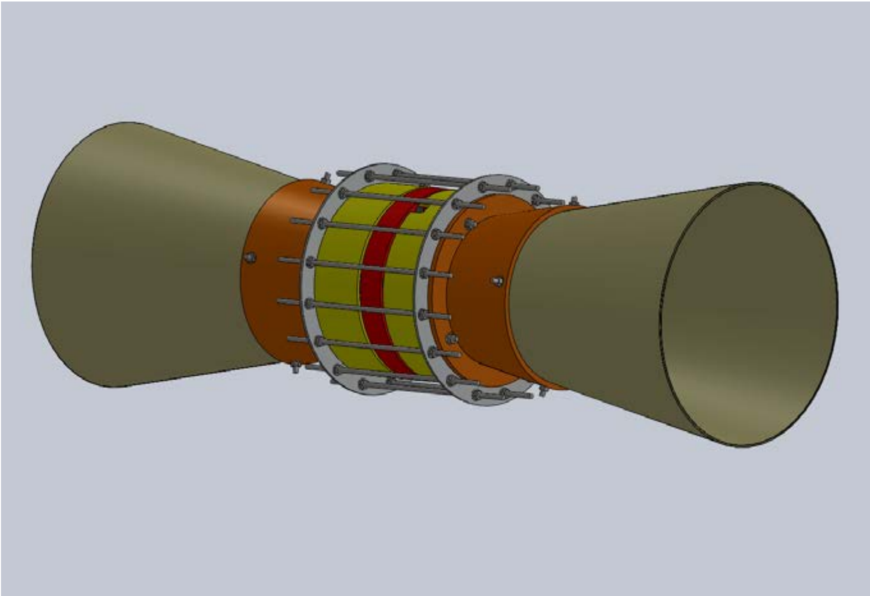

Final Design Review: Ducted Hydro Turbine

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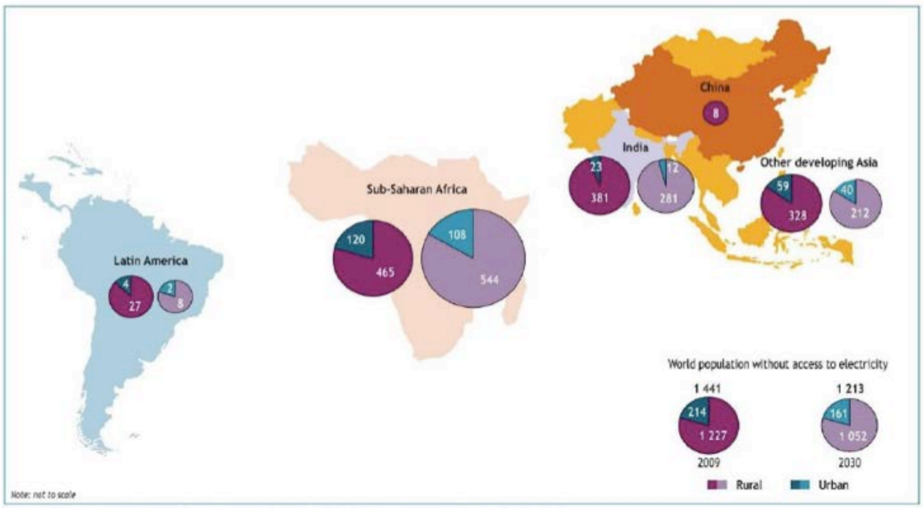
The Idea

1,441 Million People Lack Basic Access to Electricity



- An additional 1 billion people do not have access to reliable electricity networks
- Energy is critical to sustainable development and poverty reduction
- Without improved access to energy and energy services, very few of the world's development goals can be achieved
- United Nation's Millennium Goal: Eradicate extreme poverty and hunger

Other Challenges

- 85% of people living without electricity are located in rural regions
- Low population density and large geographical separation from major urban centers makes grid connection costly
- Many of these villages in developing countries with strained budgets and electricity infrastructures
- Low chance these inhabitants will gain grid access

Providing Access to Electricity and its Impact

- **Agriculture:** efficiently plough their lands to sell their crops, installing water systems for irrigation
- **Water use:** water purification, distribution, sanitation facilities, improving access to water
- **Food preparation:** use of electric stoves, reduce indoor air pollution
- **Health care:** refrigerate medicines, improve ventilation
- **Education:** distance learning possibilities, lighting of classrooms
- **Telecommunication:** strengthening infrastructure linkages that facilitate economic cooperation

Potential Uses of Electricity

Type of Appliance	Power Requirements	Purpose
Radio	70-120 watts	News/Entertainment
Television	100-150 watts	News/Entertainment
Fan	50-250 watts	Cooling/Ventilation
Computer	50-130 watts	Information
Water Purifier	100-200 watts	Water Processing
Cell Phone	1-5 watts	Communication
Lamps/Lights	40-200 watts	Lighting

How We Can Help

Vision:

Provide a cheap, sustainable, off-grid source of electricity to isolated communities in order to improve access to useful technologies and increase quality of life.

Goals:

The hydro-turbine needs to be able to function efficiently and reliably to power essential electrical appliances. Furthermore, it needs to be be inexpensive and easy to use and maintain.

Key Design Parameters

Product Characteristics	**Design Parameters**
Maximize Power Output/Minimize Power Loss	• Low intensity uses – eg: lighting, cooking, ventilation
Accessible electrical load	• Charge a portable battery • Cycling packs of battery • Aim for 100+ Watt output capacity
Ease of Use	• Ensure sufficient mechanical torque for generator self-start: minimum blade torque should be at least 10% greater than initial electrical torque • Prevent stalling: constant and moderate blade lift coefficient • Installation and disassembly possible within 2 hours with minimal labor

Key Design Parameters

Product Characteristics	**Design Parameters**
Rotational Stability	• Approximately 1/16" maximum shaft deflection
Durability/Ease of Maintenance	• Impact from small debris should not make turbine inoperable • Maximum screen mesh size $1cm^2$ to prevent debris from disrupting blades • Prevent frequent maintenance by designing for low component stress
Optimize for Physical Environment	• Floating device for easy fluvial use • Anchor should support 200% of the maximum theoretical system drag • Corrosion-resistant components
Inexpensive	• Use least expensive design possible • Goal: below ~ $500 for full product

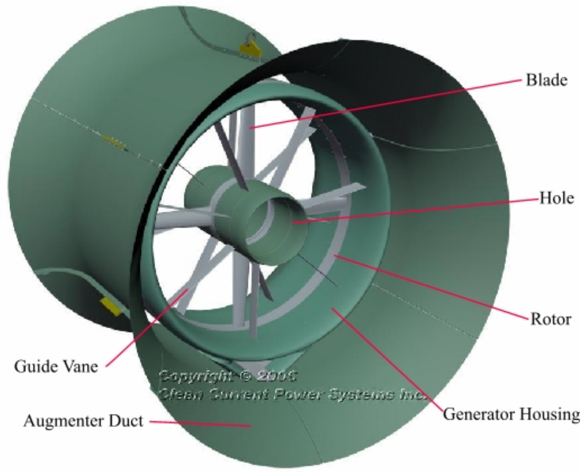
Existing Products

Amazon Aquacharger

- Unducted Horizontal-Axis Turbine
- Mounted to Boat
- Pros
  - Small Scale
  - Easy to transport and maintain
  - Inexpensive
- Cons
  - Mediocre Generation Performance
  - Requires a boat for operation
  - Non-orthogonal flow orientation

Clean Current Tidal Turbine Generator

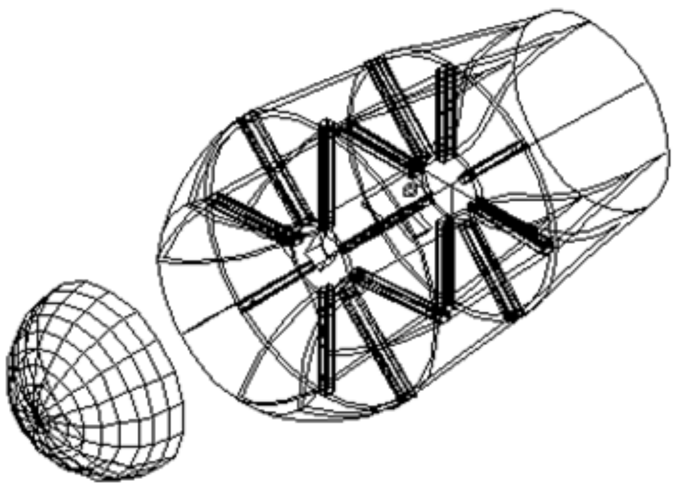
- Ducted horizontal axis turbine
- Rigidly attached to bottom
- Pros
  - No drive shaft or gearbox (PMG)
  - Magnets in blades, coils in duct
- Cons
  - Large Scale (250 KW)
  - Expensive
  - Sophisticated installation



