easier. This design better prevented yawing than the plate system.

5.5 Attaching the Turbine to the Support Frame

The turbine was manufactured with a double flanged base which is made from heavy steel. We wanted to make a replacement in order to make the base compatible with the support frame and save weight. A comparable base was designed and produced out of ABS plastic using a 3-D printer. The new base was properly fitted to the bottom of the turbine. The new base almost immediately snapped at the connection point of the pipe and flange when it was put under pressure. It was discovered that, although the ABS plastic material should have been suitable to handle the stress of the turbine, the production methods of the 3-D printer, which produced crisscrossed wafers instead of a solid part, cause a critical weakness in design. It was decided, in favor of expediency, the original base would be used with the bottom flange cut off. The original base could be slid over the PVC end of the support frame and bolted in place.

The top of the turbine was manufactured with a threaded end on which was placed a lock nut to keep the blade arms in place. In order to attach the turbine to the other side of the support frame, a threaded rod would be used to essentially extend the axis of rotation. The lock nut was removed and a female-female threaded connector was attached to the threaded end of the turbine and to the threaded rod. A rolling bearing was attached to the other end of the support frame. The free end of the threaded rod was inserted into the bearing and lock nuts and washers were used to keep the rod from sliding in and out of the bearing.

After the entire support frame was assembled and the turbine attached, it was discovered that, due to the weight of the turbine and a slight manufacturing defect in the turbine base, the threaded rod was bending and restricting the rotation of the turbine. It was found that this issue could be addressed by reinforcing the “L” section of the support frame that attached to the base of the turbine. This was accomplished by attaching an “L” metal shelving bracket to the joint. This rigid attachment would prevent the joint from bending.

6. Testing

Testing was a vital part of this project. The team conducted several different tests in different locations to test both systems. These tests included lab testing and off-site testing of the water pump, beach testing of the airborne wind turbine and kite, and wind tunnel testing of the turbine.

6.1 Water Pump Testing

Initial tests were performed in the Fluids Dynamics Lab in the basement of Higgins Laboratories. After the pump was attached to the A-Frame, the system was moved over the sub-basement. This move allowed for a small reservoir, in the form of a large, empty trash can, to be placed underneath the system on the stairs, along with approximately 3 feet of piping and the pump cylinder as shown in Figure 40.

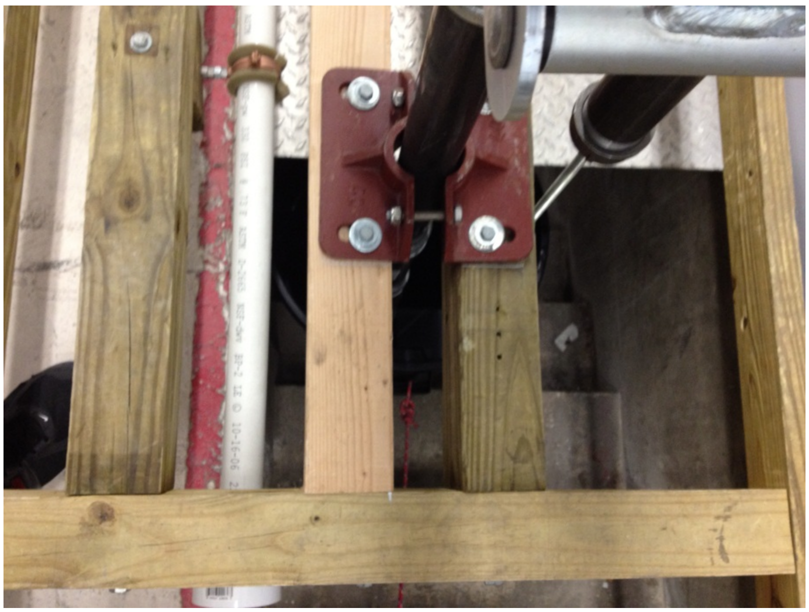

Figure 40: Lab Testing Set Up: View of Sub-Basement

Lights hanging above the entrance to the sub-basement blocked full movement of the swing arm and the possibility of attaching a rope and pulley system to move the swing arm. Therefore, these tests were to allow for the group to familiarize themselves with the pump system, test for any leaks, and prove that both the pump system and head simulation valve work together. Also, the purpose of these tests were to see how deep of a well could be simulated by the head simulation valve. Figure 41-42 show the overall set up of the system over the sub-basement including the head simulation valve.

Figure 41: Lab Testing Setup: Overall View

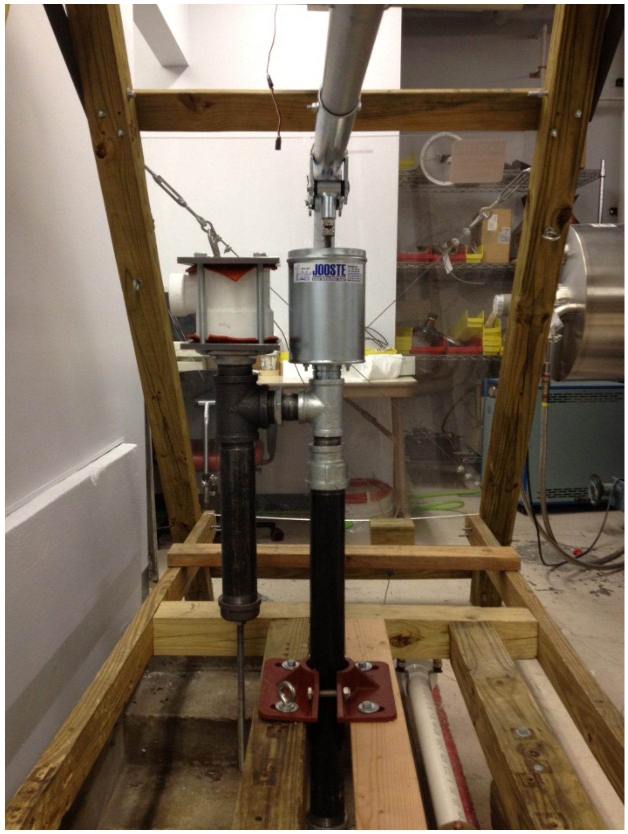

Figure 42: Lab Testing Setup: View of Pump and Head Simulation Valve

6.1.1 Off-Site Testing

The A-Frame water pump system was then moved to a barn owned by Professor Olinger. The off-site facility provided more space and multiple levels, overhead space and a basement, to fully test the performance of the system before field testing. The barn consisted of two main floors; the first floor, where the main entrance to the building is, and a basement. On the first floor, an approximate 3 inch diameter hole was drilled through the floor to allow for the well piping to pass through. Then the A-Frame was placed over the hole and the piping was placed through the hole. After the head simulation valve was re-attached, an extension tube was attached so that water could be pumped to a bucket outside of the A-Frame. In the basement the same reservoir was used, however a greater length of pipe was used (7 feet) to be able to reach the reservoir. Finally, a pulley was attached to a beam about 15 feet above the main floor and a rope was attached to the end of the swing arm where the kite would normally be attached (to the side with the sliding weight system). Known weights were attached to the other end of the rope in order to simulate the force from the kite. Figures 43-44 show the setup of the entire system at the barn.

