## Final Report

# Submersible Generator for Marine Hydrokinetics

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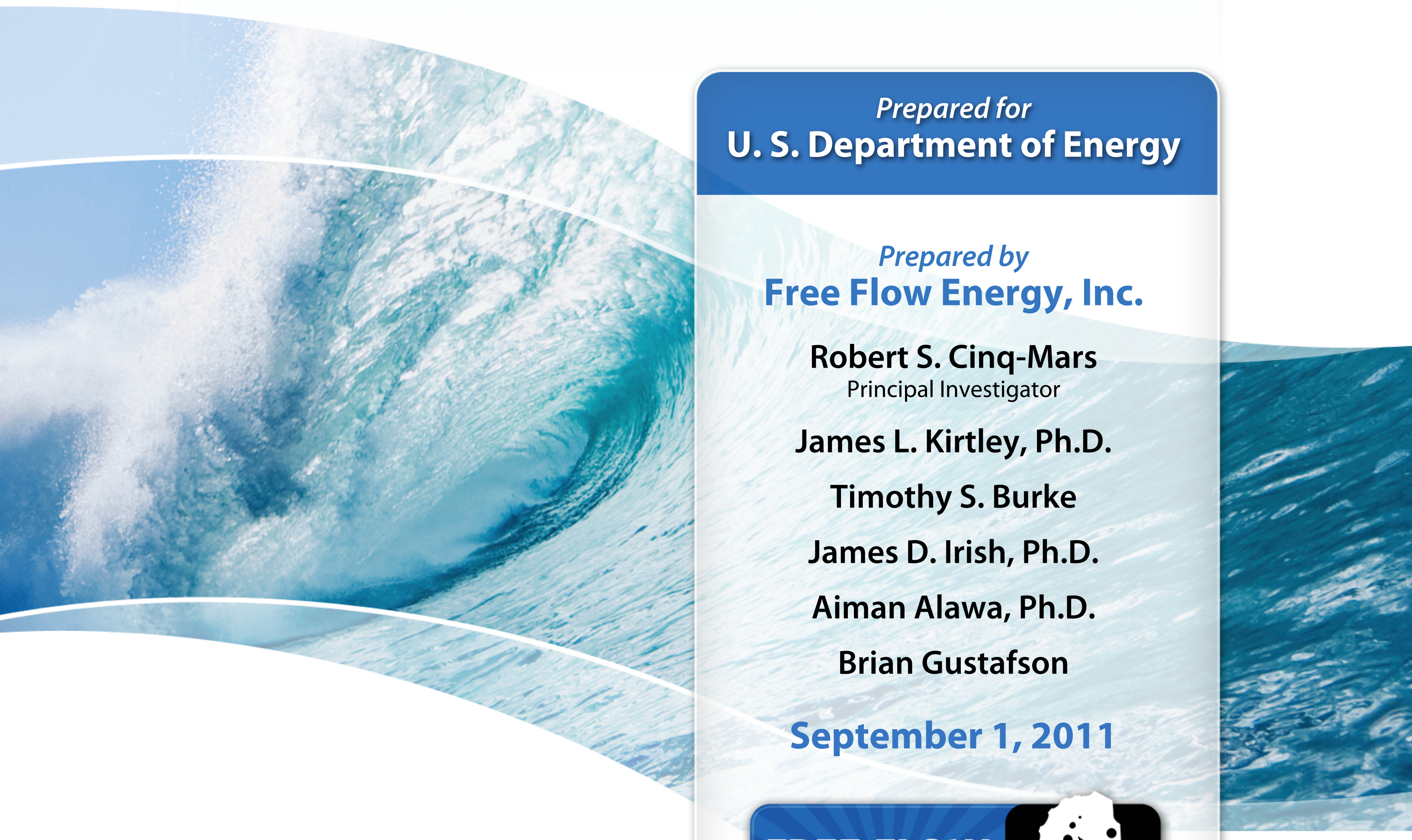

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# List of Symbols and Abbreviations

| **Symbol or Abbreviation** | **Description** | **Typical Units** |
|---|---|---|
| A | Area - as in cross sectional area of turbine to flow | $m^2$, $ft^2$ |
| D, d, or δ | Diameter - as diameter of turbine rotor | m, ft |
| R | Radius – as radius of turbine or generator | m, ft |
| v | Velocity – as in velocity of water | m/sec, fps |
| ω | Angular / rotational velocity | radians per sec |
| N | Number of blades or magnetic poles | integer |
| R | Electrical resistance | Ohms (Ω) |
| I | Electrical current | Amps |
| V | Electrical voltage (AC or DC) | Volts |
| TSR | Tip speed ratio | Dimensionless ratio |
| ρ | Water density (salt: 1025, fresh 1000) | kg / $m^3$ |
| cfs | Discharge or volume transport of water | cubic feet per second |
| P | Power as of flowing water or generator | kW, Watts |
| PPT | Parts per Thousand - as in Salinity of ocean water | 35 PPT |
| E | Energy-as of water or generator | kW-Hrs |
| eff | Efficiency as of turbine (typically 35% or 0.35) | Dimensionless ratio |
| channel discharge | USGS term for mass flow | cfs or cms |
| channel area | USGS term for channel cross sectional area | ft^2 or m^2 |
| channel velocity | USGS average water velocity in a channel | fps or mps |
| channel width | USGS reported channel width | ft or m |
| channel depth | Calculated as channel area / channel width | ft or m |
| MHK | Marine Hydrokinetics | |
| GHT | Gorlov Helical Turbine | |
| FERC | Federal Energy Regulatory Commission | |
| NID | National Inventory of Dams | |
| USACE | United States Army Corps of Engineers | |
| PTO | Power take off | |
| AFPM | Axial flux permanent magnet | |
| RFPM | Radial flux permanent magnet | |
| TFPM | Transverse flux permanent magnet | |

## List of Common Equations

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| **Equation** | **Description** |
|---|---|
| $\frac{P}{A} = \frac{1}{2} d * v^3$ | Power density from the kinetic energy of flowing water in Watts per unit area (100% efficiency) |
| $P = \frac{1}{2} d * A * v^3$ | Power of the kinetic energy of flowing water through a given area (100% efficiency) |
| $\frac{P}{A} = \frac{1}{2} d * v^3 * \mathrm{eff}$ | Power density of generator in Watts per unit area (35% efficiency) |
| $P = \frac{1}{2} d * A * v^3 * eff$ | Power of the kinetic energy of flowing water through a given area (35% efficiency) |
| $A = \pi r^2$ | Area of turbine or generator, typically using r as half of outermost diameter (OD) |
| $V_T = r\,\omega$ | Tangential velocity (of magnets some distance from a central axis) is equal to the product of the radius and the angular velocity. |

## Definitions

| Term | Definition |
|---|---|
| Vertical-axis-turbine | A turbine such as the Gorlov Helical, Darrieus, or orthogonal in which the rotating shaft or axis is perpendicular to the flow. Also called a cross flow turbine. |
| Horizontal-axis-turbine | A turbine such as that of FloDesign or Verdant Power in which rotor axis is parallel or in line with the flow. Also known as an axial flow turbine. |
| Drivetrain | The system of connections, linkages, gearing, etc. between the turbine and the generator or other power-take-off system. |
| Marine hydrokinetics | A term which has evolved from and encompasses ocean energy, in-stream, wave, tidal or river energy conversion. The present definition includes the provision that it be non-impoundment hydropower. The concept of ducting or shrouding to accelerate and direct flow into the turbine has not yet been fully clarified. |
| Coreless generator | A generator without an iron core which focuses and concentrates magnetic flux. In general this results in weight reduction, faster acceleration, and lower detent torque. |
| Axial-flux-topology | A motor / generator design in which the magnetic flux path between the magnet and coil is parallel to the axis of rotation. |
| Radial-flux-topology | A motor / generator design in which the magnetic flux path between the magnet and coil is 90 degrees to the axis of rotation – along the radius from the center of the rotor to the stator. |
| Detent torque | Torque ripple caused by the attraction of permanent magnets to the stator iron core. A magnetic rotor and stator poles tend to align themselves to positions of minimal reluctance. |

## Executive Summary

A submersible generator was designed as a distinct and critical subassembly of marine hydrokinetics systems, specifically tidal and stream energy conversion. The generator is designed to work with both vertical and horizontal axis turbines. The final product is a high-pole-count, radial-flux, permanent magnet, rim mounted generator, initially rated at twenty kilowatts in a two-meter-per-second flow, and designed to leverage established and simple manufacturing processes. The generator was designed to work with a 3 meter by 7 meter Gorlov Helical Turbine or a marine hydrokinetic version of the FloDesign wind turbine. The team consisted of experienced motor/generator design engineers with cooperation from major US component suppliers (magnetics, coil winding and electrical steel laminations). Support for this effort was provided by Lucid Energy Technologies and FloDesign, Inc.

The following tasks were completed:

- Identified the conditions and requirements for MHK generators.
- Defined a methodology for sizing and rating MHK systems.
- Selected an MHK generator topology and form factor.
- Completed electromechanical design of submersible generator capable of coupling to multiple turbine styles.
- Investigated MHK generator manufacturing requirements.
- Reviewed cost implications and financial viability.
- Completed final reporting and deliverables.

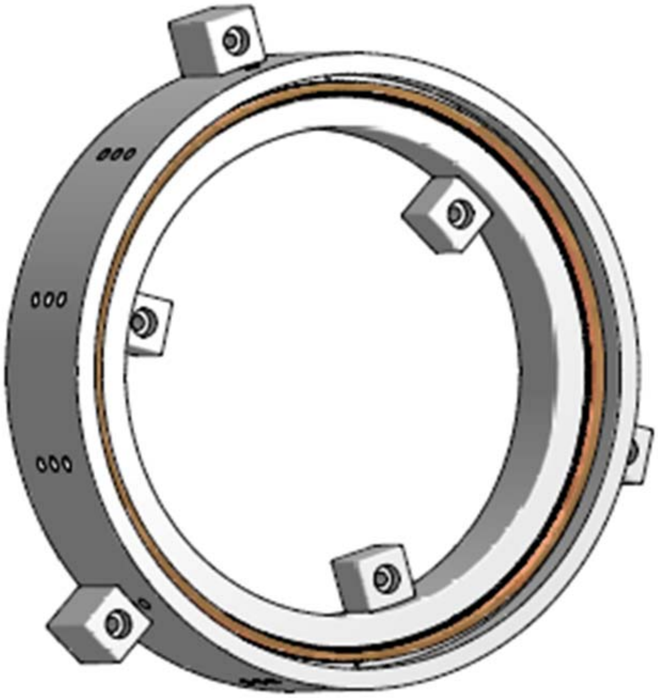

**Figure 1 MHK Generator**

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# PROJECT DESCRIPTION

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The primary objective of this effort is the design of a submersible generator as a discrete and critical subassembly of marine hydrokinetic systems. Unlike earlier designs of MHK systems, in which the generator is integrated into the turbine, this effort takes an approach similar to large industrial and conventional power generation systems in which the generator is designed exclusively for the application and manufactured and applied as a unique system component. The result is a generator optimized for the conditions of marine current energy conversion and which will work with a range of turbine sizes and styles.

The generator was designed to work with two well-known turbines: the vertical axis Gorlov helical turbine (GHT) and a marine version of the horizontal axis FloDesign wind turbine. The project team consists of a partnership of US industrial organizations actively involved in the design, development, manufacture and application of motor/generators; critical components such as laminations, windings, and magnets; and hydrokinetic turbines.

Specific tasks conducted during this project included:

1. Characterize and quantify hydrokinetic resources to reveal the conditions with the greatest probability for use in current energy conversion;
2. Characterize the ambient operating conditions for the same;
3. Design generator to work across turbine platforms.
4. Determine the appropriate generator topology;
5. Electromagnetic circuit design of generator;
6. Mechanical and structural design of generator, component selection, coupling methods and structural requirements.
7. Investigate manufacturability including: tooling, fixturing, machining, component availability and other requirements;
8. Cost analysis; and,
9. Preparation of Deliverables: Final Report and Completed Design

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# HISTORICAL DEVELOPMENT OF PROBLEM

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Current energy conversion dates back to at least 31 BC with the invention of the vertical axis water wheel by the Roman engineer Vitruvius.[1] In the United States, it is well documented that water currents were used to power grist and saw mills in 1637 when both tidal and river currents were put to use by the Shapleigh family of Eliot, Maine and surrounding areas.[2] Early applications of water turbines used mechanical direct drive techniques. It wasn't until 1880 when hydropower was first used to generate electricity with the illumination of brush arc lamps

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[1] History of Water Wheels: http://www.waterhistory.org/histories/waterwheels/
[2] The Shapleighs of England and America: http://shapleigh0.tripod.com/shapleighfamilyassociation/id1.html

at the Wolverine Chair Factory in Grand Rapids, Michigan. The first US hydroelectric plant opened shortly thereafter in Appleton, Wisconsin on September 30, 1882.[3]

By 1889 two hundred electric plants in the US used waterpower for some or all generation and plans were well underway for using the power of Niagara Falls to generate electricity. By 1900 hydroelectric power accounted for more than 40% of the United States supply of electricity. By 1902, regulatory authority began with the First Federal Water Power Act and the establishment of the Bureau of Reclamation which is now the largest electric utility in the western states operating fifty-eight hydropower plants.[4] In the 1940s hydropower provided about 75% of all electricity in the west and northwest and accounted for approximately 40% of electrical generation nationwide.

The construction of dams peaked in the US during the 1960's and has declined significantly ever since.[5] This is due to a large extent on the growing understanding and concerns over environmental impacts. It is noteworthy that less than 3% of dams are used for hydroelectricity according the statistics provided by the National Inventory of Dams. According to a report to Congress entitled, "Aging Infrastructure: Dam Safety", more than 30% of all dams in the US are now more than fifty years old and have exceeded their life expectancies. Another 17,000 dams will pass that threshold in the next ten years.

The combination of environmental risks associated with conventional (impoundment) hydropower, aging infrastructure, the need to replace depleting fossil fuels and the development of new technologies has spurred renewed interest in marine hydrokinetics including wave, tidal and stream energy conversion.

Marine Hydrokinetics has a very long history of development. U.S. patents on technologies for the extraction of power from waves and currents date back at least as far as 1844.[6] The August 1936 issue of Modern Mechanix was dedicated to wave motor technologies. In September 1980 Popular Science featured the "Coriolis Project" in which the potential of tapping the energy of the Gulf Stream was assessed by the California based company Aerovironments.

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[3] DOE EIA: http://tonto.eia.doe.gov/kids/energy.cfm?page=hydropower_home-basics-k.cfm
[4] Reclamation, Managing Water in The West: http://www.usbr.gov/history/OriginsandGrowths/Volume1.pdf
[5] Report of the USACE National Inventory of Dams.
[6] History of Wave and Current Devices: http://freeflowenergy.com/resources/posters/FreeFlowEnergy-History-of-Wave-and-Current-Devices.pdf

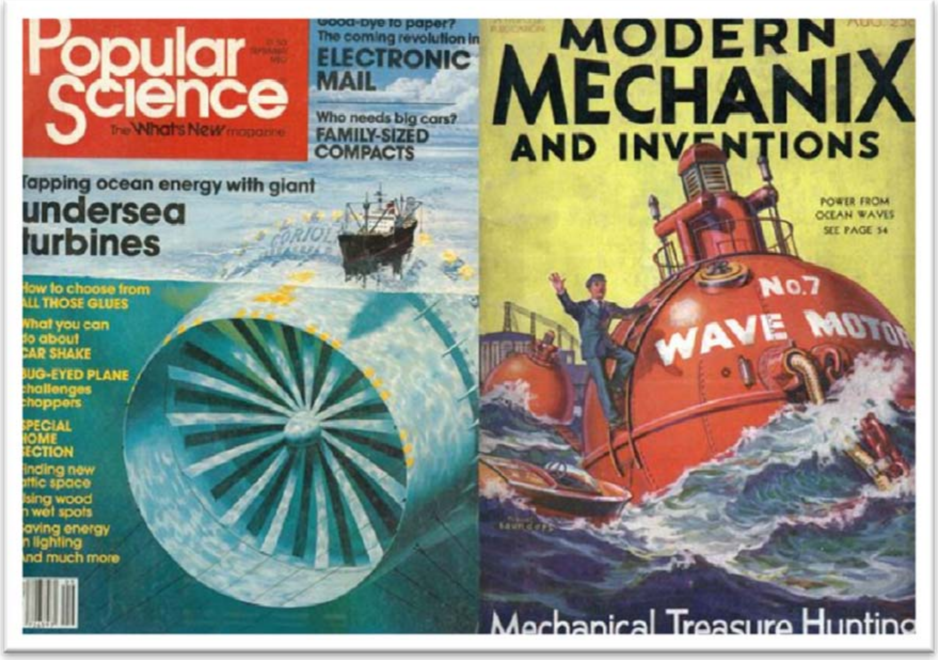

**Figure 2 MHK long history**

Successful marine hydrokinetics poses many challenges: fluid dynamics and turbine design, survivability of structures, environmental impacts, overcoming the challenges of corrosion and fouling in marine and environments and the submersible generation of electricity.

## The Biggest Challenge: Generating Electricity Underwater

Over this long history, one of the most critical challenges faced has been the physical generation of electricity in marine environments which pose unique challenges including the corrosive effects of water, the existence of a broad range of fouling agents, environmental factors such as marine life, and extremely harsh conditions and forces. Most hydropower applications including early MHK prototypes use generators positioned out of the water – for exactly the reasons mentioned above. However, submersible generation is very desirable as it will facilitate MHK installations that cannot be seen, heard, or that will interfere with marine navigation and traffic.

The development of marine hydrokinetic systems is following a path like that of wind turbines. Both water and air are technically fluids and the requirements for energy conversion are similar. The same is true for wind turbine and MHK generator technology. Many different generator technologies have been applied in attempts to convert the kinetic energy from fluids in motion. There are different generator topologies, sizes, power ratings, weight and form factor issues, materials and etc. All of these approaches are being experimented with in pursuit of one or more optimal designs. Most recently, DOE continues to sponsor research and development of direct drive generators for wind turbines, as well as this effort for marine hydrokinetic generators.

A study conducted by Free Flow Energy, Inc. on behalf of the US Minerals Management Service revealed a wide range of generator sizes, types, power ratings, coupling methods, sealing, gearing and mounting techniques being applied.[7] Several recent MHK system designs include a rim mounted generator integrated into the turbine and or shroud. Others have used off-the-shelf generators enclosed in a nacelle and including shaft seals and gear boxes to keep water out of electronics and increase speed. Still other designs have used hydraulic (oil or water) or pneumatic (air) power take-off systems (not relevant to the scope of this effort.)

Perhaps the most significant issue relating to generators for wind or water applications is the use or non-use of a gearbox in the drivetrain for speed enhancement. A report by wind turbine manufacturer Northern Power Systems entitled, "The Gearbox Problem" points out that approximately 80% of wind turbine failures are attributable to gearbox failures. The gearbox is added to the drive train to increase rotational speed going into the generator. In addition to drivetrain and power take off options there are also a wide range of generator types to consider including: single and poly-phase, synchronous, permanent magnet and wound-field, rim-mounted and shaft-mounted, radial, axial or transverse flux paths. There are many options to consider for converting the shaft torque and rotational speed from a turbine and converting that mechanical power to electrical.

To date, only one manufacturer of commercial grade submersible generators is known to exist – Hayward Tyler, Ltd of the UK. Hayward Tyler offers submersible generators, primarily to the subsea gas and oil markets. A second company NGenTec Limited of Scotland is working towards the commercialization of a generator designed at the University of Edinburgh for wind, wave and tidal applications. At the time of the writing of this report SmartMotor of Norway announced that they offer a permanent magnet generator for tidal energy.[8] Submersible pumps are a related technology. Other industries and applications offer technologies related to the design of submersible generators including propulsion systems for submersible autonomous underwater vehicles, naval applications, submersible bow thrusters, power systems for ocean sensors and subsea monitoring and certain aspects of marine aquaculture. Offshore wind is now offering the potential for dual use technologies relating to offshore generation, power conditioning, control, connections, transformation, power transmission and grid interconnection.

Due to its relevance and long history, wind energy conversion, especially wind generator technology was carefully reviewed as a part of this effort. This project reviewed and considered much of the historical development of submersible power generation and related technologies, including wind, for applicability to the design of a submersible generator optimized for current energy conversion.

## BASELINE – PRELIMINARY CONSIDERATIONS, BEFORE START OF PROJECT

Prior to the start of this project it was recognized that a great deal of testing, development and experimentation relevant to this effort has already been completed. What follows is a discussion of the state of the art and relevant information at the time this project was started.

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[7] MMS Project 628 Assess the Design/Inspection Criteria/Standards for Wave and/or Current Energy Generating Devices http://www.boemre.gov/tarprojects/628.htm

[8] SmartMotor announcement: http://www.rechargenews.com/energy/wave_tidal_hydro/article264890.ece

### *The critical difference between renewable and conventional generation*

In conventional (fuel based) power generation, the prime mover is most often an engine which rotates the generator shaft at 3600 or 1800 rpm with fuel provided through a control system capable of responding quickly to constant changes in load. Conventional hydropower can be viewed as “fuel based” since the gravitational potential energy of water stored behind an impoundment can be controlled and regulated to meet demand. This is not the case with renewable energy systems in which the power to the system is constantly changing as well as the load. Therefore, an understanding of the availability, amount, variability and extremes of the prime mover are absolutely critical to the design and development of all of the MHK system components – especially the generator. This will be addressed in Task1 of this effort.

### *Appreciation of the difference between power, energy and nameplate capacity*

One of the most common and misleading practices in the application of renewable energy technologies is the use of nameplate capacity. This term, originates in and is relevant to fuel based generation systems in which fuel can be fed to the prime mover as needed to meet the anticipated or real electrical loads. For renewable energy systems including wind, photovoltaic and marine hydrokinetics – power to be converted is diffuse, intermittent and often non-existent. The nameplate capacity and power numbers do not accurately characterize the value of a renewable resource or the potential of an energy conversion system. The persistent use of these parameters in the media is problematic. In short, our generator will be physically sized based upon our own thoughtful and considerate analysis of realistic MHK resources and not based upon power ratings appearing in the media or even necessarily prior reports. This project is about energy converted from a constantly varying power source over a long period of time.

### *Understanding the differences between inland stream, near coastal and tidal flow regimes*

The term “optimal” is used throughout this project to describe a generator which can be used under a variety of siting conditions, power ratings, and turbine styles. Obviously, compromises must be made. Inland waterways provide a far more consistent unidirectional flow in water with a significantly lower salinity than bidirectional tidal flows. Inland and near coastal waterways differ in many obvious ways: environmentally, ecologically, use, variations and extremes. These differences are given careful consideration in an attempt to design a robust generator that will work under a wide range of MHK siting conditions and flow regimes.

### *Design for rare or more common siting conditions*

In general, FFE embraced the concept that our proposed generator should be designed for more realistic MHK siting conditions: those that can be reasonably found and which may exist within the acceptable and realistic limits of power transmission to load centers. Several sites throughout the world offer extreme water velocities; however, those sites are not necessarily “conveniently located” and they are rare. The same is true for tidal ranges and periods.

### *Appreciation of many different turbine styles, shapes, sizes, ratings and stages of development*

As in the early development of wind turbine technology, many different turbine styles are being studied, developed and experimented with. Most significantly to our project, few to none are in full production and readily available for wide scale commercial application. (Exceptions may be the vertical axis turbine with above surface generator from New Energy Corporation of Canada and the Gorlov Helical Turbines now being installed in Korea.) The generator for this project is designed to work with the vertical axis Gorlov and horizontal axis FloDesigns turbines. No MHK systems with submersible generators are, to our knowledge, commercially viable and readily available at the time of this project.

### *A review and understanding of prior MHK testing to date- especially with regard to generators.*

Although energy generation data is scarce, the Principals and Team of Free Flow Energy, working on this generator design have read and reviewed most of the reports publically available and pertinent to MHK research test and development including those from the U.S. and Europe. Reports which contain information concerning measured site conditions and verifiable turbine performance data were particularly beneficial to this project.

A careful review was made of competing generator technologies and to the greatest extent possible, given the proprietary nature of such information, we investigated generators presently used in MHK testing and demonstration projects.

### *An understanding of regulatory permitting, siting, and applications filed to date*

FFE has closely monitored permitting activity of the Federal Energy Regulatory Commission to be certain to understand the intent and desires of the MHK development community with regard to siting. It is duly recognized that flow constrictions and curves where water velocities are accelerated, while minimizing turbulence, environmental and dual use factors are most desirable. Water velocity, at this time, is of paramount concern of permit applicants due to its “cubic” contribution to power generation.

It should be noted that MHK is a mass flow problem and velocity only part of the story. If the definition of MHK is expanded to allow for a significant diversion (not impoundment) of water resources, then volume discharge in cubic feet per minute may be most significant in that a percentage of that flow may be channeled and accelerated into an MHK system then returned to the flow downstream.

### *Making a baseline estimate of “realistic” siting conditions*

After reviewing considerable MHK siting data and given the Principals of FFEs familiarity with ocean and river currents - a first approximation of water velocity at sites would initially be on the order of 2 meters per second (maximum). While it is recognized that higher velocities are most desirable given their “cubic” contribution to the power equation; it was our professional estimation that water velocities higher than two meters per second are rare. Such velocities are also only likely to occur in natural constrictions of waterways making them both small in cross sectional area as well as having the potential for very high environmental impacts and competing use issues. Assuming a water velocity of two meters per second did not bias our analysis of the prime move, but provides a rough baseline of what may be realistic for MHK siting based upon our knowledge at the start of this project.

Using the first pass velocity of 2 m/sec; it was then very easy to determine how much area would be required to generate “meaningful” power keeping in mind that in most regimes, water velocities are constantly changing and in tidal flows the speed is actually zero, four times per day. We could also then crafting estimates for cross sectional areas in flow, depth, turbine/generator diameters and etc.

These cursory assumptions begin to form the framework necessary for both sizing and power rating the generator.

An excellent example follows that supports the first approximation assumption of using 2 m/sec water velocity as reasonable and that the cross sectional area in such sites can be rather limited in such constrictions.

The Piscataqua River under the General Sullivan Bridge in Portsmouth, NH is listed by many sources as having some of the strongest currents in the U.S. This particular constriction in the Piscataqua River is an area through which an enormous volume of water must flow four times a day filling and draining "Great Bay". As with other such constrictions it was ideally suited for locating a bridge.

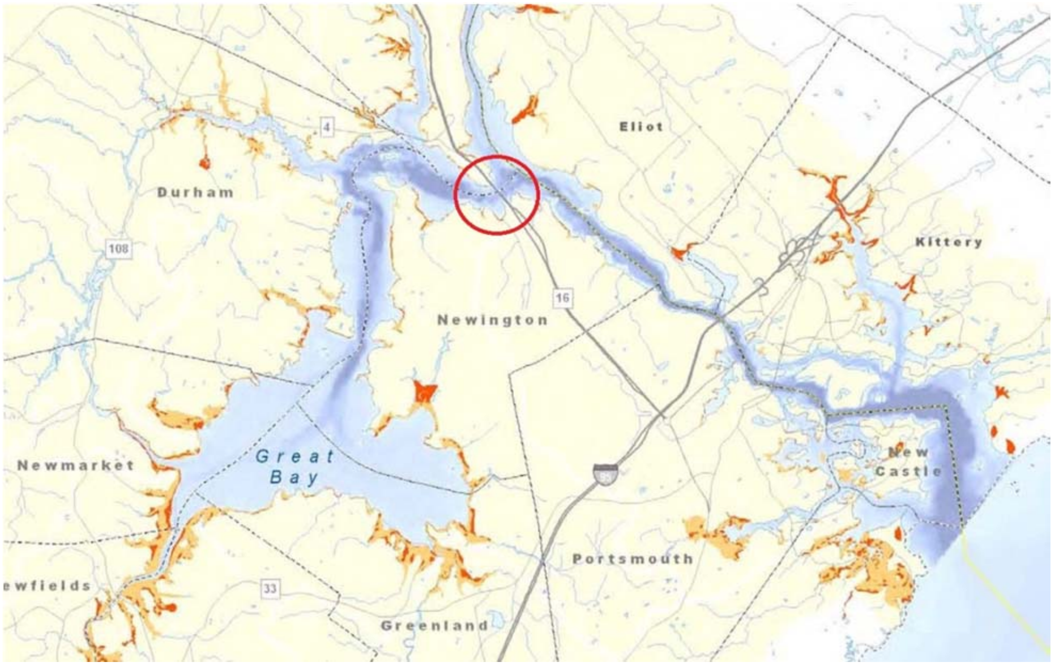

**Figure 3. The General Sullivan Bridge, Piscataqua River, New Hampshire**

This site offers an 8 foot tidal range and currents that (on occasion) can reach more than three meters per second. Two applications were filed with FERC with tidal energy generation potential of ten megawatts total in the general vicinity of the constriction. The potential environmental impact are obvious given that Great Bay represents a critical ecosystem for the entire region and the waterway must be shared by recreational, industrial and commercial competing uses.

What is even more significant, is the reality of how limited the potential area for energy conversion at these desirable velocities and the range of velocities that can occur across such a channel.

