REDC

RENEWABLE ENERGY DESIGN CONCEPTS

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I. INTRODUCTION

This report responds to the Request for Proposal (RFP) from Renewable Energy Design Concepts (REDC) found in Appendix A. REDC specializes in small and micro hydropower with a focus on analyzing current systems and their adaptability to generate environmentally friendly energy. REDC is now interested in developing an inline flow hydrokinetic solution that is cost competitive to traditional hydro power. Inline flow systems are designed to use the kinetic energy from flowing water to produce electricity as opposed to the potential energy of impounded water that traditional hydro generation uses. The scalability of an inline flow system allows it to be implemented in areas where the construction of traditional hydro generation is not feasible. This permits for the generation of electricity in areas where connection to an existing power grid is not viable.

A. Background

REDC is a company focused on producing electric energy environmentally friendly and from renewable sources by utilizing the current infrastructure in cities of all sizes. REDC specializes in micro and small hydropower installations. Hydropower is implemented in new and innovative ways to capture the kinetic energy of moving water, an abundant energy resource, with little to no environmental impact. One way that REDC employs hydropower systems is in the replacement of pressure reducing valves (PRVs) in water distribution and collection facilities. This allows for the harnessing of environmentally friendly energy that would otherwise go to waste through the displacement of the large spring in a traditional PRV. In addition to their hydropower work, REDC also conducts energy audits and feasibility studies for its clients through the Federal Energy Regulatory Commission (FERC), making good use of the integrated Smart Grid of the United States.

Currently, REDC is focusing on in-line flow and run-of-the-river hydropower projects. REDC plans to apply its technologies in Less Economically Developed Countries (LEDCs) and More Economically Developed Countries (MEDCs), helping to bridge the energy gap around the world without making a negative impact on the environment. With the recent emergence of innovative prime mover technologies and designs, inline flow has become a method of recently renewed popularity for the generation of hydropower without the need for traditional dams or diversions.

In an inline flow system, hydrokinetic electric power is generated by capturing the energy of flowing water from one of various prime mover designs, which can include turbines, water wheels and other appropriate design schemes. The kinetic energy harnessed with a prime mover in an inline flow system is converted to mechanical shaft rotation. The shaft rotation drives an electric generator, producing electric power. REDC believes, through the harnessing of the hydrokinetic energy of water, they can help to reduce energy costs and decrease buildings' carbon footprint.

B. Statement of the Problem

Due to the vast amounts of underutilized hydrokinetic resources in both LEDCs and MEDCs, energy is left unharnessed all over the world [1]. Water flows, such as rivers and streams all store energy where a hydrokinetic system could be implemented to produce power. Hydrokinetic systems impose less of an impact on the surrounding environment compared to traditional hydrogenation systems. Having access to these resources can be a superior alternative and can be more feasible than traditional hydro projects

Hydroelectric dams are significant not only in cost, but also have a very significant impact on the surrounding environment. The area behind the dam floods, forcing the relocation of many different animal species and people too. It also prevents fish migration which can have a negative impact on both the wildlife and the human population in the area [2]. An inline flow system would provide a better alternative with less environmental impact than a hydroelectric dam. This will allow energy to be extracted from a river without having to dam the area and displace any wildlife.

The design of this system requires the collaboration of both mechanical and electrical engineers The mechanical system required the design of a prime mover, along with all necessary components needed to rotate the generator at the appropriate revolutions per minute (RPM). The electrical system generates the power output requested and required the design of a system that makes the power useable. Challenges to these systems present themselves when coming up with a design that provides a very high efficiency while producing the necessary torque and RPM needed to generate the output desired.

In order to overcome these challenges, the prime mover was designed and analyzed with the help of a computer aided design program. This allowed for a design that provided the highest efficiency while also meeting the rotational speed requirements of the electrical system. The system is independent of a larger power grid in order to avoid the complexity of synchronizing the output frequency, however, it can be adapted for on grid use in later applications. Because the system is independent of grid power, a generator with a permanent magnet was used to eliminate the need for an excitation system.