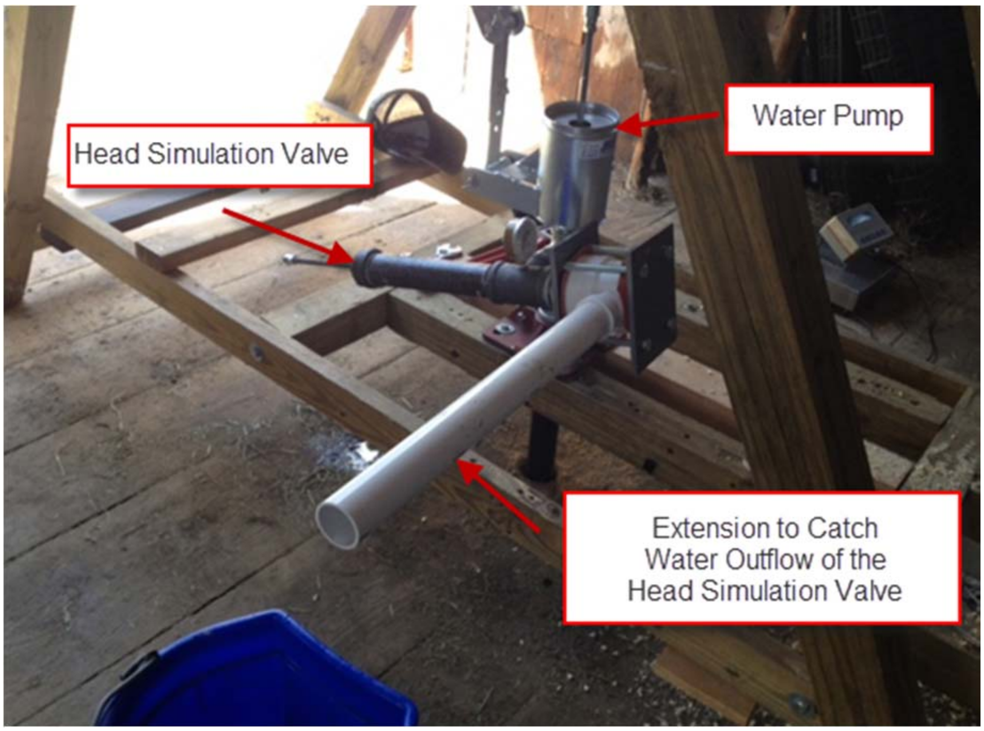

Figure 43: Off-Site Test Setup: View of Head Simulation Valve with Extension

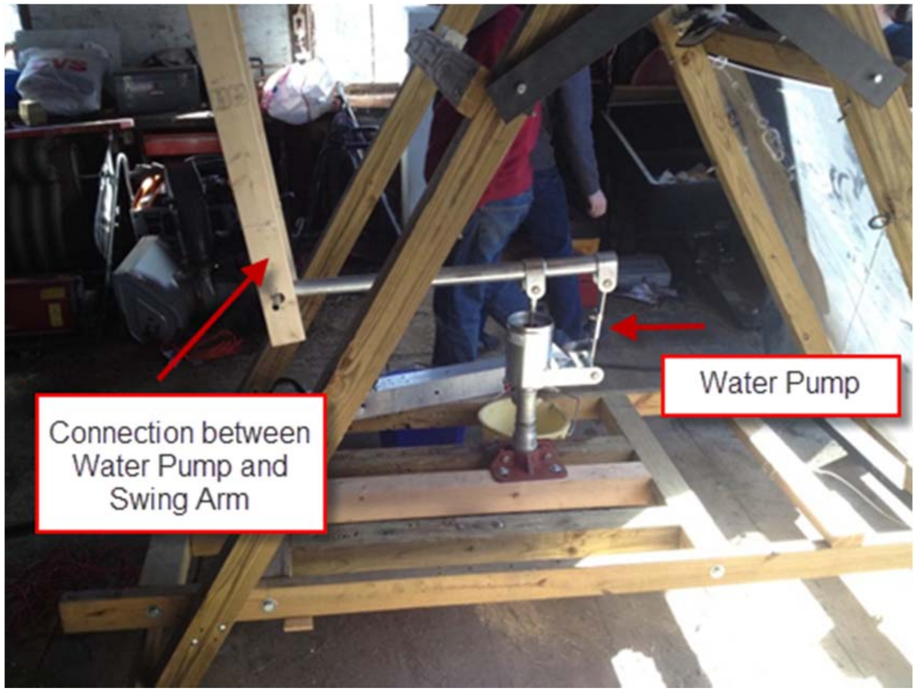

Figure 44:Off-Site Test Setup: Overall View of Barn Testing Setup

Figure 45: Off-site Test Set Up: Basement Reservoir (Left) Pulley System (Right)

6.2 Airborne Wind Turbine Beach Testing

Testing of the kite and airborne wind turbine system occurred on a beach in Seabrook, NH. Winds that day were estimated at being less than 10 miles per hour. A location with sufficient space to lay out the entire system on the ground was selected and marked off with orange safety cones and yellow rope. The kite was laid out along with its tail and weights were placed on it to keep it in place while the rest of the system was put in place. A 100 foot tether was tied to the bridals of the kite and laid out with the other end tied to a fixed point which was the towing hitch of a truck. Once the kite and tether were tied off, the weights were removed and the kite was lifted up by two team members until it was caught by the wind. The kite quickly rose and stabilized.

Figure 46: First Test Flight of Kite

For the second test a sandbag weighing 10 pounds, the same weight of the entire turbine system, was tied on where the tether met the kite's bridals. The purpose of this test was to evaluate if the kite would be capable of lifting the airborne wind turbine system. It was tied off at the point where the turbine system would be attached. When the kite was released, it had difficulty raising more than a few feet off the ground. The kite was then lowered and the weight of the sand bag was reduced. This time the kite rose higher, but only to approximately a third as the original height. Note the sharp angle in the kite tether where the sand bag is attached in Figure 47.

Figure 47: Kite with Sandbag Attached

The kite was then lowered and the sandbag was replaced with the turbine support frame. At first, only the support frame was flown to assure that the connection points to the tether were secure. In case of a failure, it would have been easier to repair the support frame than the turbine. The kite flew close to the height it did when it had nothing attached. The “double V” feature at the attachment points worked well and there was no yawing movement. A slight rolling movement was observed, see Figure 48.

Figure 48: Kite with Turbine Support Frame, Note Roll of Frame

After considering that the weight estimates may have been slightly off, it was decided to fly the turbine. The kite was lowered and the turbine attached to the support frame. When the kite was released, it quickly rose and stabilized at a height close to the first test flight of the kite. The added weight of the turbine did reduce the rolling motion, but did not completely eliminate it. Due to the bending of the frame mentioned in the construction section, the turbine did not rotate. The decision was made to remove the supporting rod from the support frame. Once the kite was lowered and the bar was removed, excessive bending was observed in the frame, but it was determined that it was still sturdy. The kite was released and when it reached a stable altitude the turbine rotated freely, see Figure 49.

Figure 49: Kite Successfully Lifting Support Frame and Turbine

6.3 Airborne Wind Turbine Lab Testing

To determine the turbine's power output over a varying range of wind speeds we conducted wind tunnel tests of the airborne wind turbine in WPI's Fluid Dynamics Lab. This test was necessary to compare the power output of our turbine rig to the manufacturer's specifications. The turbine was secured in the WPI closed circuit wind tunnel, see Figure 50, and connected to two lengths of 100 feet of 12 gauge copper wire that will be used as the kite tether for the system. The wind tunnel test section is 60 cm x 60 cm x 240 cm and the turbine was tested at wind speeds ranging from 4 m/s to around 18 m/s. The reason 12 gauge copper wire was chosen was due to its yield strength. Ideally for the entire turbine system the tether running from the ground to the turbine would be removed, and replaced with just the copper wire, thus the system would require a stronger wire to withstand a constant pulling force from the kite.

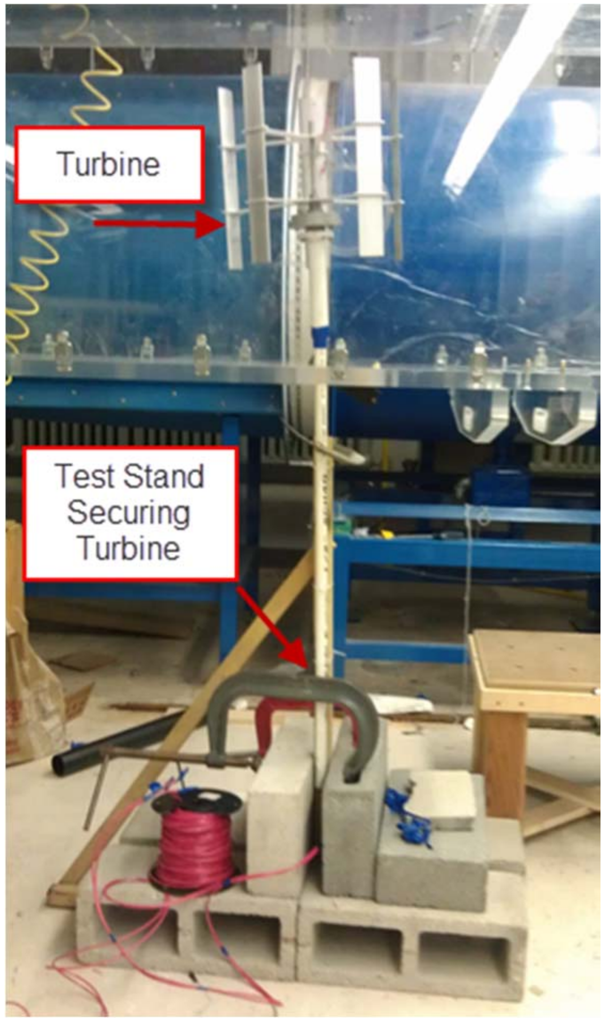

Figure 50: Test Setup for Wind Tunnel Testing of Turbine

The wind tunnel testing was performed multiple times with different resistances across the circuit to simulate different loads that might be attached to the turbine. The loads ranged from just the 12 gauge wire, all the way up to 100k Ohm, and the wind speeds ranged from 4-18 m/s. The 100 ft of 12 gauge wire has an internal resistance of 0.159 Ohms. A digital multimeter was used to determine the voltage across the load being tested. Throughout the test, it was found that 12 volts was the maximum output of the turbine itself. This is true because of the design of the turbine itself, which is only supposed to be connected to a 12 volt battery. According to the manufacturer, there is no limit to the output of amps, which keeps increasing as wind speeds increase, see Figure 51 below. The equation that was used to calculate the power output was:

$$P = \frac{V^2}{R}$$

This method seemed to work until a problem arose when the voltage maxed out at 12. The power also could be calculated by multiplying the voltage by the amps, but the digital multimeter was not working correctly for amp output, thus no data could be gathered for amps. A time constraint led to the inability to find better working equipment and the gathering of more data.

FSW Gyro 10watt Mini-V.A.W.T.						
Wind(m/s)	RPM	Power	Line Voltage(ac)	Line Ampere (ac)	V (dc)	Ampere (dc)
4	300	0.64	5.2	0.095	7.02	0.091
5	375	1.25	6.5	0.148	8.775	0.142
6	450	2.16	7.8	0.213	10.53	0.205
7	525	3.43	9.1	0.290	12	0.286
8	600	5.12	10.4	0.379	12	0.427
9	675	7.29	11.7	0.480	12	0.608
10	750	10	13	0.592	12	0.833
11	785	12	14.3	0.646	12	1.000
12	818	13.8	15.6	0.681	12	1.150
13	849	15.4	16.9	0.701	12	1.283
14	878	16.8	18.2	0.711	12	1.400
15	905	18.2	19.5	0.719	12	1.517
16	930	19.6	20.8	0.725	12	1.633
17	953	21	22.1	0.732	12	1.750
18	974	22.7	23.4	0.747	12	1.892
19	993	24.3	24.7	0.757	12	2.025
20	1010	25.8	26	0.764	12	2.150

Figure 51:Four Seasons Wind Power 10 watt Mini-V.A.W.T Specifications

In order to determine the strength of the copper wire to be used as the kite tether for the new system, tests were conducted. To perform this wire test, one end of a single lead 3 foot section of copper wire was secured to a stationary platform, while the other end was secured to a 2 inch bore air cylinder. The wire was then pulled 5 times to 60 psi, which corresponded to a pull force of about 150 lbs. This value already exceeded the pull force of the kite (around 80 lbs). The next step was to determine the breaking point of the wire, so the psi of the testing rig was slowly increased. The final breaking point occurred at around 75 psi, which corresponds to around 200 lbs, shown as the red line in Figure 52 below. The conclusion was drawn that since a double lead wire is necessary for power generation from the turbine, the combined strength of the 12 gauge copper wire was more than enough to be a viable replacement for the ground to turbine tether.