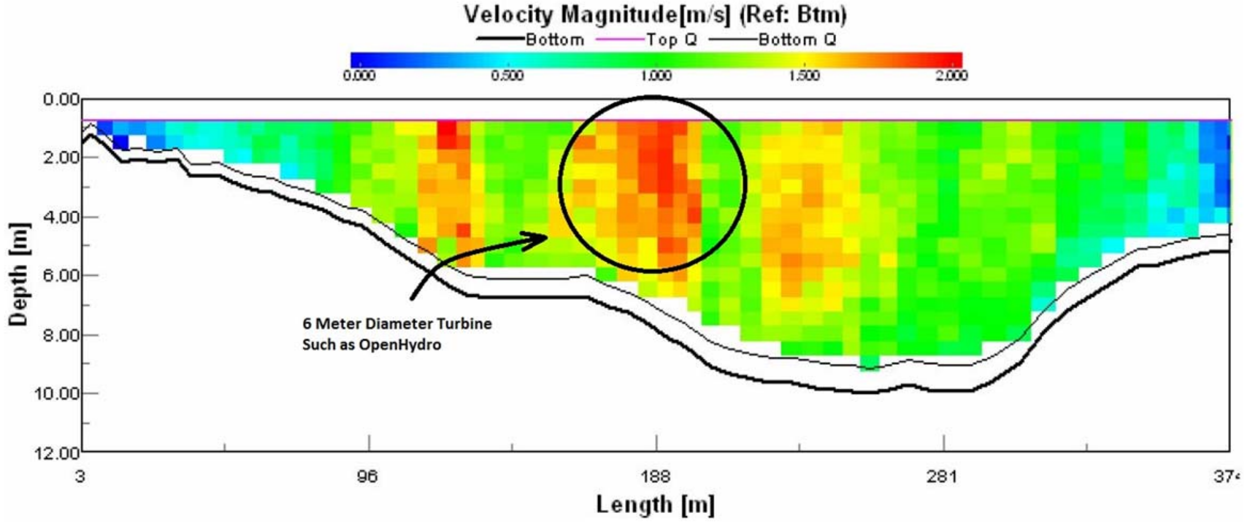

**Figure 4. Cross section under General Sullivan Bridge**

A section across the Piscataqua River is shown in Figure 4. The water velocity was measured just before the strongest inflow. The red areas are the strongest flow, which are separated by green areas of low flow caused by the bridge abutments. The increased velocity results from a large amount of water being moved through a relatively small constriction. For reference, a six meter circle is drawn, showing that a turbine the size of the OpenHydro 1 MW, demonstration turbine would not fit in the area at mean low tide much less taking into account navigational clearances.

Free Flow Energy, Inc. had also previous measured the water in area well known for tidal energy conversion – Eastport, Maine.[9] FFE measured water velocities in Eastport as a part of a study conducted for Tidewalker Associates, who are proposing a tidal barrage at the mouth of Half Moon Cove in Eastport. Although the area has an extreme tidal range on the order of twenty feet, the naturally occurring water velocity is on the order of 1.5 meters per second.

Half Moon Cove (Figure 5), like the area under the General Sullivan Bridge, is a narrow constriction to a flow filling and draining a large tidal bay or reservoir. The twenty foot tidal range must fill and drain Half Moon Cove twice a day making it a site well suited to tidal barrage technology. It is important to mention that these examples are consistent with other sites, examples and research supporting our initial and baseline estimates.

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[9] Irish, J.D., An ADCP Survey of Half Moon Cover, ME, 16 & 17 May 2008, FFE Report, 2008

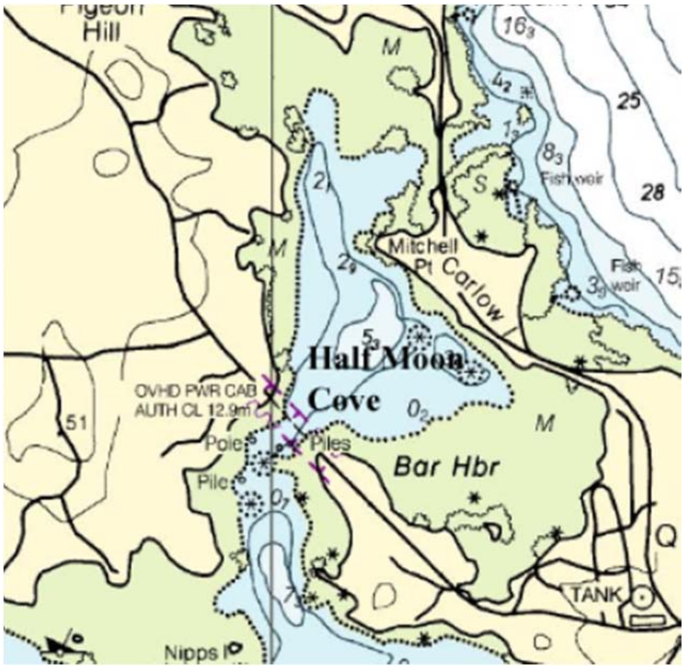

**Figure 5. Chart showing Half Moon Cove Eastport, ME**

As can be seen in Figure 6 below, the rather small area and distribution of currents is particularly relevant to sizing and power rating a marine hydrokinetic system. The data also supports our first approximation of a design current velocity on the order of two meters per second. Again, a six meter diameter turbine is drawn for scaling purposes (based upon the Open Hydro prototype design.)

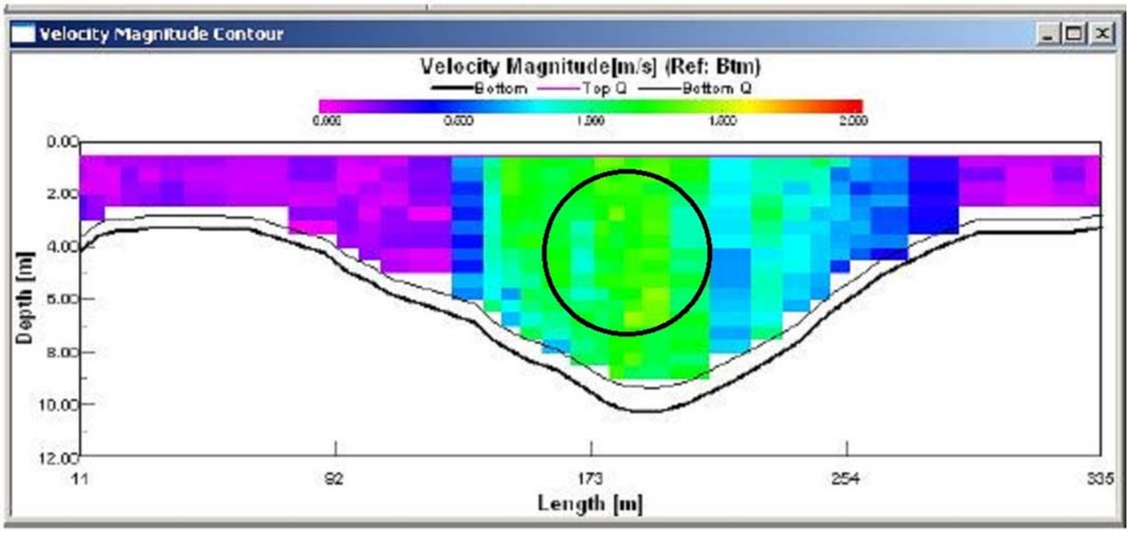

**Figure 6. Half Moon Cove Water Velocity and Distribution**

## BACK OF ENVELOPE CALCULATION OF POWER AND DISCHAGE FOR 1 MEGAWATT AT DIFFERENT FLOW VELOCITIES USING 35% WATER TO WIRE EFFICIENCY

A few basic calculations are helpful for form some baseline estimates relating to the following:

- water velocity,
- cross sectional area,
- generator form factor and
- power rating,

Using the standard marine hydrokinetic power density equation,

$$P/A = \frac{1}{2} \rho v^3 \qquad \text{Equation. 1}$$

and an assumption that 1 MW is "good" power; some estimates can be made of how much area is required and how much energy can be realistically converted to electricity. The Gorlov recommended efficiency for marine turbines of 35% is used. (Note that this value has been experimentally confirmed several times and is considered a very reliable water to wire efficiency number.)

The table below answers the question of how much area is required to generate 1 MW of power (instantaneously) from various flow regimes and assuming 35% water to wire conversion efficiency:

Table 1. Area required to Convert 1 MW in Various flow regimes (35% eff)

| | | | | Turbine sizes based upon prior MHK demonstration projects | | |
|---|---|---|---|---|---|---|
| Water Velocity (m/sec) | A (m^2) | Side (Square) (m) | Diameter (circle) (m) | Number of Turbines Required with 6 m diameter (A = 28.3 m^2) | Number of Turbines Required with 5 m diameter (A=19.6 m^2) | Number of Turbines Required with 3 m diameter (A= 7.1 m^2) |
| 0.5 | 45712 | 214 | 241 | 1615 | 2332 | 6438 |
| 1 | 5714 | 76 | 85 | 202 | 292 | 805 |
| 1.5 | 1693 | 41 | 46 | 60 | 86 | 238 |
| **2** | **714** | **27** | **30** | **25** | **36** | **101** |
| 2.5 | 366 | 19 | 22 | 13 | 19 | 52 |
| 3 | 212 | 15 | 16 | 7 | 11 | 30 |

One particularly important number from the table above is the area requirement for one Megawatt of power at 2 meters per second velocity. This can be correlated to some of the turbines currently under test. Turbines with a five meter diameter, for example, have an area of 19.6 square meters. To achieve 714 square meters of area, and therefore 1MW in a 2 m/sec flow would require 39 turbines. Twenty five turbines with a six meter diameter (area = 28.3 m^2) would be required to accomplish the same.

Turbines presenting a rectangular profile to the current are proposed in the range of 7 X 36 feet to 12 X 107 feet in size. These would have metric areas of 23.1 and 122 square meters respectively. In these cases it would be reasonable to assume that a total of 31 of the smaller or six of the larger turbines would be required to provide 1 MW during times at which the water velocity is at 2 m/sec.

The calculations above suggest that significant cross sectional area is required to convert power from non-impounded or diverted sources. The numbers provide critical information pertinent to the physical size, form factor and power rating of the proposed generator.

## DEFINE PRIME MOVER

***Characterize and quantify hydrokinetic resources to reveal the conditions with the greatest probability for use in current energy conversion.***

The purpose of Task 1 then was to understand, as well as possible, the availability, dynamic nature, and extremes of potential MHK sites such that the proposed generator can be properly sized and designed. The challenge, of course, is to identify what a "reasonable" current energy conversion site might be rather than a handful of sites with extreme water velocities found around the globe yet not necessarily located near load centers.

Sub-tasks include:

- Make a justifiable and defensible determination of the range of water velocities likely to be encountered in the majority of hydrokinetic installations.
- Make a justifiable and defensible determination concerning how water velocities are distributed in a cross section of river or tidal waterway and how this will impact the size, power rating and structure of hydrokinetic systems. Table 1 provides examples showing how water velocities are spatially distributed across a channel.
- Identify probable extreme conditions to which the generator and hydrokinetic system are likely to be exposed.
- Identify hydrokinetic conditions under which the hardware can be installed, serviced and maintained.

Task 1 addresses the resource assessment by presenting and discussing different cases,

- Coastal and Continental Shelf Resources
- Coastal Tidal Resources
- Inland Water Resources

## COASTAL AND CONTINENTAL SHELF RESOURCE ASSESSMENT

Oceanographers have been working for years to understand the continental shelf circulation. This is generally wind and density driven and rarely reaches 1 m/s in restricted areas. The major exception is the Gulf Stream, which is off the east coast continental shelf from Florida up to Cape Hatteras where it breaks away from the US and heads across the North Atlantic to Europe. Water velocities in the Gulf Stream can reach 2 m/s and the depth is deep enough for large turbines, but the logistics of putting large turbines there is significant. Also, the consequences of making alterations in the Gulf Stream and European weather need to be seriously considered. There are very few studies of the consequences of removing significant amounts of energy from a flow. Blanchfield et al.,[10] showed that you could only remove something like 15% of the energy from an estuary like the Piscataqua-GreatBay, before you reduced the tidal range in the bay to the point where you were getting lower energy. Also, his concluded that you could place the turbines anywhere along the estuary as well as in a "wall" across the estuary and have the same results.

A DOE sponsored an initiative by Georgia Tech modeled near coastal water velocities and depths. The website for the GA Tech models can be found at: http://www.tidalstreampower.gatech.edu/ A few typical examples follow to illustrate typical continental shelf currents.

Figure 7 shows modeled currents along the East coast of the US from Long Island down to the Chesapeake. Generally the shelf currents are in the 0.2 to 0.3 m/s (about ½ knot). At the mouth of the Delaware and Chesapeake Bays, the currents can reach ½ m/s (about 1 kt). The screen capture can't resolve the East River between Ling Island and New York, but a blowup shows stronger flows there which are mainly tidal.

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[10] J Blanchfield, C Garrett, P Wild, and A Rowe1, The extractable power from a channel linking a bay to the open ocean, *Jour. Power and Energy*, 222(3), 289-297, 2008.

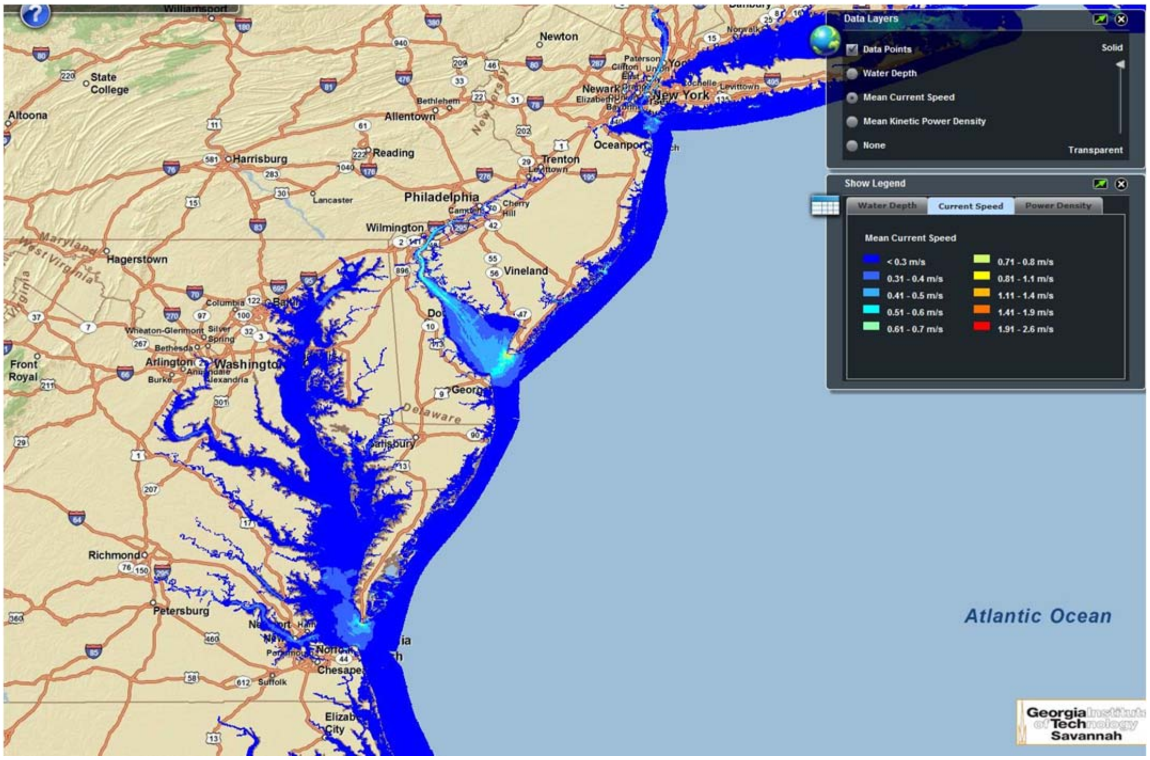


**Figure 7. Water Velocities - Mid-Atlantic coast (Screen Capture)**

The water depths in the same region are shown in Figure 7. The higher velocities at the mouths of the Delaware and Chesapeake Bays are associated with restrictions at the mouth and shallower waters. Again the balance between faster water with enough depth for turbines needs to be studied as part of siting evaluations. Where there is good depth on the shelfs, the velocity is too low.

Figure 9 shows coastal velocities from the Hudson River north to the Canadian border. Again the flows are too low except in a few regions. – The region between Block Island and the mainland shows accelerated flows, but Figure 10 also shows shallower water there. The second region is around Martha’s Vineyard and Nantucket. Between Martha’s Vineyard and Cape Cod there is faster flow, but it only reaches 1 m/s (2 knots). Here the water is shallower, and there is heavy pleasure and commercial traffic to contend with. East of Marth’s Vineyard there is also some regions of flow that exceed 1 m/s, but the water here is very shallow. Again this region is not conducive of viable MHK.

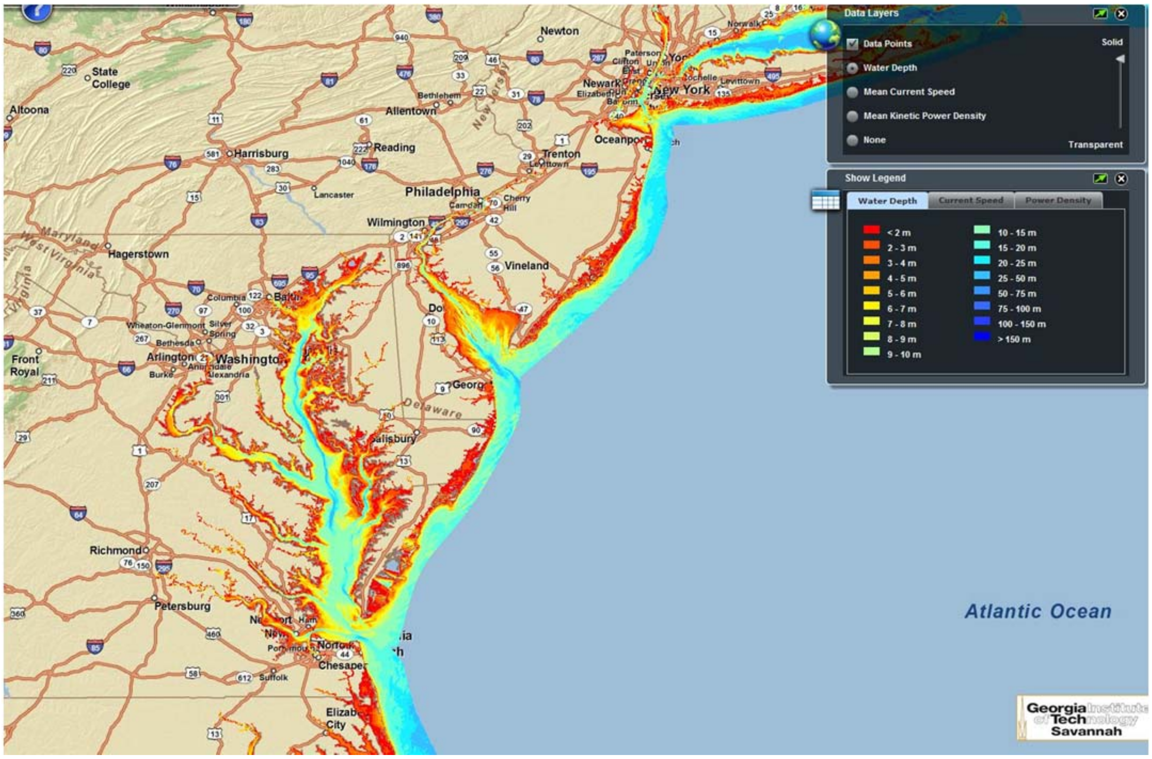


**Figure 8. Water depths – Mid-Atlantic coast (Screen Capture)**

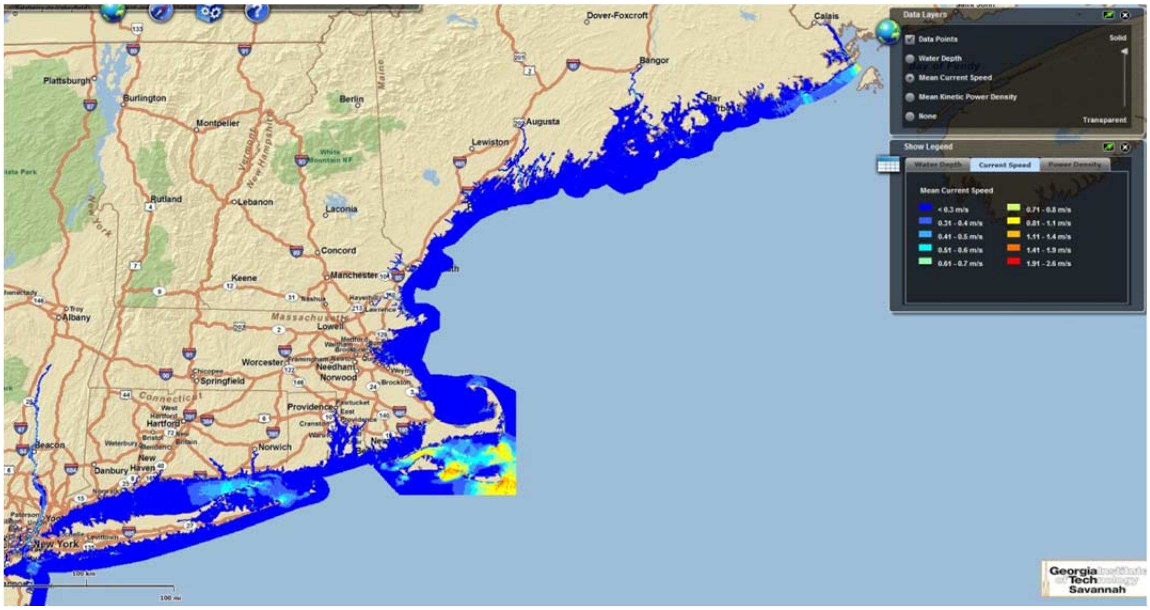


**Figure 9. Water velocities – Northeast U.S. (Screen Capture)**

**Figure 10. Water depths – Northeast U.S. (Screen Capture)**

Finally, the region around Eastport Maine is shown in Figure 11. As the Canadian border is the northern edge of the model, the 1 m/s velocities seen toware Campobello Island are artifacts of the model boundary. The flow along the Canadian border to the NW should also be viewed with suspicion. However, the flows to the west that shows higher velocities reaching toward 1.5 m/s (3 knots). However, again these are shallow water regions as shown in Figure 12, with deeper, narrower channels. This indicates a possible site, as others have recognized. However, the model predictions do support our conclusions that the continental shelves are not viable sites for MHK developments, and that restrictions in flow and rivers and inlets where there may be strong tidal flows may be better sites for MHK development.

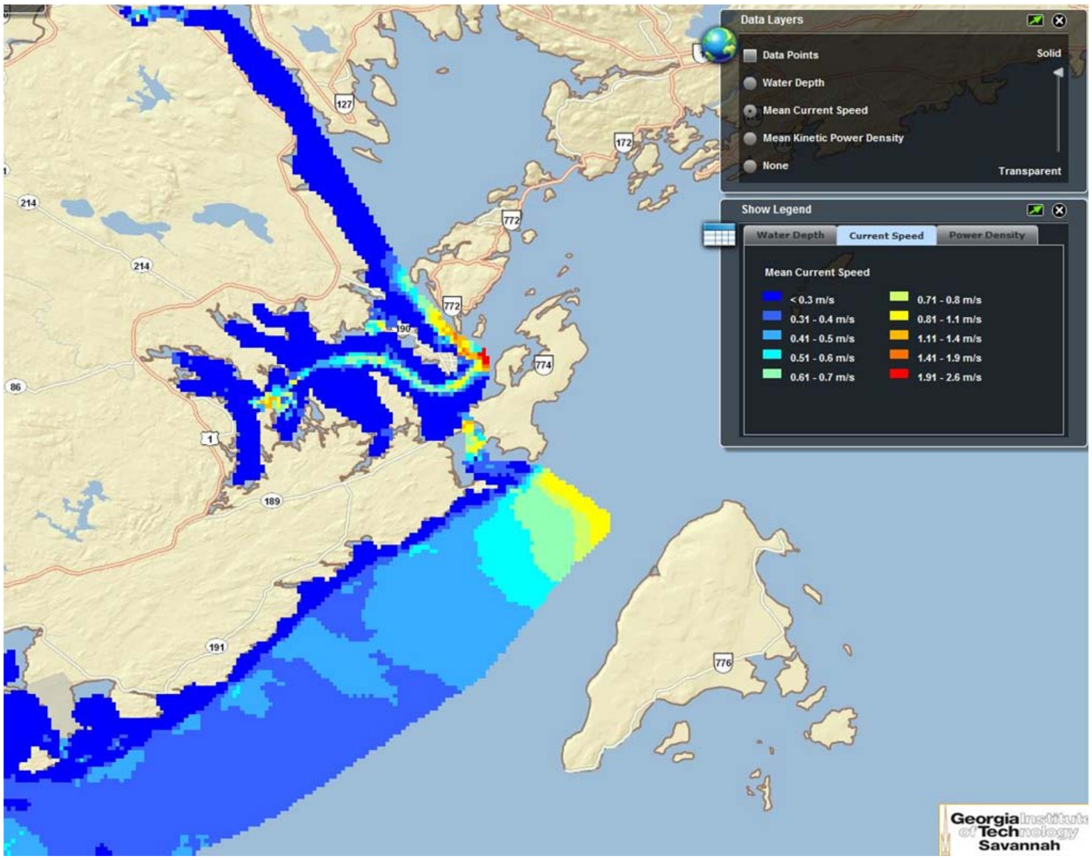


**Figure 11. Water velocities – Eastport, ME (Screen Capture)**

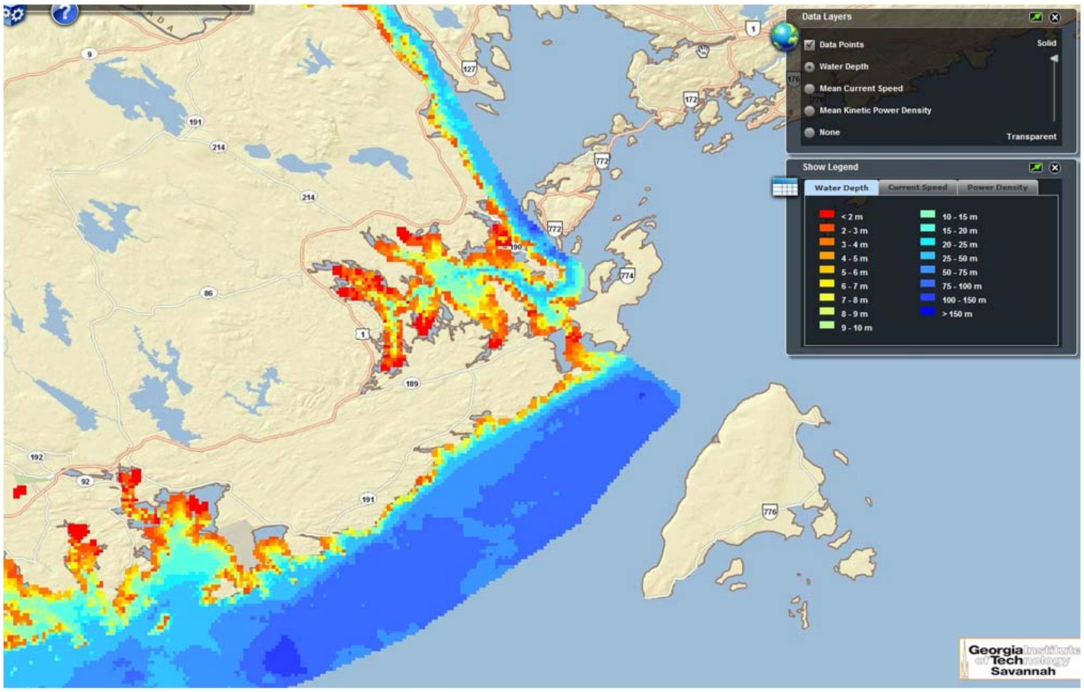


**Figure 12. Water depths – Eastport Maine (Screen Capture)**

# NEAR COASTAL "TIDAL" RESOURCE ASSESSMENT

Tidal flows have long been considered as possible sources of energy. A main attraction to tidal power is that it is very predictable – that is since it is due to the ocean's response to the gravitational forcing of the sun and the moon, once measurements of the tide have been made at a site, then predictions can be made in the past and future for this site. This is necessary since the tides are a temporally varying flow. As the moon is a stronger generating source than the sun, there are normally 2 high and low tides in a lunar day. This means that the high tide moves later by about 50 minutes each day. The major downside to tidal power is that you don't control the time of maximum tidal flow, and that it doesn't occur at times of maximum load. Therefore, unless there is some method of storing power, or changing the output of a traditional generating plant to take up the load when the tidal velocities are minimum, tidal power is not really viable. However, generating hydrogen gas that can be later burned to produce energy at times of higher load, might be a solution, but much technology development needs to be done before this approach can be made economical.

Another point to consider is the variability of the currents not only with time, but with distance across a river and with depth. As shown earlier in Figures 4 and 6, the flow varies across the channel and with depth. This is largely boundary layer effects. Friction causes the flow to go to zero at the bottom and edges of the river. Thus the highest flows are generally found near the surface and in the center of the channel. However, bends in the channel and channel shape can alter this generalization.