II. DESIGN

A. Generator

The electrical generator needed to meet power output requirements and be readily available and inexpensive. After research of various generator types, two generators were purchased for further testing. A WindBlue Power DC-540 three-phase permanent magnet alternator and a Fisher and Paykel direct drive washing machine motor, were selected and tested on a test bench designed by the team (see Appendix C). This testing was used to compare power outputs of the generators at different RPM's as well as the durability under constant rotation.

1. WindBlue Power Permanent Magnet Alternator

WindBlue Power offers a permanent magnet alternator that can be used in wind or hydro applications. The design of the generator uses the body from an automotive alternator and replaces the rotor and stator with a permanent magnet rotor and a three-phase stator. There is also an internal rectifier that allows for DC power directly out of the alternator. An output pigtail allows for an external rectifier to be connected if needed.

2. *Fisher and Paykel Washing Machine Motor*

The Fisher and Paykel (F&P) washing machine direct drive motor is a permanent magnet, synchronous motor with 36 poles. The motor was chosen due to the large number of poles which limits the amount of cogging, resulting in easy and smooth rotations. In addition, the generator can be run at variable speeds which is required due to fluctuating river flow rates. Research by team ECE 13.5 (2013) showed that "the generator was current limited and begins to approach its peak power output when the load voltage approached the open circuit voltage" [3]. This research suggested the motor be rewired as shown in Figure 1 to provide a higher power output at a lower voltage.

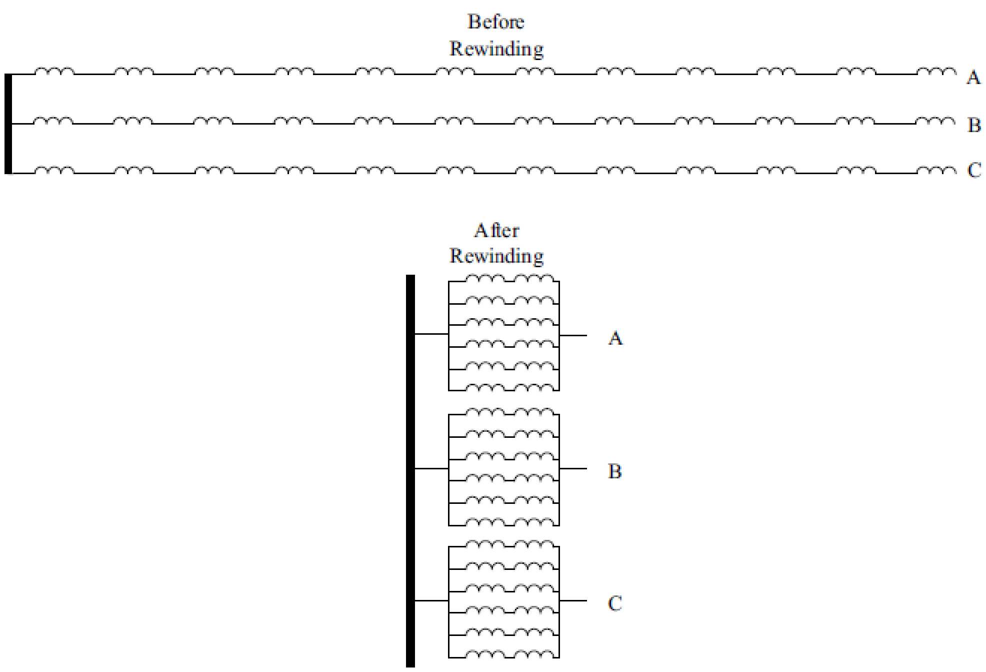

Figure 1: Rewiring the Generator

The parallel rewiring of the coils shown in Figure 1 eliminated the higher voltage addition along all 12 coils, which lead to a lower open circuit voltage. However, each coil still produced the same amount of current. This current was added at the output node, which increased the overall current. This increase in current and decrease in voltage allowed for the output power to maintain a similar value.