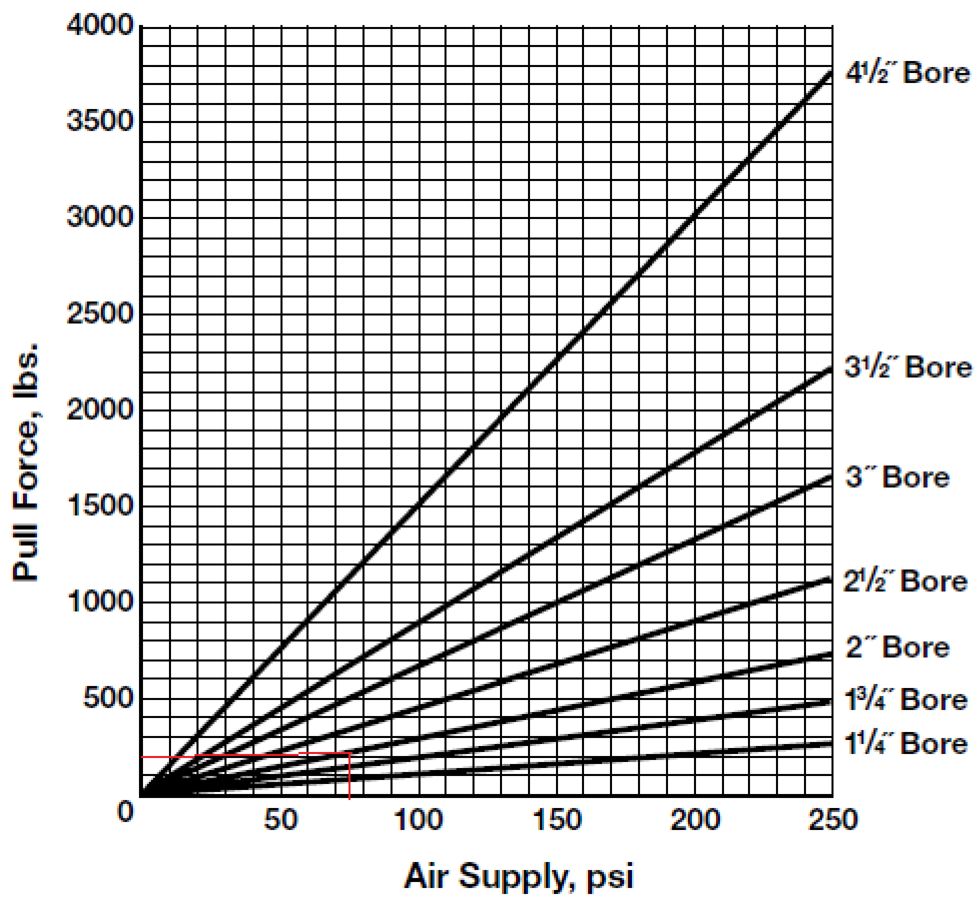

Figure 52: Performance Data for Aluminum Tie Rod Air Cylinders[48]

7. Results

7.1 Water Pump Results

The testing done in the lab was successful for checking the system was functioning properly. The pump worked properly and we were able to pump water fairly easily. There was some minimal leaking; we used a pipe sealant to prevent the leaking. This solution worked very well. When we attached the head simulation valve it also proved to be working well. In the lab we were able to simulate a pressure of 25 psi which is approximately equivalent to a 58 ft well. Unfortunately during this testing, the spring failed and came detached from the valve. We were able to make a design change, adding a washer with an additional, offset hole to attach the spring to, allowing the spring to rotate freely. Once everything was sorted out in the lab we continued onto testing at the off-site barn.

When testing at the off-site barn we had three successful volumetric flow rate tests. We started by testing the system with the head simulation valve and finished with just a long garden hose attached. We would attach weights to one end of the pulley system then drop the weight to simulate the force of the kite.

PSI= 10		
Avg Force from kite	Inches of water in bucket/stroke	Flowrate (lb/10 strokes)
86	0.818181818	18
71	0.795454545	17.5
55	Balance	

Figure 53: Volumetric Flow Rate Data for Test at 10 psi

PSI= 15		
Avg Force from kite	Inches of water in bucket/stroke	Flowrate (lb/10 strokes)
75	0.727272727	16
86	0.727272727	16
65	Balance	

Figure 54: Volumetric Flow Rate Data for Test at 15 psi

After these two tests with the head simulation valve the spring came detached again. We attempted to reconnect it inside the valve using zip ties, however, when we attempted to re-pressurize the system it failed before we could tighten it past 15 psi. The spring should be replaced in the future with a stronger and more durable one. We believe that the hook on the end of the spring where it attached to the washer connection was weakened by the loading and unloading of the system and its strength became compromised. The spring did not fracture so it is reasonable to suspect that the metal was elastically stretched to the point where it slipped off of the washer.

Figure 55: Spring Attachment

We continued testing without the head simulation valve, but because of the piping this was still actually 7 ft of head. We were able to measure the flow rate for four different force weights.

PSI=0		
Avg Force from kite	Liters/Stroke	Flowrate (lb/10 strokes)
86	0.954545455	21
76	0.795454545	17.5
71	0.727272727	16
65	0.772727273	17
70	0.772727273	17
50 Balance		

Figure 56: Volumetric Flow Rate Data for 0 psi

We used a scale to measure the amount of water after ten strokes. The scale had an accuracy of +/- 0.5 pounds. We used the weight to find the volumetric flow rate.

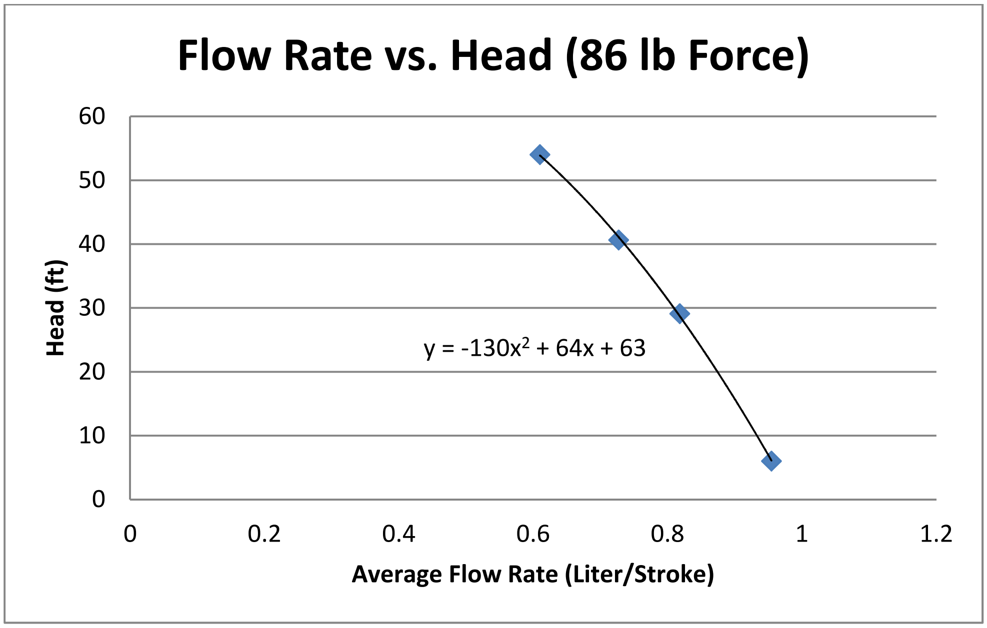

Figure 57: Barn Testing Results, Maximum Flow Rate at Different Head Levels

Figure 57 shows the pump curve generated from our data for the maximum weight used at each pressure setting. In this data, a test case involving pumping water over 300 feet of garden hose was added to the flow rate study. The distance of the hose corresponds to an equivalent height that the water would be pumped from a well. The following equation explains this height calculation:

$$h_l = f \frac{L}{D} \frac{V^2}{2g}$$

Where f is a fraction coefficient, found from a Moody table, L is the length of the hose, D is the diameter of the hose, V is the velocity of the fluid in the hose, and g is the gravity constant. In order to fulfill this calculation, the Reynolds number for the hose had to be calculated. To do this, velocity and volume flow rate were required. The volume flow rate is based on the total volume of water we pumped in our test. In the test, we pumped 7 liters of water over 10 strokes of the pump, or about 0.7 liters per stroke. Assuming each stroke takes about 2 seconds, the volume flow rate, or Q, is 350 cm^3/sec. Using this, we could calculate the Velocity through the hose using the cross sectional area as well, about 1.98 cm^2.

$$V_{hose} = \frac{Q}{A}$$

This velocity was discovered to be about 1.77 m/sec. Using this and a few constants (density, ρ, and viscosity, μ, of water at 70 degrees Fahrenheit, approximately 977.8 kg/m^3 and 0.000404 Ns/m^2 , respectively) The Reynolds number can be calculated

$$Re = \frac{\rho V D}{\mu}$$

Looking at a Moody chart, we were able to determine the friction coefficient to be about 0.018. This is entered into the h_l equation above, and discovered to be 53.9 feet of vertical pumping distance.

7.2 Airborne Wind Turbine Results

One of the results was that with no resistance attached besides the wire, it seemed that the power output of the turbine rose at an exponential rate. At first it seemed that this result was promising, for it held potential that even with a small load put on the system, the power output would still be in the realm of the manufacturer's rating. This, however, held untrue as shown in Figure 58. Even at the smallest resistance of 10 Ohm, the power output of the system was cut dramatically. As the resistance was increased, the power was cut even more severely at the corresponding wind speed (Figure 59).