Existing Products

Hydroreactor Stream Accelerator

- Horizontal-Axis ducted turbine
- Attached to an anchored float
- Pros
  - Venturi nozzle speeds up flow
  - Passively orients normal to flow
- Cons
  - Generator requires a watertight chamber
  - Long duct required for Venturi nozzle design
  - Large and Expensive

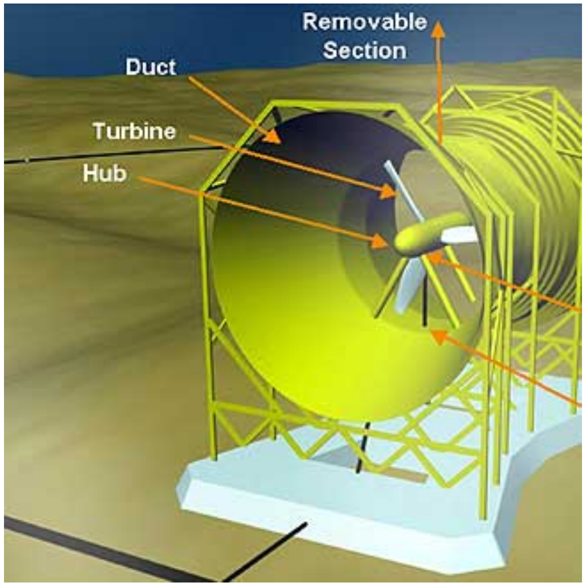


Kabold Turbine

- Vertical Axis Unducted Turbine
- Attached to floating barge
- Pros
  - Flow direction independent rotation
  - Large power output
- Cons
  - Large Scale
  - Sophisticated Installation
  - Expensive

Concepts: Project Scope

- Several design challenges:
  - Support Structure
  - Turbine/Duct Design
  - Rotary Infrastructure
  - Ease of Maintenance/Human Factors
  - Waterproofing
  - Electrical Transduction Optimization
  - Environmental Considerations
- Several of these will be the subject of design efforts
- Remaining ones will be considered as design parameters, but of lesser overall importance
- Project intent is to create working proof-of-concept prototype that can be used to ultimately create a small scale production turbine



Concept Evaluation: Overall Design

		Positioning System			Turbine Alignment		Flow Control	
Selection Criteria	Weighting	Tethered Barge	Riverbed Bolt	Bridge Attachment	Horizontal Axis	Vertical Axis	Ducted	Unducted
Maximize Power Output	5	4	4	4	5	4	4	2
Optimize for Physical Environment	4	4	1	3	3	4	4	2
Optimize for Flow Regime	3	4	5	4	4	3	5	3
Ease of Deployment	5	4	1	3	3	3	3	4
Ease of Manufacture	3	4	4	4	3	5	3	4
Ease of Retrieval	5	5	1	4	3	3	3	3
Serviceability	4	4	2	5	3	3	2	4
Aesthetics	1	3	5	3	4	3	3	3
Durability	4	3	5	3	4	3	5	3
Reliability	4	4	3	4	5	3	5	3
Weight	2	3	5	3	3	3	2	4
Cost	5	3	2	3	3	3	3	4
Result	1	2.88	2.10	2.72	2.68	2.50	2.67	2.42

Conclusion: Hydro-Turbine design will incorporate a *tethered barge*, a *horizontal axis turbine assembly*, and an *external duct* for flow control and optimization

Concept Evaluation: Design Focus

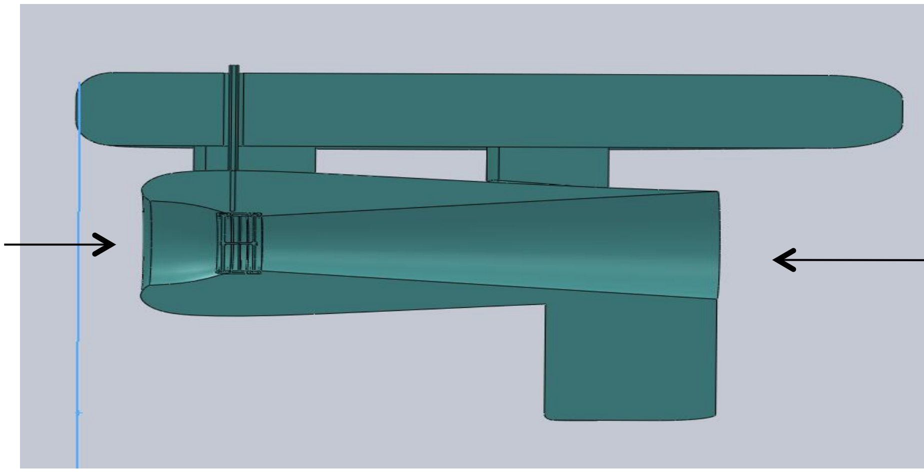
	Transmission Method			Transduction Method			Bearing Type		
Selection Criteria	Geared Shaft	Geared Rotor Ring	Magnetic Transmission	Geared Motor	PMG	Solenoid Reciprocation	Ball Bearing	Fluid Lubricate Journal Bearing	Smooth Thrust Bearing
Minimize Power Loss	0	0	0	+	+	-	-	+	0
Ease of Startup	-	+	+	-	+	0	-	0	0
Optimize for Physical Environment	-	-	+	+	+	0	-	0	+
Rotational Stability	+	0	0	0	0	-	+	+	-
Ease of Manufacture	0	-	-	0	-	0	+	0	0
Serviceability	0	0	0	0	-	0	-	-	+
Durability	+	-	0	+	+	0	-	0	-
Reliability	0	-	+	+	+	0	+	+	+
Weight	0	0	0	-	0	+	0	0	0
Cost	0	-	0	0	0	0	0	0	+
Sum of '+'s	2	1	3	4	5	1	3	3	4
Sum of '0's	6	4	6	4	3	7	2	6	4
Sum of '-'s	2	5	1	2	2	2	5	1	2
Score	0	-4	2	2	3	-1	-2	2	2
Rank	2	3	1	2	1	3	2	1	1

Conclusion: Transmission infrastructure will consist of ***magnetic transmission*****,** ***permanent magnetic generation*****, and a bearing system that combines the functions of** ***thrust and journal bearings***

The Product

Overview of System Fluid Mechanics

$$P_{T_U} = P_\infty + \frac{1}{2}\rho V_U^2 \longrightarrow$$



$$\longleftarrow P_{T_D} = P_\infty + \frac{1}{2}\rho V_D^2$$

$$\Delta P = P_{T_U} - P_{T_D} = \left(P_\infty + \frac{1}{2}\rho V_U^2\right) - \left(P_\infty + \frac{1}{2}\rho V_D^2\right) = \frac{1}{2}\rho(V_U^2 - V_D^2)$$

$$\rho V_U A_U = \rho V_P A_P = \rho V_D A_D \longrightarrow V_D = V_P\left(\frac{A_P}{A_D}\right)$$

$$\Delta P = \frac{1}{2}\rho\left(V_U^2 - V_P^2\left(\frac{A_P}{A_D}\right)^2\right) \longrightarrow V_P = \left(\frac{A_D}{A_P}\right)\sqrt{V_U^2 - \frac{2\Delta P}{\rho}}$$

$$\overline{W} = V_P A_P \Delta P$$

$$\overline{W} = \left(\left(\frac{A_D}{A_P}\right)\sqrt{V_U^2 - \frac{2\Delta P}{\rho}}\right) A_P \Delta P = \Delta P A_D \sqrt{V_U^2 - \frac{2\Delta P}{\rho}}$$

$$\boxed{\Delta P_{max} = \frac{\rho V_U^2}{3}} \qquad \boxed{\overline{W}_{max} = \frac{\rho V_U^3 A_D}{3^{1.5}}}$$