Finally, when considering tidal flow in a coastal estuary, the normal river flow must be considered. As an example, in the Piscataqua river with an 1/8 m/s outflow added to the tidal 2 m/s currents, the energy in the flood tide is reduced and the ebb tide increased, so the ebb tide has 1.5 times the power (Equation 1) than the flood tide.

Data from various sources showing river and tidal water velocities and frequency distributions were collected. Some examples follow:

In addition to Figure 4, Figure 13 shows several cross sections. These were made with Doppler current profilers at one point in time, generally at maximum tidal flow. The top two panels in Figure 13 show tidal flow, and the strong currents in the Tacoma Narrows in the right top panel. This flow is concentrated in the surface waters, on one side of the channel and does exceed 2 m/s. The bottom 5 panels show more standard river flow. Again notice that the maximum currents tend to be in upper part of the water column in the center of the channel. This has strong implications if mounting a generator to the bottom is part of the plan. Floating it just below the surface so it is always near the maximum current depth makes the most sense, but is logistically and technically more difficult, and can present a danger to pleasure boaters and commercial shipping as well as a potential eye sore to the public.

Again notice that while there are time s that the currents get up to 2 m/s (the yellow sections in the bottom 5 panels of Figure 11, much of the volume of the cross section contains lower velocity flow.

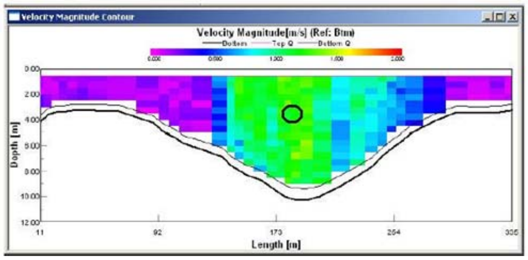
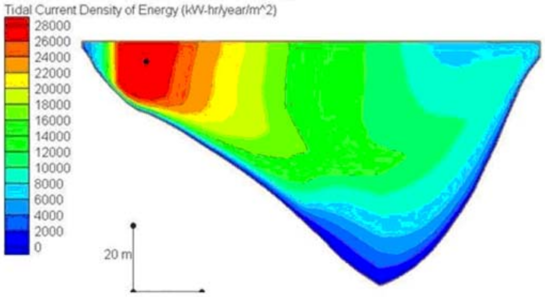
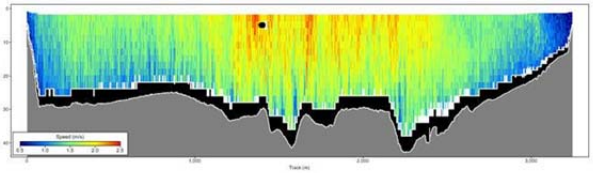
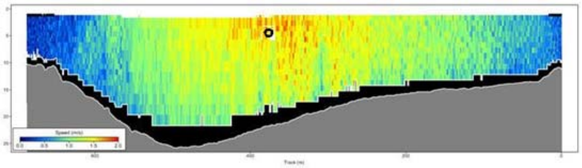
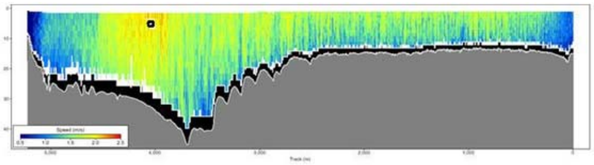
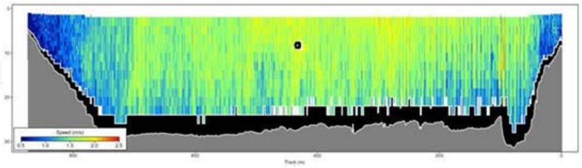
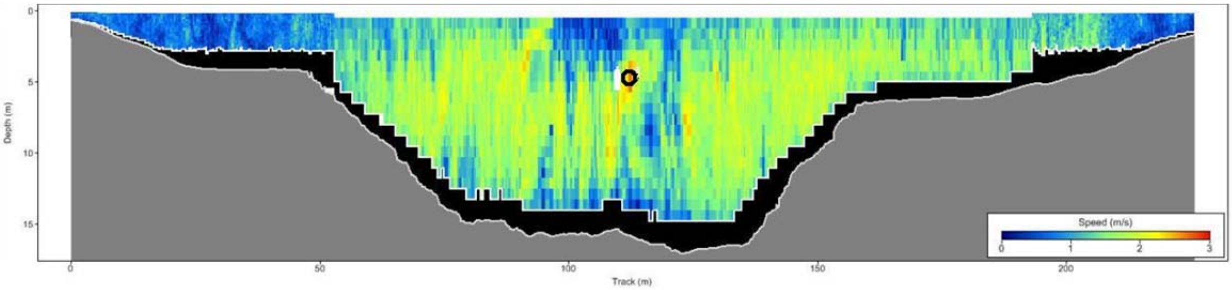
| | |
|---|---|
| **Distribution of tidal and river current velocities over a cross-section**<br>**(Note: Black Circles have one meter diameter for reference.)** | |
|  <br>**Entrance to Half Moon Cove, Eastport, ME, (Tidal)**<br>**(Data of Free Flow Energy, Inc.)** |  <br>**Tacoma Narrows, Washington State, (Tidal)** |
|  <br>**River 1 Example (Provided by Sontek YSI)** |  <br>**River 2 Example (Provided by Sontek YSI** |
|  <br>**River 3 Example (Provided by Sontek YSI)** |  <br>**River 4 Example (Provided by Sontek YSI)** |
|  <br>**River 5 Example (Provided by Sontek YSI)** | |

**Figure 13. Examples of cross-channel velocity distribution**

A report entitled “Analysis and Comparison of Tidal Datasets for Resource Assessment and Network Modeling” prepared by the Institute for Energy Systems of the University of Edinburgh offers the following graphic depiction of tidal mean spring currents around the United Kingdom (Figure 12, left panel). Again, velocities of two plus meters per second are immediately noticeable as relatively rare, with most of the velocities being much lower. However, remember that these are tidal velocities and vary with time. They have plotted peak spring tidal velocities. Spring tides are when the sun and moon are opposite and expert the maximum gravitational pull on the oceans, and so cause the highest tides and strongest velocities.

To get a more realistic idea of the currents, and current histogram (Figure 14 right side). This shows the number of hours each month that the current is at a certain velocity. It is obvious that the number of hours that the currents exceed 2 m/s is less than 10 hours per month or less than 2% of the time.

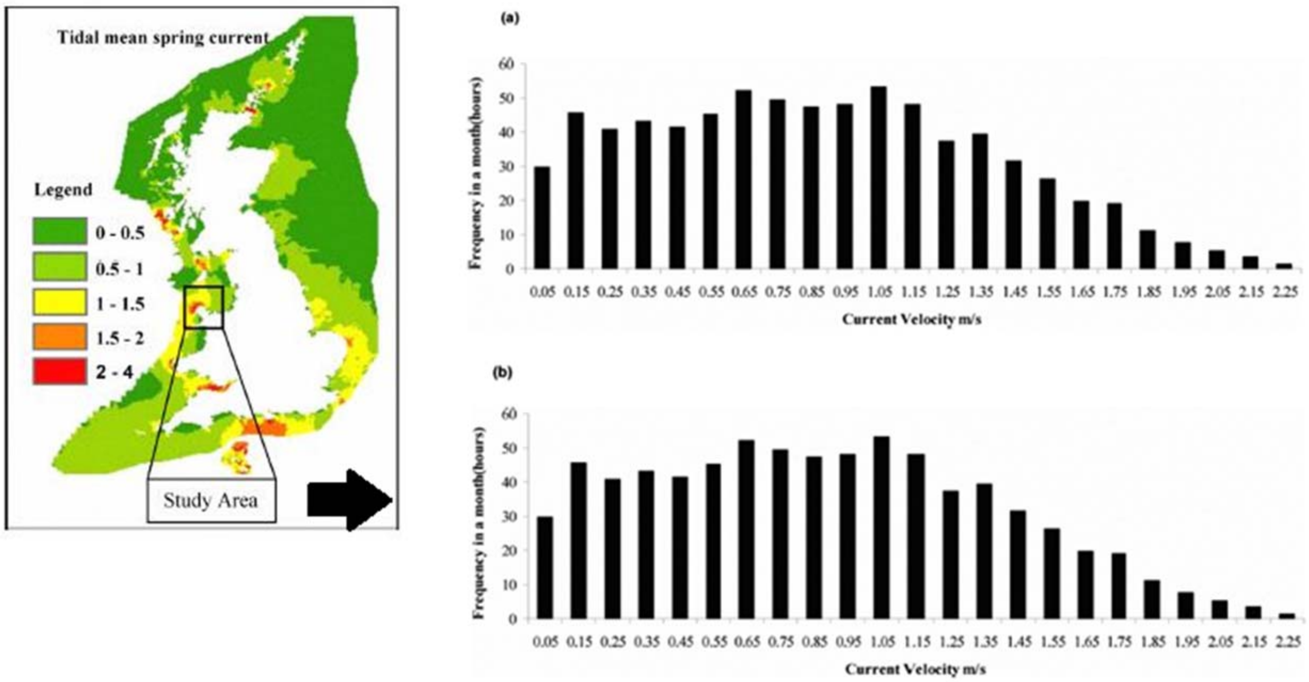


**Figure 14. Velocities around the United Kingdom and frequency histograms**

The Tacoma Narrows Washington State tidal energy study was one of the most extensive done in the U.S. A velocity section is shown in the upper right panel of Figure 16. This is only one point in time, Figure 15 shows a time series made by a moored profiling Doppler current meter which shows the time variability. The high velocities approaching 3 m/s are again seen, but they don’t occur all the time and for not that long a duration. Again, a velocity histogram, Figure 16, shows four mid-water locations. The upper left histogram shows greater than 3 m/s velocities, but as in the time series in Figure 15, these times are not that frequent or long in duration.

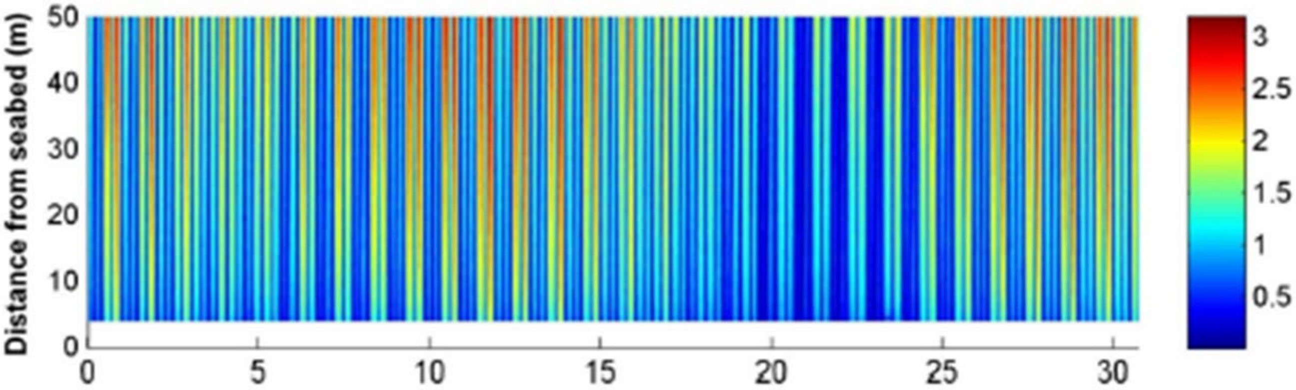


**Figure 15. An ADCP velocity time series plotted as contoured velocity as a function of elevation above the bottom versus days.**

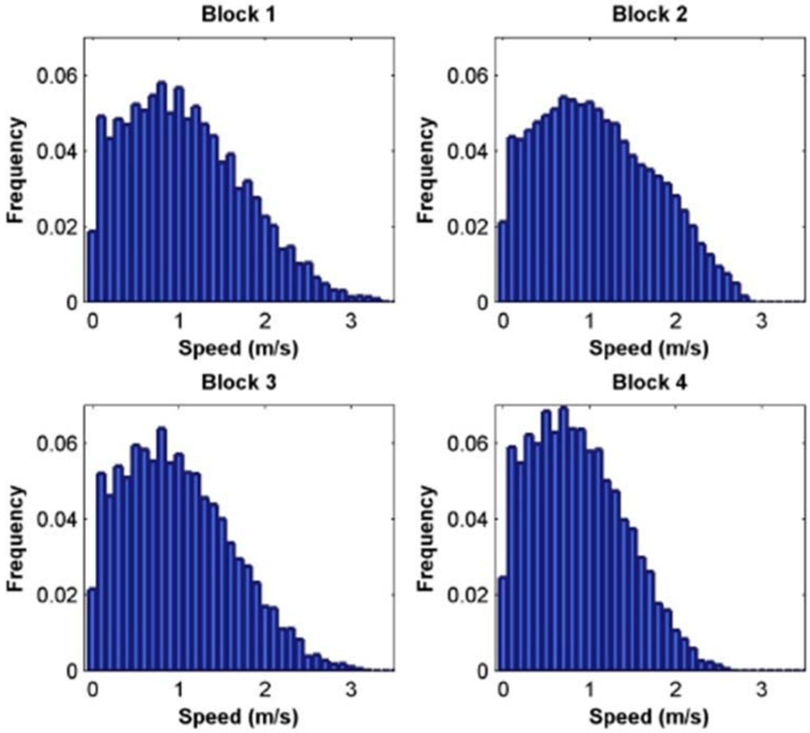
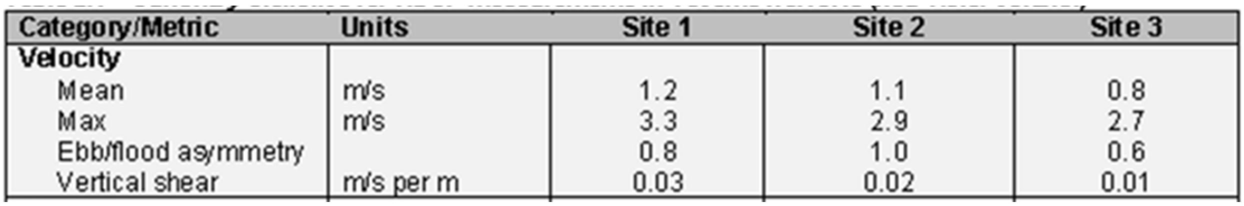


**Figure 16. Velocity Histograms for Tacoma Narrows –**
**(data is from four resource block, located mid-water column)**

The Tacoma Narrows report tabulates the statistics for tidal current velocities at three different sites in Tacoma Narrows. They show the maximum at 3.3 m/s, but the mean is nearer 1 m/s. They also show the flood/ebb asymmetry in flow mentioned above, which at Site 3 is as asymmetric as the Piscataqua River flow. The vertical shear also is important as it shows how the velocity varies with depth as the bottom boundary layer brings it to zero at the bottom. This is the difference in flow that a turbine would see over its upper to lower blade distance, and shows that turbine design should consider the structure in the flow. In the Piscataqua River one can see the 5 m eddies on the side of the central flow which can cause the current to vary significantly in the horizontal as well as vertical direction.



| Category/Metric | Units | Site 1 | Site 2 | Site 3 |
|---|---|---|---|---|
| **Velocity** | | | | |
| Mean | m/s | 1.2 | 1.1 | 0.8 |
| Max | m/s | 3.3 | 2.9 | 2.7 |
| Ebb/flood asymmetry | | 0.8 | 1.0 | 0.6 |
| Vertical shear | m/s per m | 0.03 | 0.02 | 0.01 |

**Table 2. Water Velocity Data from Tacoma Narrows study**

One of the better sites at Admiralty Inlet in Puget Sound (Figure 15, shows periods of time with water velocities in excess of 2 meters per second. Note that unlike the ADCP data above for Tacoma Narrows (Figure 13) , the Figure below is for a single day. In this case, it's reasonable to assume that velocities above two meters per second occurred for approximately five hours per day or about 20% of the time . However, this may not by typical of a whole month or year, but is indicative of someplace for further study.

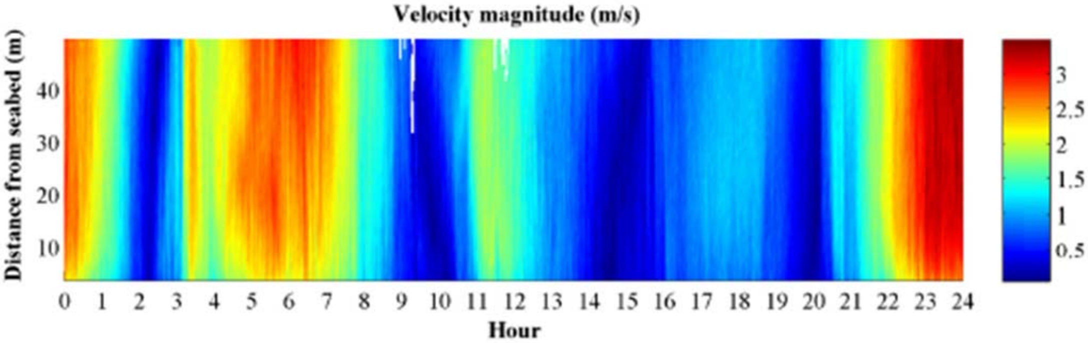
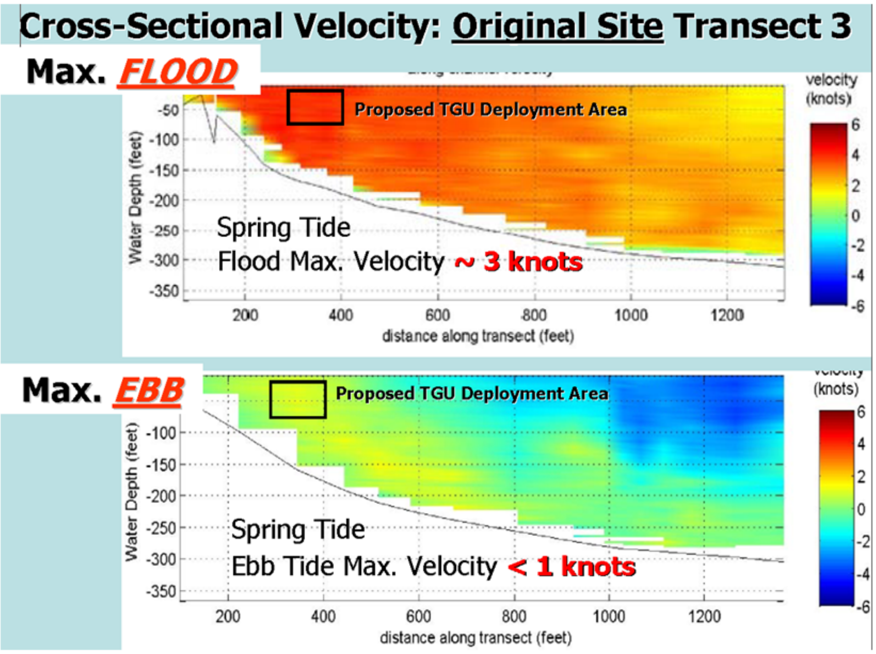


**Figure 17. ADCP currents observed for one day in Admiralty Inlet**

In Figure 9, the modeled shelf currents gave an indication that Eastport, Maine, might be worth further examination. Figure 16 was presented at the 2009 Marine Renewable Energy Conference and offers a glimpse of water velocities (in knots) and depths for one tidal energy site proposed in the Eastport Maine area. The proposed site with 3 knots currents, is about 1.5 m/s, and lower flow than FFE is designing the generator for. Also note that the difference between the flood and ebb, again showing the asymmetry in the flood/ebb currents.

Still more velocity histograms appear in the media and are shown below in Figure 17, again supporting the idea that velocities in the range of two meters per second are possible to find, but are limited in duration and are not likely to be found with a wide geographical distribution. Also, note that this is depth averaged velocity, where the maximum velocity higher in the water column, is reduced by the lower velocity in the bottom boundary layer.



Cross-Sectional Velocity: Original Site Transect 3

Max. FLOOD

Proposed TGU Deployment Area

Spring Tide
Flood Max. Velocity ~ 3 knots

Max. EBB

Proposed TGU Deployment Area

Spring Tide
Ebb Tide Max. Velocity < 1 knots

**Figure 18. A section showing velocities and a proposed energy development site in Eastport, Maine from Presentation Slide at Marine Renewable Energy Center Conference**

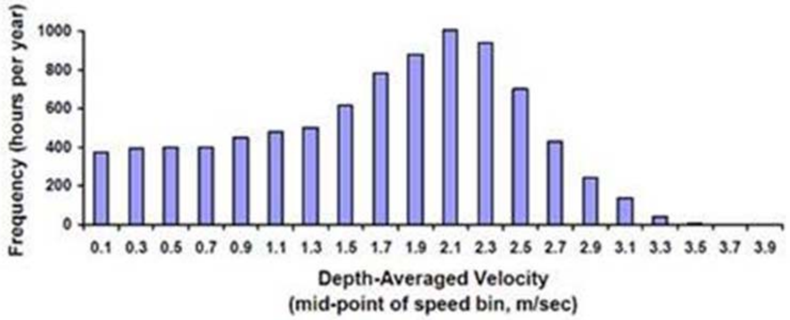
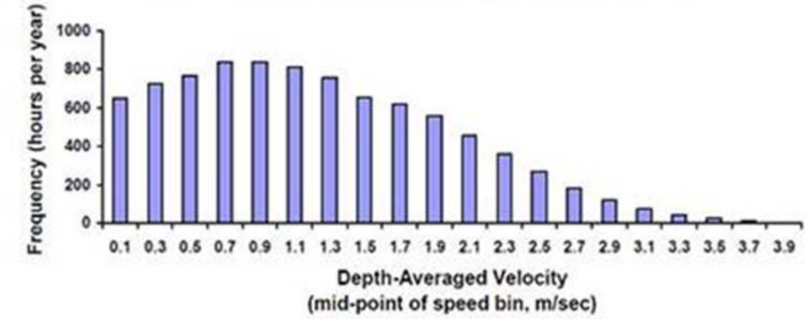
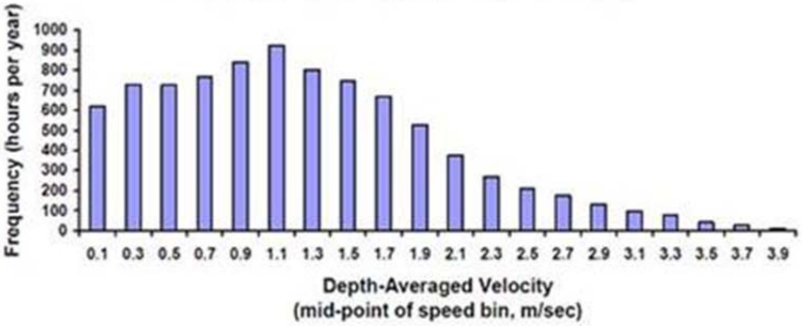


**Figure 3-2: -Annual Average Tidal Current Speed Probability Distributions for Dog Island transect, Western Passage, ME (East Coast)**



**e 3-3: Annual Average Tidal Current Speed Probability Distributions for Point Evans Transect, Tacoma Narrows, WA (West Coast)**



**e 3-4: Annual-Average Tidal Current Speed Probability Distributions for Cairn Point Transect, Knik Arm, AK (West Coast)**

**Figure 19. Additional histograms of the depth-averaged velocity at three potential energy development sites.**

## INLAND WATERWAY RESOURCE ASSESSMENT

One of the best sources of data for inland waterways is the USGS National Water Information System: Web Interface.[11] Free Flow Energy, downloaded and analyze two million rows of data from streams and rivers throughout the U.S. to be used to determine realistic water velocities for MHK, cross sectional areas, channel widths and (average) depths and channel discharge also called mass transport or flow.

At a glance, it is clear that the data set is large, comprehensive, geographically well distributed and likely to provide some very clear evidence of how to physically size and power rate the generator. The image below provides an indication of number and location of USGS gaging stations.

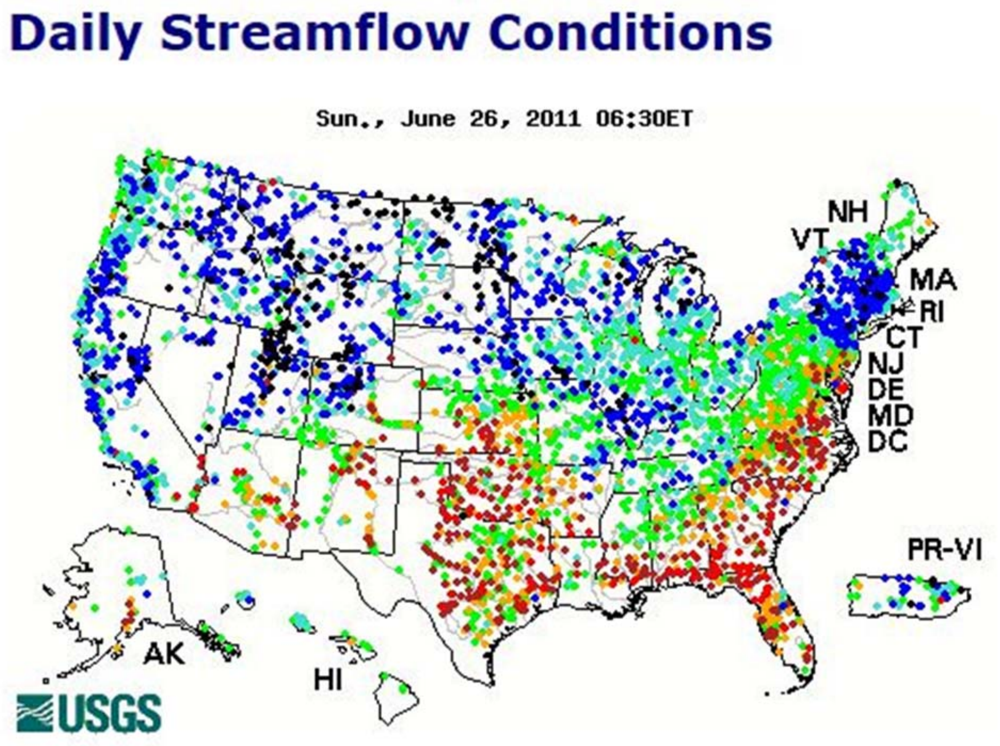


**Figure 20. General location of USGS stream-flow sites**

What follow is a discussion of how the data was manipulated and the relevant results of analysis.

The two million plus rows of data were loaded into an Access database and reviewed to eliminate bad or irrelevant data. "Bad" data would be numbers entered which are most unrealistic and indicate such things as a missing decimal point. For example: water velocities in thousands of feet per second. Data which had

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[11] USGS Streamflow Data: http://waterdata.usgs.gov/nwis/rt

parameters missing that are critical to our purpose were also removed. Examples are any data sets not providing velocity, channel width, area or discharge.

The database contained a considerable amount of water with zero velocity. This is not surprising given the volume and locations of stations. For the purpose of our analysis, all data sets with a velocity of less than or equal to 0.3 meters per second were eliminated. The final result was a database of 1,016,367 records.

The fields on which most of the analysis was performed are as follows:

**Table 3. USGS field description headings used in this report**

| | | |
|---|---|---|
| chan_discharge | Channel Flow | The channel discharge in cubic feet per second |
| chan_width | Channel Width | The channel width in feet |
| chan_velocity | Channel Velocity | The mean velocity in feet per second |
| chan_area | Channel Area | The channel area in square feet |

A fifth field of data was added by calculating the ***average*** channel depth by dividing the channel area by the channel width. Lastly, the numbers were all converted from feet to meters – accordingly.