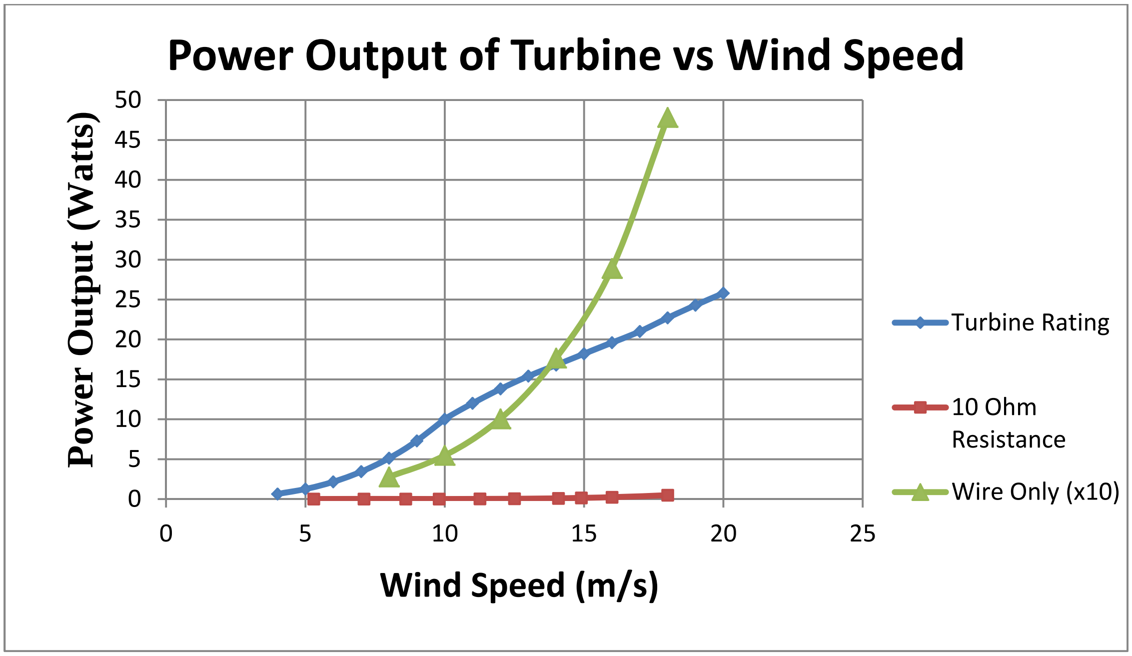

Figure 58: Power Output of Turbine vs. Wind Speed Test 1

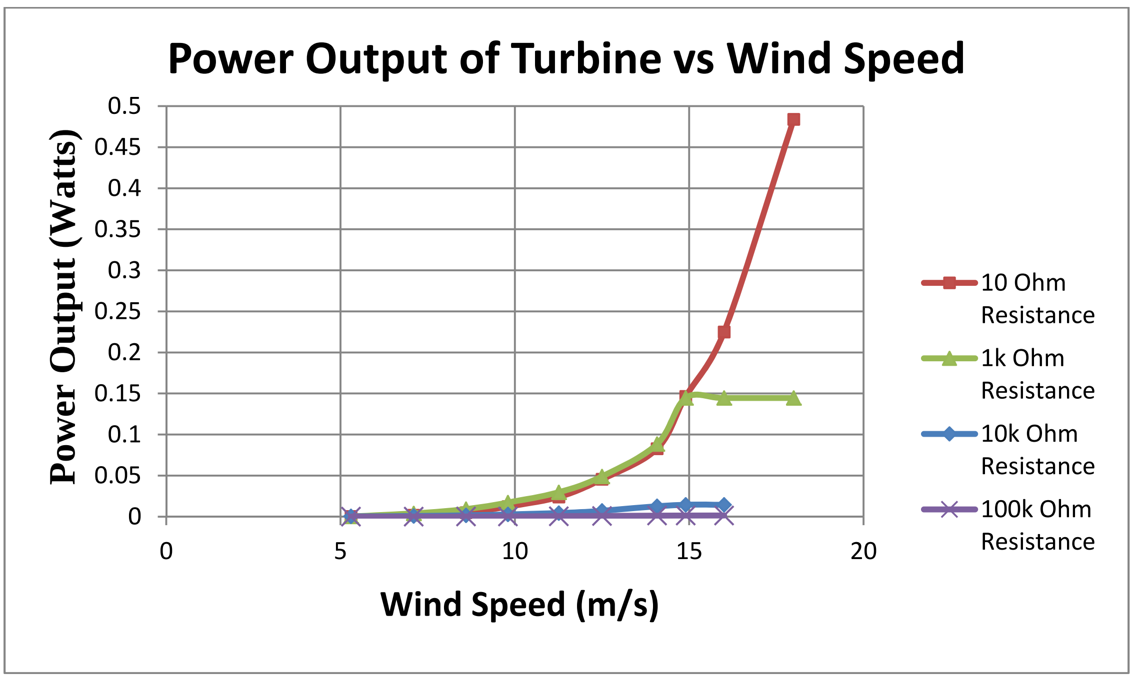

Figure 59: Power Output of Turbine vs. Wind Speed Test 2

A few conclusions were drawn as a result of this testing. One result was that there is a massive power loss along the cable as soon as a load is placed upon the system. This turbine was only designed to charge a 12 volt battery within close proximity of itself. The 12 gauge wire may be too long for sufficient power to be transported without heavy losses. The combined wire and external resistance may be straining the turbine so much that power output suffers catastrophically. The lack of output current/voltage could also be attributed to the wiring and soldering right around the control board connections. During testing the connection became loose, thus no power could be transferred along the wire. It had to be fixed before further data could be gathered. The external resistance must be as small as possible with the design of the system to get a reasonable output. But even connected to the 100 feet of copper wiring, the losses were too great to be considered a viable output, and that could be contributed to the intended design of the turbine. Further research into the wiring and resistance would be required to increase the power output to an acceptable level.

7.3 Simulation Results

After the previous code was modified, a baseline run with the following input parameters, kite area = 8 m^2, wind speed = 6 m/s, tether length = 100 m, kite weight = 20 Newtons, well depth = 20 meters, well pipe diameter = 5 cm, static pump force = 125 Newtons, sliding angle of attach weight = 40 Newtons, linkage length=0.92 m, pump arm pivot to linkage length=0.88 meters, pump arm pivot to pump rod length=0.2 m, and swing arm pivot to linkage length=1 meter.

Results from this baseline run are shown in Figure 60.

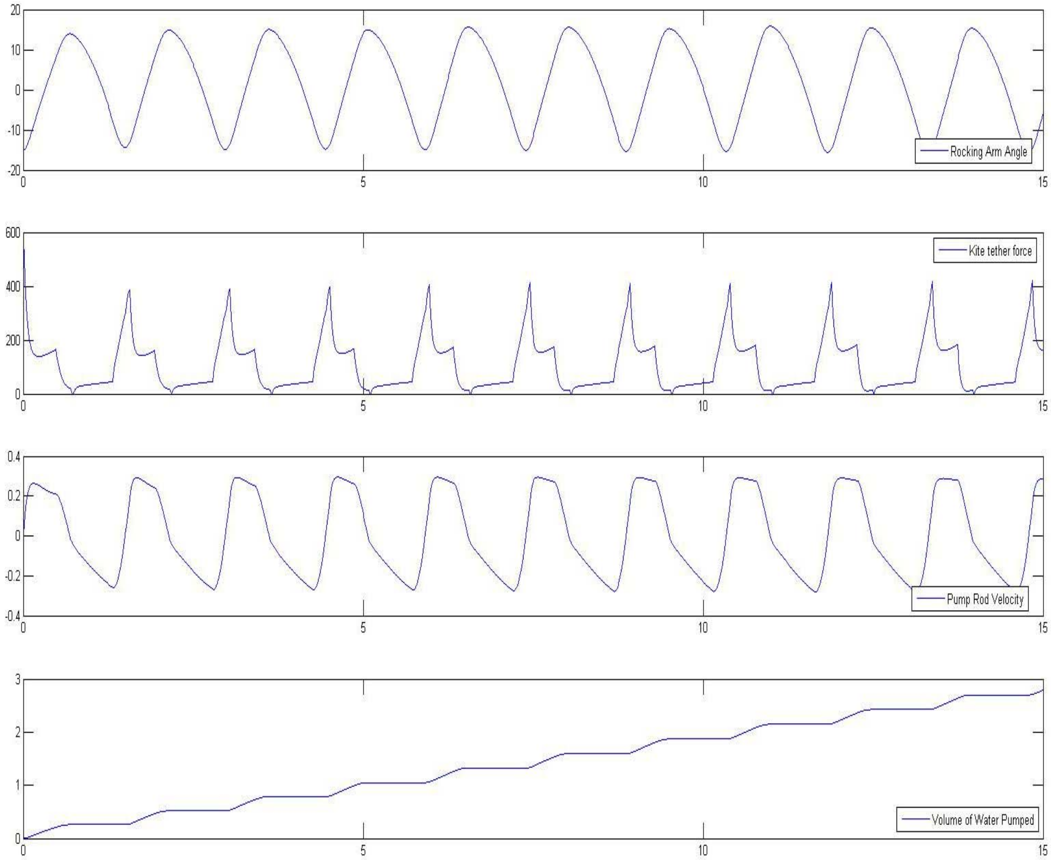

Figure 60: Simulation Graphical Results

The first three plots are rocking arm angle, kite tether force, and pump rod velocity respectively. Since the kite powered water pump system was not tested with the kite all of the plots could not be verified. However, during offsite testing, a kite force of approximately 90 lbs, or 400 Newtons, was applied to the system which is the maximum force from the kite in the simulation.

The simulation showed that about 0.25 liters of water were pumped per stroke for a 20 meter deep well. During offsite testing, the maximum depth of well simulated was approximately 12 meters deep which resulted in approximately 0.2 gallons, or 0.76 liters per stroke. This error could be due to the static friction since it was never properly measured. Also, during offsite testing, the weight of water was measured instead of the volume directly. This weight was measured using a common household scale with an accuracy of 0.5 lbs which could also add to any inconsistencies between the simulation and the testing results. Further work and field testing of the kite pump system is needed to validate the developed simulation against actual system performance.

Next, the simulation was run at several depths to compare with the results from the field testing. At 10 meters deep the simulation shows a drastic decrease in flow rate, however at 20 meters the flow rate returns to a more reasonable number. If the 10 meter data point is ignored a much better exponential curve fit can be calculated as shown below.