Fluids Design Specifications

Quantity	Value
Radius at Blade Disk	**4.00”**
Downstream Duct-Disk Area Ratio	2.0
Rear Duct Radius	**5.65”**
Rear Duct Angle	**5.0^{o}**
Rear Duct Length	**18.93”**
Inlet Velocity	3.0 mph
Velocity at Blade Disk	3.5 mph
Optimal Pressure Drop	**600.0 Pa**
Optimal Power Delivered	**30.0 W**
Betz Limit Power	22.6 W
Theoretical Power-Betz Power Ratio	**1.33**

Review of Blade Design Principles

- Blades translate pressure drop into torque
- Need two basic quantities
  - Blade twist
  - Blade taper
- Most quantities are set by system constraints or physical optimization
  - Radius
  - Velocity
  - Pressure drop
- Major optimization variables:
  - Blade number
  - Angle of attack
  - Frequency
- Design Issues:
  - Design against stall
  - Blade structural integrity
  - Adequate torque for self-start
  - Design for constant lift coefficient

$$\frac{dF}{dr} = 2\pi r \Delta P = N\rho\omega r\Gamma$$

$$T_L = \frac{P}{\omega} = \frac{\Delta P A_P V_P}{\omega} = \frac{\pi(R_P^2 - R_0^2)V_P \Delta P}{\omega}$$

$$\frac{1}{2}\rho V_R^2 c c_l = \frac{1}{2}\rho((\omega r)^2 + V_P^2)c c_l = \rho V_R \Gamma$$

$$c_l = 2\pi\alpha \quad 0.1 < c_l < 1 \quad \phi = \tan^{-1}\left(\frac{\omega r}{V_P}\right)$$

$$c(r) = \left(\frac{1}{\alpha N}\right)\left(\frac{2\Delta P}{\omega\rho}\right)\left(\frac{1}{\sqrt{(\omega r)^2 + \left(\frac{V_U A_U}{A_P}\right)^2}}\right)$$

$$\beta = \alpha + \phi = \alpha + \tan^{-1}\left(\frac{\omega r}{V_P}\right)$$

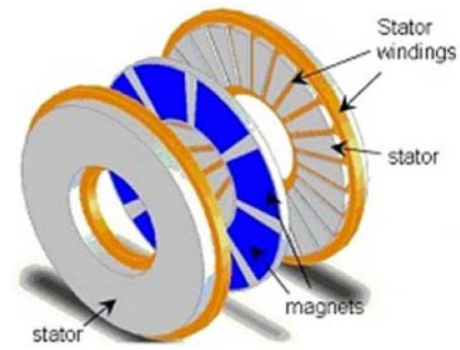
Blade Geometry Specification

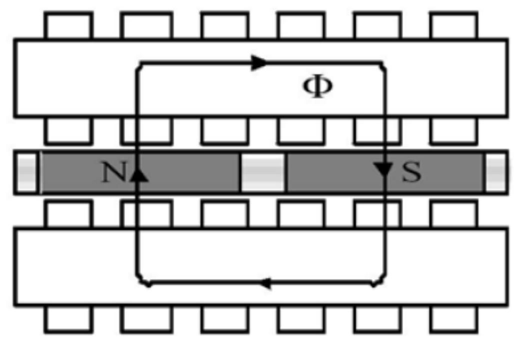
Quantity	Value
Blade Number	6
Tip-Speed Ratio	0.10
Angular Frequency	1.5 Hz
Mechanical Efficiency (Assumed)	0.6
Efficiency Adjusted Power Delivered	**18 W**
Available Torque	**1.91 N-m**
Lift Coefficient Per Unit Span	0.6
Flat Plate Angle of Attack (α)	5.47^{o}
Root Chord	**5.65”**
Tip Chord	**4.80”**
Root Angle of Attack (β)	**5.47^{o}**
Tip Angle of Attack (β)	**37.20^{o}**

Review of System Electrodynamics

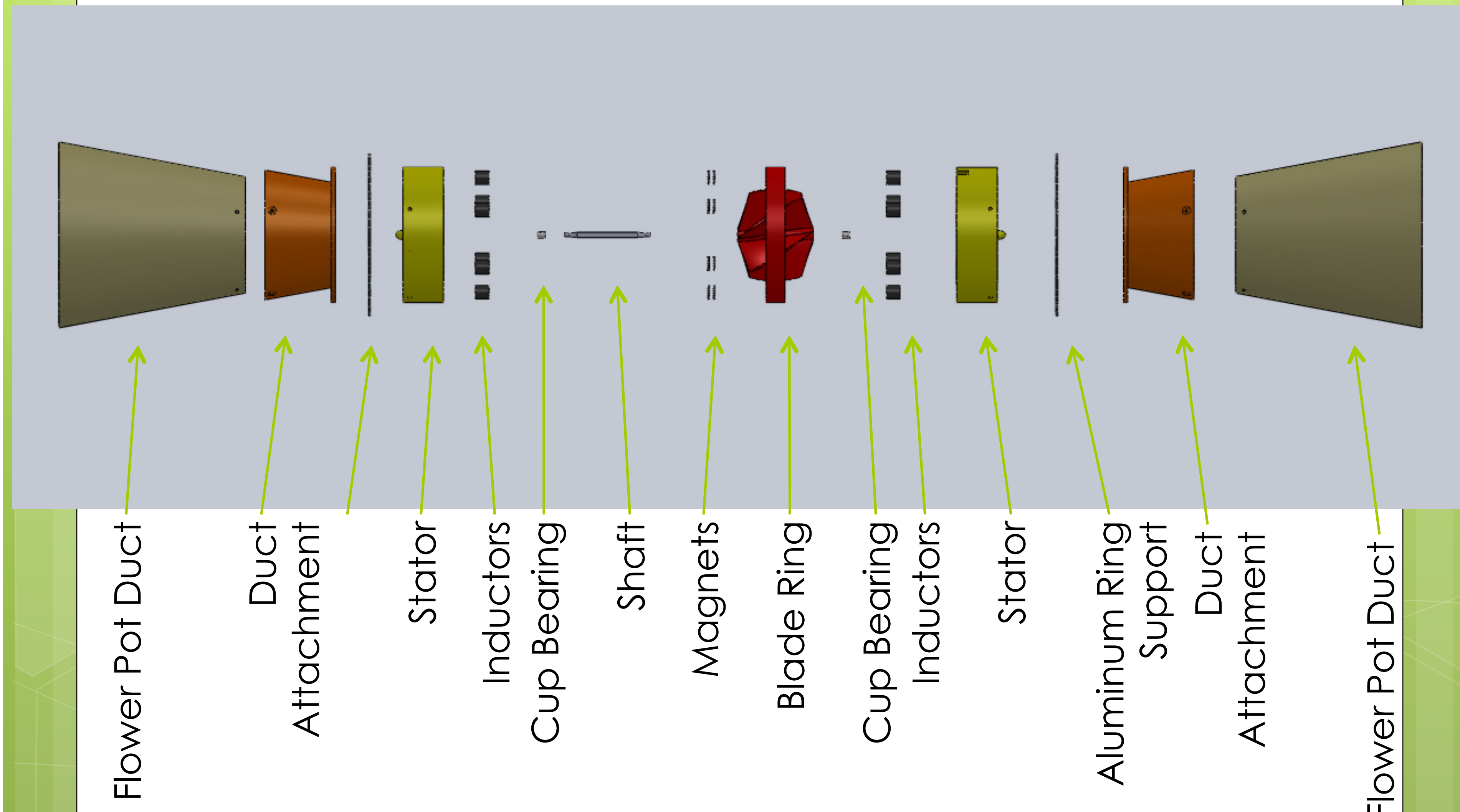
- Axial Flow Internal Rotor (AFIR) Permanent Magnetic Generator
- One Rotor-Two Stator Design
- Complex electrodynamics dependent on:
  - Pole pair number
  - Flux density
  - Pole Area
  - Inductive load
  - Stator voltage
  - Frequency
- Design Issues:
  - Maximum torque must be generated by turbine blades to maintain motion
  - Mutivariable optimization of output power