Detailed analysis is included in the Addenda at the end of this document, specifically showing the actual numbers for each bar on the frequency histograms.

| **Channel Velocity (mps)** | | | |
|---|---|---|---|
| Minimum value | 0.30 | | |
| Maximum value | 6.00 | | Std Deviation |
| Average value | 0.66 | | 0.372671323 |
| If the value is: | **0.66** | 64% | of the values are equal to or lower |
| | | 36% | of the values are higher |

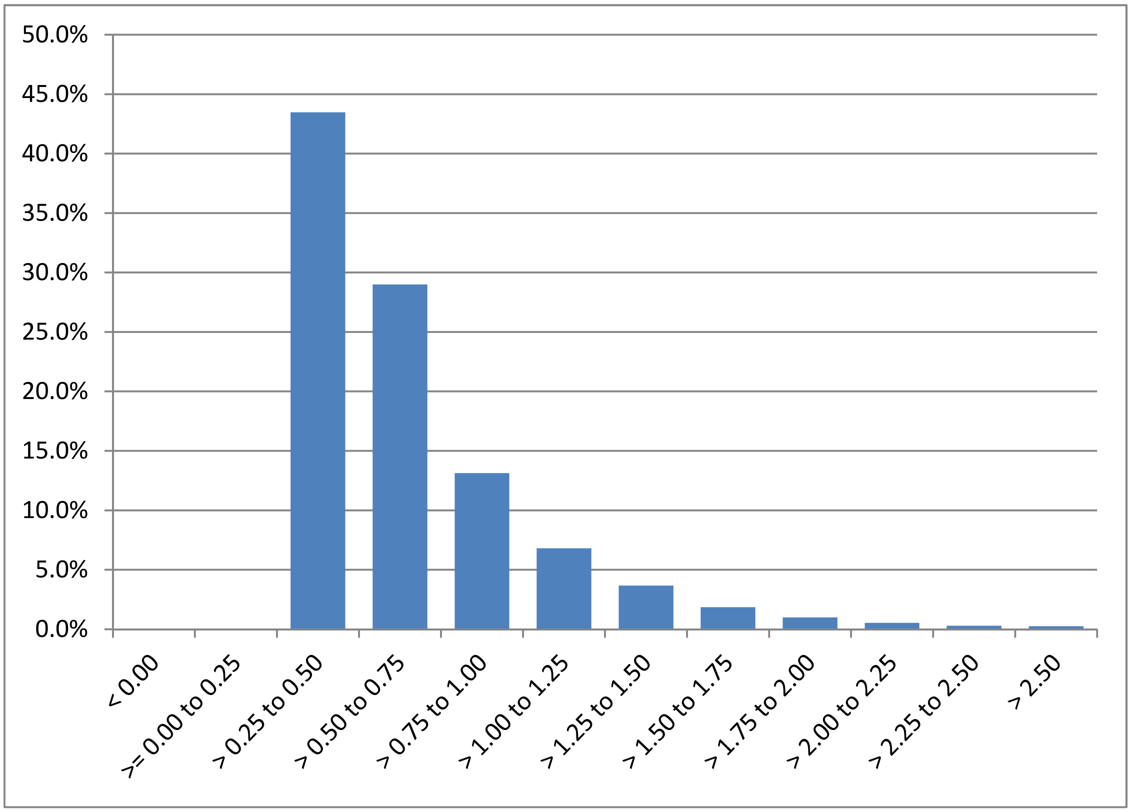

**Figure 21. Channel velocity table and histogram**

Discussion: Velocity which is cubed in the power equation is most critical to current energy conversion. In this analysis it should be noted that velocity is not coupled with area or channel discharge – both parameters also necessary for MHK siting. The higher speed water above therefore may be quite limited in volume and area. Just the same, the point is clear that relatively few sites offer water flowing at or in excess of two meters per second.

In 64% of all records the water velocity was at or below 0.66 meters per second and that data below 0.3 meters per second, from the original two million record data set, was discarded as not relevant. Due to the large number of records, 1.1% or of the records recorded flows at or in excess of 2 m/s.

This data is consistent with other studies in which "average" US river velocities were on the order of 0.7 meters per second. A study published in the American Journal of Science (Vol 251, 1953), entitled "Downstream Change of Velocity in Rivers" by Luna B. Leopold reports the following:

"As indicated previously, velocity in a stream is a conservative quantity. Even the maximum point velocity (maximum at any point in the cross section) does not ordinarily greatly exceed the mean velocity for the cross section. An unpublished study by the Geological Survey of 2950 measurements of maximum point velocity values from a variety of rivers showed a median value of 4.11 f t per sec., mean of 4.84 ft per sec. and less than one per cent of the total exceeded 13 f t per sec. The largest value of maximum point velocity in a natural river channel ever measured by stream-gaging personnel of the U. S. Geological Survey was about 22 f t per sec."

Putting these values into metric units provides the following "**Maximum Point Velocities**":

- Median – 1.25 meters per second
- Mean – 1.5 meters per second
- Maximum – 6.7 meters per second

The actual number of records (frequencies) at the selected velocity ranges from the USGS data follow:

| | | | | Frequencies: | | | Cumulative Frequencies: | |
|---|---|---|---|---|---|---|---|---|
| **>** | **0.25** | **to** | **0.50** | **441831** | **43.5%** | **<= 0.50** | **441831** | **43.5%** |
| **>** | **0.50** | **to** | **0.75** | **294678** | **29.0%** | **<= 0.75** | **736509** | **72.5%** |
| **>** | **0.75** | **to** | **1.00** | **133427** | **13.1%** | **<= 1.00** | **869936** | **85.6%** |
| **>** | **1.00** | **to** | **1.25** | **69183** | **6.8%** | **<= 1.25** | **939119** | **92.4%** |
| **>** | **1.25** | **to** | **1.50** | **37294** | **3.7%** | **<= 1.50** | **976413** | **96.1%** |
| **>** | **1.50** | **to** | **1.75** | **18886** | **1.9%** | **<= 1.75** | **995299** | **97.9%** |
| **>** | **1.75** | **to** | **2.00** | **10119** | **1.0%** | **<= 2.00** | **1005418** | **98.9%** |
| **>** | **2.00** | **to** | **2.25** | **5408** | **0.5%** | **<= 2.25** | **1010826** | **99.5%** |
| **>** | **2.25** | **to** | **2.50** | **2944** | **0.3%** | **<= 2.50** | **1013770** | **99.7%** |
| **>** | **2.50** | | | **2597** | **0.3%** | | | |

**Channel Area (m^2)**

| | | | |
|---|---|---|---|
| Minimum value | 0.09 | | |
| Maximum value | 185800.00 | | Std Deviation |
| Average value | 165.62 | | 820.2744789 |
| If the value is: | **165.62** | 87% | of the values are equal to or lower |
| | | 13% | of the values are higher |

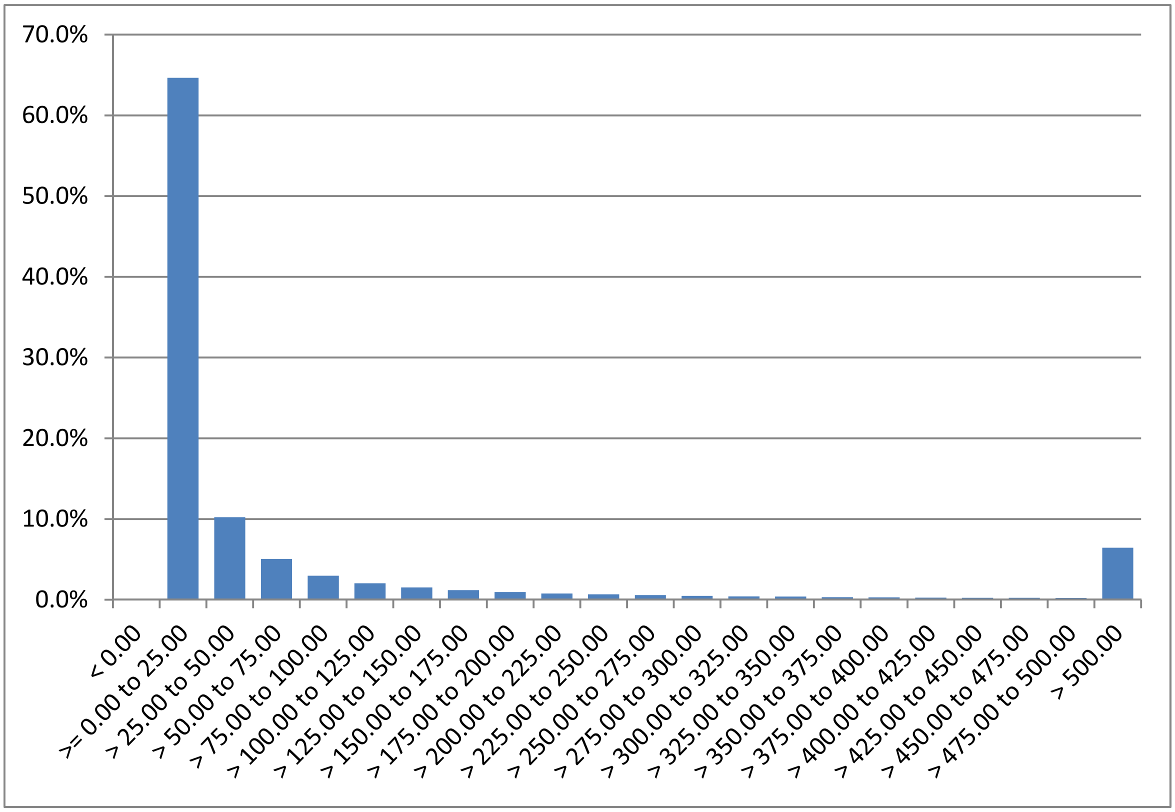

**Figure 22. Channel area and histogram**

Discussion: As calculated earlier, more than 700 square meters of water flowing at two meters per second are required to provide 1 MW of power to the grid. It becomes clear that only a small percentage of the records had adequate area for 1 MW and this would assume that 100% of the resource is used for power generation.

Taking a closer look at sites with at least 700 square meters of area produces the following results show in the next graph.

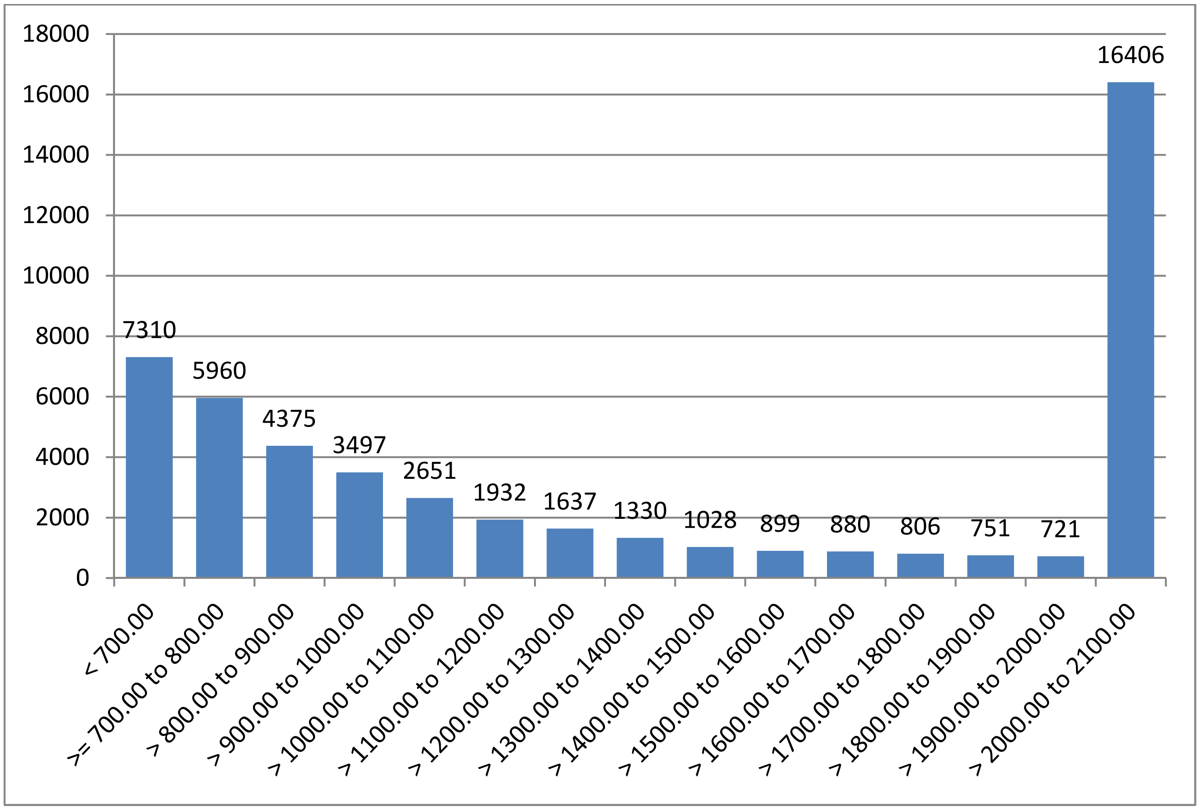

**Figure 23. Number of sites with channel cross sectional area greater than 700 square meters.**

The data above begins to indicate the general availability of sites with cross sectional area adequate to provide 1 or more MW of power and assuming a flow of 2 m/sec. Given the database of more than one million records, the availability of sites with adequate cross sectional area is relatively small and on the order of five percent.

| **Channel Width (m)** | | | |
|---|---|---|---|
| Minimum value | 0.00 | | |
| Maximum value | 18806.16 | | Std Deviation |
| Average value | 51.53 | | 111.9846892 |
| If the value is: | **51.53** | 77% | of the values are equal to or lower |
| | | 23% | of the values are higher |

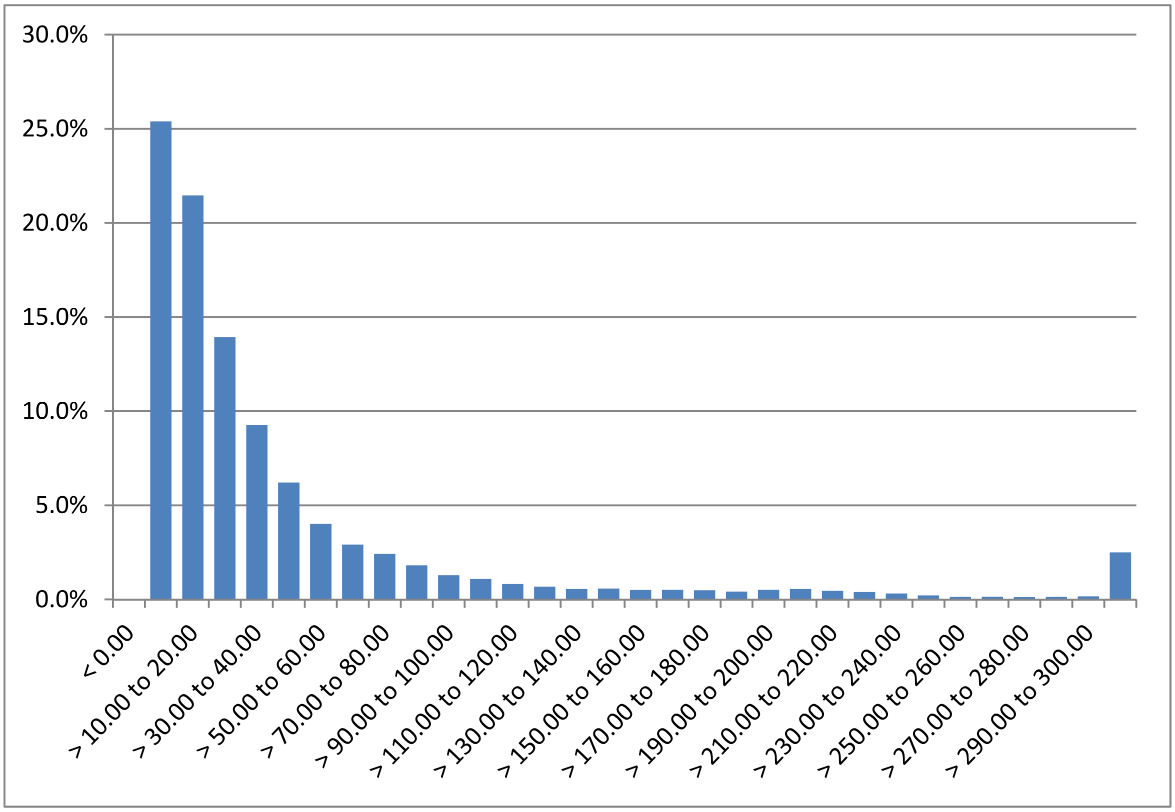

**Figure 24. Channel width table and histogram**

Discussion: Channel width is important in providing some indication of the number of turbine units that could be fit side by side across a flow, as well as providing clearance for other uses such as maritime, recreation, environmental / biological uses.

Seventy seven percent of the records used in this analysis had a cross sectional area of less than 51 meters. It is important to recognize that most rivers and inland waterways do not have steep banks and that the width of the river may be quite shallow for much of its width.

The width measurements along with a mean depth calculation begin to suggest what a reasonable diameter for in-stream turbines might be and what length is recommended for cross flow turbines.

**Channel Depth (m) Average Calculated)**

| | | | |
|---|---|---|---|
| Minimum value | 0.00 | | |
| Maximum value | 2746.70 | | Std Deviation |
| Average value | 1.16 | | 7.071096701 |
| If the value is: | **1.16** | 74% | of the values are equal to or lower |
| | | 26% | of the values are higher |

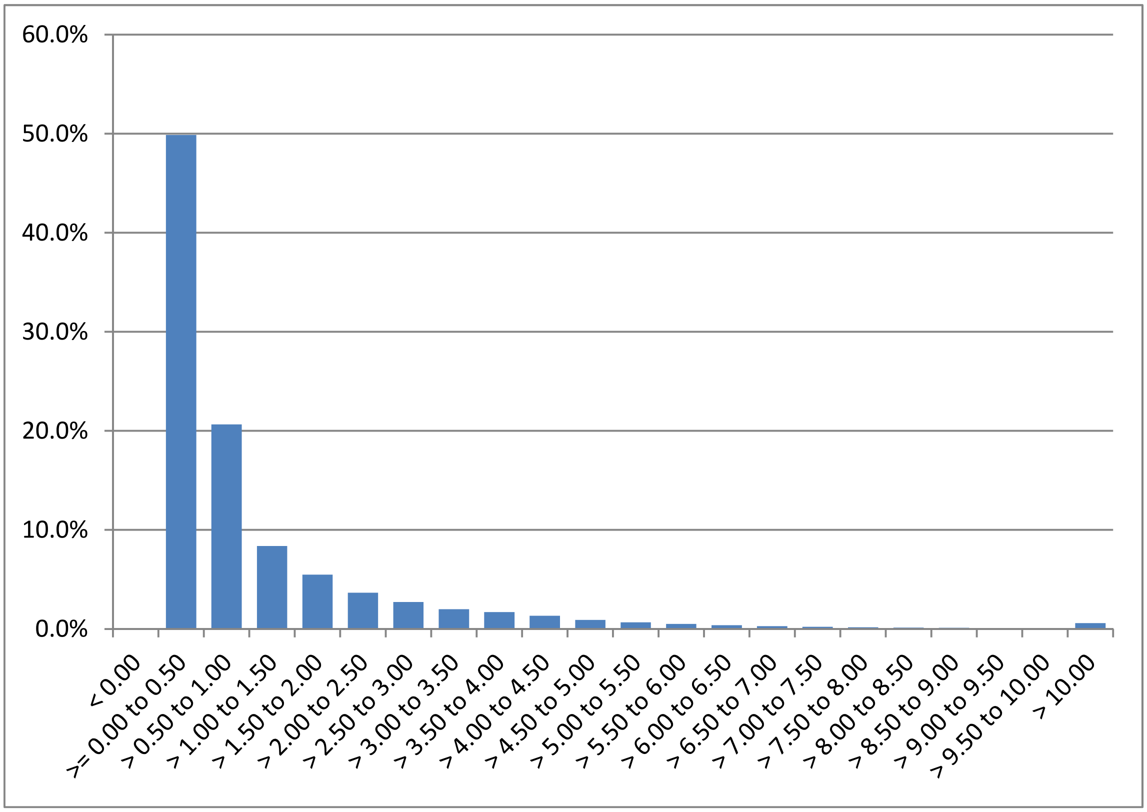

**Figure 25. Mean channel depth table and histogram.**

Channel Depth (Figure 24) is calculated from the cross sectional area and channel width. As such, this would be an average value for depth in meters. Again, this begins to provide some indication of reasonable dimensions for turbine systems and generators to be applied in inland waters.

The average depth of rivers is quite low. In fact, it becomes exceedingly rare to find depths greater than ten meters – which is likely needed to provide the kind of areas required for meaningful electricity generation.

This data is not surprising as bottom profiles show that most waterways do not have steep banks and are deepest at the center where the highest velocity water can be found and bottom scouring occurs. An exception would be around curves.

| | | | |
|---|---|---|---|
| **Channel Discharge (cms)** | | | |
| Minimum value | 0.00 | | |
| Maximum value | 212683.20 | | Std Deviation |
| Average value | 179.14 | | 1059.95438 |
| If the value is: | **179.14** | 89% | of the values are equal to or lower |
| | | 11% | of the values are higher |

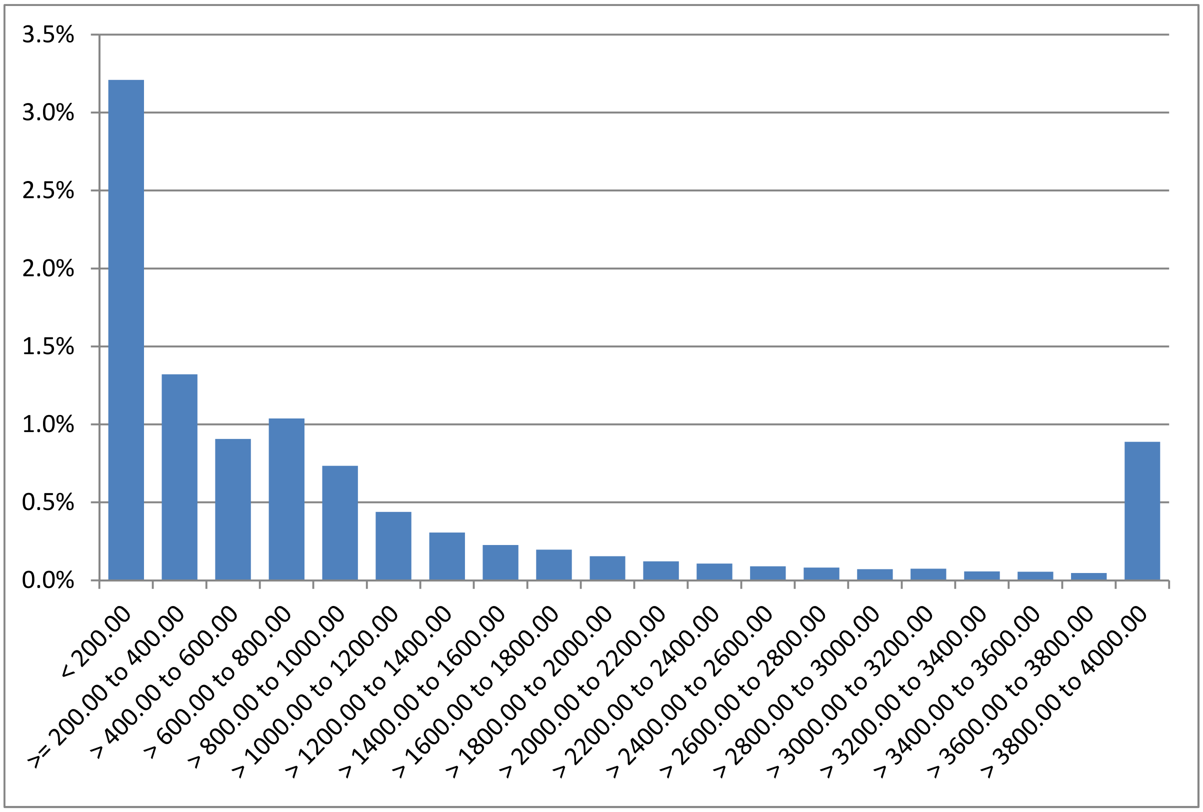

**Figure 26. Channel discharge table and histogram.**

Discussion: Channel Discharge, also called mass flow or volume transport is perhaps the most critical parameter in determining the probability of a site for current energy conversion. Channel discharge and cross sectional area account for water velocity as well as the availability of power for conversion to electrical energy.

A river with 1000 cubic meters per second of discharge and a cross sectional area of 100 square meters would offer a water velocity of 10 meters per second!

It is significant that 90% of the data analyzed had a channel discharge of less than 180 cubic meters per second.

Perhaps the greatest significance of channel discharge is its relevance to "diversionary" hydropower in which a percentage of the water is taken

The analysis of Task 1 resulted in a decision to design a generator with a two meter diameter, rated at 20 kW in a 2 meter per second flow. This comes from a well-informed understanding of both tidal and inland waterways and carefully considers probable water velocities, depths, channel widths, cross sectional area and volume discharge.

## CHARACTERIZE AMBIENT OPERATING ENVIRONMENT

The National Electrical Manufacturers Association publishes the standards to which electric motors and generators are asked to conform. Standards such as the NEMA MG-1 lists motor parameters, tests and specifications for such things as physical size, mounting dimensions, power ratings, sound limits, vibration, mounting techniques, insulation class and etc. Many of these specifications and parameters are based upon the operating conditions in which the motor or generator is designed for and expected to operate in. Motors and generators designed to operate in a walk-in freezer, hospital operating room, outdoors, or food-prep kitchen (hosed down nightly) are all designed differently to meet the requirements of the environments in which they must operate.

Electromechanical power ratings are most often based upon insulation class of magnet wire and tested under "ambient operating conditions". A common power rating test involves embedding temperature sensors in motor / generator windings and attaching the same to the outside of the stator then applying power to the device until the acceptable temperature is reached for any given insulation class. There are, of course, other considerations, but temperature is critical to power rating any electromechanical device.

Temperature in the world's oceans and up rivers and estuaries does not vary as greatly as on land. The freezing point of water sets the lower point – 0 degrees C for fresh water and up to -2 degrees C for salt water. Water in the open ocean generally gets up to about 30 degrees C, so that sets the operating range. For most locations, this range can be reduced – e.g. mid-latitude might only get up into the low 20's and equatorial regions now down to 10 degrees C. Figure 26 shows a typical open ocean temperature profile.

Another advantage of operating in oceans/rivers is the heat capacity of the water. It has the ability to act as a heat sink, and flowing water would increase the heat transfer from a HMK system so that overheating would not be as significant as in an on-land installation.

If one is in the ocean or tidal rivers, than salinity becomes important. Salinity is a measure of the dissolved material in the water and does several things – makes the water electrically conductive, and thereby promoting corrosion and electrochemical interactions. Thus, a MHK system designer must be aware of materials that do well in the ocean. Salinity will vary from near zero in rivers upstream from tidal flows, to 35 PSU in the open ocean. And up to 37 PSU in low latitude regions where there is much evaporation. The units of salinity are PPT (parts per thousand) or PSU (Practical Salinity Units), which are the same for all practical purposes. Figure 26 shows a typical mid-latitude, open ocean profile salinity. In shelf regions the thermocline and halocline may be shallower and change more with time. There are abundant data in the National Oceanographic Data Center (NOAA) to provide reasonable values for most places in the coastal ocean.

Materials used in the ocean often are different than used on shore based or fresh water installations. For example many people successfully use 304 series stainless steel in fresh water. However, this series does not hold up as well in salt water, and people use 316 stainless steel. However, in an anoxic environments this is subject to crevice corrosion so also has a short life. Aluminum is often used because of its light weight and reasonable strength. However, the 7071 series with high zinc content for added strength is very subject to corrosion. The 6061 series is used for many structures, and is relatively corrosion free if used with zinc anodes or some active catholic protection. The 5000 series aluminum is the least strong, but is the least subject to corrosion. Note that aluminum must have some kind of catholic protection such as zinc anodes. 17-4ph stainless is also used, but it requires a soft iron anode. Finally, good old steel works well if properly coated and anode protected. Galvanizing helps here. Plastics and composites hold the most promise for future structures as they are strong and don't have the corrosion problems of most metals. However, technology is not fully developed to provide full structures of composite construction. Titanium also works well in the ocean environment, but the costs can be prohibitive and machining requires extra effort. Also, not as full range of parts, such as tubes, are available.

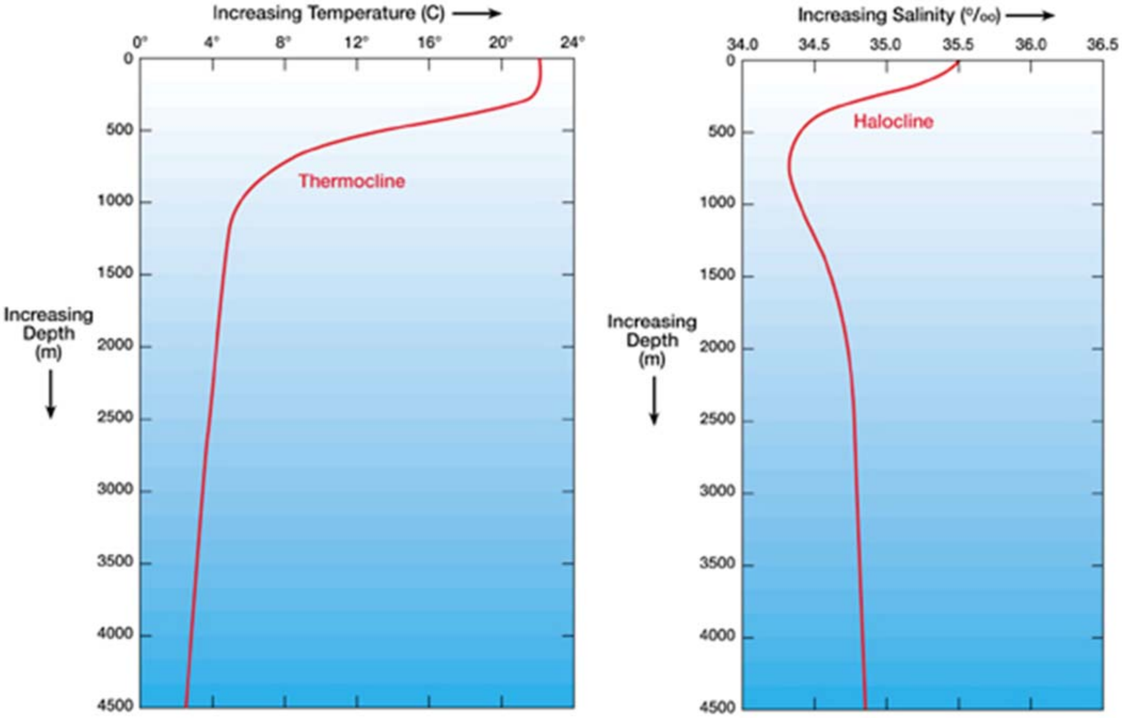

**Figure 27. A "standard" open-ocean profile of temperature and salinity. (Source: "Windows to the Universe" website)**

Another factor of working in the ocean is pressure affects. Pressure increases with depth at the rate of about 1 atmosphere per 10 meters. Thus, seals that work on land with near atmospheric pressure on both sides, will not work in the ocean. If one is going to run motors or generators under water, many applications place them in a silicone oil bath, and put a positive pressure inside the housing. Then if the seal, which needs to be more specifically designed for the application, were to leak, it would only let the oil out. The main idea is to prevent salt water intrusion into the motor or generator components. Saltwater can quickly kill an unsealed electrical device. A more difficult case is to have air in the motor or generator, and use seals to keep out the water. The air offers less friction to the moving parts, which makes them more efficient, but also makes the seals more difficult and critical to the design.