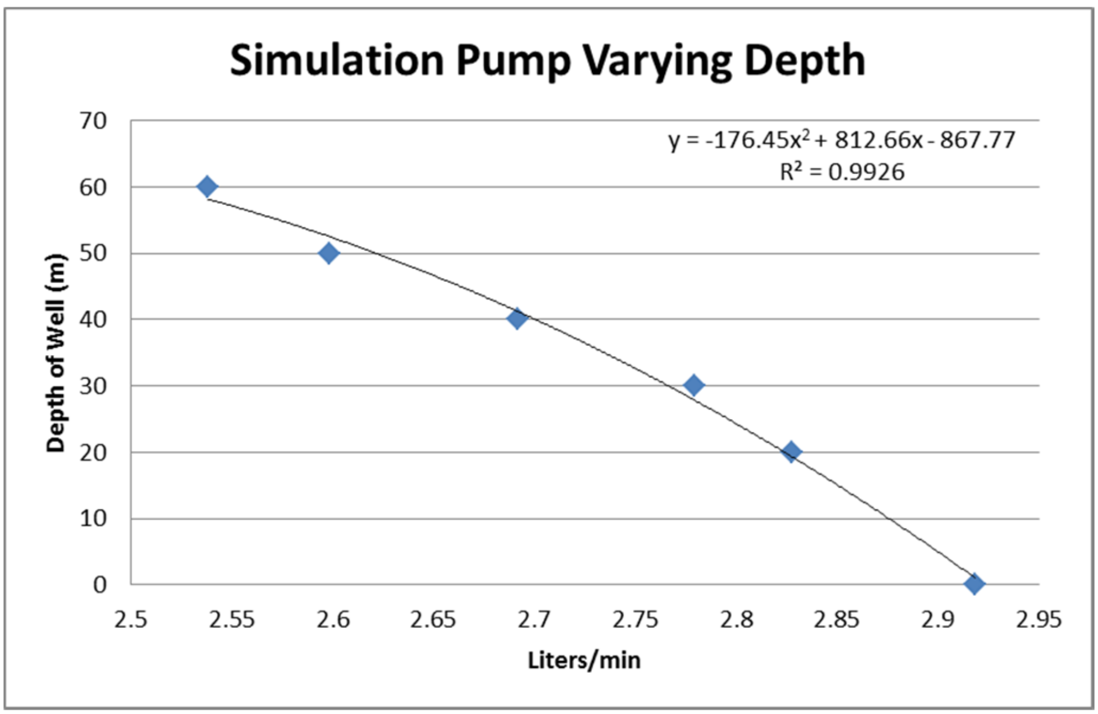

Figure 61: Simulation Flow Rate vs. Depth of Well without 10 meter Data Point

The simulation plots of flow rate versus depth of well show the same negative exponential shape as the field testing, however, as said before the values are off and further testing and refinement of the simulation are needed in order to properly account for all variables.

8. Conclusions and Future Work

This project of the WPI Kite Powered System was a departure from all previous MQPs. It is the intention that the groundwork laid on this project will continue on in the coming years. Here are the recommendations for future work on the Kite Powered Water Pump and Airborne Wind Turbine System.

8.1 Water Pump Conclusions and Future Work

In the end, all of our goals were met to make the project successful. We were able to complete a fully functional water pump system attached to the A-frame. As well, we were able to successfully able to attach the water pump to the sway arm of the A-frame in order to convert angular motion to linear motion, which the pump would not be usable without. With these successes, we were able to run multiple tests under different operating conditions in order to see how the pump would work and gain a better understanding of the feasibility of this idea. These tests allowed us to evaluate the stability and functionality of the system we had created.

While testing, we were able to determine the forces required by the kite in order to operate the pump, as well as the different depths of wells that the pump could pump water from given the forces we could work with. Inferring from the data, the deeper the well, the higher the force we need to pump water. However, the kite can only generate a certain amount of force, limiting the ability of the pump. As well, with these changing conditions, we were able to determine flow rates at different forces and well depths.

This is important for the scope of the project so that the system can effectively provide enough water for the required user group.

To successfully test some parts, such as the depth from which we could pump, the head simulation valve was a key component of the project. While using this in the testing, we were able to modify the resistance of the internal spring loaded valve to simulate varying depths. This was successful for a short amount of testing time, and enough data was attained to have some data. However, the valve broke several times, leaving us unable to fully experiment with varying depths. Overall, the head simulation valve was able to provide us with significant data pointing to how the project can be continued and improved.

Finally a modified MATLAB simulation was developed to model the kite pump system. Preliminary runs were conducted that predicted the correct physical trends in volume flow rate pumped as well depth is varied. For future projects on the kite powered water pump system, there are several recommendations and areas that need work. First, further testing needs to be done. This would be more geared towards testing the system as a whole, instead of parts at a time. In doing this, the head simulation valve would need to be maintained properly so that a wide range of test cases can be observed. As well, better materials such as better piping, and better connectors for the pump to the sway arm are needed to make the system stronger and more efficient. With the connectors, determining the optimum length for the connection is critical in order to get the longest stroke possible and maximize the efficiency of the pump by raising the forces transferred. Finally, a long term test setup would be beneficial in order to look at long term stability, material strength of the setup, and the feasibility of minimal human interaction for upkeep purposes. This field testing will most likely be conducted at the Heifer International Organization's Overlook Farm in Rutland, MA.

Overall, this project was a success. We were able to achieve all of the goals that were set to complete the project. A useable system was developed and proved that the setup was within the realm of feasible and useful. In order to make a system that could be useful in the setting it was intended for, however, a lot more testing and optimizing is needed to develop a fully functional and stable system. Within the scope of this project, functionality was proven and the foundation for future work was laid.

8.2 Airborne Wind Turbine Conclusions and Future Work

The research and results of the airborne wind turbine tests prooved it is possible to suspend a conventional wind turbine beneath a kite to generate electricity. This conclusion, however, does not come without many challenges and obstacles. Determining what type and size of turbine is the most crucial part of the project. This decision affects how the turbine will be housed and suspended, and what type of power will be generated. In the beginning a goal of 1kW output was desirable, but upon further investigation and with time and budget concerns, a starting point of 10W seemed much more reasonable.

In terms of the support frame, the yoke design was the simplest, lightest, and most cost effective design. The ½ inch PVC pipe is an effective material, but the small amount of bending due to the weight of the turbine caused the threaded rod on the opposite side of the turbine to bend, thus adding resistance and preventing the turbine from spinning efficiently. These issues can be addressed with either a thicker threaded rod, lighter turbine, or strengthening the support frame itself to prevent so much bending. The whole unit (support frame and turbine combined) weighed less than 10 lbs.

The turbine itself was a good place to start testing and trying to achieve the concept of an airborne wind turbine. Trying to design a turbine from scratch, and then trying to make sure it was light enough to suspend from a kite contained too many variables to be a viable jumping off point with the airborne turbine idea. The more logical, and successful choice was to start small with an established and already manufactured turbine, and alter it to suit the needs of the project. While the power output was less than ideal, the fact that rig worked and data was gathered proved a success. All of information gathered from the tests and research showed that the concept of an airborne wind turbine is not only possible, but very achievable.

Suggestions for teams continuing this project work could include performing detailed aerodynamic testing on the wind turbine in order to determine if changing the airfoil shape and/or angle of attack could make the turbine more efficient. This project laid out a proof of concept with the intent that future work would be done to scale up the turbine for greater power generation. With the turbine scaled up, the support frame and possibly the kite would also need to be scaled up.

References

[1].S. Department of Engery. Securing american energy. in The White House [database online]. Washington, DC, 2011 [cited 9/30 2011]. Available from http://www.whitehouse.gov/energy/securing-american-energy.

[2] WaterAid America. Statistics. in WaterAid, Inc. [database online]. New York, NY, 2011 [cited 9/30 2011]. Available from http://www.wateraidamerica.org/what_we_do/statistics.aspx?gclid=CL772PanqqsCFcNM4AodJH7O3A.

[3] David Olinger, "Wind Energy 1" (Lecture, 2011).

[4] Vanek, Energy Systems Engineering, 2008, McGraw-Hill

[5] Buckley, Ryan Patrick et al. Design of a One Kilowatt Scale Kite Power System. WPI MQP Report. 2008. [cited 4/23 2012].

[6] Buckley et al., 2008. [cited 4/23 2012].

[7] Alex, Lauren et al. Design of a Data Acquisition System for a Kite Power Demonstrator. WPI MQP Report. 2009. [cited 4/23 2012].

[8] Buckley et al., 2008. [cited 4/23 2012].

[9] Toydemir, Kuthan. Design of a Dynamometer for the WPI Kite Power System. WPI MQP Report. 2010. [cited 4/23 2012].

[10] Frewin, Michael et al. Design of a Remote Controlled Tether System for the WPI Kite Power System. WPI MQP Report. 2011. [cited 4/23 2012].

[11] Alex, Lauren et al. Design of a Data Acquisition System for a Kite Power Demonstrator. WPI MQP Report. 2009. [cited 4/23 2012].

[12] Poe, Christopher. The in's and out's of metering pumps. in Cole-Palmer [database online]. 2000 [cited 10/5 2011]. Available from http://www.coleparmer.com/techinfo/techinfo.asp?htmlfile=meteringpumps.htm&ID=409.

[13] Scout Directories. Pump types guide - finding the right pump for the job. in Scout Directories, LLC [database online]. 2011 [cited 10/5 2011]. Available from http://www.pumpscout.com/articles-scout-guide/pump-types-guide-aid100.html.

[14]Scout Directories. Pump types guide - finding the right pump for the job. in Scout Directories, LLC [database online]. 2011 [cited 10/5 2011]. Available from http://www.pumpscout.com/articles-scout-guide/pump-types-guide-aid100.html.

[15]Scout Directories. Pump types guide - finding the right pump for the job. in Scout Directories, LLC [database online]. 2011 [cited 10/5 2011]. Available from http://www.pumpscout.com/articles-scout-guide/pump-types-guide-aid100.html.

[16]Poe, Christopher. The in's and out's of metering pumps. in Cole-Palmer [database online]. 2000 [cited 10/5 2011]. Available from http://www.coleparmer.com/techinfo/techinfo.asp?htmlfile=meteringpumps.htm&ID=409.

[17] Scout Directories. Pump types guide - finding the right pump for the job. in Scout Directories, LLC [database online]. 2011 [cited 10/5 2011]. Available from http://www.pumpscout.com/articles-scout-guide/pump-types-guide-aid100.html.

[18] General Pump and Machinery. in General Pump and Machinery [database online]. 2010 [cited 9/30 2011]. Available from http://netpumps.com/gear-pumps.html.

[19] Scout Directories. Pump types guide - finding the right pump for the job. in Scout Directories, LLC [database online]. 2011 [cited 10/5 2011]. Available from http://www.pumpscout.com/articles-scout-guide/pump-types-guide-aid100.html.