$$E = k_E \Phi \omega_e$$



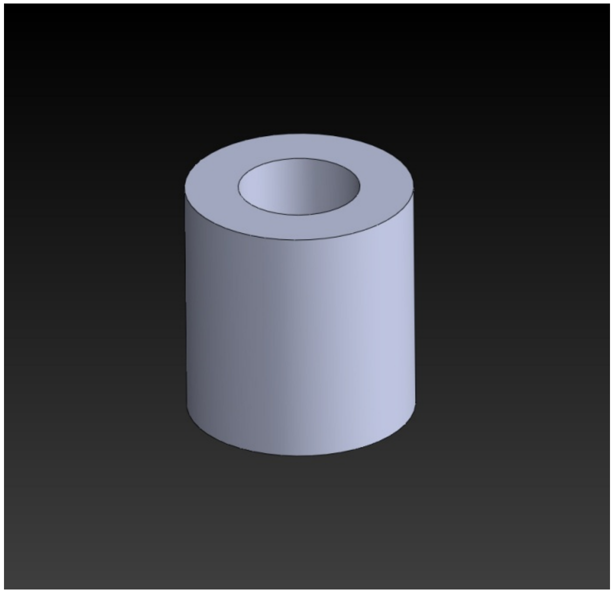


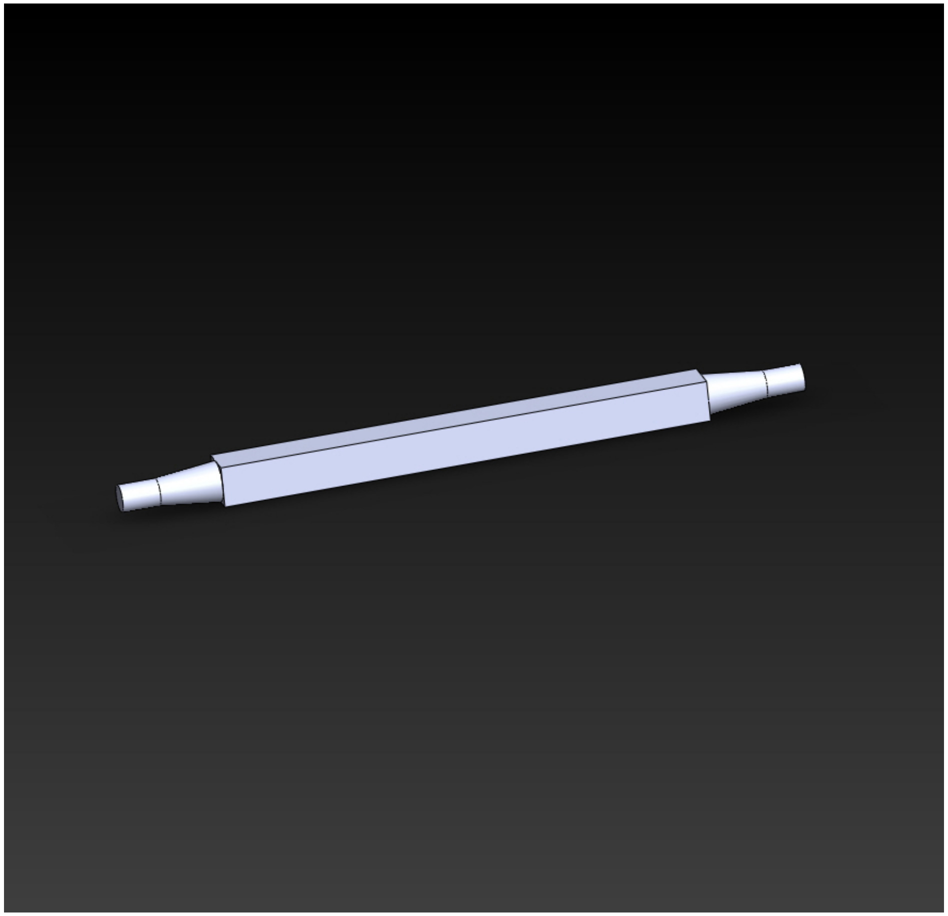
The Design



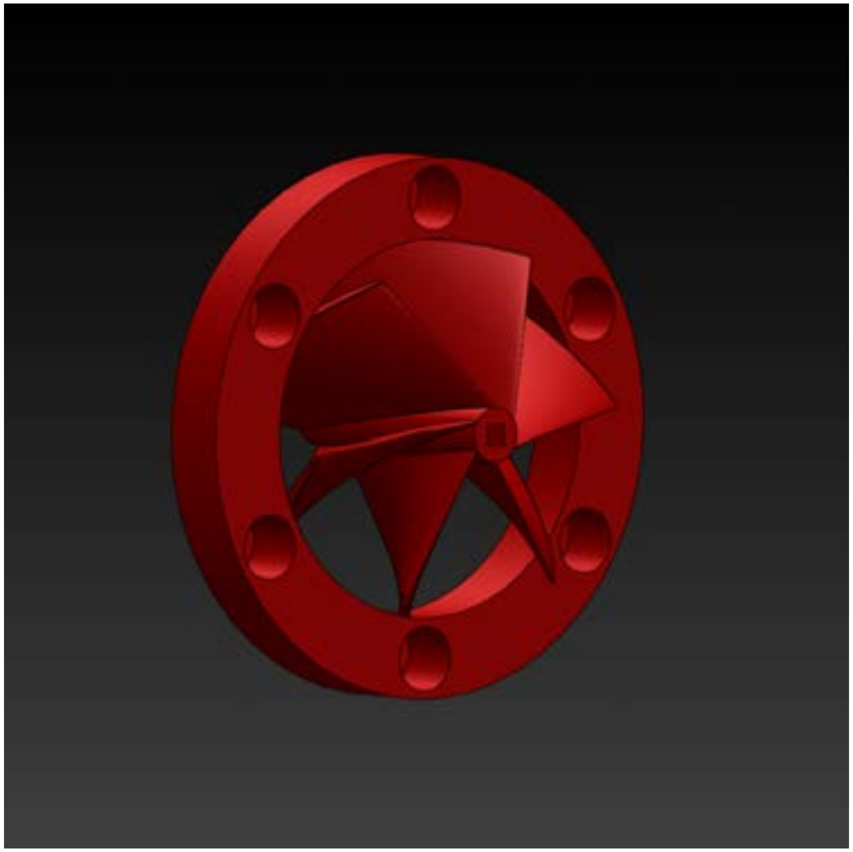
Flower Pot Duct
Duct Attachment
Stator
Inductors
Cup Bearing
Shaft
Magnets
Blade Ring
Cup Bearing
Inductors
Stator
Aluminum Ring Support
Duct Attachment
Flower Pot Duct