If the device is to operate in a flooded condition, with the fluid being the ambient water, then the electrical components must be sealed with urethane or similar compounds or special epoxy paints to seal the electrical components from the water. This is the case with the proposed FFE MHK generator.

Besides the corrosive effects of sea water there are several other factors that need to be considered. The marine environment is vary biologically productive. In some areas barnacles will grow on structures, and provide a very hard contamination that is difficult to remove. Also, general biological “growth” of seaweed, algae, etc. is likely to grow on any structure put in fresh or salt water. Mussels are another bother in regions of high productivity, as they are filter feeders and like to live in regions where there is water flow past them to bring their food to them. There are many cases of mussels growing on the blades of current meters to the extent that the meters stop turning because there is no “pitch” left on the blades. They turn easily with their load of mussels, but don’t work. Therefore, it is beneficial to prevent bio fouling on an underwater turbine/generator system.

There are many forms of anti-bio fouling materials that have been used over the years to reduce the growth. Nothing really stops it but just delays its growth. The tri-butyl tin compounds that have worked so well are now generally outlawed because of their toxic effects. Any antifouling compound has a toxic component to make it work, so it is a major problem for structures left in place for more than a few months. Marine bronze has been used on propellers to prevent corrosion and retard growth, but this can become expensive. Also, if an aluminum structure were painted with any of the standard copper bearing antifouling paint, the copper will interact with the aluminum and the aluminum will corrode away very quickly. Hence, aluminum vessels use an epoxy paint as a barrier between the aluminum hull and the copper antifouling paint. If a composite material were used for the structure, then the limitations of substrate might allow new antifouling compounds to be used without worry of damage to the structures due to chemical interactions.

Another important factor is suspended sediments in both fresh and salt water that is moving rapidly. In river and coastal environments there is a constant movement of sediments from the mountains through the rivers and coastal regions to the deep oceans. The fine sediments remain in suspension and can act as an abrasive, wearing away protective coatings and paint on underwater structures. Also, this fine grit can get into small crevices and fill them up. On a submerged generator such as proposed by FFE, this may be a problem and be a factor in selecting a larger gap between stator and rotor than would be optimal for energy production. Also, any protective coatings on components moving close to one another with fine suspended sediments may be subject to accelerated wear and so subject to salt water corrosion effects. Studies with prototype systems will demonstrate how significant this issue may be.

A final problem that is really related to the turbine is floating debris in the water. This may be as simple as eel grass, or as destructive as logs floating subsurface. It is not clear how the added generator will change the system in terms of making it more or less subject this this kind of fouling/damage (sudden stoppage of the rotating system). Again, testing and prototype MHK systems will help to educate the community on such issues.

There are another host of problems associated with the mounting of the MHK system in the environment that are ignored here as they are really how the turbine system will be deployed. However, there are many factors to be considered. A MHK device in a flow will change the flow. The sediment in a river is generally near equilibrium with the flow. If the flow were reduced, there may be an added accumulation of sediment on the bottom, blocking the flow of water to or from the turbine. Also, putting the turbine on the bottom, will change the flow around the structure and erosion and scouring of sediment around the MHK system may result in significant changes in the mounting of such systems

## ANALYSIS OF GORLOV HELICAL AND FLODESIGN TURBINES

In this effort, the generator was designed to work with both the Gorlov Helical and FloDesigns turbine. Free Flow Energy met with representatives of both companies and obtained information relating to torque and revolutions per minute at given water velocities as well as some indication of turbine dimensional data and other considerations.

The Gorlov Helical turbine has been tested longer than the water version of the FloDesign turbine. As such, Lucid also provided FFE with test data confirming the dynamic performance of the turbine, points of maximum power transfer and etc. in various flow regimes.

***None of the data provided by Lucid Energy Technologies and FloDesigns is available for publication and public dissemination per non-disclosure agreements.***

Neither turbine is in production as yet so a great deal of latitude is possible with regard to the sizing, dimensions, coupling methods and power ratings of the generator.

Perhaps the most significant factor was a recommendation by Lucid Energy Technologies to design around a 3 meter by 7 meter helical turbine. This would provide a cross sectional area to the flow of 21 square meters. A round, horizontal axis turbine would present a diameter of slightly more than five meters to the flow.

It was confirmed that a rim mounted design is most desirable and can be accommodated on both turbines.

## DETERMINE APPROPRIATE GENERATOR TOPOLOGY

Selecting the appropriate generator topology (arrangement of critical components / form factor / etc.) is critical to the success of this project. Greater detail is provided below; however, in summary the selection of the generator topology involves considering the benefits and compromises of such things as: axial, radial or transverse flux designs; gearbox or not; shaft or rim mount; core or coreless design; induction, synchronous or permanent magnet; and, etc. These decisions begin to form the basic design of the generator from upon which the final electrical and mechanical design will be based.

### Motor / Generator Basics

The relationship between magnetism and electrical current was discovered and documented by Oerstad in 1819. He found that if an electric current was caused to flow through a conductor that a magnetic field was produced around that conductor.

In 1831, Michael Faraday discovered that if a conductor is moved through a magnetic field, an electrical voltage is induced in the conductor.

The magnitude of this generated voltage is directly proportional to the strength of the magnetic field and the rate at which the conductor crosses the magnetic field. The induced voltage has a polarity that will oppose the change causing the induction – Lenz’s law.

This natural phenomenon is known as Generator Action and is described today by Faraday’s Law of Electro Magnetic Induction: ($Vind = \Delta O/\Delta t$), where $Vind$ = induced voltage, $\Delta O$ = change in flux density, $\Delta t$ = change in time All rotary generators built today use the basic principles of Generator Action.

## Common Hydroelectric Generators and Possible Generator Topologies.

### *Induction, Synchronous, or Permanent Magnet*

Most conventional hydropower and some wind turbines use singly or doubly fed induction or synchronous generators. While some of these devices are used in wind and MHK systems, they have shortcomings. The biggest shortcoming of these designs for MHK is the lack of speed from the prime mover and turbine rpm. (This can be on the order of 15 – 20 rpm.) A second major shortcoming is the need for excitation of a "field winding", in which the magnetic field is generated by current flowing from the power grid (not available at sea.)

When induction or synchronous generators are applied it is most common to also use a gearbox to provide the speed enhancement required of the asynchronous generator. Gearboxes have a well-documented history of failure and need for maintenance especially in applications, such as wind, where strong velocity fluctuations (gusts) are common.

For the reasons listed above permanent magnet generators are a popular alternative. PM motors provide a strong magnetic field without requiring a field winding excited by the power grid, not available in offshore applications. Permanent magnet generators are generally more efficient because field excitation losses are eliminated and higher power densities can be achieved.

### *Gearbox or Direct Drive*

Even with permanent magnet designs, speed enhancement is still desirable as induced voltage is proportional to the speed at which the magnetic field passes the coils. To accomplish speed enhancement without a gearbox the rotor diameter is increased such that for any given rotation of the shaft the magnets move much faster, the farther they are located from the central axis. The tangential velocity of magnets, as they are moved farther away from the axis of rotation is equal to the product of the radius and the angular velocity. Therefore, if the radius is doubled, the tangential velocity is doubled.

Whether or not a gearbox is used, the existence of a central shaft from the turbine, into the nacelle, and connected either to the gearbox or directly to the generator can lower efficiency and introduce mechanical and maintenance problems. A central shaft needs to be sealed from the environment to keep water, at high pressure, out of the generator and associated electronics and gearboxes require periodic maintenance and lubrication.

### *Core or Coreless Design*

A core, simply refers to the existence of magnetic steel used to focus and concentrate flux. This is generally considered good because, in general, less magnetic material is required and higher flux densities can be achieved. Increasing the amount of expensive rare earth magnets required would likely drive up cost. Another potential negative of "core" designs is the existence of "detent torque" in which the magnets of the rotor tend to align themselves with the iron in the electrical steel poles. The result is torque ripple and slightly higher harmonic content of the generated voltage.

Coreless designs do not use iron for flux focusing. On the positive side, this would eliminate detent torque and significantly lighten the generator by eliminating steel. However, this would almost certainly require more rare earth magnets to achieve comparable flux densities and that which would likely have a negative impact on component cost.

### *Axial, Radial or Transverse Flux*

***Axial*** - In axial flux designs the magnetic flux path is parallel to the axis of rotation of the turbine as seen below. There is one significant drawback to this design – thrust load. Simply put, the incoming water, in the same axis as the magnetic flux, applies a force to the rotor. Given that air gaps are typically on the order of 0.002 to 0.003 inch or on hydropower generators on the order of 2 to 3 millimeters, the thrust load must be dealt with mechanically to prevent the rotor magnets and stator windings from contacting one another. Contact between the rotor and stator or debris lodging in the air gap and causing a “locked rotor” situation, is one of the more common failure modes of motors and generators. Axial flux generators must be carefully designed to avoid high thrust load which can lead to bearing issues and have a a complicated assembly process.

It should be noted that there are many proponents of axial core designs as there are several distinct advantages over radial flux designs. Specifically, they can have a higher power-to-weight ratio resulting in less core material and they have a planar air gap. Reduced weight may benefit wind energy conversion but it is not necessarily beneficial to MHK applications.

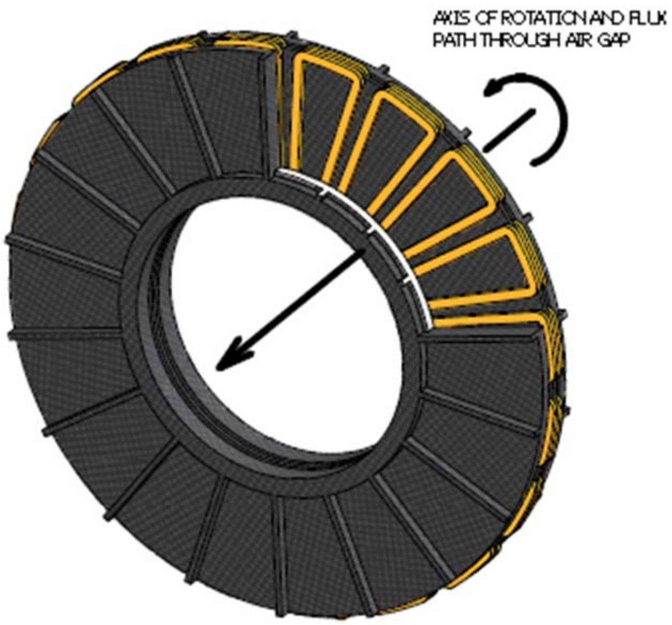

**Figure 28. Axial-flux generator**

***Radial –*** In a radial flux generator the flux path is at 90% to the axis of rotation in the direction of the radius. Conventional radial flux permanent magnet machines have been used extensively for decades and they are the most common type of PM machine used in industry. In a well-balanced design the magnetic poles are arranged such that side loading of the bearings is minimized.

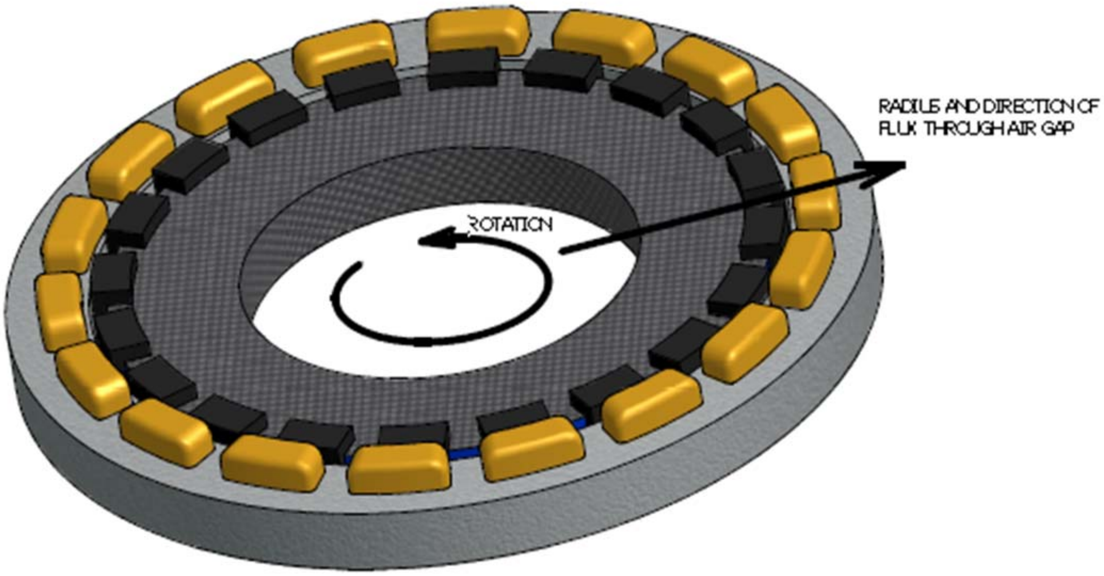

**Figure 29. Radial-flux generator**

Transverse Flux: In a transverse permanent magnet machine the flux lines are in a perpendicular (transversal) plane to the direction of movement and the flow of the torque producing current. The main benefit is high torque density. One of the important drawbacks of a TFPM is its high flux leakage, resulting in a poor power factor. TFPM topologies can be more difficult and therefore more expensive to manufacture than conventional RFPM designs and for this reason, TFPM was not selected as the topology for the proposed generator.

### *Rotor Diameter*

As the diameter of the rotor increases, so does the rotational velocity of the magnetic field – the desired effect. However, there are cost and manufacturing considerations that impose limits on rotor size. Specifically, the volume and cost of magnet, wire and steel all increase. Non-productive "end turns" of copper wire, which do not contribute to output power, increase with a negative impact on cost. Therefore a balancing act of sorts is required to optimize the size of the rotor given the input torque and rpm while considering the quantity and use of components.

### *Competitive Design Analysis*

There are a number of companies in various stages of design and demonstration of generator technology suitable to MHK. A far greater number, of course, exist for the wind industry. In MHK three prominent companies are identified: Hayward Tyler of England, NGenTec of Edinburgh, Scotland; and Smartmotor of Norway.

As a part of this effort, many different generator designs, companies and approaches to generators for MHK were reviewed, analyzed and considered. Without addressing specifics, it was our collective opinion that:

- There is often inadequate and somewhat misleading information in the public domain concerning competitive generator designs preventing a complete assessment or comparison. This may be attributable to the proprietary nature of novel designs as well as a lack of expertise on the part of the author.
- In each case of a competitive design compromises made. The benefit of one approach almost always comes at the expense of a compromise elsewhere. Examples include: increased use of rare earth magnets, increased cost, more difficult to manufacture, lower efficiency, higher losses, etc.

### *Selected Topology for this effort*

Based upon careful analysis, a rim mounted, high pole count, radial flux, permanent magnet, three phase generator topology was selected for our design. This topology leverages established and simplified manufacturing processes.

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# ELECTROMAGNETIC DESIGN

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The electromechanical design for the resulting generator comes from many runs of a Matlab program written for the purpose of designing the RFPM rim mounted generator using a variety of input parameters including rotor radius, power ratings, air gap, magnet selection, etc.

The design chosen is listed below.

Table 4. Matlab® program output for 20 kW generator design

```
PM Generator
Permanent Magnet Generator Design: Surface Magnet, Conventional Stator
Program Build November 27, 2010
Preliminary stuff
Pole pair count =           14        Stator Slots =          252
Water Power =            24620 W      Output Power =        20183 W
Water Speed =             1.75 m/S    Rotation speed =      33.42 RPM
Magnet Remanence  =       1.40 T      Fund Field =           0.44 T
Rating =                 24620 W      Speed        =        33.42 RPM
Tooth Flux Den    =       0.62 T      Back Iron Flux         0.88 T
Armature Cur Den  =    8.9e+05 A/m^2  Tip Speed             3.500 m/s
Output Voltage (DC)     137.57 V      Current    =         146.71 A
Core Loss =                197 W      Armature Loss          4165 W
Windage Loss      =         58 W      EM Drag Loss            4.8 W
Harmonic Load Loss =        12 W      Input Power  =        24620 W
Output Power          20183.25 W      Check on that      20183.25 W
Efficiency  =            0.820
Torque                7034.180 N-m    Shear              3731.748 Pa
Demag Field             452289 A/m              =            5684 Oe
Geometric Details
Rotor Radius           1000.00 mm     Active Length        300.00 mm
Magnet Height             5.00 mm     Retaining Shell        0.00 mm
Rel Rot Gap               5.00 mm     Total Mag Gap          5.00 mm
Slot Top Width           12.60 mm     Slot Bot Width        13.10 mm
Slot Depression W         2.28 mm     Slot Depr Height       1.50 mm
Slot Height              40.00 mm     Back Iron Height      25.00 mm
Magnet Diameter        2000.00 mm     Stator ID           2010.00 mm
Shaft Diameter         1990.00 mm
Tooth Width =            12.50 mm     Slot Top Width =      12.60 mm
Slot height =            40.00 mm     Magnet Angle            150 Deg
Pole Pairs =                14        Stator Slots  =         252
Overall Diameter =     2143.00 mm     Overall Length =     351.19 mm
Weights
Core   =                704.12 kg     Shaft =              361.13 kg
Magnet =                 24.29 kg     Armature =           281.94 kg
Tooth Fraction  =       0.4979        Slot Fill      =     0.3361
Fund Winding Fact =     0.9452        Fund Gap Factor      0.2539
```

```
Fifth Winding Fact      0.1398        Seventh                0.0607
Neg zigzag W Fact      -0.9452        Pos Zigzag             0.9452
Coil Details                      Armature Turns          168
Circuits:     Series        14                     Parallel          1
Phase Resistance           0.10 Ohms   Inductance            11.048 mHy
Conductor Diameter         1.00 mm     In Hand                   55
Concentric Coils:
      Series Turns                  Coil Throw
              8                             8
              4                             6
Capital Cost = $ 5968.86
Cost of Energy = $ 0.040 /kwh
.
```

## MECHANICAL DESIGN OF GENERATOR

The magnetic circuit design above leads to the the specification and configuration of the core components of the generator including magnetics, coils and laminations.

### Stator and Rotor Assembly

The Stator outer diameter is 2.3 meters. The rotor inner diameter is 1.76 meters. The stator / rotor width is 0.54 meter. Air gap between the stator and rotor is tentatively set at 5 mm, which is unconventionally large; however the design is for a flooded air gap. The large air gap also provides for a bit more play room for maintaining concentricity between the rotor and stator.

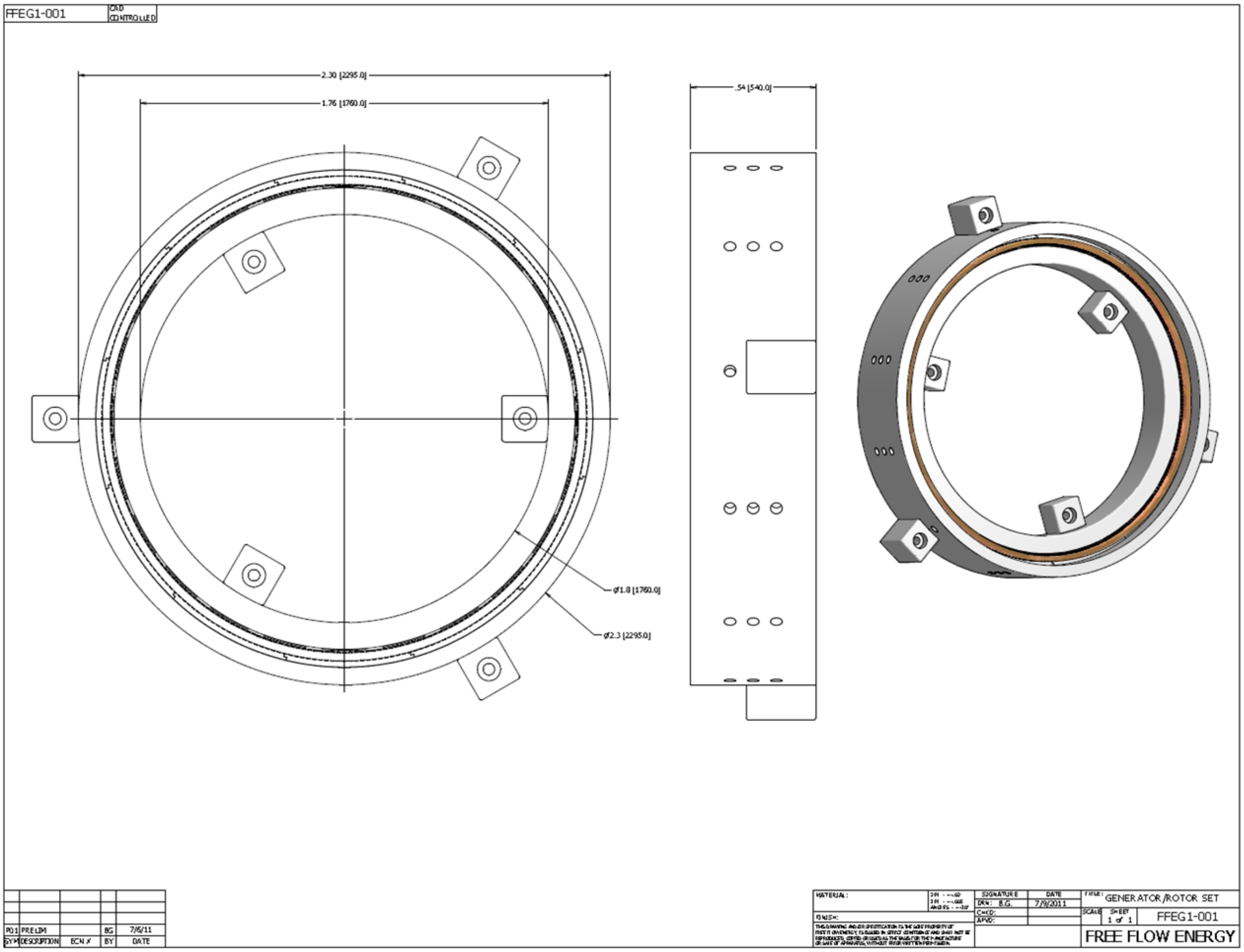
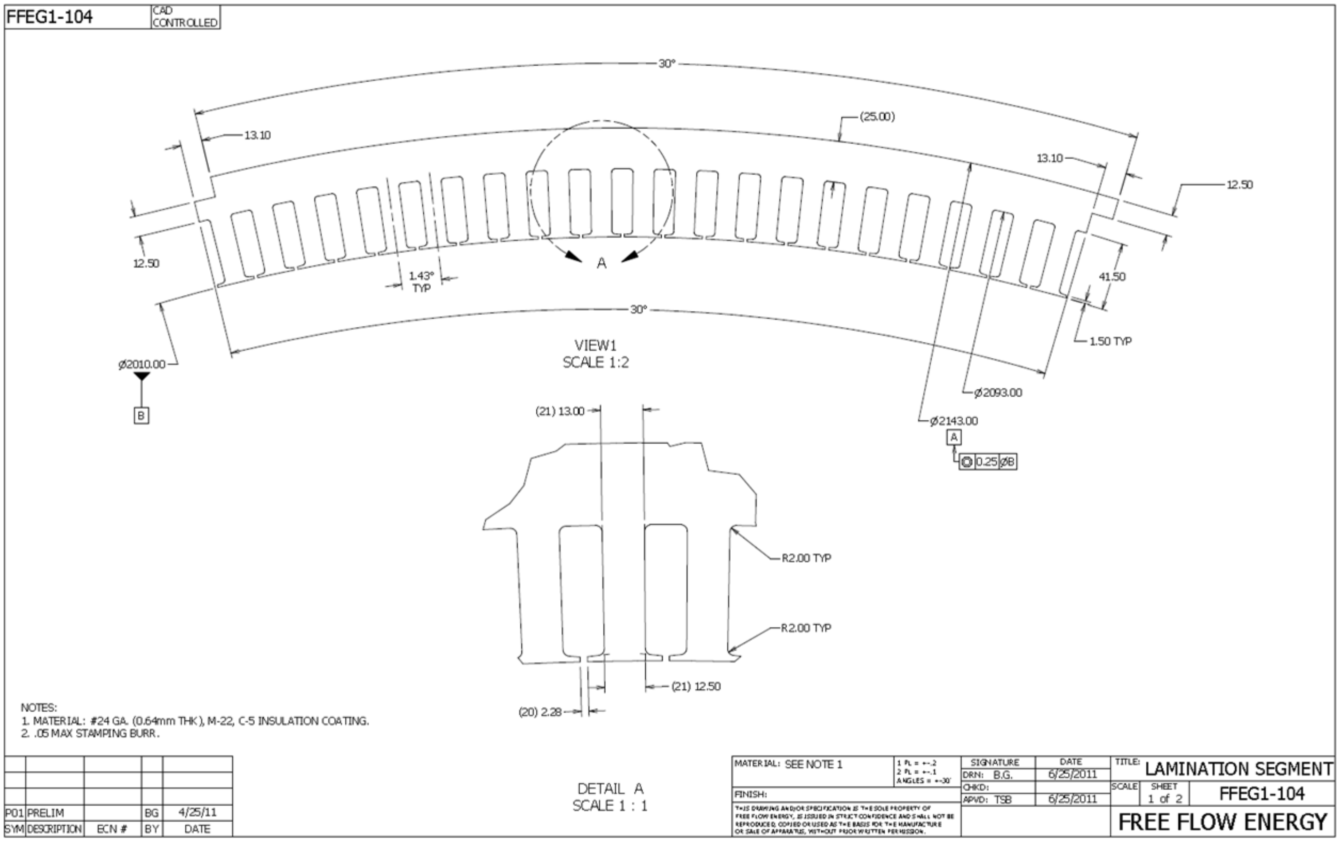


**Figure 30. Stator and rotor assembly**

Stator Segment Lamination

Large laminations for stators and rotors cannot be stamped full size due to the cost of tooling and incredible material waste. In this case, they are "segmented" or cut into smaller sections and then assembled together into a single larger stator or rotor lamination. Segmented laminations are cut by laser. Each is cut from twenty four gauge, M-22 electrical grade steel.



NOTES:
1. MATERIAL: #24 GA. (0.64mm THK), M-22, C-5 INSULATION COATING.
2. .05 MAX STAMPING BURR.

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**Figure 31. Segment lamination drawing**

**Core Segment**

Four hundred and sixty eight 24 gauge segment laminations (0.64 mm thick) are assembled into a single core segment. Twelve core segments each representing 30 degrees are then assembled into the 360 degree stator.