[20]HPLC pumps. in LC Resources, Inc. [database online]. 2001 [cited 9/30 2011]. Available from http://www.lcresources.com/resources/getstart/2b01.htm.

[21] Scout Directories. Pump types guide - finding the right pump for the job. in Scout Directories, LLC [database online]. 2011 [cited 10/5 2011]. Available from http://www.pumpscout.com/articles-scout-guide/pump-types-guide-aid100.html.

[22] Megator. Mega flex vane pump. in Megator Corporation [database online]. 2011 [cited 9/30 2011]. Available from http://www.megator.com/mega_flex_vane_pump.htm.

[23] Scout Directories. Pump types guide - finding the right pump for the job. in Scout Directories, LLC [database online]. 2011 [cited 10/5 2011]. Available from http://www.pumpscout.com/articles-scout-guide/pump-types-guide-aid100.html.

[24]Scout Directories. Pump types guide - finding the right pump for the job. in Scout Directories, LLC [database online]. 2011 [cited 10/5 2011]. Available from http://www.pumpscout.com/articles-scout-guide/pump-types-guide-aid100.html.

[25] Hydraulic Institute. Hydraulic institute pupm FAQs october 2008. in Pumps & Systems Magazine [database online]. 2008 [cited 9/30 2011]. Available from http://www.pump-zone.com/pumps/rotary-pumps/hydraulic-institute-pump-faqs-october-2008.html.

[26]Jooste, Christie. Jooste cylinder & pump co. South Africa, 2011 [cited 9/12 2011]. Available from http://www.joostecylinders.com/index.html.

[27]Scott, Owen. The playpump - A review from teachers. WorldPress.com, 8/18/2010 [cited 9/10 2011]. Available from http://barefooteconomics.ca/2010/08/18/the-playpump-a-review-from-teachers/.

[28] Water for People. How playpumps works. 2011 [cited 9/10 2011]. Available from http://www.waterforpeople.org/extras/playpumps/how-playpumps-works.html.

[29] Scott, Owen. The playpump - A review from teachers. WorldPress.com, 8/18/2010 [cited 9/10 2011]. Available from http://barefooteconomics.ca/2010/08/18/the-playpump-a-review-from-teachers/.

[30] PumpAid. PumpAid: Water for life. London, 2011 [cited 9/10 2011]. Available from http://www.pumpaid.org/.

[31] Lifewater Canada. Because water is life. 2011 [cited 9/15 2011]. Available from http://lifewater.ca/.

[32]Kick Start. Super money maker. San Francisco, CA, 2011 [cited 9/26 2011]. Available from http://www.kickstart.org/products/super-moneymaker/.

[33] Kick Start. Super money maker. San Francisco, CA, 2011 [cited 9/26 2011]. Available from http://www.kickstart.org/products/super-moneymaker/.

[34] Santos, Dave. Kite lab. 2011 [cited 9/1 2011]. Available from http://energykitesystems.net/KiteLab/index.html.

[35]Santos et al., 2011 [cited 9/1 2011].

[36]Santos et al., 2011 [cited 9/1 2011].

[37] Santos et al., 2011 [cited 9/1 2011].

[38] Horse Head Pump Jack. [cited 12/18/2011]. http://upload.wikimedia.org/wikipedia/commons/thumb/3/3f/Pump_Jack_labelled.png/350px-Pump_Jack_labelled.png

[39] http://www.thecollaboratoryonline.org/w/images/Final_Report_5-4_final_version4_readable.pdf

[40] Olinger, D. J., & Goela, J. S. (2010, November). Performance Characteristics of a 1 kW Scale Kite-Powered System. *Journal of Solar Energy Engineering. Vol. 132, 0410009-1 – 041009-11* .

[41] Olinger et al., 2010.

[42] Honeywell Wind Turbine with Blade tip power system. 2011. [cited 12/18/2011]. http://www.northerntool.com/shop/tools/product_200405533_200405533

[43] Wind Turbine Syndrome. Wind turbine turbulence. What are the micro-climate effects?. 4/28/2011. http://www.windturbinesyndrome.com/news/2011/wind-turbine-turbulence-what-are-the-micro-climate-effects/

[44] Hivawt. DS-300W Vertical Wind Terbine. 2011 [cites 12/18/2011]. http://www.hi-vawt.com.tw/en/ds300w.html

[45] Stranwind. Urban Green Energy: 600W Wind Turbine Specifications. 2011 [cited 12/18/2011]. http://www.stranwind.com/pdf/600_Specs.pdf

[46] Stranwind. Urban Green Energy: 600W Wind Turbine Specifications. 2011 [cited 12/18/2011]. http://www.stranwind.com/pdf/1K_Specs.pdf

[47] Four Seasons Windpower. 10 Watt Mini Vertical Axis Wind Turbine. 2011 [cited 12/18/2011]. http://www.fswindpower.com/Mini10W.html

[48] McMaster-Carr. 2011. [cited 4/22/2012] Available from http://www.mcmaster.com/#6491kac/=h7y5gy

Appendix A: Messiah College Head Simulation Valve

Item	Quantity
1/4” x 6” x 8” Steel Plate	2
2" NPT cast pipe flange	1
2" NPT x 2" cast pipe nipple	1
2" NPT cast T	1
2" NPT x 12" cast pipe nipple	1
2" NPT cast pipe cap	1
2" NPT male / 2" female PVC coupling	1
4"/2" PVC T	1
1/2"-13x6" bolts (cap screw)	4
3/8"-16x1" bolts	4
1/8"x1"x4" aluminum flat stock	1
1/2"x1.5" aluminum rod	2
1/4"-28x1.75" bolts (cap screws)	2
1/2" OD x 5/16" ID x 3" stainless steel tube	1
3/8"-16 x 2" eye bolt and nut	1
extension spring, max load 50lb	1
1/2"-13 nut	3
no.8-32 x 3/16" set screw	1
1/2"-13 x 12" threaded rod	1
1/8" x 1" x 3" steel flat stock	1

1/2" x 3" x 3" aluminum stock	2
6" x 18" rubber sheet	1
pipe joint compound	
4" PVC pipe, flattened for cutting disks	

Tool	**Purpose**
Horiz. Band Saw	cutting steel plate
Hack Saw	cutting smaller metal stock
Drill press	drilling and tapping holes in plate stock, cutting valve port
Metal lathe	tapping stainless rod, facing and drilling valve guide support pegs, turning and facing valve disk
Hand taps	tapping plate stock: 1/2"-13, 3/8"-16, 1/4"-28, no.8-32
Machine taps	tapping stainless rod: 3/8"-16
Metal sander/grinder	cleaning edges of cut stock, rounding ends of valve support plate
2" metal hole saw	cutting valve port
Drill bits	17/32, 1/2, 7/16, 27/64, 5/16, 13/64, 7/64
Countersink	needed for tapping: 1/2", 1/4"
Metal scribe	
Compass with divider point	
Vernier calipers & steel rule	
Center punch	making holes for drilling
Adjustable cresent	

wrench	
3" pipe wrench	connecting pipe fittings
Bench vise	bending lower spring attachment bracket, assembling pipe fittings
Drill press vise	
Deburring tool	rounding edges of valve guide hole
2 1/4" hole saw	cutting PVC discs for pipe restriction

Manufacturing Process

1. Cut Materials

- Top and bottom plates of the valve housing: Cut two 8 inch pieces of 3/8 x 6 inch steel flat stock, preferably using a horizontal bandsaw.
- Valve guide plate: Cut a 4 1/8 inch piece of 1/8 x 1 inch aluminum flat stock using a hacksaw or vertical bandsaw.
- Support pegs for valve guide plate: Cut two 1.25 inch pieces of 1/2 inch aluminum rod, leaving some excess material for facing later.
- Valve disc: Rough cut a 2.8 inch circle from 1/2 inch aluminum flat stock, leaving some excess material for turning down later.
- Valve guide rod. Cut a 3 inch section of 1/2 inch OD 5/16 inch ID stainless steel tube; the exact length is not critical.
- Valve housing: Cut the 4 inch PVC T down to 5 1/4 inches. Draw a cutting line the entire way around the T and cut around the perimeter with a hacksaw, rather than sawing straight through the middle; this will make it easier to get a perpendicular cut.

- Lower spring attachment: cut a 3 inch piece of 1/8 x 1 inch steel flat stock.
- Tensioning rod: Cut a 12 inch piece of 1/2 inch threaded rod.
- Rubber seals: Cut two circles slightly wider than the rim of the PVC T housing. The lower seal will need the center removed in order to fit around the valve port, but the upper can remain solid. Cut a circle the diameter of the valve disc and punch and 3/8 inch hole in the center for the eye bolt. Cut a rubber washer to match the dimensions of a metal washer for a 1/2 inch bolt. Cut a circle with the outside diameter of the pipe flange and inner diameter of 2 3/8 inch.

2. Shape materials

- Top and bottom plates: Remove sharp edges using a metal sander or grinder.
- Bottom plate: Use a 2 inch hole saw and drill press to cut the valve port in the center of the plate. Drill and tap two 1/4"-28 holes for the valve disc guide bolts according to the schematic. These need not be stopped holes, as a miniscule amount of water will leak through them. Drill and tap four 3/8"-16 holes for attaching the pipe flange. These may be through holes. Drill and tap four 1/2"-13 holes for the valve housing bolts. Countersink the pilot holes before tapping, as this will enable the tap to grab better and will help bolts start easier in the holes.
- Top plate: drill four 1/2 inch holes for the valve housing bolts according to the schematic.
- Valve guide plate: locate the center of the plate and center punch it. Using a compass with scribe point, draw a 4 inch diameter circle on the plate. Grind the

ends down to this scribed line. Center punch two marks on either end of the plate, 1 3/4 inch from the center. Drill 17/64 inch holes at both marks. Drill a 17/32 inch hole in the center of the plate.