Cup Bearing & Shaft

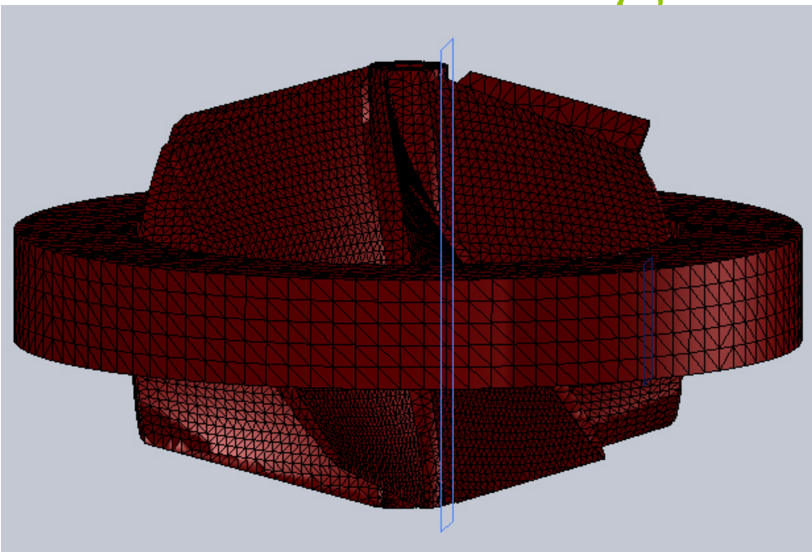


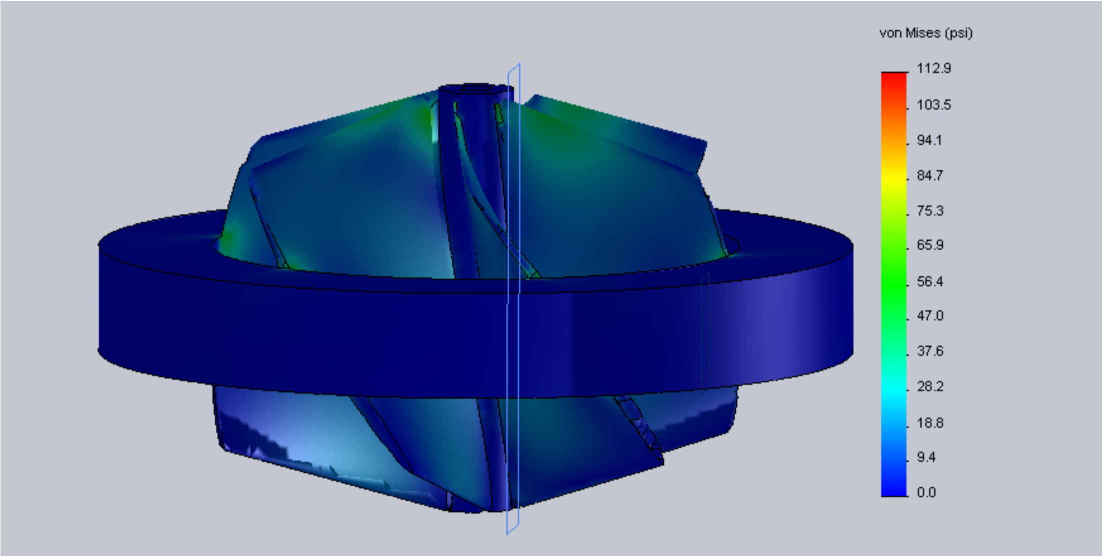


Blade Ring & Stator Ring

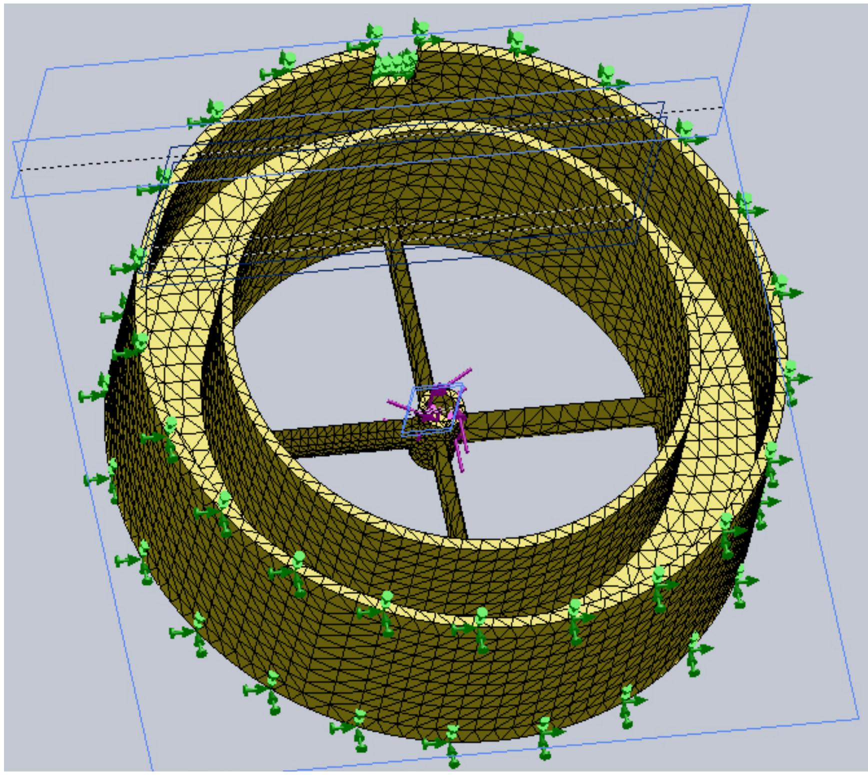


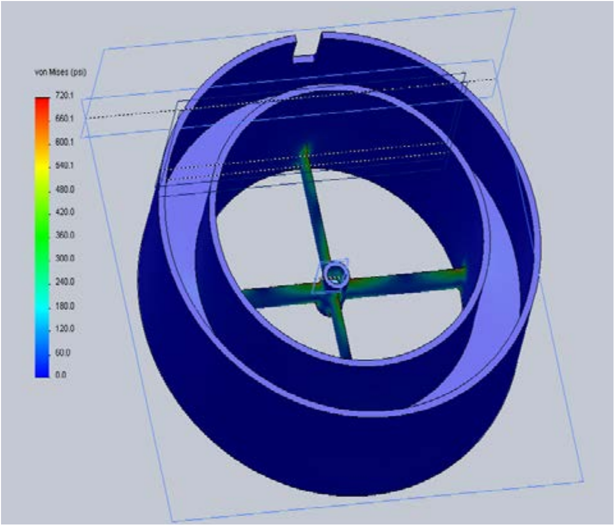
Blade Ring Mesh & FE Model

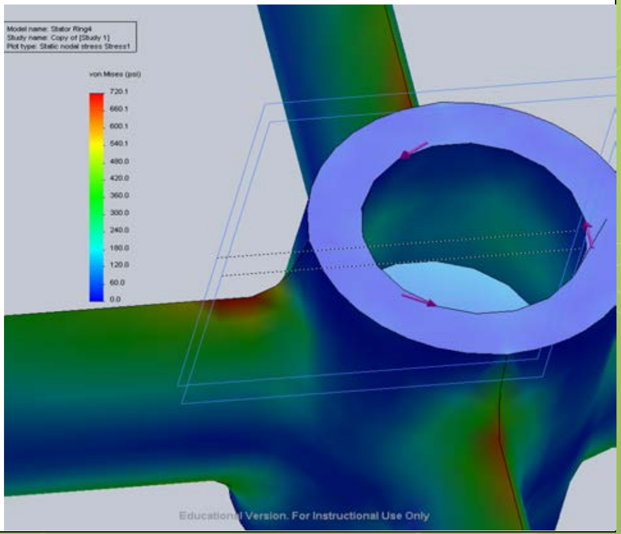




Stator Ring Mesh & FE Model

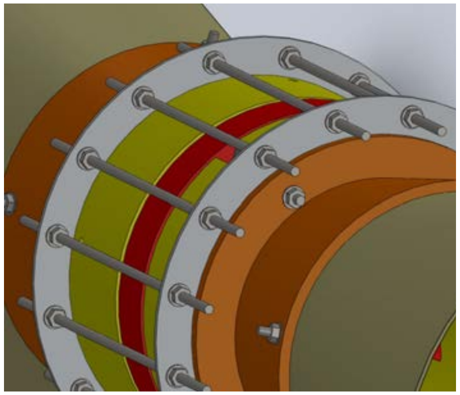


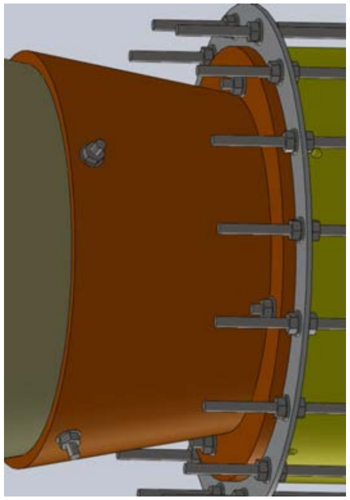


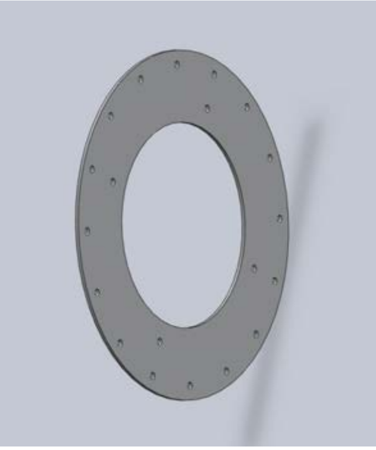


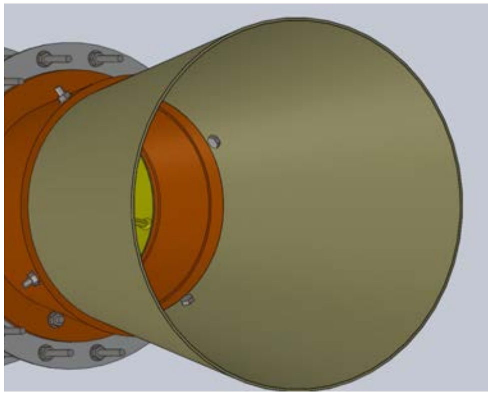
Design Updates

- Aluminum Rings
- Threaded Rods
- Printed Duct Starter
- Flower Pot Duct Attachment
- Extended Stators