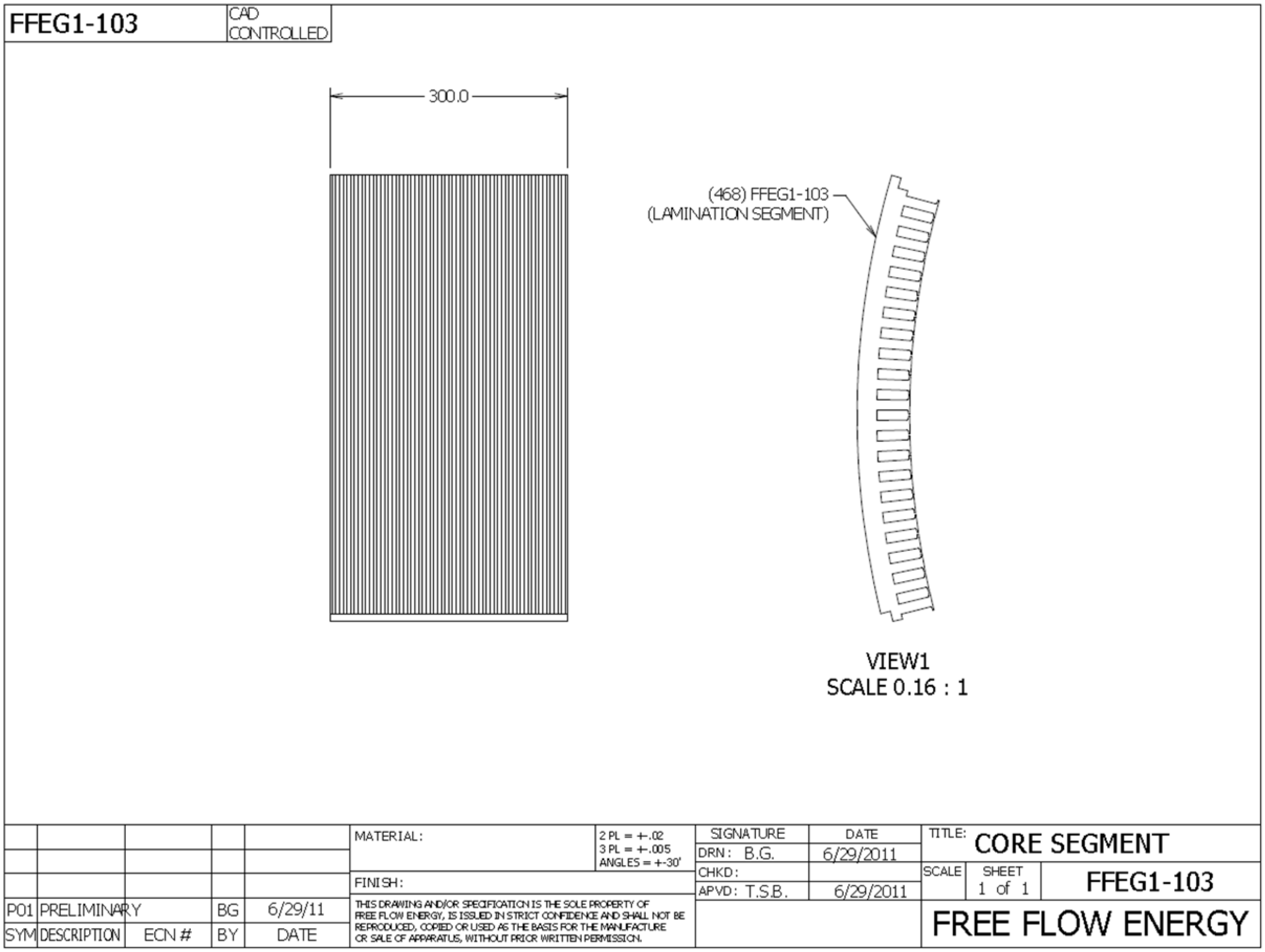
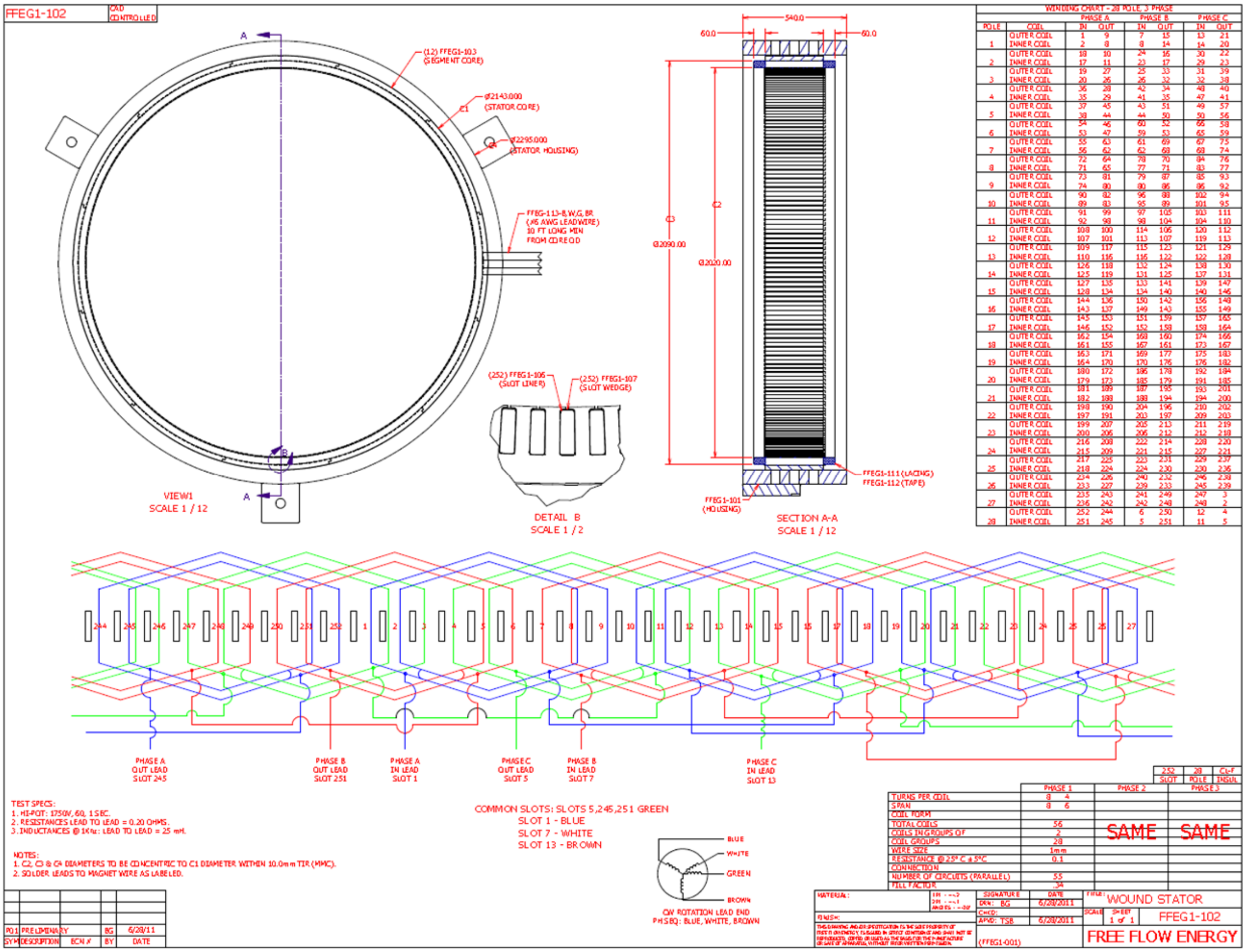


**Figure 32. Segmented core drawing**

**Complete stator and winding diagram**

The stator assembled from twelve stator cores and finished with a three phase winding is shown below.



WINDING CHART - 28 POLE, 3 PHASE

| | | PHASE A | | PHASE B | | PHASE C | |
|---|---|---|---|---|---|---|---|
| POLE | COIL | IN | OUT | IN | OUT | IN | OUT |
| 1 | OUTER COIL | 1 | 9 | 7 | 15 | 13 | 21 |
| | INNER COIL | 2 | 8 | 8 | 14 | 14 | 20 |
| 2 | OUTER COIL | 18 | 10 | 24 | 16 | 30 | 22 |
| | INNER COIL | 17 | 11 | 23 | 17 | 29 | 23 |
| 3 | OUTER COIL | 19 | 27 | 25 | 33 | 31 | 39 |
| | INNER COIL | 20 | 26 | 26 | 32 | 32 | 38 |
| 4 | OUTER COIL | 36 | 28 | 42 | 34 | 48 | 40 |
| | INNER COIL | 35 | 29 | 41 | 35 | 47 | 41 |
| 5 | OUTER COIL | 37 | 45 | 43 | 51 | 49 | 57 |
| | INNER COIL | 38 | 44 | 44 | 50 | 50 | 56 |
| 6 | OUTER COIL | 54 | 46 | 60 | 52 | 66 | 58 |
| | INNER COIL | 53 | 47 | 59 | 53 | 65 | 59 |
| 7 | OUTER COIL | 55 | 63 | 61 | 69 | 67 | 75 |
| | INNER COIL | 56 | 62 | 62 | 68 | 68 | 74 |
| 8 | OUTER COIL | 72 | 64 | 78 | 70 | 84 | 76 |
| | INNER COIL | 71 | 65 | 77 | 71 | 83 | 77 |
| 9 | OUTER COIL | 73 | 81 | 79 | 87 | 85 | 93 |
| | INNER COIL | 74 | 80 | 80 | 86 | 86 | 92 |
| 10 | OUTER COIL | 90 | 82 | 96 | 88 | 102 | 94 |
| | INNER COIL | 89 | 83 | 95 | 89 | 101 | 95 |
| 11 | OUTER COIL | 91 | 99 | 97 | 105 | 103 | 111 |
| | INNER COIL | 92 | 98 | 98 | 104 | 104 | 110 |
| 12 | OUTER COIL | 108 | 100 | 114 | 106 | 120 | 112 |
| | INNER COIL | 107 | 101 | 113 | 107 | 119 | 113 |
| 13 | OUTER COIL | 109 | 117 | 115 | 123 | 121 | 129 |
| | INNER COIL | 110 | 116 | 116 | 122 | 122 | 128 |
| 14 | OUTER COIL | 126 | 118 | 132 | 124 | 138 | 130 |
| | INNER COIL | 125 | 119 | 131 | 125 | 137 | 131 |
| 15 | OUTER COIL | 127 | 135 | 133 | 141 | 139 | 147 |
| | INNER COIL | 128 | 134 | 134 | 140 | 140 | 146 |
| 16 | OUTER COIL | 144 | 136 | 150 | 142 | 156 | 148 |
| | INNER COIL | 143 | 137 | 149 | 143 | 155 | 149 |
| 17 | OUTER COIL | 145 | 153 | 151 | 159 | 157 | 165 |
| | INNER COIL | 146 | 152 | 152 | 158 | 158 | 164 |
| 18 | OUTER COIL | 162 | 154 | 168 | 160 | 174 | 166 |
| | INNER COIL | 161 | 155 | 167 | 161 | 173 | 167 |
| 19 | OUTER COIL | 163 | 171 | 169 | 177 | 175 | 183 |
| | INNER COIL | 164 | 170 | 170 | 176 | 176 | 182 |
| 20 | OUTER COIL | 180 | 172 | 186 | 178 | 192 | 184 |
| | INNER COIL | 179 | 173 | 185 | 179 | 191 | 185 |
| 21 | OUTER COIL | 181 | 189 | 187 | 195 | 193 | 201 |
| | INNER COIL | 182 | 188 | 188 | 194 | 194 | 200 |
| 22 | OUTER COIL | 198 | 190 | 204 | 196 | 210 | 202 |
| | INNER COIL | 197 | 191 | 203 | 197 | 209 | 203 |
| 23 | OUTER COIL | 199 | 207 | 205 | 213 | 211 | 219 |
| | INNER COIL | 200 | 206 | 206 | 212 | 212 | 218 |
| 24 | OUTER COIL | 216 | 208 | 222 | 214 | 228 | 220 |
| | INNER COIL | 215 | 209 | 221 | 215 | 227 | 221 |
| 25 | OUTER COIL | 217 | 225 | 223 | 231 | 229 | 237 |
| | INNER COIL | 218 | 224 | 224 | 230 | 230 | 236 |
| 26 | OUTER COIL | 234 | 226 | 240 | 232 | 246 | 238 |
| | INNER COIL | 233 | 227 | 239 | 233 | 245 | 239 |
| 27 | OUTER COIL | 235 | 243 | 241 | 249 | 247 | 3 |
| | INNER COIL | 236 | 242 | 242 | 248 | 248 | 2 |
| 28 | OUTER COIL | 252 | 244 | 6 | 250 | 12 | 4 |
| | INNER COIL | 251 | 245 | 5 | 251 | 11 | 5 |

TEST SPECS:
1. HI-POT: 1750V, 60, 1 SEC.
2. RESISTANCES LEAD TO LEAD = 0.20 OHMS.
3. INDUCTANCES @ 1KHz: LEAD TO LEAD = 25 mH.

NOTES:
1. C2, C3 & C4 DIAMETERS TO BE CONCENTRIC TO C1 DIAMETER WITHIN 10.0mm TIR (MMC).
2. SOLDER LEADS TO MAGNET WIRE AS LABELED.

COMMON SLOTS: SLOTS 5,245,251 GREEN
SLOT 1 - BLUE
SLOT 7 - WHITE
SLOT 13 - BROWN

| 252 | 28 | Cl-F |
|---|---|---|
| SLOT | POLE | INSUL |

| | PHASE 1 | PHASE 2 | PHASE 3 |
|---|---|---|---|
| TURNS PER COIL | 8 4 | SAME | SAME |
| SPAN | 8 6 | | |
| COIL FORM | | | |
| TOTAL COILS | 56 | | |
| COILS IN GROUPS OF | 2 | | |
| COIL GROUPS | 28 | | |
| WIRE SIZE | 1mm | | |
| RESISTANCE @ 25° C ± 5°C | 0.1 | | |
| CONNECTION | | | |
| NUMBER OF CIRCUITS (PARALLEL) | 55 | | |
| FILL FACTOR | .34 | | |

| | | | | |
|---|---|---|---|---|
| P01 | PRELIMINARY | | BG | 6/28/11 |
| SYM | DESCRIPTION | ECN # | BY | DATE |

| | | | |
|---|---|---|---|
| MATERIAL: | | SIGNATURE | DATE |
| | | DRN: BG | 6/28/2011 |
| FINISH: | | CHCD: | |
| | | APVD: TSB | 6/28/2011 |
| | | (FFEG1-001) | |

TITLE: WOUND STATOR
SCALE
SHEET 1 of 1
FFEG1-102
FREE FLOW ENERGY

Figure 33. Stator winding diagram

## Rotor Magnets

Due to the brittleness of N45M, Sintered Neodymium Iron Boron material, the rotor magnets were reduced in size for manufacturability and assembly into sections of 62 by 75 mm. (Roughly the size of a playing card but 5 mm thick.) Half of the magnets (168) are polarized N/S and the other half (168) S/N. Twelve of the smaller magnets are assembled together into a single rotor pole. (See next drawing.)

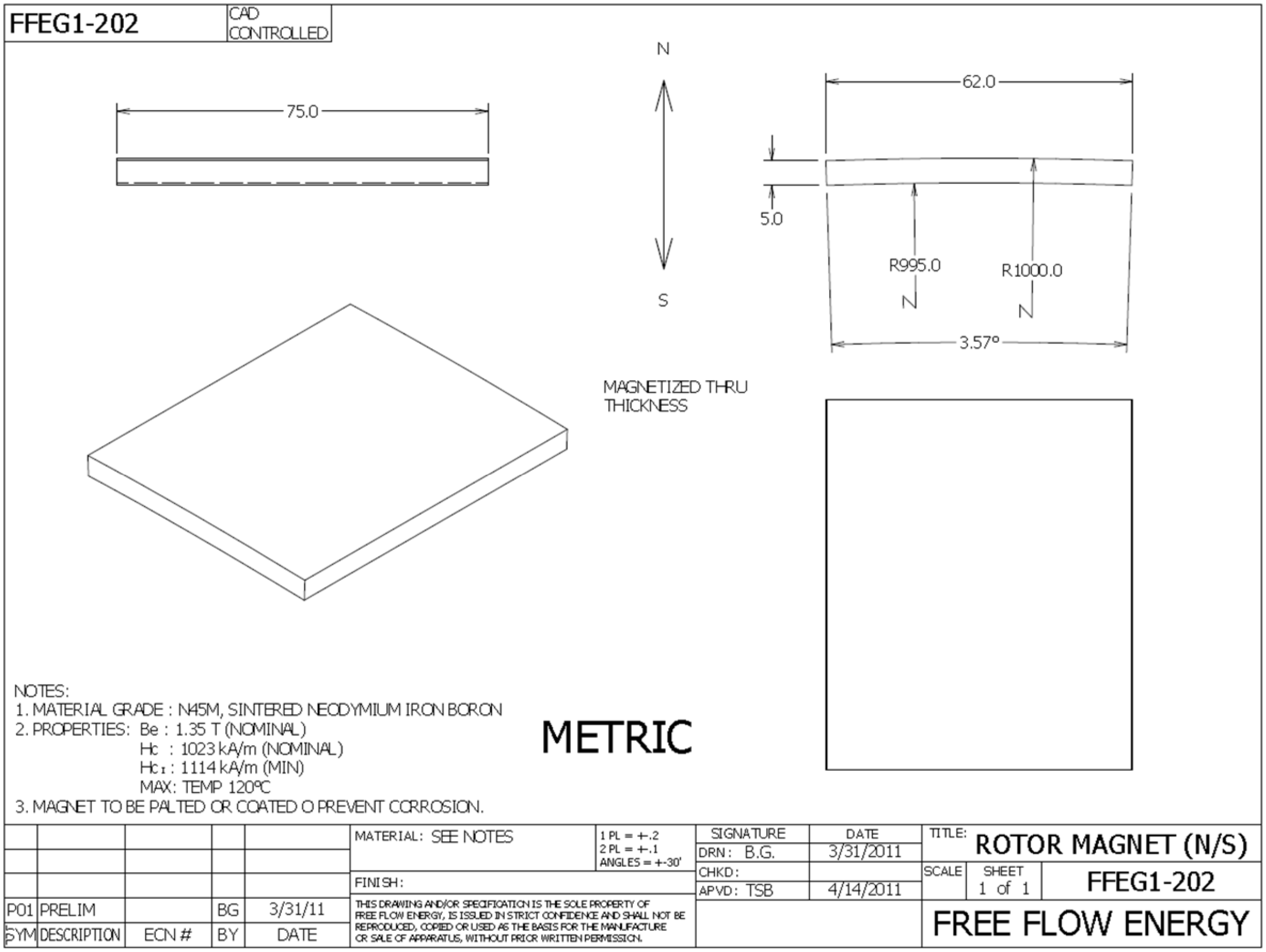


Figure 34. Rotor magnet (N/S)

## Rotor Assembly

Each rotor pole consists of twelve magnets alternating in polarity N/S then S/N. This results in 14 pole pairs or a total of 28 magnetic poles around the circumference of the rotor. Tabs are installed on the inner diameter of the rotor for connection to either inflow turbine blades or a hub attached to the central shaft of a cross flow turbine such as the Gorlov helical turbine.

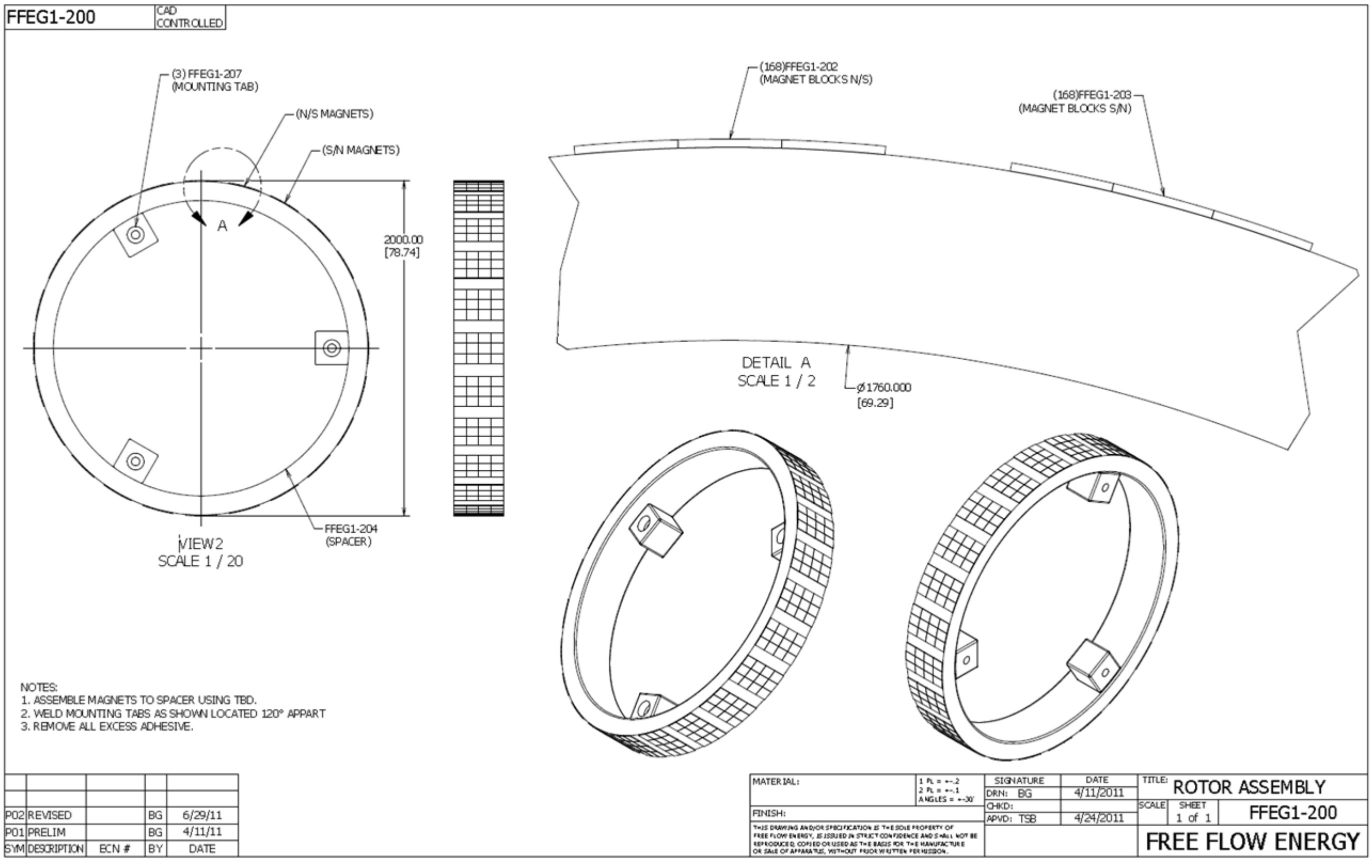


**Figure 35. Rotor assembly**

## Generator with Single GHT – Concept Drawing

Below is a concept drawing showing the method of attaching the generator to a single Gorlov style crossflow turbine. In the case below the single crossflow turbine would be approximately 3 meters in diameter and 7 meters long and presenting a cross section to the flow of 21 square meters. A structure holding the rotor, turbine, and stator is required in the final implementation.

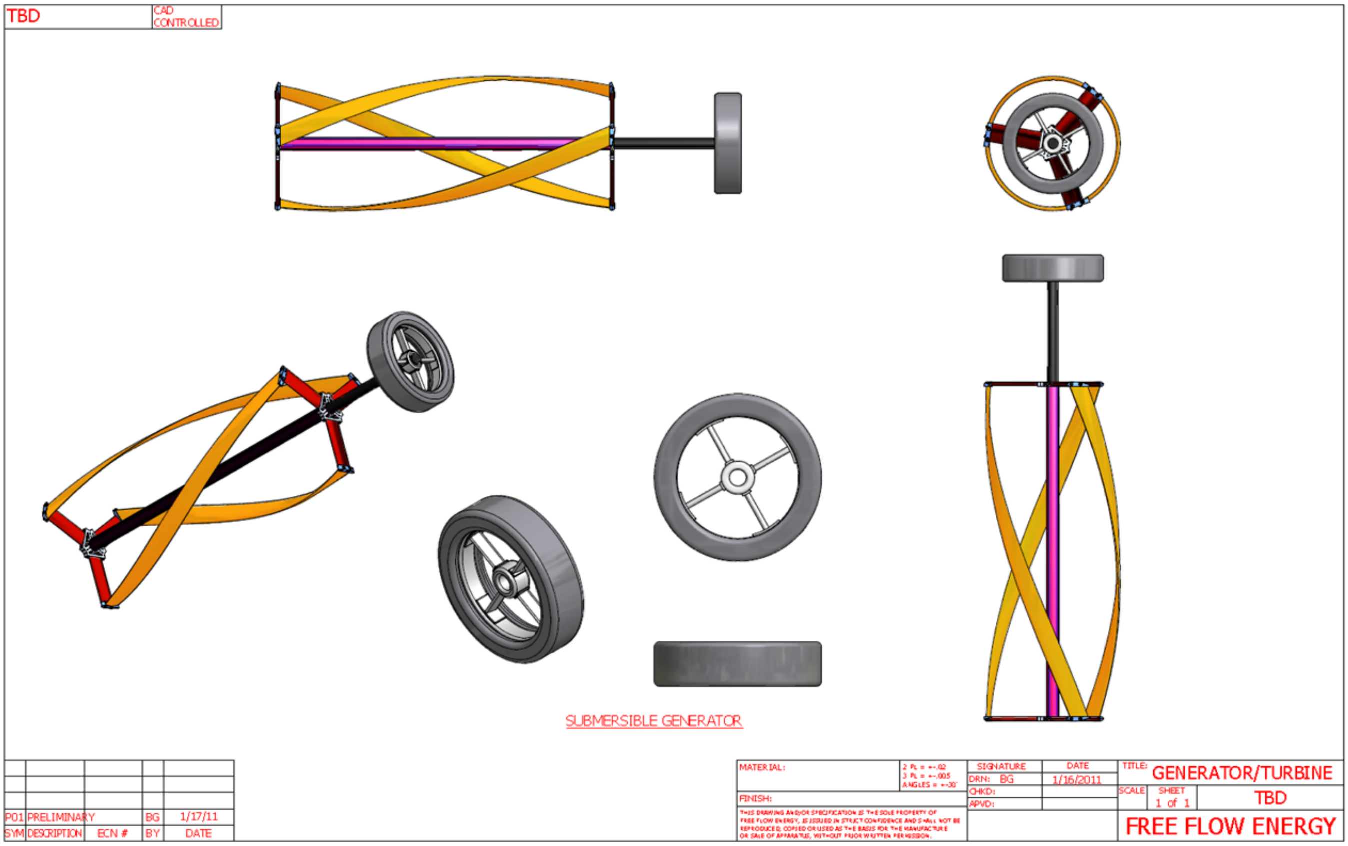


**Figure 36. Generator concept with single Gorlov-style turbine**

## Generator with Double GHT – Concept Drawing

Below is a concept drawing showing the method of attaching the generator to twin Gorlov style crossflow turbines. One novel concept would be to obtain twice the speed by applying the Gorlov turbines in a manner such that they counter-rotate in the flow. This would double the speed and be very desirable; however, to accomplish such a feat would require the application of "slip rings" to access the electrical power and the resistance and limitations of slip rings make this solution implausible.

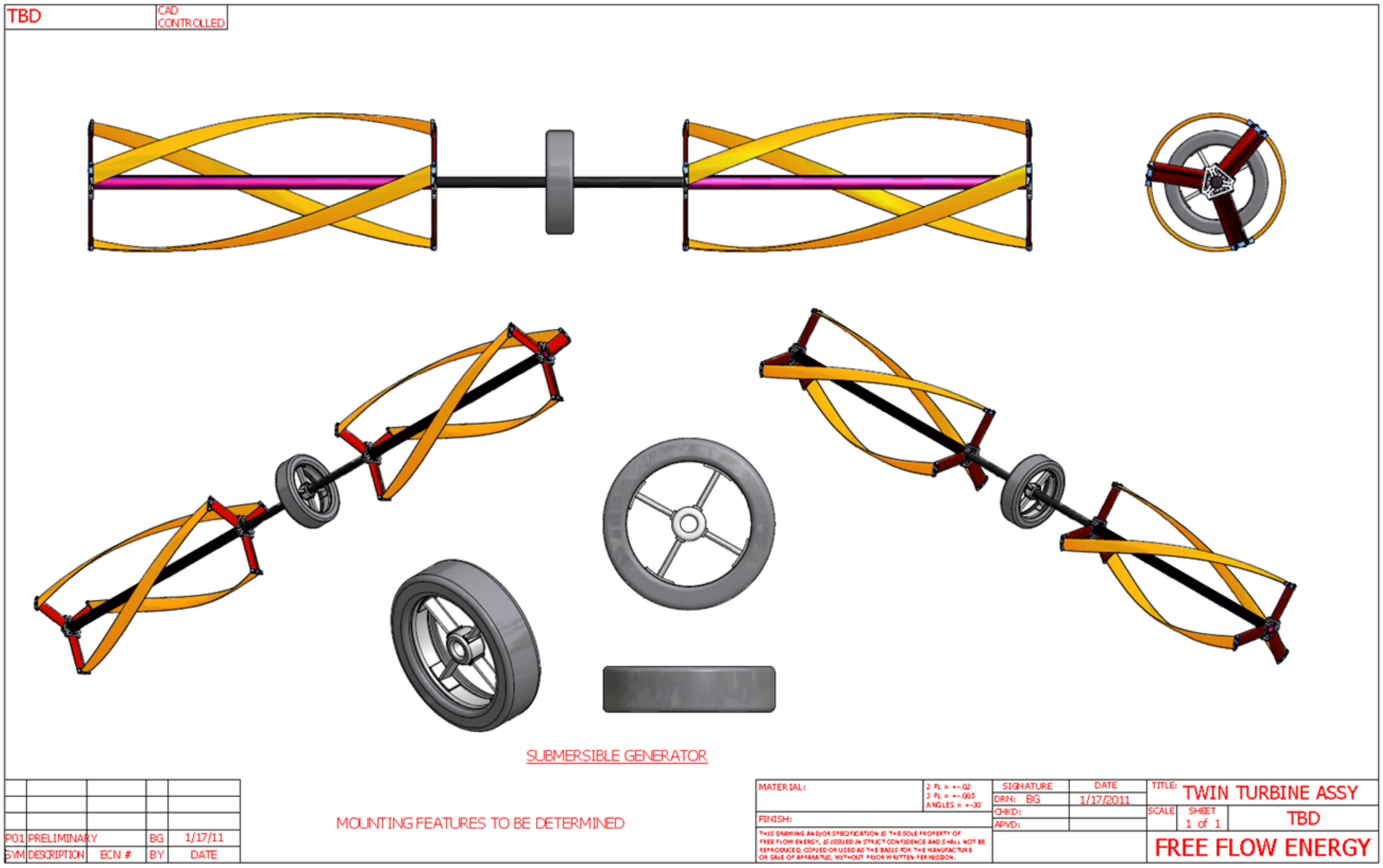


**Figure 37. Generator concept with double Gorlov-style turbines**

**Generator with Ducted Vertical Axis Turbine – Concept Drawing**

Below is a concept drawing of the generator attached to a ducted turbine. The entrance to the duct would be approximately five meters in diameter and two meters across at the turbine.