B. Prime Mover

1. Bucket

The prime mover design aspect included designing and sizing a number of components, the most important being the bucket system. Multiple bucket designs were modeled using SolidWorks and analyzed using SolidWorks Flow Simulation. Due to inconclusive results produced by the SolidWorks Simulations, a five-gallon bucket was attached to a force gauge and tested in the Cowlitz River in Washington at multiple flow rates. The results from this testing helped estimate the force that would be produced by each of the bucket systems based on flow trajectories and pressure profiles. The three bucket shapes can be seen in Figure 2.

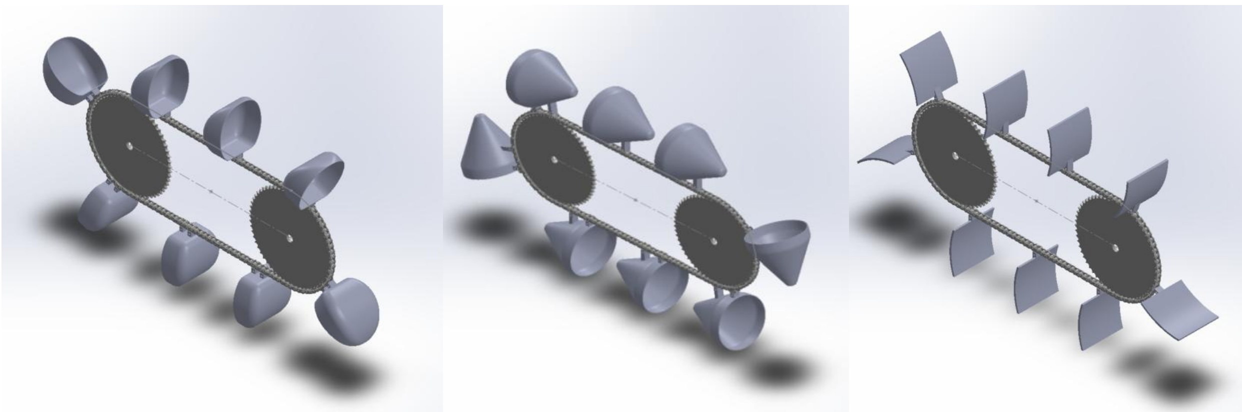

Figure 2: Proposed Bucket Designs

Force data on each of the buckets was found to be comparable, and due to manufacturing simplification the bent plate design was chosen. Once the bucket shape was selected, size was based on a flow rate of 1.5 meters per second (m/s) and the electrical generator torque requirement at 150 to 200 RPM's. Ultimately, a one-foot by one-foot plate was selected due to its ability to provide the necessary torque while not being oversized for the system. Refer to Appendix D for relevant equations and calculations.

2. Chain, Sprockets, Shaft, and Bearings

Following the bucket design and sizing, the chain, sprockets, and bearings could be sized appropriately. Taking into account the weight and force of the buckets, an ANSI #50 steel chain was chosen in order to provide the necessary support and durability. The length of the chain was decided arbitrarily based on the height of the system defined by the sprocket. The overall length of the chain was chosen in order to produce a five-foot overall prime mover length. The necessary dimensions can be seen in Figure 3.