Design Successes

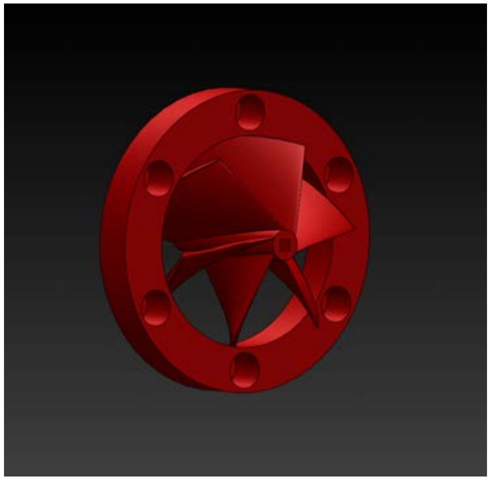
- Integrated PMG
- Threaded rods allow stator separation fine tuning
- Ducts have significant impact
- Electronics successfully potted
- Shaft spins efficiently in water
- Low blade startup torque
- Ease of setup, portability

Reliability/Durability

- Simple design
- Not intricate PMG
- Lightweight rotating parts
- Low torque
- Potential for debris
- Wave tank success

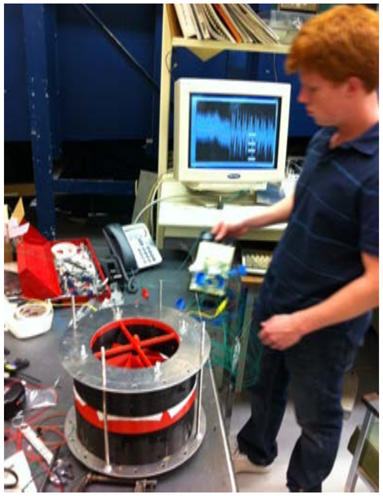
Experimental Design and Testing Plan

- Phase 1: Isolated Electromagnetics
  - Purpose 1: Confirm generation of electric power using moving magnets
  - Purpose 2: Ensure that waterproofing method does not affect magnetic flux propagation
  - Purpose 3: Determine optimal orientation of magnets and inductors
  - Procedure: Move magnets over basic induction coils, measure voltage; repeat procedure with potted magnet; vary inductor orientation relative to magnet
  - Completed 02/05/2011
- Phase 2: Isolated Blade Ring
  - Purpose 1: Confirm blade design effectiveness and self-start
  - Purpose 2: Investigate how low density plastic material behaves in water
  - Procedure: Push blade ring downwards into stagnant water on round shaft; release ring and visually determine startup
  - Completed 03/02/2011

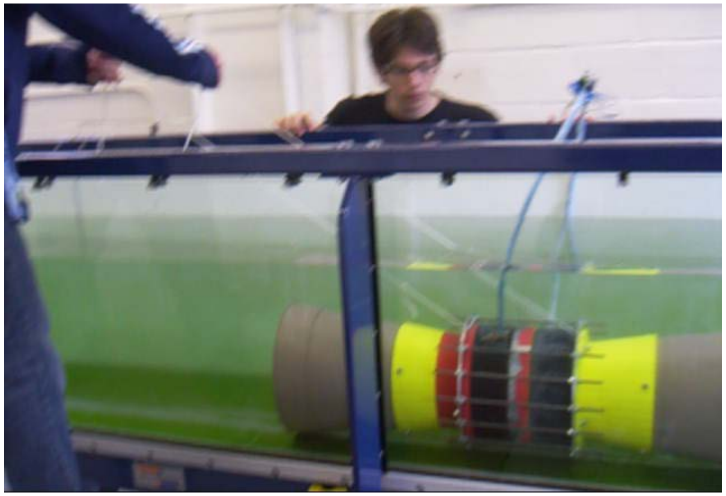


Experimental Design and Testing Plan

- Phase 3: Generator Testing
  - Purpose 1: Measure electrical output of complete generator with rotor and stators
  - Purpose 2: Determine relationship between open circuit voltage and generator frequency
  - Purpose 3: Determine effects of stator offset and magnet number on electrical performance
  - Procedure: Vary magnet number and inductor offset; collect voltage signal from turbine with Labview software using digital DAQ card
  - Completed 04/14/2011



- Phase 4: Wave Tank Testing
  - Purpose 1: Confirm effective water-borne operation of complete prototype
  - Purpose 2: Test design durability by buffeting the prototype with waves
  - Purpose 3: Determine relationship between flow velocity and turbine rotational speed
  - Procedure: Place turbine in Duke Wave Tank; propel with tow lines; measure distance, rotational speed, and time elapsed
  - Completed 04/23/2011

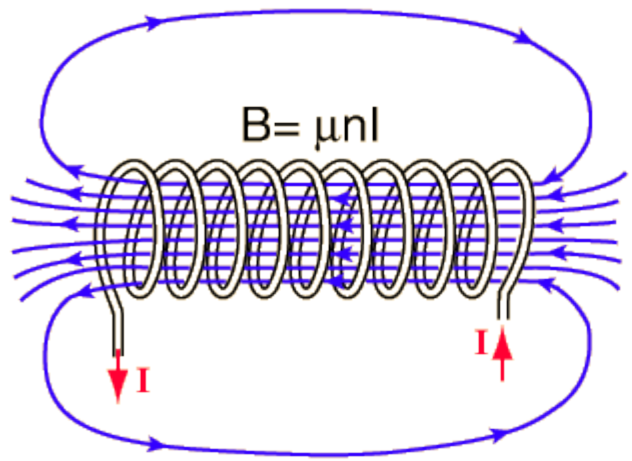


Experimental Design and Testing Plan

- Phase 5: Eno River Testing
  - Purpose 1: Confirm turbine self-start in an actual low-speed river environment
  - Purpose 2: Observe turbine operation actual environmental conditions
  - Purpose 3: Quantify performance improvement resultant from ducted design
  - Procedure
    - Transport turbine to Eno River
    - Place turbine in Eno River
    - Observe startup and measure angular speed
    - Determine flow speed using a floating object, tape measure, and timer
    - Estimate mechanical torque on blade ring
    - Remove ducts
    - Repeat startup and angular speed observations
  - Completed 04/24/2011

Test Results: Phases 1 & 2

- Phase 1:
  - Millivolt scale electrical signals detected within solenoidal coils
  - Voltage signal increases in magnitude with increasing magnet velocity
  - Voltage signal increases in magnitude with decreasing magnet distance
  - Voltage signal maximized for "top-down" inductor alignment
- Phase 2:
  - Rotor spins upward and self-starts
  - Plastic takes on significant amounts of water, but performance is not affected



The magnetic field is concentrated into a nearly uniform field in the center of a long solenoid. The field outside is weak and divergent.