- Support pegs for valve guide plate: Face both ends of the pegs on the lathe. Measure the length of both pegs and take the difference. Place the longer peg back in the lathe, set the zero when the tool just touches the face, and take off the required difference.
- Valve guide rod: Face the tube. If using a solid rod instead of tube, first drill the center out to 5/16 inch. Tap the hole using a 3/8”-16 machine tap according to established procedure. Drill and tap a no.8-32 setscrew into the side of the rod 1 1/8 inch on center from the threaded end. This will keep the valve from coming unscrewed.
- Valve disc: On the drill press, drill and tap a 3/8”-16 hole in the center of the disc. Bolt the guide rod to the disc and place in the lathe chuck. Turn the outside diameter smooth. It should be approximately 2.8 inch diameter, but this dimension is not critical. Face the disc as far in as possible without hitting the bolt head. It is only important that the faced portion will be sure to cover the 2 inch valve port.
- Valve housing: both ends of the T smooth using a stationary belt sander. Use the miter fence to align the housing perpendicular to the belt.
- Lower spring attachment: Drill 1/2 inch holes in either end of the flat stock. Clamp it in the vise and bend one end over until the axis of one hole is aligned with the top of the other hole, as shown in the schematic. Make sure that

the tensioning rod and top nut can rotate freely when the spring attachment is under tension.

- Upper tensioning rod nut: This nut holds the lower spring attachment on the rod and allows it to rotate freely. Drill and tap a 1/4"-28 setscrew in the side of the nut to prevent it from coming loose. Drill a small divot in the side of the rod to enable the setscrew to grab better.
- Pipe Cap: Drill and tap a 1/2"-13 hole in the center for the tensioning rod.

- Tensioning rod handle: This is specified as a 3 inch square of 1/2 inch aluminum; it can be shaped however desired or an entirely different design substituted. The only requirement for this piece is to enable turning of the tensioning rod to change the head produced by the valve. The piece has a 1/2"-13 hole tapped in it so it can thread onto the rod.

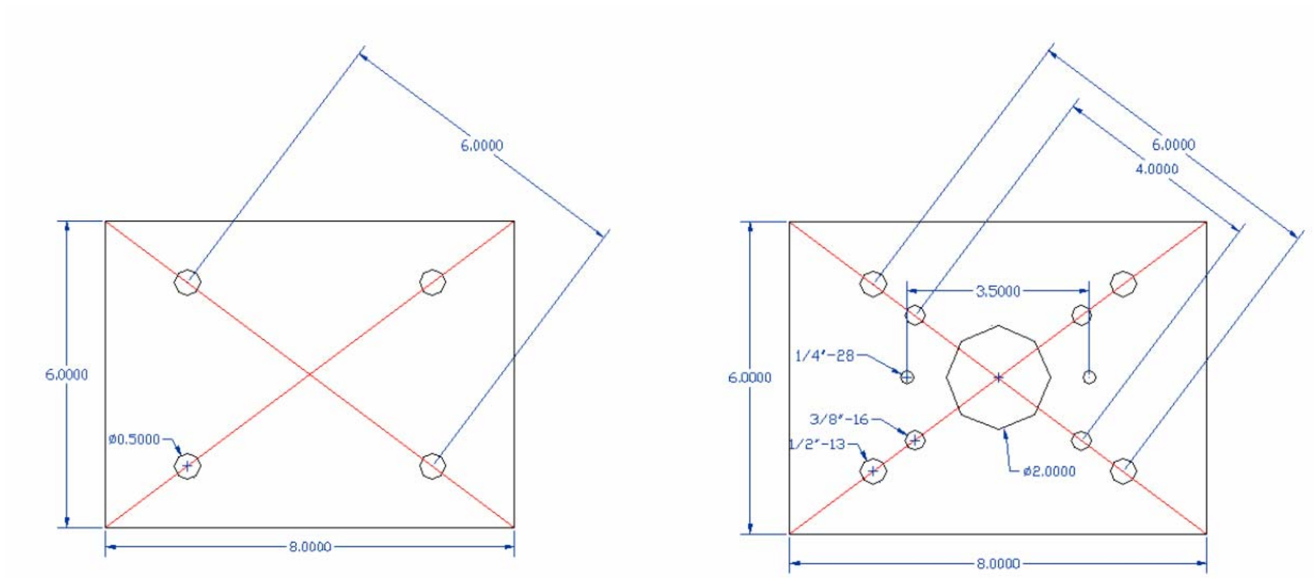

Figure 62: Top Plate (Left) and Bottom Plate (Right)

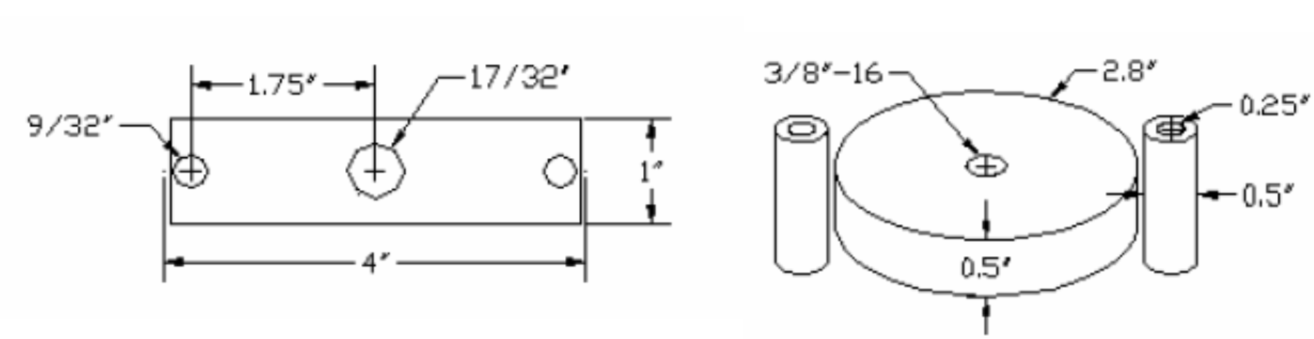

Figure 63: Support Plate (Left) Valve Disk and Supports for Guide Plate (Right)

Assembly

- Attach the metal T to the pipe flange with the 2” nipple. Attach the 12” nipple to the other end of the T. Use pipe joint compound to seal the threads and tighten as far as possible with a pipe wrench. Make sure that the T outlet points perpendicular to the valve housing plates.
- Bolt the pipe flange to the underside of the bottom housing plate using 3/8”-16x1” bolts. Tape the rubber seal in place with double stick tape for convenience. Cut the bolts to size or use washers under the bolt heads to keep the bolt ends under flush with the other side of the plate. The bolt ends will interfere with the housing seat if they stick up.
- Put the lower spring attachment over the top of the tensioning rod and thread on the nut. Tighten the set screw firmly without stripping it out. The spring attachment should be able to rotate freely without interference from the nut.
- Thread the tensioning rod though the end cap and put a rubber washer, metal washer, and nut onto it. These will be tightened against the cap so seal it. Then thread on the rod handle followed by another nut and tighten these against each other.
- Thread a nut onto the eye bolt as far as it will go. Thread the valve disc and guide rod on. If the hole in the rod is not tapped deep enough, grind the threads off of the end of the eye bolt. Make sure there is an adequate surface for the set screw to grip.
- Remove the valve disc and rod from the eye bolt. Attach the spring to the lower attachment bracket and eye bolt. Turn the simulation valve upside down and

drop the spring and eye bolt down through the pipe to you can grab them outside of the valve plate.

- Drop a metal washer followed by the rubber valve seal onto the eye bolt. Thread the valve disc and guide rod onto the bolt and tighten the set screw.
- Bolt the valve support plate and pegs to the top of the valve plate using 1 ¾ inch 1/4"-28 bolts.
- Screw the end cap onto the 12 inch pipe nipple, using plenty of joint compound. Tighten with a pipe wrench.
- Turn the tensioning rod knob until the valve is seated. From then on it is best to adjust the tension with water flowing through the valve. Although the lower spring attachment is designed to rotate on the rod, there is much less resistance when the valve disc can spin on a cushion of water.
- Tape the rubber seals to the valve housing plates using double stick tape, or set the simulation valve vertical and let gravity hold them in place.
- Set the PVC T over the valve support structure and make sure it is centered. Place the upper plate over the T and tighten it down with the valve housing bolts.
- Attach short lengths of pipe to the outlet of both Ts. The head simulation valve is now complete.

Constructing the restriction to shunt water through the head simulation valve

This device allows the rod to pass through freely, but creates the maximum resistance to water passing through. A series of stacked discs with gaps in-between creates large amounts of turbulence as water flows past each disc in turn. If the hole were long and smooth, in contrast, the moving rod and stationary hole would result in Couette flow, a laminar flow condition. Turbulence dissipated more energy, causing the flow to back up, which is the desired effect.

- Flatten a section of 4 inch PVC pipe. Cut out four discs using a 2 1/4 inch hole saw. This will produce discs that are slightly larger than 2 inch diameter.
- Bolt the discs securely to a piece of wood though their center holes. Drill two 1/4 inch hole through the stack of discs.
- Bolt the stack of discs together with 5/16 inch nuts as spacers between the discs.
- Measure the distance between centers of the inlet and outlet of the head simulation valve.
- Measure the length of pipe needed to connect two 2” American PVC T fittings so they line up with the simulation valve. Cut two pieces of pipe half this length and glue them to the T’s.
- Soften the pipe on the lower T by heating with a heat gun or torch. Push the stacked disc assembly down into the pipe as far as it will go. If part of the stack remains above the top of the pipe, heat the end of the pipe on the other T and push it over the discs to flare it out slightly.
- After the pipes have cooled, the discs will be snugly fitted into the pipe and cannot be removed except by heating the entire assembly. (This, however, will

result in the discs returning to the shape of the pipe they came from and they will have to be re-flattened before they can be assembled again.)

- Connect the two pipes together with a rubber hose clamp connector.
- An alternative is to use a single piece of pipe and glue the second T to it, but this would eliminate the possibility of removing the discs if they wear out. It also might not make a good glue joint because the pipe shrinks slightly when heated and would not fit snugly in the T fitting.