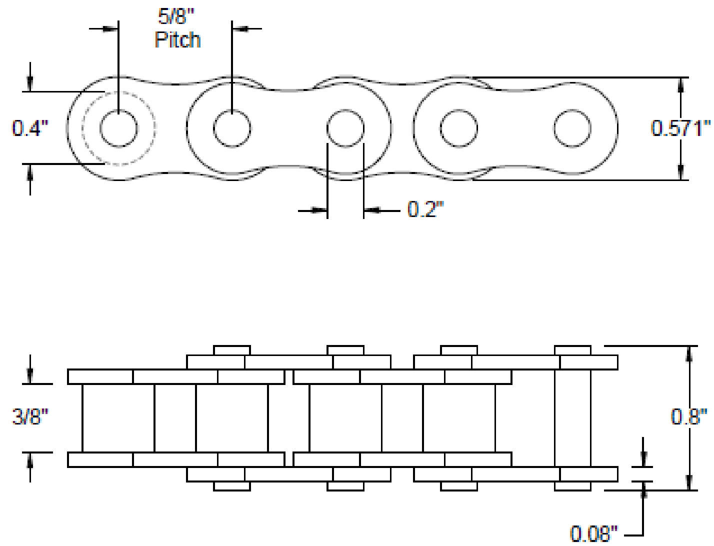

Figure 3: ANSI #50 Chain Link Segment

Due to the torque requirement from the electrical generator, a steel sprocket with dimensions shown in Figure 4 was chosen in order to properly match with the chosen ANSI #50 chain as well as provide the correct moment arm with the calculated force from the bucket. Due to manufacturing limitations and cost considerations, the 12.3-inch diameter sprocket was the maximum diameter available. A larger diameter sprocket, however, would have been beneficial as it would provide a larger torque arm.

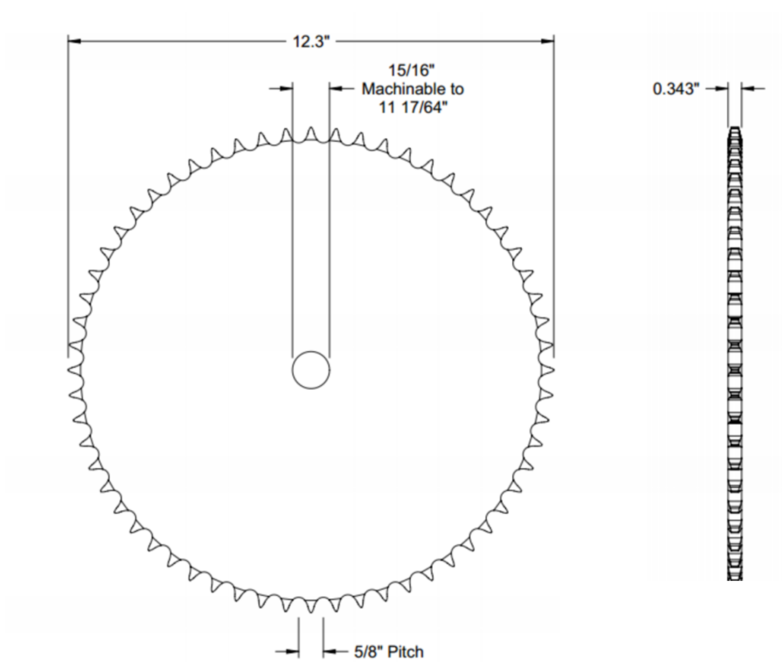

Figure 4: ANSI #50 Sprocket

With the chain, sprockets, and buckets sized, an approximation of the weight and force on the system was calculated and a 0.5-inch diameter aluminum shaft was found suitable to withstand the forces from the prime mover assembly. This shaft was later replaced with a 0.5-inch diameter steel shaft due to bending in the initial design. Finally, the bearings could be sized based on the shaft diameters and projected RPM. A polytetrafluoroethylene (PTFE) filled bearing was chosen with the dimensions seen in Figure 5 in order to properly rotate when submerged underwater.

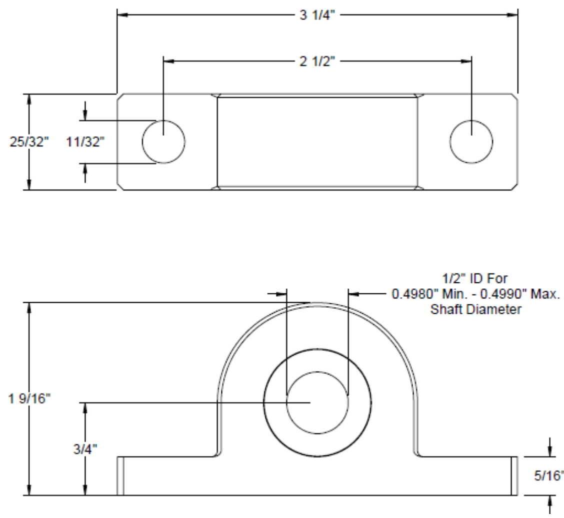

Figure 5: Mounted PTFE Sleeve Bearing

3. Bucket Attachment

The next phase of the prime mover design included the attachment of the plates to the chain. Chain attachment pieces with tabs to bolt onto were found to match the ANSI #50 dimensions of the specified chain. This attachment piece and its dimensions can be seen in Figure 6.