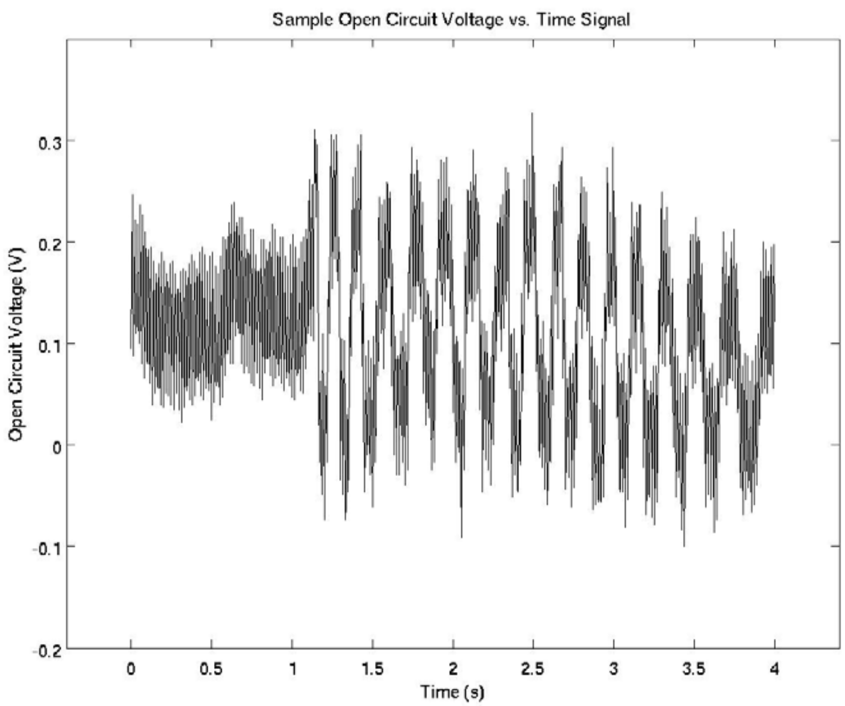
$$L = \frac{\mu N^2 A}{\ell}$$

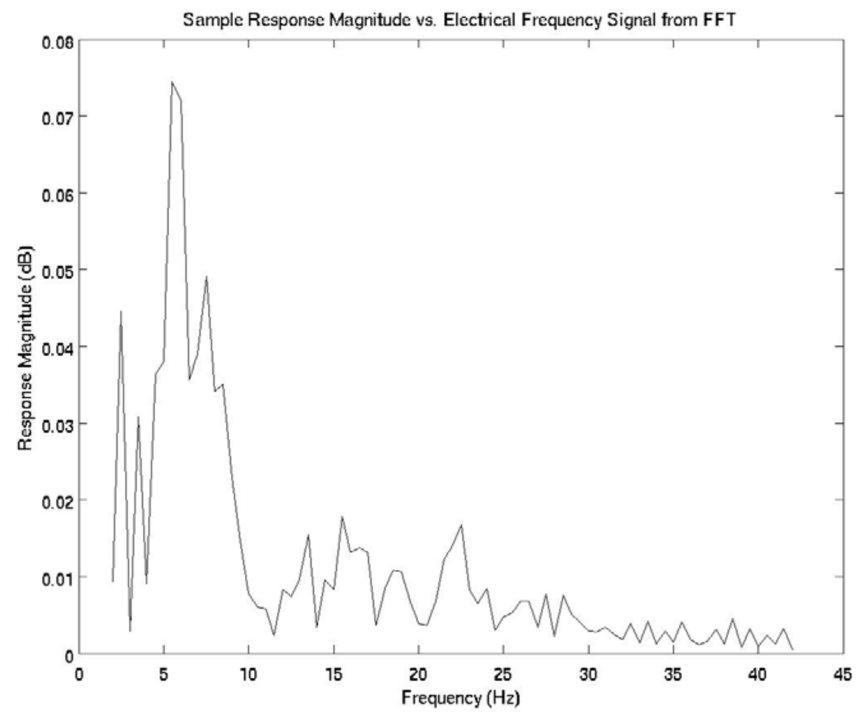
ℓ = length of solenoid

A = cross-sectional area

Test Results: Phase 3

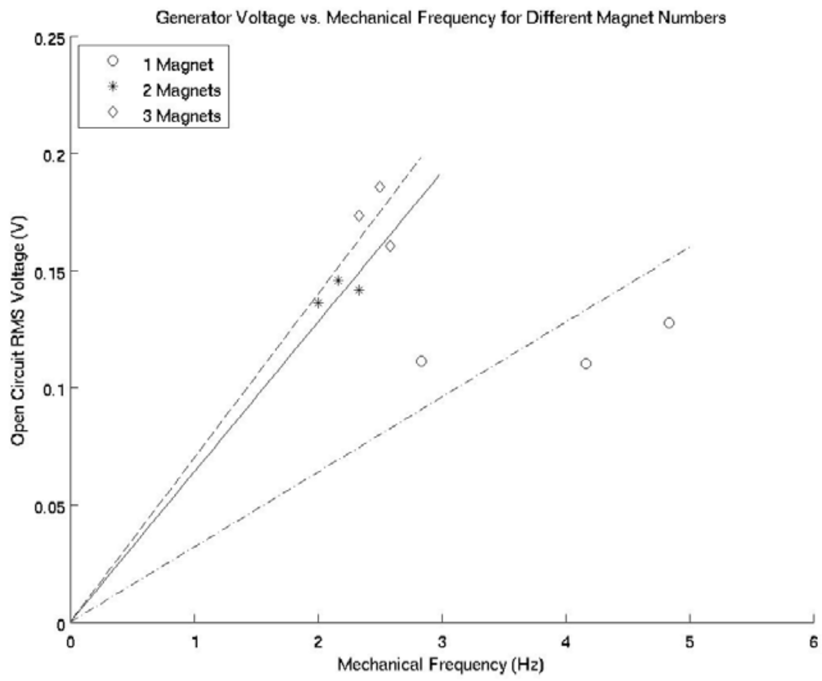
Data Acquisition and Signal Processing

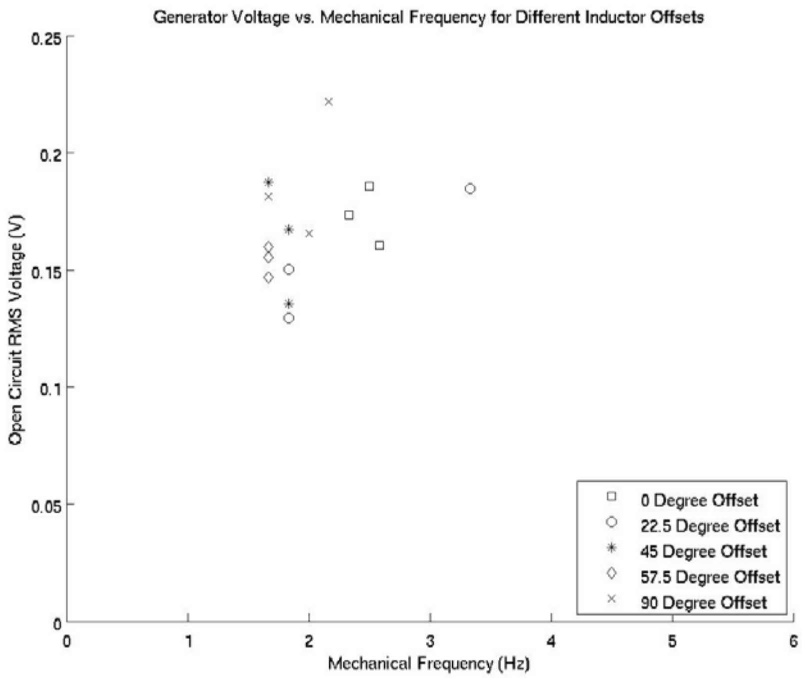




- Voltage time history signal acquired using custom LabView setup
- Fast Fourier Transform (FFT) code used to extract frequency data from voltage time history signal