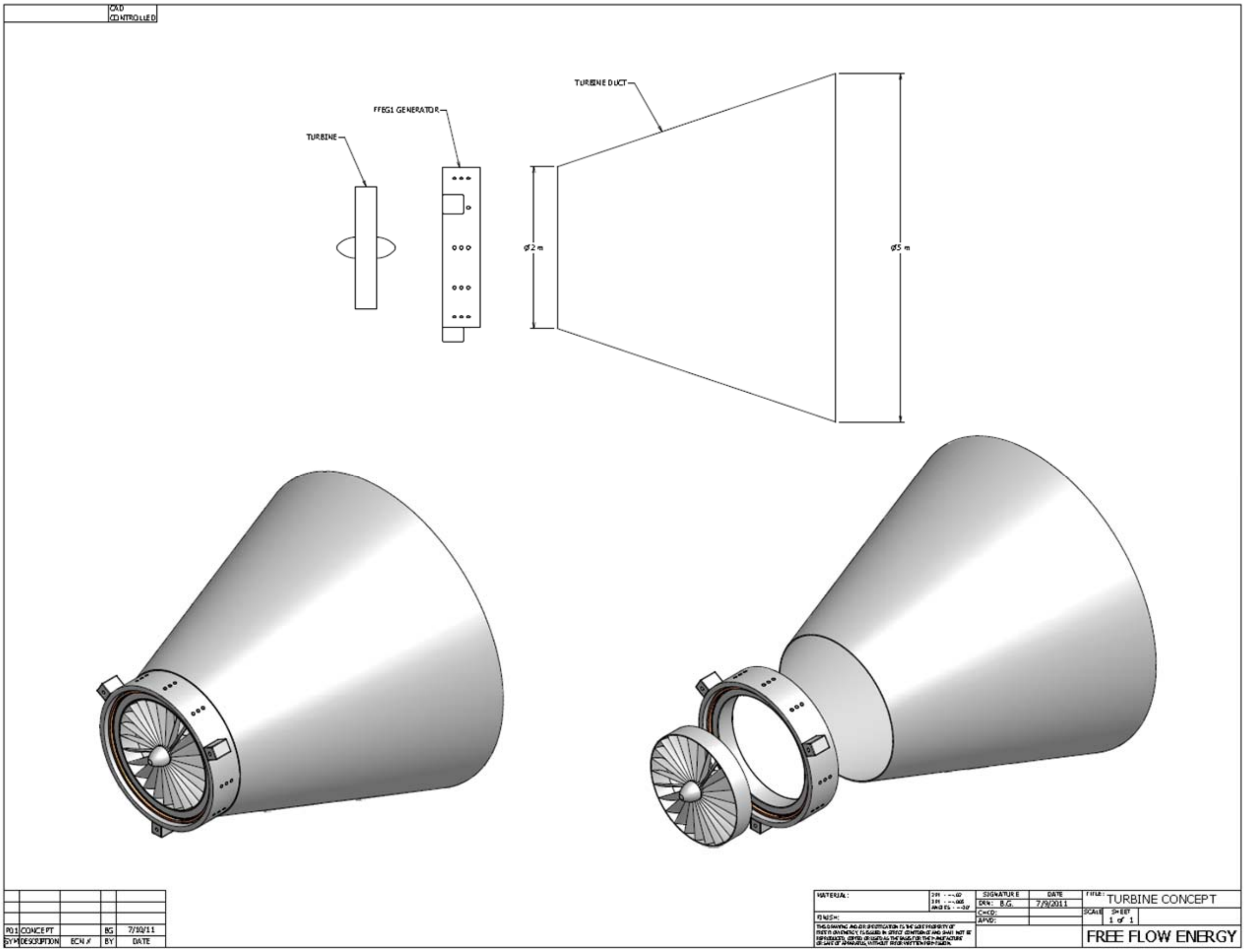


Figure 38. Generator concept with ducted in-flow turbine

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## Investigation of Manufacturing Requirements and Manufacturability

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There are 2 major components (stator & rotor) requiring separate and unique manufacturing processes. Initial builds of the generator will largely use manual processes as automated equipment such as winding insertion equipment would be custom equipment costing $400,000.00 or more. Also the large size of the device allows easy access to the bore of the stator thus simplifying the manual processes involved.

### Stator

The sequence of steps involved in the manufacture of the stator are:

1. Machine Housing, the bore of the steel case must be precisely machined to accept the stack core segments.
2. Stack Core Segments, the stator core segments are produced by bonding the individual laminations using a high strength, low viscosity adhesive. The laminations are initially held in place using fixturing then dipped in an adhesive bath and cured. The vendor responsible for laser cutting the laminations will also stack and bond the core segments.
3. Insert Core Segments and Weld, the lamination segments are inserted and then welded in place. Fixturing is required to align each segment as it is welded.
4. Paint Interior Surfaces, after completing the installation of the 12 core segments all interior surfaces will be painted to provide corrosion protection.
5. Insulate winding slots in stator core, each of the 252 winding slots in the core must be insulated to prevent electrical shorts. Nomex sheets bent to the shape of the slot are inserted into each slot.
6. Wind Coils, the winding coils are wound over a coil form using an automated winder. The coil form contains 56 stages allowing each coil forming a motor phase to be wound in series. Each winding phase is wound then removed from the form and inspected for resistance and insulation integrity.
7. Insert Coils, the 56 coils for each phase are carefully inserted in sequence so that 28 electromagnetic poles are formed around the circumference of the core. Each pole consists of 2 coils, a larger coil surrounding an inner coil. Each phase must be inserted in a precise spatial relationship to the other 2 phases so that balanced and symmetric electrical signals are produced. The operation of inserting the coils involves spreading the conductors of each coils so that the a coil side can be slipped through the narrow opening at the ID of a slot then stretching the coil and inserting the other coil side into a slot either 6 or 8 slots clockwise from the initial insertion slot.
8. Connect Coils, the three generator phases are connected in a Y pattern with one end of each phase forming a common connection. Because of the large number of wires forming each phase (55 conductors) a terminal block with 15 connection points connected together will be used. The other end of each phase winding is connected to a power cable, again a terminal block will be used to facilitate the connection.

9. Test winding, after all connections are made electrical checks are performed to check for satisfactory performance. Tests include insulation integrity checks using a high voltage (2000V), resistance check, inductance check and a high energy pulse or surge check. This last test is useful to determine whether the coil insertion pattern is correct.
10. Encapsulate Winding, the final stator manufacturing operation is an encapsulation process. This process is critically important to the life of the device since sea water should not be allowed to come in contact with the winding. An electrical insulating epoxy will be poured into a mold that captures both sides of the winding.

Fixturing Required: Following is a list of fixturing required to aid manufacturing of the generator stator:

1. Crane – the stator assembly will weigh 4800 lb so a crane will be required to lift and manipulate the stator.
2. Core Locating Fixture - to hold core segments in place while welding.
3. Coil Forms – form containing bobbins for 56 coils on a common shaft so that all coils of a phase can be wound in series.
4. Encapsulation Mold

Challenges: handling 55 wires in parallel, will likely need to separate into manageable bundles, encapsulation process (vacuum needed?)

## Rotor

Rotor process steps:

1. Machine rotor sleeve, the outside diameter of the steel cylinder must be machined to a close tolerance to match the radius of the magnet segments.
2. Bond Magnets, each of the 28 permanent magnet poles located around the periphery of the rotor consist of 12 magnet segments. Each segment must share the same magnetic polarity with its neighbors so the magnets will try to repel one another until the epoxy used to secure the segment cures. Fixturing will be used to hold the magnet segments in place.
3. Paint, an epoxy paint will be used to provide corrosion protection over the rotor surface. Note that the magnets are plated with a Nickel coating to provide an additional protection layer.

Fixturing Required: Following is a list of fixturing required to aid manufacturing of the generator rotor:

1. Crane – the rotor assembly weighs 3500 lb so a craned will be required to manipulate the rotor.
2. Magnet Locating Fixture – fixturing to locate and clamp a magnet segment in place while curing.

Challenges: Aligning magnets

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# COST ANALYSIS

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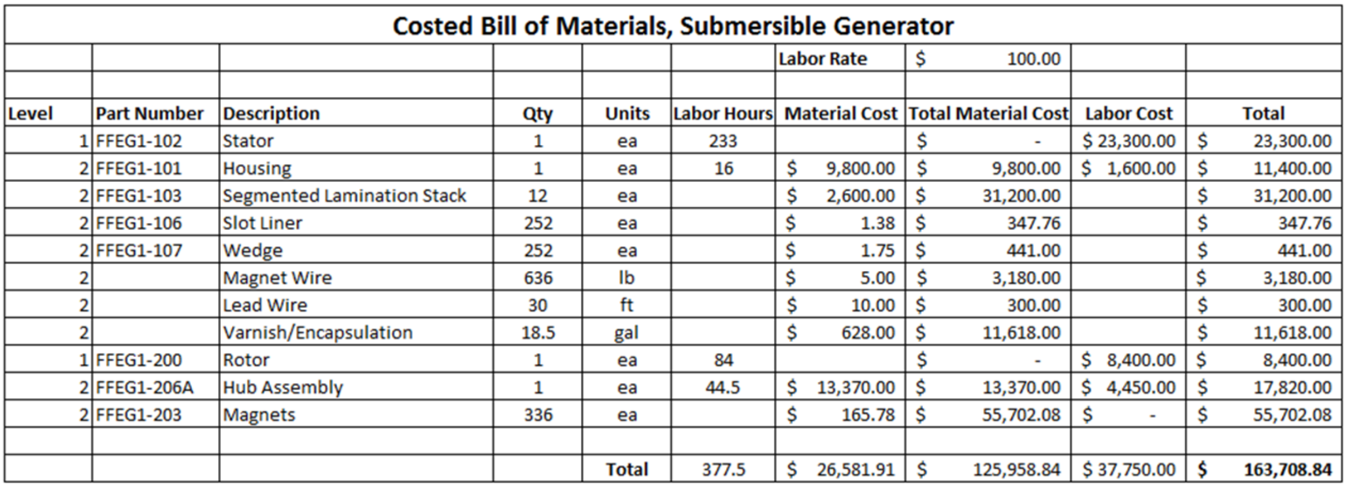
## Table 5. Generator cost analysis



**Costed Bill of Materials, Submersible Generator**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | **Labor Rate** | $ 100.00 | | |
| | | | | | | | | | |
| **Level** | **Part Number** | **Description** | **Qty** | **Units** | **Labor Hours** | **Material Cost** | **Total Material Cost** | **Labor Cost** | **Total** |
| 1 | FFEG1-102 | Stator | 1 | ea | 233 | | $ - | $ 23,300.00 | $ 23,300.00 |
| 2 | FFEG1-101 | Housing | 1 | ea | 16 | $ 9,800.00 | $ 9,800.00 | $ 1,600.00 | $ 11,400.00 |
| 2 | FFEG1-103 | Segmented Lamination Stack | 12 | ea | | $ 2,600.00 | $ 31,200.00 | | $ 31,200.00 |
| 2 | FFEG1-106 | Slot Liner | 252 | ea | | $ 1.38 | $ 347.76 | | $ 347.76 |
| 2 | FFEG1-107 | Wedge | 252 | ea | | $ 1.75 | $ 441.00 | | $ 441.00 |
| 2 | | Magnet Wire | 636 | lb | | $ 5.00 | $ 3,180.00 | | $ 3,180.00 |
| 2 | | Lead Wire | 30 | ft | | $ 10.00 | $ 300.00 | | $ 300.00 |
| 2 | | Varnish/Encapsulation | 18.5 | gal | | $ 628.00 | $ 11,618.00 | | $ 11,618.00 |
| 1 | FFEG1-200 | Rotor | 1 | ea | 84 | | $ - | $ 8,400.00 | $ 8,400.00 |
| 2 | FFEG1-206A | Hub Assembly | 1 | ea | 44.5 | $ 13,370.00 | $ 13,370.00 | $ 4,450.00 | $ 17,820.00 |
| 2 | FFEG1-203 | Magnets | 336 | ea | | $ 165.78 | $ 55,702.08 | $ - | $ 55,702.08 |
| | | | | | | | | | |
| | | | | **Total** | 377.5 | $ 26,581.91 | $ 125,958.84 | $ 37,750.00 | **$ 163,708.84** |

## COMMERCIALIZATION AND FUTURE RESEARCH

As mentioned earlier in this report, there appear to be two major obstacles to the commercialization of this generator and related MHK technology: lack of adequate resource and (therefore) few turbines in production. They are, in the opinion of this report: It is relatively rare to find water moving at or above two meters per second, or even close to that. Clearly this is evident in regulatory permitting to date which has focused on naturally occurring constrictions in river and near coastal waterways or the outside edge of curves where water is accelerated. This is also supported by the tendency to site downstream of river locks (man-made constrictions) which accelerate flow.

In the absence of natural or manmade ducting, there appear to be few areas with truly strong velocity. For clarity, it should be noted that extreme tidal ranges do not necessarily equate to high velocities. A tight constriction is still required to accelerate the water. In sites with “typical” flow velocities but adequate discharge (mass flow or cubic feet per second), considerable manipulation of the resource (ducting, shrouding or damming) may be required. In the absence of some sort of flow accelerator, the area required for meaningful energy conversion and therefore the size of hardware would be both considerable, costly and challenging to install and maintain.

It should also be noted that cut-in speed, typically 0.5-0.7 meters per second is also a concern. That is, it often takes substantial water velocity before turbine/generators begin converting kinetic energy into electricity.

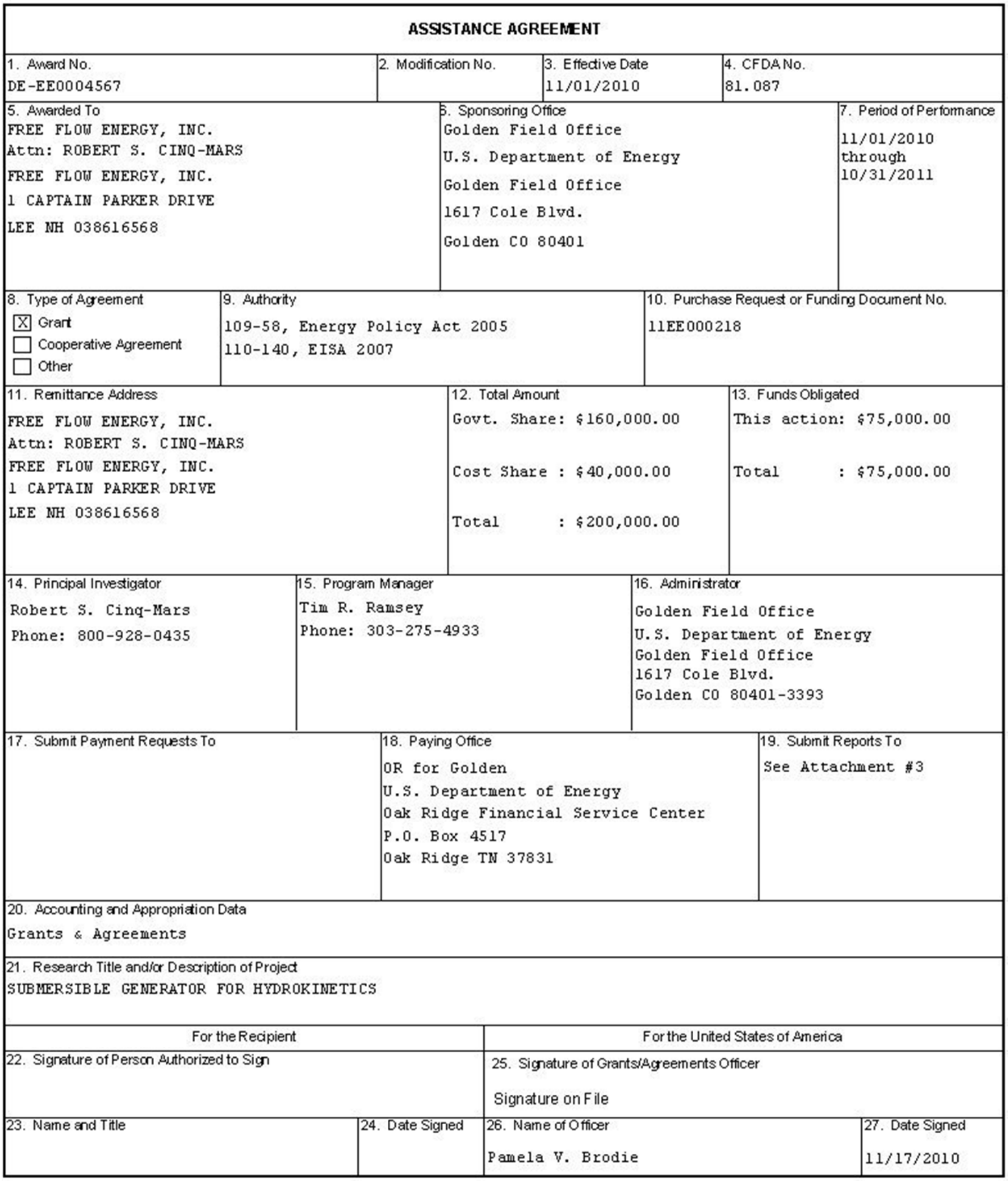
Due to the lack of available resources, it is our belief that this is why very few (close to none) turbines are in production. Until turbines begin moving into full manufacturing production, the generator will only be required for demonstration purposes. The generator must ultimately be designed around the size, power rating and dynamic performance of turbines that will ultimately be manufactured.

Until that time, Free Flow Energy, Inc. has demonstrated the ability to quickly and efficiently design rim mounted, direct drive, permanent magnet, submersible generators.

A great deal more work must be accomplished before practical underwater generation can be achieved. This includes the construction and test of hardware with particular emphasis on protecting the air gap – a critical problem in all motors and generators.

# ADDENDA

## Assistance Agreement Form (Project Description, Sponsoring Agency, Officers, and Costs)



**ASSISTANCE AGREEMENT**

1. Award No.
DE-EE0004567

2. Modification No.

3. Effective Date
11/01/2010

4. CFDA No.
81.087

5. Awarded To
FREE FLOW ENERGY, INC.
Attn: ROBERT S. CINQ-MARS
FREE FLOW ENERGY, INC.
1 CAPTAIN PARKER DRIVE
LEE NH 038616568

6. Sponsoring Office
Golden Field Office
U.S. Department of Energy
Golden Field Office
1617 Cole Blvd.
Golden CO 80401

7. Period of Performance
11/01/2010
through
10/31/2011

8. Type of Agreement
☒ Grant
☐ Cooperative Agreement
☐ Other

9. Authority
109-58, Energy Policy Act 2005
110-140, EISA 2007

10. Purchase Request or Funding Document No.
11EE000218

11. Remittance Address
FREE FLOW ENERGY, INC.
Attn: ROBERT S. CINQ-MARS
FREE FLOW ENERGY, INC.
1 CAPTAIN PARKER DRIVE
LEE NH 038616568

12. Total Amount
Govt. Share: $160,000.00
Cost Share : $40,000.00
Total : $200,000.00

13. Funds Obligated
This action: $75,000.00
Total : $75,000.00

14. Principal Investigator
Robert S. Cinq-Mars
Phone: 800-928-0435

15. Program Manager
Tim R. Ramsey
Phone: 303-275-4933

16. Administrator
Golden Field Office
U.S. Department of Energy
Golden Field Office
1617 Cole Blvd.
Golden CO 80401-3393

17. Submit Payment Requests To

18. Paying Office
OR for Golden
U.S. Department of Energy
Oak Ridge Financial Service Center
P.O. Box 4517
Oak Ridge TN 37831

19. Submit Reports To
See Attachment #3

20. Accounting and Appropriation Data
Grants & Agreements

21. Research Title and/or Description of Project
SUBMERSIBLE GENERATOR FOR HYDROKINETICS

For the Recipient

22. Signature of Person Authorized to Sign

23. Name and Title

24. Date Signed

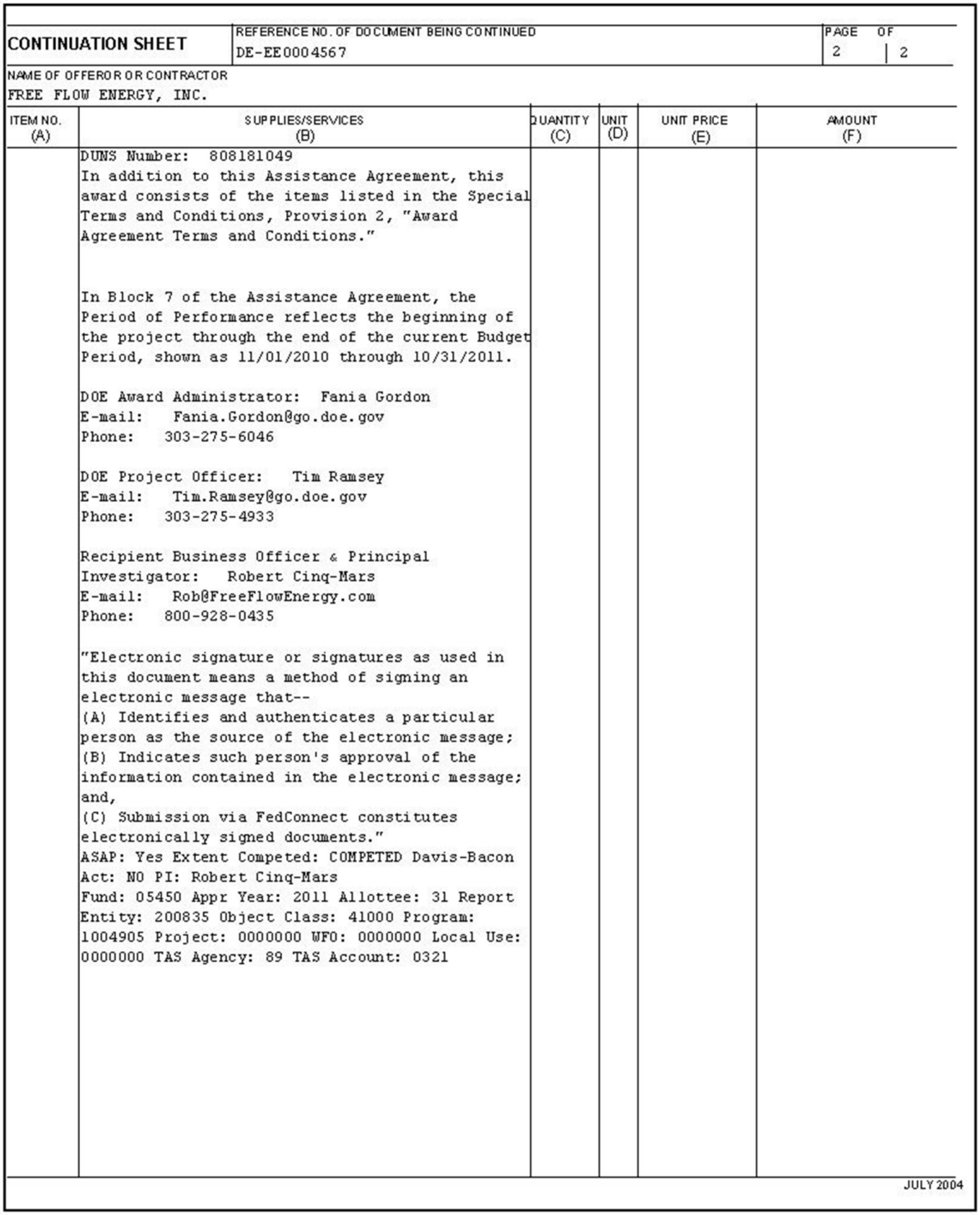
For the United States of America

25. Signature of Grants/Agreements Officer
Signature on File

26. Name of Officer
Pamela V. Brodie

27. Date Signed
11/17/2010

## Assistance Agreement Form (Page 2)



**CONTINUATION SHEET**

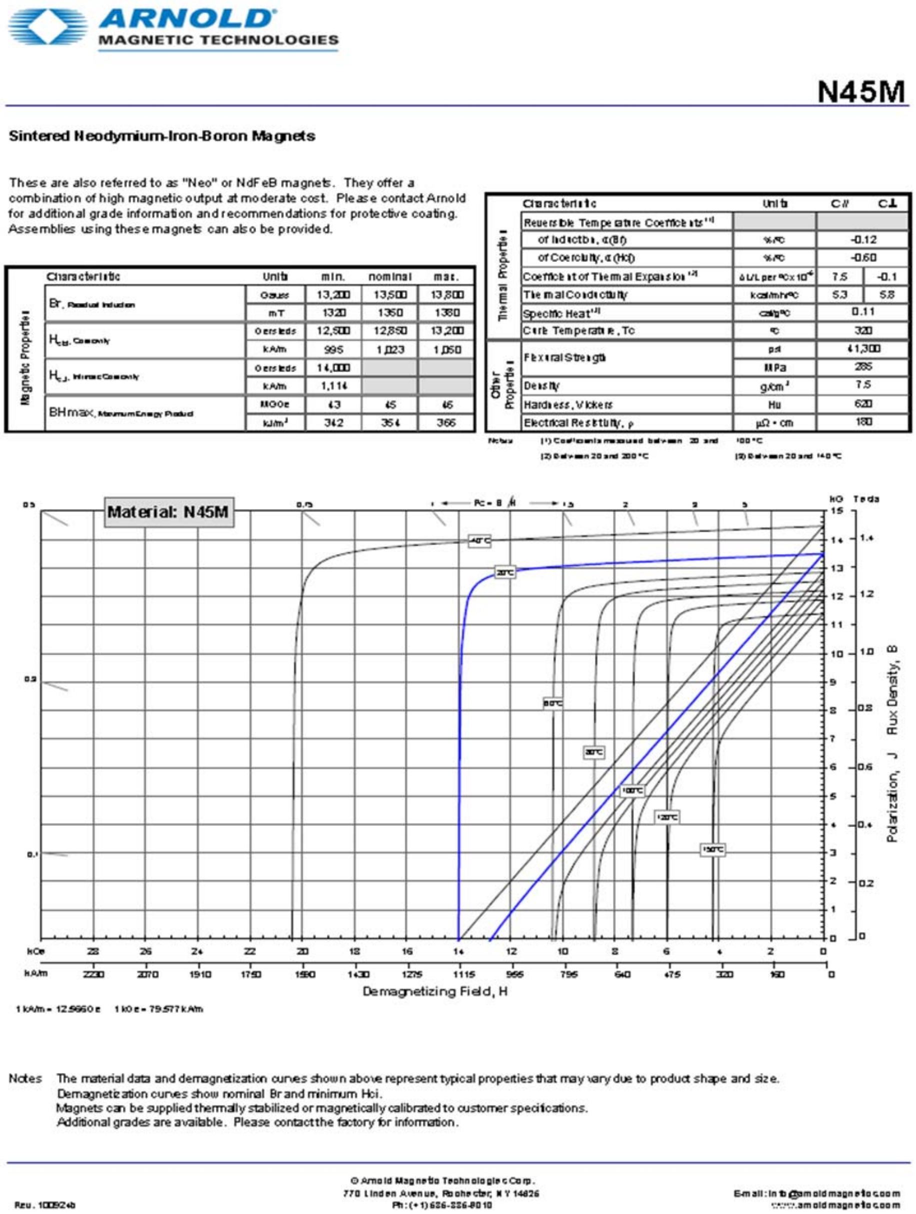
REFERENCE NO. OF DOCUMENT BEING CONTINUED: DE-EE0004567

PAGE 2 OF 2

NAME OF OFFEROR OR CONTRACTOR: FREE FLOW ENERGY, INC.

| ITEM NO. (A) | SUPPLIES/SERVICES (B) | QUANTITY (C) | UNIT (D) | UNIT PRICE (E) | AMOUNT (F) |
|---|---|---|---|---|---|
| | DUNS Number: 808181049<br>In addition to this Assistance Agreement, this award consists of the items listed in the Special Terms and Conditions, Provision 2, "Award Agreement Terms and Conditions."<br>In Block 7 of the Assistance Agreement, the Period of Performance reflects the beginning of the project through the end of the current Budget Period, shown as 11/01/2010 through 10/31/2011.<br>DOE Award Administrator: Fania Gordon<br>E-mail: Fania.Gordon@go.doe.gov<br>Phone: 303-275-6046<br>DOE Project Officer: Tim Ramsey<br>E-mail: Tim.Ramsey@go.doe.gov<br>Phone: 303-275-4933<br>Recipient Business Officer & Principal Investigator: Robert Cinq-Mars<br>E-mail: Rob@FreeFlowEnergy.com<br>Phone: 800-928-0435<br>"Electronic signature or signatures as used in this document means a method of signing an electronic message that--<br>(A) Identifies and authenticates a particular person as the source of the electronic message;<br>(B) Indicates such person's approval of the information contained in the electronic message; and,<br>(C) Submission via FedConnect constitutes electronically signed documents."<br>ASAP: Yes Extent Competed: COMPETED Davis-Bacon Act: NO PI: Robert Cinq-Mars<br>Fund: 05450 Appr Year: 2011 Allottee: 31 Report Entity: 200835 Object Class: 41000 Program: 1004905 Project: 0000000 WFO: 0000000 Local Use: 0000000 TAS Agency: 89 TAS Account: 0321 | | | | |

JULY 2004



ARNOLD
MAGNETIC TECHNOLOGIES

## N45M

**Sintered Neodymium-Iron-Boron Magnets**

These are also referred to as "Neo" or NdFeB magnets. They offer a combination of high magnetic output at moderate cost. Please contact Arnold for additional grade information and recommendations for protective coating. Assemblies using these magnets can also be provided.

| | Characteristic | Units | min. | nominal | max. |
|---|---|---|---|---|---|
| Magnetic Properties | Br, Residual Induction | Gauss | 13,200 | 13,500 | 13,800 |
| | | mT | 1320 | 1350 | 1380 |
| | $H_{cB}$, Coercivity | Oersteds | 12,500 | 12,850 | 13,200 |
| | | kA/m | 995 | 1,023 | 1,050 |
| | $H_{cJ}$, Intrinsic Coercivity | Oersteds | 14,000 | | |
| | | kA/m | 1,114 | | |
| | BHmax, Maximum Energy Product | MGOe | 43 | 45 | 46 |
| | | kJ/m³ | 342 | 354 | 366 |

| | Characteristic | Units | C// | C⊥ |
|---|---|---|---|---|
| Thermal Properties | Reversible Temperature Coefficients[1] | | | |
| | of Induction, α(Br) | %/°C | -0.12 | |
| | of Coercivity, α (Hcj) | %/°C | -0.60 | |
| | Coefficient of Thermal Expansion[2] | ΔL/L per °C x 10⁻⁶ | 7.5 | -0.1 |
| | Thermal Conductivity | kcal/m·hr·°C | 5.3 | 5.8 |
| | Specific Heat[3] | cal/g·°C | 0.11 | |
| | Curie Temperature, Tc | °C | 320 | |
| Other Properties | Flexural Strength | psi | 41,300 | |
| | | MPa | 285 | |
| | Density | g/cm³ | 7.5 | |
| | Hardness, Vickers | Hv | 620 | |
| | Electrical Resistivity, ρ | μΩ • cm | 180 | |

Notes
(1) Coefficients measured between 20 and 100 °C
(2) Between 20 and 200 °C
(3) Between 20 and 140 °C

1 kA/m = 12.566 Oe  1 kOe = 79.577 kA/m

Notes The material data and demagnetization curves shown above represent typical properties that may vary due to product shape and size.
Demagnetization curves show nominal Br and minimum Hci.
Magnets can be supplied thermally stabilized or magnetically calibrated to customer specifications.
Additional grades are available. Please contact the factory for information.