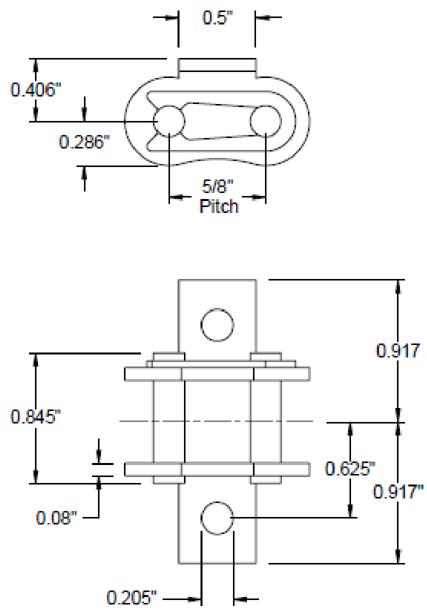

Figure 6: ANSI #50 Chain Attachment Piece

In order to make the prime mover system fully submersible, the buckets must collapse at the top of the rotation around the sprocket system to produce minimal drag through the water. A one-foot piano hinge was chosen for this purpose, welded onto the bottom of each bucket, and then bolted onto the respective chain attachment pieces. This allows for the buckets to rotate from a position parallel to the chain for rotating at minimal drag to a position perpendicular the chain for capturing the force of the water. Nine buckets were attached to the chain to provide sufficient room for plate folding based on the length of the prime mover.

4. Housings and Structures

In order to function properly, the prime mover, energy transfer, generator, and other systems must be secured. This is accomplished through the use of housings and structures. In the prime mover system, the prime mover plates are attached to a chain, which drive two sprockets. The two sprockets drive a shaft that interfaces with energy transfer system. All of these components are secured within a frame, as shown in Figure 7.