Experimental Results: Phase 3
Data Processing, Analysis, and Conclusions

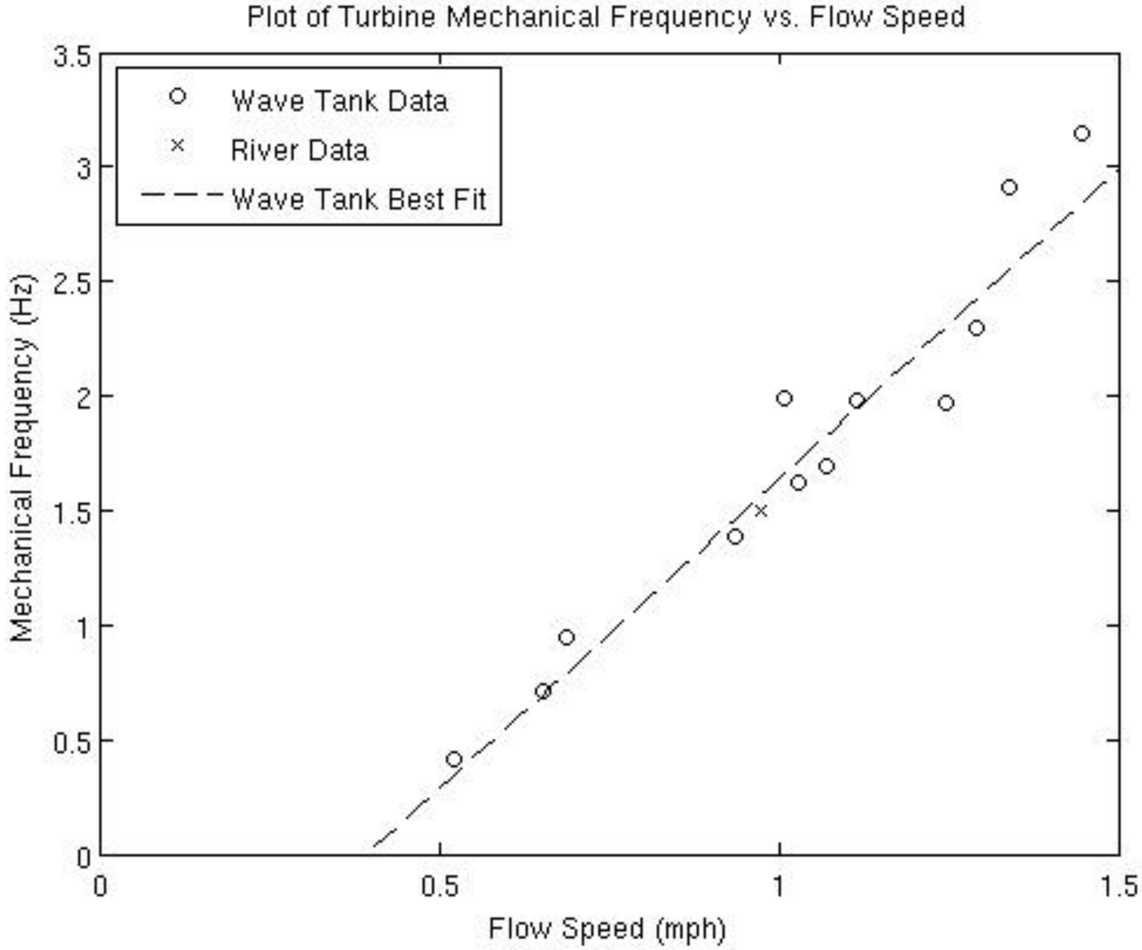




- Experiment 1: vary magnet number
- Result: Significant performance gain from second, less from third magnet

- Experiment 2: vary inductor offset angle
- Result: 90 degree offset appears optimal

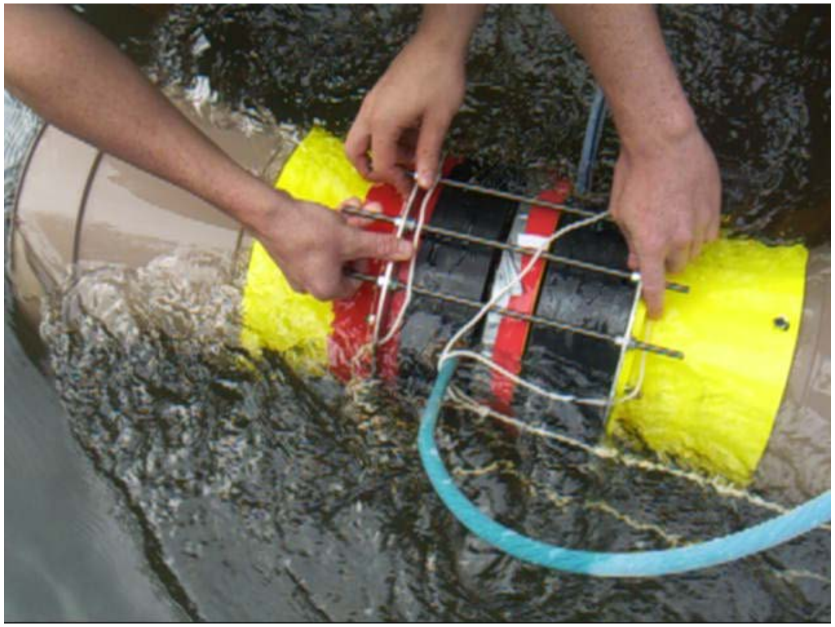
Test Results: Phase 4



Test Results: Phase 5

Turbine Self-Start in 1 MPH Flow Speed

Test Results: Phase 5
Ducting Effects



Ducted Turbine: 1.5 Hz

Unducted Turbine: 0.5 Hz

Potential Reasons for Improvement

Duct flow smoothing

Effective area increase

Pressure increase

Test Results: Phase 5

Power and Voltage Estimates

$$V_{RMS} \approx (0.064)(3\omega_{Mech}) = (0.064)(3)(1.5) = 0.288\,V$$

$$P_{Flow}^{Rotor} = \frac{1}{2}\rho V^3 A = \left(\frac{1}{2}\right)\left(1000\frac{kg}{m^3}\right)\left(0.447\frac{m}{s}\right)^3(\pi)(.0889\,m)^2 = 1.025\,W$$

$$P\downarrow Mech = T\omega = (0.14\ N-m)(9.425 rad/sec) = 1.330\ W$$

$$C_{P_{Mech}} = \frac{P_{Mech}}{P_{Flow}^{Rotor}} = \frac{1.330\,W}{1.025\,W} = 1.298$$

Future Work

- Impact of Potential System Improvements
  - Optimize magnet airgap: 4x increase
  - Increase magnet surface area: 4x increase
  - Increase coil surface area: 4x increase
  - Increase total size: 2x increase
  - Potential increase in electric power: 128x
- Further Development Areas
  - Design barge or anchoring system
  - Impedance match electrical load
  - Optimize flux capture ring size
  - Make tubing more robust & color code wires
  - Create screen to keep out macroscale debris
  - Optimize frequency-torque interaction
  - Define efficient manufacturing process
    - Injection molding of plastic components
    - Mass production of bearing, shaft, etc.
    - Supply chain for inductors, magnets, electronics

Implementation Site: Mekong Delta, Vietnam

- 4 million poor people living in the Mekong Delta
- Poor households often spend a large share of income on fuelwood or charcoal
- Education infrastructure is relatively good
- 65% of villagers have primary schools, higher than the national average of 54%
- Enrollment rate is one of the lowest
- Poverty has limited their opportunity to formal education

Cost Per Generator Unit

Description	Cost
1'x1'x.4" Sheet Metal X2 @ $14.68/unit	$29.36
3/8"by3/8" square aluminum shaft 8" length	$.75
Teflon Rod 5/8" Diameter, 2" length	$.90
Neodymium Disc Magnets X 24 @ .35/unit	$8.40
PVC Tubing	$7.90
Fiber Glass Resin X 2 @11.99/qt	$23.98
Inductors X 12 @ 4.85/unit	$58.20
Cap Screws	$4.40
Threaded Rod X 14 @ $2.21/unit	$30.94
Polymer Body	$12.00
Aluminum Sheet	$20.80
Electrical Wire 100 ft	$10.43
Flower Pot Duct X 2 @$5.49/unit	$10.98
Total	$219.04

Roll-out strategy

- Initial Targets: Villages in Mekong Delta, Vietnam
- Form relationships with NGOs operating in these regions
  - Specific NGOs in the region – East meets West Foundation, Vietnam Plus, Mekong River Commission
  - Arrange for test cases to demonstrate utility of product
  - Aim to provide around 100 units for initial venture

Milestones and Future Directions

Year 1
- Raising funds
- Joint venture with NGO

Year 2
- Vietnam

Year 3
- Laos
- Cambodia

Year 4
- Timor Leste

The end