Attach the pump cylinder to the pipe restriction with a rubber hose coupling. The diameter of the pipes has been increased by a ring of 3” pipe so it will fit the coupling. Couplings can only be purchased in 2 or 3 inch increments. The ring was heated and compressed around the pipe end using the metal sleeve around the rubber coupling. Then the ring was glued. It was later caulked on the inside edge to eliminated small amounts of leakage. [49]

Figure 64: Head simulation Valve Water Restrictor

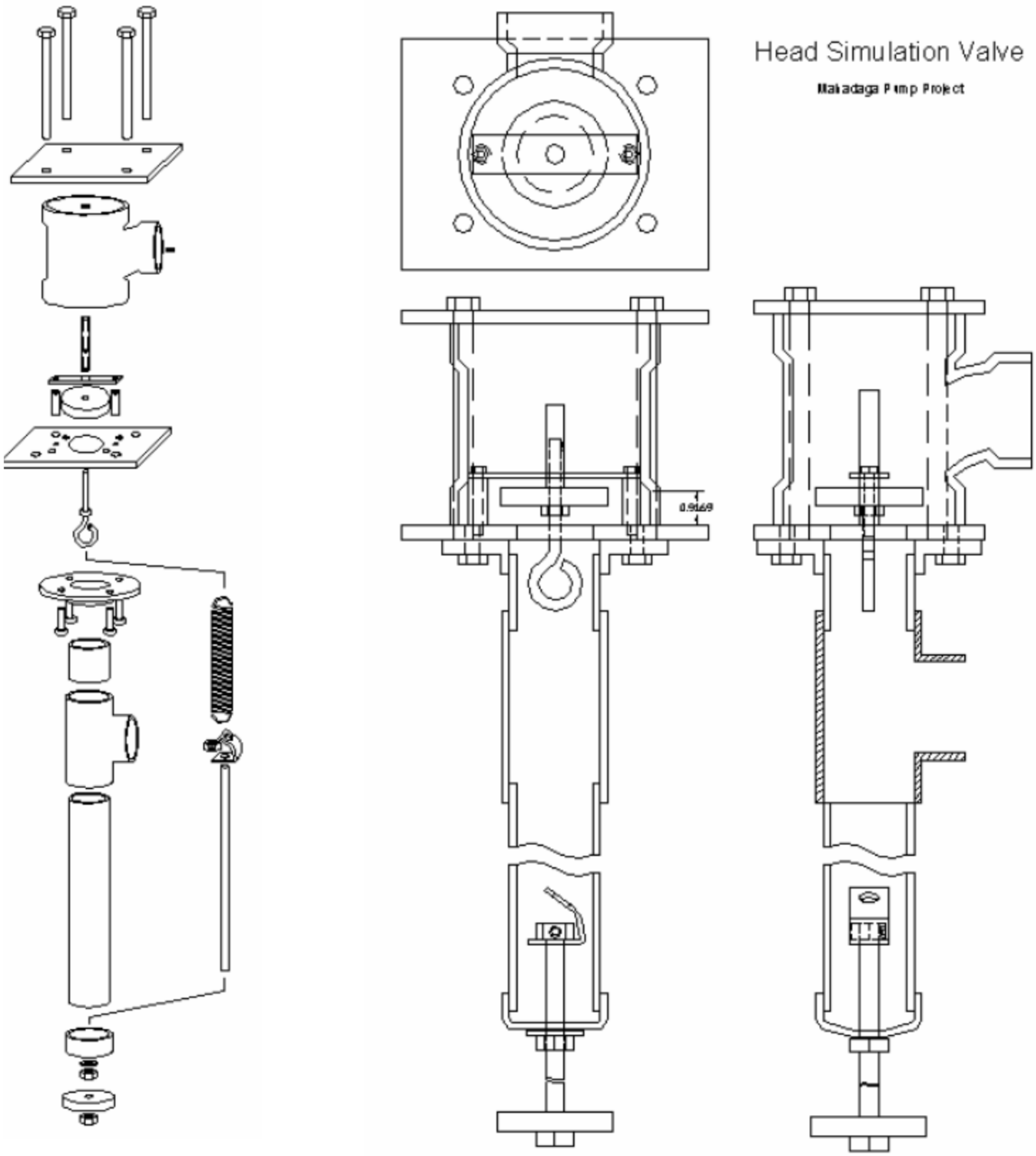

Figure 65: Head Simulation Valve Diagram

Appendix B: WPI Head Simulation Valve

1. Cut Materials

- Top and bottom plates of the valve housing: Cut two 8 inch pieces of 3/8 x 6 inch steel flat stock, preferably using a horizontal bandsaw.
- Valve guide plate: Cut a 4 1/8 inch piece of 1/8 x 1 inch aluminum flat stock using a hacksaw or vertical bandsaw.
- Support pegs for valve guide plate: Cut two 1.25 inch pieces of 1/2 inch aluminum rod, leaving some excess material for facing later.
- Valve disc: Rough cut a 2.8 inch circle from 1/2 inch aluminum flat stock, leaving some excess material for turning down later.
- Valve guide rod. Cut a 3 inch section of 1/2 inch OD 5/16 inch ID stainless steel tube; the exact length is not critical.
- Valve housing: Cut 2 inches off of one side of the PVC T. Draw a cutting line the entire way around the T and cut around the perimeter with a hacksaw or belt saw, rather than sawing straight through the middle; this will make it easier to get a perpendicular cut.
- Tensioning rod: Cut a 12 inch piece of 1/2 inch threaded rod.
- Rubber seals: Cut two circles slightly wider than the rim of the PVC T housing. The lower seal will need the center removed in order to fit around the valve port, but the upper can remain solid. Cut a circle the diameter of the valve disc and punch and 3/8 inch hole in the center for the eye bolt. Cut a rubber washer to match the dimensions of a metal washer for a 1/2 inch bolt. Cut a

circle with the outside diameter of the pipe flange and inner diameter of 2 3/8 inch.

2. Shape materials

- Top and bottom plates: Remove sharp edges using a metal sander or grinder.
- Bottom plate: Use a 2 inch hole saw and drill press to cut the valve port in the center of the plate. Drill and tap two 1/4”-28 holes for the valve disc guide bolts according to the schematic. These need not be stopped holes, as a miniscule amount of water will leak through them. Drill and tap four 3/8”-16 holes for attaching the pipe flange. These may be through holes. Drill and tap four 1/2”-13 holes for the valve housing bolts. Countersink the pilot holes before tapping, as this will enable the tap to grab better and will help bolts start easier in the holes.
- Top plate: drill four 1/2 inch holes for the valve housing bolts according to the schematic.
- Valve guide plate: locate the center of the plate and center punch it. Using a compass with scribe point, draw a 4 inch diameter circle on the plate. Grind the ends down to this scribed line. Center punch two marks on either end of the plate, 1 3/4 inch from the center. Drill 17/64 inch holes at both marks. Drill a 17/32 inch hole in the center of the plate.
- Support pegs for valve guide plate: Face both ends of the pegs on the lathe. Measure the length of both pegs and take the difference. Place the longer peg back in the lathe, set the zero when the tool just touches the face, and take off the required difference.

- Valve guide rod: Face the tube. If using a solid rod instead of tube, first drill the center out to 5/16 inch. Tap the hole using a 3/8”-16 machine tap according to established procedure. Drill and tap a no.8-32 setscrew into the side of the rod 1 1/8 inch on center from the threaded end. This will keep the valve from coming unscrewed.
- Valve disc: On the drill press, drill and tap a 3/8”-16 hole in the center of the disc. Bolt the guide rod to the disc and place in the lathe chuck. Turn the outside diameter smooth. It should be approximately 2.8 inch diameter, but this dimension is not critical. Face the disc as far in as possible without hitting the bolt head. It is only important that the faced portion will be sure to cover the 2 inch valve port.
- Valve housing: both ends of the T smooth using a stationary belt sander. Use the miter fence to align the housing perpendicular to the belt.
- Lower spring attachment: Drill a 1/2 inch hole in a large washer, and a small hole large enough to feed the end of the spring through. Make sure that the tensioning rod and top nut can rotate freely when the spring attachment is under tension.
- Upper tensioning rod nut: This nut holds the lower spring attachment on the rod and allows it to rotate freely. Drill and tap a 1/4"-28 setscrew in the side of the nut to prevent it from coming loose. Drill a small divot in the side of the rod to enable the setscrew to grab better.
- Pipe Cap: Drill and tap a 1/2"-13 hole in the center for the tensioning rod. Thread the hole for better leak control.

Assembly

- Attach the metal T to the pipe flange with the 2” nipple. Attach the 12” nipple to the other end of the T. Use pipe joint compound to seal the threads and tighten as far as possible with a pipe wrench. Make sure that the T outlet points perpendicular to the valve housing plates.
- Bolt the pipe flange to the underside of the bottom housing plate using 3/8”-16x1” bolts. Tape the rubber seal in place with double stick tape for convenience. Cut the bolts to size or use washers under the bolt heads to keep the bolt ends under flush with the other side of the plate. The bolt ends will interfere with the housing seat if they stick up.
- Put the lower spring attachment over the top of the tensioning rod and thread on the nut. Tighten the set screw firmly without stripping it out. The spring attachment should be able to rotate freely without interference from the nut.
- Thread the tensioning rod though the end cap and put a rubber washer, metal washer, and nut onto it. These will be tightened against the cap so seal it. Then thread on the rod handle followed by another nut and tighten these against each other.
- Thread a nut onto the eye bolt as far as it will go. Thread the valve disc and guide rod on. If the hole in the rod is not tapped deep enough, grind the threads off of the end of the eye bolt. Make sure there is an adequate surface for the set screw to grip.

- Remove the valve disc and rod from the eye bolt. Attach the spring to the lower attachment bracket and eye bolt. Turn the simulation valve upside down and drop the spring and eye bolt down through the pipe to you can grab them outside of the valve plate.
- Drop a metal washer followed by the rubber valve seal onto the eye bolt. Thread the valve disc and guide rod onto the bolt and tighten the set screw.
- Bolt the valve support plate and pegs to the top of the valve plate using 1 ¾ inch 1/4"-28 bolts.
- Screw the end cap onto the 12 inch pipe nipple, using plenty of joint compound. Tighten with a pipe wrench.
- Turn the tensioning rod until the valve is seated. From then on it is best to adjust the tension with water flowing through the valve. Although the lower spring attachment is designed to rotate on the rod, there is much less resistance when the valve disc can spin on a cushion of water.
- Tape the rubber seals to the valve housing plates using double stick tape, or set the simulation valve vertical and let gravity hold them in place.
- Set the PVC T over the valve support structure and make sure it is centered. Place the upper plate over the T and tighten it down with the valve housing bolts.
- Attach short lengths of pipe to the outlet of both Ts. The head simulation valve is now complete