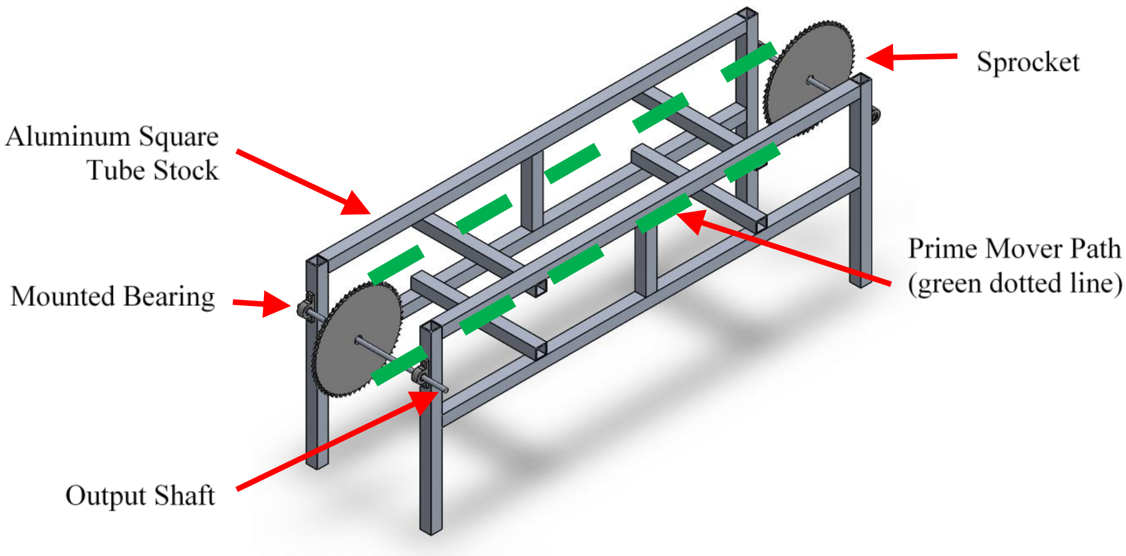

Figure 7: Frame

The frame designed to support the prime mover system was chosen to be constructed of square aluminum tube stock. Aluminum was chosen as a material because it is strong, light, relatively inexpensive, and has some resistance to corrosion. For strength, stiffness, and simplicity the frame was welded together. Square tube stock was chosen because it provides relatively large flat surfaces that make welding the frame easier than if round tube stock were used. Also, square tube stock spreads out joint forces over a larger surface area of material, which allows joints to withstand greater forces without failing.

Each square tube has a cross-sectional width of 1.5-inches and has a thickness of 0.125-inches. The frame is 17-inches wide, with a 14-inch space between leg members. The 14-inch space between leg members allows for the 12-inch wide plates to pass freely between the leg members. The frame, excluding the length of the legs, is 12-inches high, with the legs extending down 12-inches from the rest of the frame. The frame is approximately five feet in length (60-inches), which allows for nine prime mover plates to be attached to the chain that rotates around the sprockets, the path of which is shown by the green dotted lines in Figure 7.

III. RESULTS

A. Generator

Testing was performed to determine the electrical properties of the F&P generator. A pair of batteries were used as a load and voltage and current measurements were taken at different RPM's. From the measured values of current and voltage, the power output was calculated.

An endurance test was also performed to observe how the two generators act in response to being run for a period of two hours. The generators were connected to the same load as before, and temperature measurements were taken at two different locations every 30 minutes.

The results of the testing provided the necessary RPM needed by the prime mover in order to produce 50 Watts. This data can be seen in Tables 1 and 2 and Figure 8.

Drive Motor (RPM)	Generator (RPM)	Generator VDC (V)	I DC (A RMS)	Pout (W)
0.0	0.0	22.8	0.0	0.0
0.0	150.0	23.2	0.0	0.0
150.0	156.0	23.5	2.4	56.4
180.0	186.0	24.0	4.9	117.6
213.0	218.0	24.5	7.3	177.6
266.0	272.0	24.7	9.6	237.1
340.0	349.0	25.0	11.4	286.1
415.0	427.0	25.2	12.4	311.9
484.0	500.0	25.2	13.0	326.8
550.0	572.0	25.2	13.3	334.8

Table 1: F&P 24V Battery Load Test Data (2 in Series, 6 pairs in Parallel)

403 RPM @ generator			Temp (F)				
(VFD=16Hz)	Time	Time (min)	Rotor	Winding	Voltage (VDC @ battery terminals)	Battery Amps	Power
	3:30	0	79	89	24.24	0	0
	4:00	30	83	116	26.49	11.5	304.635
	4:30	60	83	115	26.68	11.69	311.8892
	5:00	90	85	115	27.01	11.4	307.914
	5:30	120	84	111	28.13	10.1	284.113

Table 2: F&P Durability Test

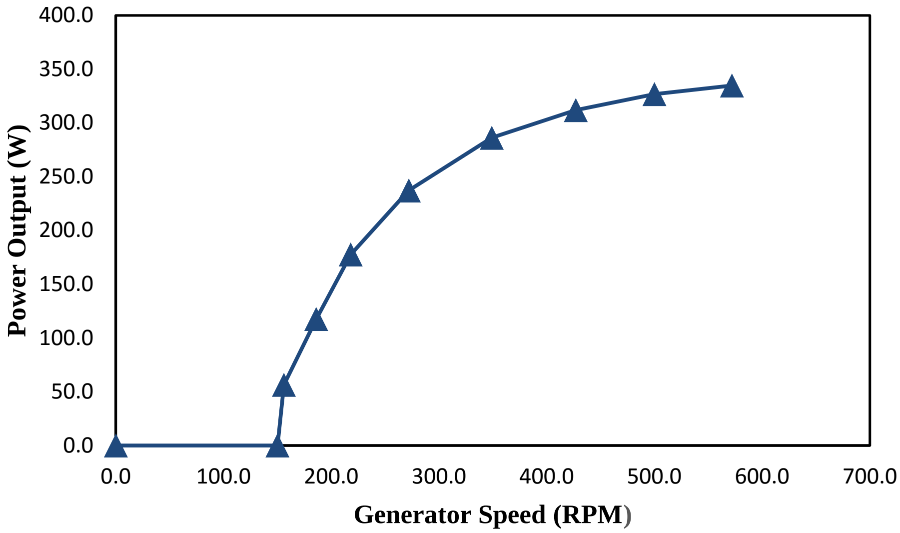

Figure 8: F&P Power Output vs. Generator Speed

B. Prime Mover

The prime mover was tested on the Cowlitz River and Mayfield Lake in Washington. Initial testing occurred on the Cowlitz River with the prime mover system suspended from a raft. The Cowlitz was estimated to be flowing from 2.5 to 3 miles per hour (mph) in the testing location. The plate rotational speed was measured and later converted to a sprocket rotational speed in order to determine the needed gear ratio. Both the RPM and the observed torque were significantly less than previously calculated. This required multiple changes to the prime mover before considering a proper gear ratio.

After changes were made to the prime mover, including adding a fender and moving the bearings closer together, secondary testing was required. The secondary testing required towing the prime mover behind a boat on Mayfield Lake in order to simulate a faster flow speed. The boat was run at various speeds providing data at both 3 and 5 mph. The plate rotational speed was again measure and converted to a sprocket rotational speed. The observed torque appeared to be significantly higher than the original testing, however, no exact value was obtained. Results from the secondary testing provide a gear ratio that is on the verge of successful power output. However, due to time constraints, a third testing with an energy transfer system was not able to be completed. The summary of the results from the various tests can be seen in Table 3.

Test Day 1 (Original Design)		**Test Day 2** (Modified Design)			
Estimated Flow Speed Range 2.5 - 3.0 mph (~ 1.12 - 1.34 m/s)		Approximate Flow Speed 3.0 mph (~ 1.34 m/s)		Approximate Flow Speed 5.0 mph (~ 2.24 m/s)	
Measured Plate Rotational Speed (RPM)	3.5	Measured Plate Rotational Speed (RPM)	5	Measured Plate Rotational Speed (RPM)	5.5
Measured Sprocket Rotational Speed (RPM)	14.88	Measured Sprocket Rotational Speed (RPM)	21.25	Measured Sprocket Rotational Speed (RPM)	23.18
Estimated Sprocket Torque Range (ft-lb)	1.0-5.0	Estimated Sprocket Torque Range (ft-lb)	5.0-15.0	Estimated Sprocket Torque Range (ft-lb)	10.0-20.0
Calculated Gear Ratio Required to Achieve Generator Cut-In RPM	1.0:11.0	Calculated Gear Ratio Required to Achieve Generator Cut-In RPM	1.0:8.0	Calculated Gear Ratio Required to Achieve Generator Cut-In RPM	1.0:7.5
Estimated Torque Range after Speed Increase (ft-lb)	0.10-0.48	Estimated Torque Range after Speed Increase (ft-lb)	1.88-5.65	Estimated Torque Range after Speed Increase (ft-lb)	4.31-8.63

Table 3: Testing Results

IV. CONCLUSIONS

Team INT 15.4 designed and built a prototype prime mover that was to be mechanically connected to an electrical generator to output the 50 to 200 Watts requested. After testing the prime mover operation in many different environments, the team found that the original design was not able to produce the RPM or torque necessary. The design of the prime mover was then modified to try to improve those aspects and increase efficiency. Unfortunately an electrical generator was not able to be connected.