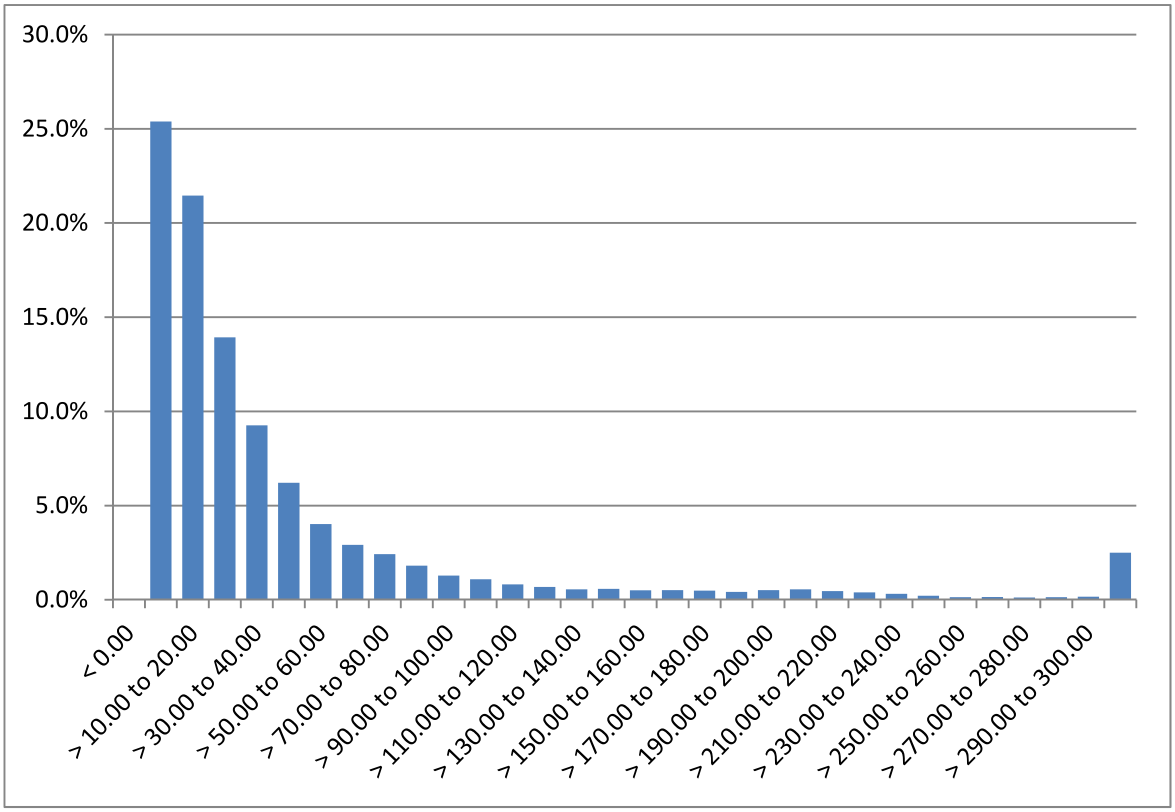
Rev. 100924b

770 Linden Avenue, Rochester, NY 14626
Ph: (+1) 585-385-9010

E-mail: info@arnoldmagnetics.com
www.arnoldmagnetics.com

**Channel Width (m)**

| | | | |
|---|---|---|---|
| Minimum value | 0.00 | | |
| | | | Std Deviation |
| Maximum value | 18806.16 | | |
| Average value | 51.53 | | 111.9846892 |
| If the value is: | **51.53** | 77% | of the values are equal to or lower |
| | | 23% | of the values are higher |



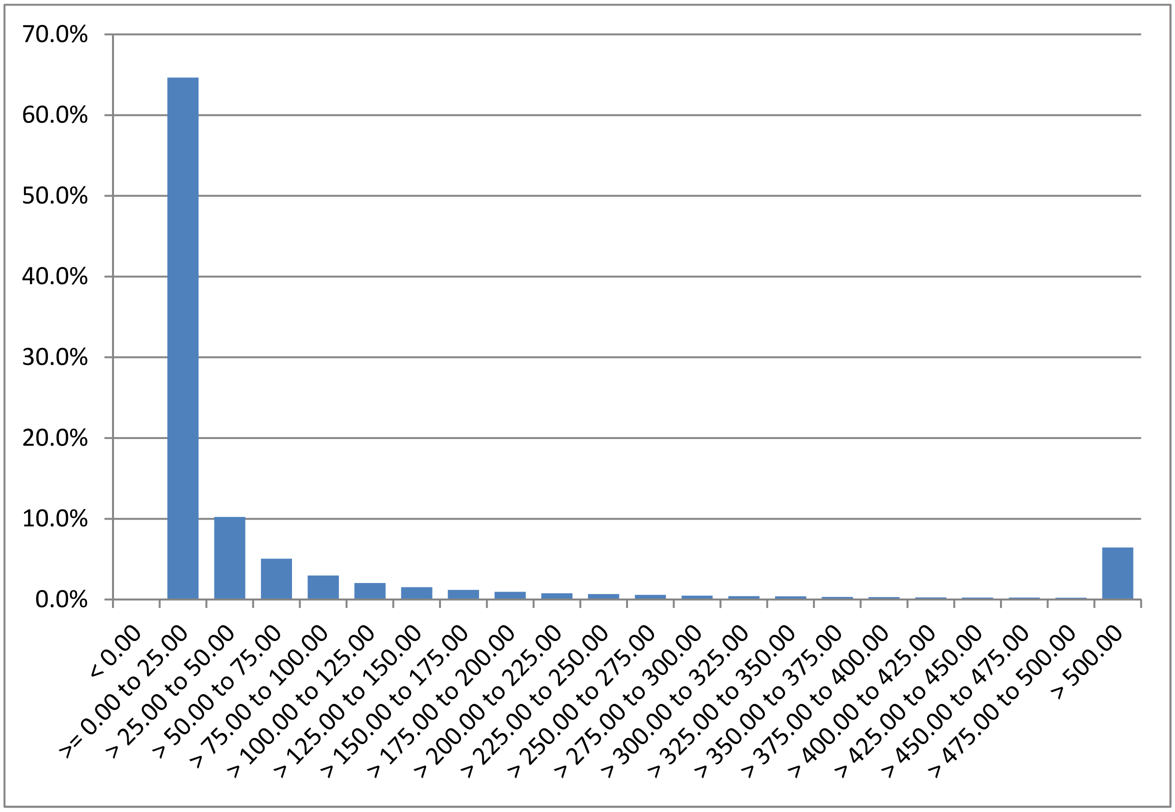
| | |
|---|---|
| Data values | 1,016,367 |
| Error values | 0 |
| Bin Size | 10 |
| Number of bins | 32 |

| | | | | Frequencies: | | Cumulative Frequencies: | | |
|---|---|---|---|---|---|---|---|---|
| < | 0.00 | | | 0 | 0.0% | < 0.00 | 0 | 0.0% |
| >= | 0.00 | to | 10.00 | 258030 | 25.4% | <= 10.00 | 258030 | 25.4% |
| > | 10.00 | to | 20.00 | 218101 | 21.5% | <= 20.00 | 476131 | 46.8% |
| > | 20.00 | to | 30.00 | 141613 | 13.9% | <= 30.00 | 617744 | 60.8% |
| > | 30.00 | to | 40.00 | 94119 | 9.3% | <= 40.00 | 711863 | 70.0% |
| > | 40.00 | to | 50.00 | 63078 | 6.2% | <= 50.00 | 774941 | 76.2% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| > | 50.00 | to | 60.00 | 40892 | 4.0% | <= 60.00 | 815833 | 80.3% |
| > | 60.00 | to | 70.00 | 29645 | 2.9% | <= 70.00 | 845478 | 83.2% |
| > | 70.00 | to | 80.00 | 24648 | 2.4% | <= 80.00 | 870126 | 85.6% |
| > | 80.00 | to | 90.00 | 18420 | 1.8% | <= 90.00 | 888546 | 87.4% |
| > | 90.00 | to | 100.00 | 13081 | 1.3% | <= 100.00 | 901627 | 88.7% |
| > | 100.00 | to | 110.00 | 11079 | 1.1% | <= 110.00 | 912706 | 89.8% |
| > | 110.00 | to | 120.00 | 8287 | 0.8% | <= 120.00 | 920993 | 90.6% |
| > | 120.00 | to | 130.00 | 6960 | 0.7% | <= 130.00 | 927953 | 91.3% |
| > | 130.00 | to | 140.00 | 5608 | 0.6% | <= 140.00 | 933561 | 91.9% |
| > | 140.00 | to | 150.00 | 5895 | 0.6% | <= 150.00 | 939456 | 92.4% |
| > | 150.00 | to | 160.00 | 5117 | 0.5% | <= 160.00 | 944573 | 92.9% |
| > | 160.00 | to | 170.00 | 5220 | 0.5% | <= 170.00 | 949793 | 93.4% |
| > | 170.00 | to | 180.00 | 4900 | 0.5% | <= 180.00 | 954693 | 93.9% |
| > | 180.00 | to | 190.00 | 4260 | 0.4% | <= 190.00 | 958953 | 94.4% |
| > | 190.00 | to | 200.00 | 5240 | 0.5% | <= 200.00 | 964193 | 94.9% |
| > | 200.00 | to | 210.00 | 5588 | 0.5% | <= 210.00 | 969781 | 95.4% |
| > | 210.00 | to | 220.00 | 4677 | 0.5% | <= 220.00 | 974458 | 95.9% |
| > | 220.00 | to | 230.00 | 3965 | 0.4% | <= 230.00 | 978423 | 96.3% |
| > | 230.00 | to | 240.00 | 3243 | 0.3% | <= 240.00 | 981666 | 96.6% |
| > | 240.00 | to | 250.00 | 2183 | 0.2% | <= 250.00 | 983849 | 96.8% |
| > | 250.00 | to | 260.00 | 1434 | 0.1% | <= 260.00 | 985283 | 96.9% |
| > | 260.00 | to | 270.00 | 1458 | 0.1% | <= 270.00 | 986741 | 97.1% |
| > | 270.00 | to | 280.00 | 1214 | 0.1% | <= 280.00 | 987955 | 97.2% |
| > | 280.00 | to | 290.00 | 1358 | 0.1% | <= 290.00 | 989313 | 97.3% |
| > | 290.00 | to | 300.00 | 1673 | 0.2% | <= 300.00 | 990986 | 97.5% |
| > | 300.00 | | | 25381 | 2.5% | | | |

**Channel Area (m^2)**

| | | | |
|---|---|---|---|
| Minimum value | 0.09 | | |
| Maximum value | 185800.00 | | Std Deviation |
| Average value | 165.62 | | 820.2744789 |
| If the value is: | **165.62** | 87% | of the values are equal to or lower |
| | | 13% | of the values are higher |



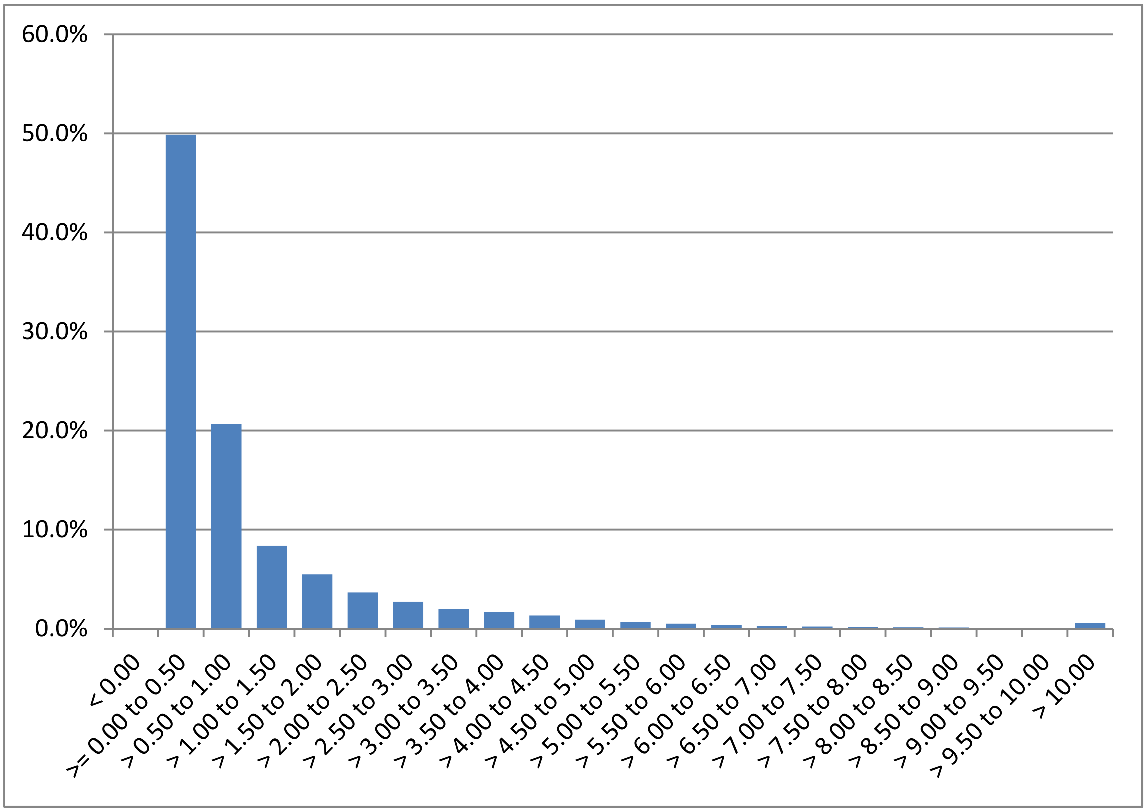
| | |
|---|---|
| Data values | 1,016,367 |
| Error values | 0 |
| Bin Size | 25 |
| Number of bins | 22 |

| | | | | Frequencies: | | Cumulative Frequencies: | | |
|---|---|---|---|---|---|---|---|---|
| < | 0.00 | | | 0 | 0.0% | < 0.00 | 0 | 0.0% |
| >= | 0.00 | to | 25.00 | 657004 | 64.6% | <= 25.00 | 657004 | 64.6% |
| > | 25.00 | to | 50.00 | 103952 | 10.2% | <= 50.00 | 760956 | 74.9% |
| > | 50.00 | to | 75.00 | 51416 | 5.1% | <= 75.00 | 812372 | 79.9% |
| > | 75.00 | to | 100.00 | 30263 | 3.0% | <= 100.00 | 842635 | 82.9% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| > | 100.00 | to | 125.00 | 20844 | 2.1% | <= 125.00 | 863479 | 85.0% |
| > | 125.00 | to | 150.00 | 15472 | 1.5% | <= 150.00 | 878951 | 86.5% |
| > | 150.00 | to | 175.00 | 12133 | 1.2% | <= 175.00 | 891084 | 87.7% |
| > | 175.00 | to | 200.00 | 9689 | 1.0% | <= 200.00 | 900773 | 88.6% |
| > | 200.00 | to | 225.00 | 7818 | 0.8% | <= 225.00 | 908591 | 89.4% |
| > | 225.00 | to | 250.00 | 6884 | 0.7% | <= 250.00 | 915475 | 90.1% |
| > | 250.00 | to | 275.00 | 5851 | 0.6% | <= 275.00 | 921326 | 90.6% |
| > | 275.00 | to | 300.00 | 4935 | 0.5% | <= 300.00 | 926261 | 91.1% |
| > | 300.00 | to | 325.00 | 4371 | 0.4% | <= 325.00 | 930632 | 91.6% |
| > | 325.00 | to | 350.00 | 4002 | 0.4% | <= 350.00 | 934634 | 92.0% |
| > | 350.00 | to | 375.00 | 3321 | 0.3% | <= 375.00 | 937955 | 92.3% |
| > | 375.00 | to | 400.00 | 3049 | 0.3% | <= 400.00 | 941004 | 92.6% |
| > | 400.00 | to | 425.00 | 2745 | 0.3% | <= 425.00 | 943749 | 92.9% |
| > | 425.00 | to | 450.00 | 2545 | 0.3% | <= 450.00 | 946294 | 93.1% |
| > | 450.00 | to | 475.00 | 2469 | 0.2% | <= 475.00 | 948763 | 93.3% |
| > | 475.00 | to | 500.00 | 2200 | 0.2% | <= 500.00 | 950963 | 93.6% |
| > | 500.00 | | | 65404 | 6.4% | | | |

**Channel Depth (m)**

| | | | |
|---|---|---|---|
| Minimum value | 0.00 | | |
| | | | Std |
| Maximum value | 2746.70 | | Deviation |
| Average value | 1.16 | | 7.071096701 |
| If the value is: | **1.16** | 74% | of the values are equal to or lower |
| | | 26% | of the values are higher |



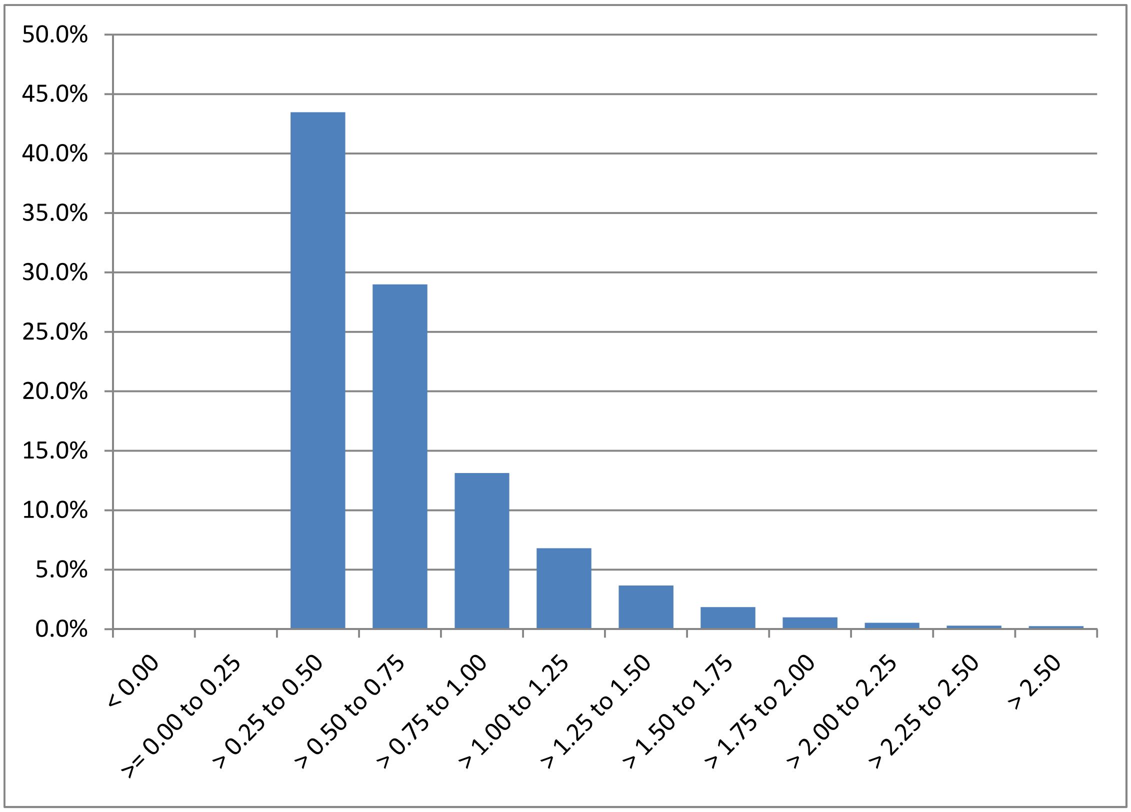
| | |
|---|---|
| Data values | 1,016,367 |
| Error values | 0 |
| Bin Size | 0.5 |
| Number of bins | 22 |

| | | | | Frequencies: | | | Cumulative Frequencies: | |
|---|---|---|---|---|---|---|---|---|
| < | 0.00 | | | 0 | 0.0% | < 0.00 | 0 | 0.0% |
| >= | 0.00 | to | 0.50 | 506907 | 49.9% | <= 0.50 | 506907 | 49.9% |
| > | 0.50 | to | 1.00 | 209897 | 20.7% | <= 1.00 | 716804 | 70.5% |
| > | 1.00 | to | 1.50 | 85106 | 8.4% | <= 1.50 | 801910 | 78.9% |
| > | 1.50 | to | 2.00 | 55755 | 5.5% | <= 2.00 | 857665 | 84.4% |
| > | 2.00 | to | 2.50 | 37146 | 3.7% | <= 2.50 | 894811 | 88.0% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| > | 2.50 | to | 3.00 | 27631 | 2.7% | <= 3.00 | 922442 | 90.8% |
| > | 3.00 | to | 3.50 | 20300 | 2.0% | <= 3.50 | 942742 | 92.8% |
| > | 3.50 | to | 4.00 | 17340 | 1.7% | <= 4.00 | 960082 | 94.5% |
| > | 4.00 | to | 4.50 | 13562 | 1.3% | <= 4.50 | 973644 | 95.8% |
| > | 4.50 | to | 5.00 | 9236 | 0.9% | <= 5.00 | 982880 | 96.7% |
| > | 5.00 | to | 5.50 | 6875 | 0.7% | <= 5.50 | 989755 | 97.4% |
| > | 5.50 | to | 6.00 | 5235 | 0.5% | <= 6.00 | 994990 | 97.9% |
| > | 6.00 | to | 6.50 | 3935 | 0.4% | <= 6.50 | 998925 | 98.3% |
| > | 6.50 | to | 7.00 | 2883 | 0.3% | <= 7.00 | 1001808 | 98.6% |
| > | 7.00 | to | 7.50 | 2168 | 0.2% | <= 7.50 | 1003976 | 98.8% |
| > | 7.50 | to | 8.00 | 1811 | 0.2% | <= 8.00 | 1005787 | 99.0% |
| > | 8.00 | to | 8.50 | 1480 | 0.1% | <= 8.50 | 1007267 | 99.1% |
| > | 8.50 | to | 9.00 | 1172 | 0.1% | <= 9.00 | 1008439 | 99.2% |
| > | 9.00 | to | 9.50 | 994 | 0.1% | <= 9.50 | 1009433 | 99.3% |
| > | 9.50 | to | 10.00 | 862 | 0.1% | <= 10.00 | 1010295 | 99.4% |
| > | 10.00 | | | 6072 | 0.6% | | | |

**Channel Velocity (mps)**

| | | | |
|---|---|---|---|
| Minimum value | 0.30 | | |
| Maximum value | 6.00 | | Std Deviation |
| Average value | 0.66 | | 0.372671323 |
| If the value is: | **0.66** | 64% | of the values are equal to or lower |
| | | 36% | of the values are higher |



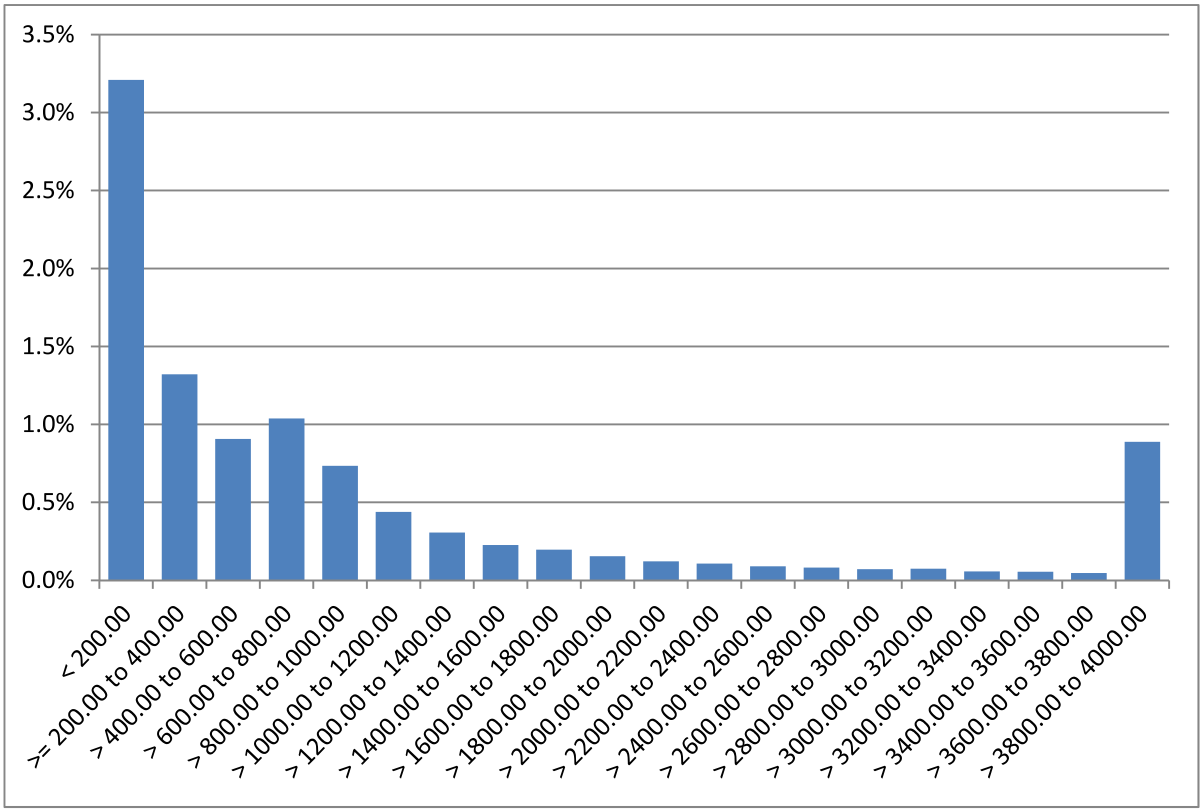
| | |
|---|---|
| Data values | 1,016,367 |
| Error values | 0 |
| Bin Size | 0.25 |
| Number of bins | 12 |

| | | | | Frequencies: | | | Cumulative Frequencies: | |
|---|---|---|---|---|---|---|---|---|
| < | 0.00 | | | 0 | 0.0% | < 0.00 | 0 | 0.0% |
| >= | 0.00 | to | 0.25 | 0 | 0.0% | <= 0.25 | 0 | 0.0% |
| > | 0.25 | to | 0.50 | 441831 | 43.5% | <= 0.50 | 441831 | 43.5% |
| > | 0.50 | to | 0.75 | 294678 | 29.0% | <= 0.75 | 736509 | 72.5% |
| > | 0.75 | to | 1.00 | 133427 | 13.1% | <= 1.00 | 869936 | 85.6% |
| > | 1.00 | to | 1.25 | 69183 | 6.8% | <= 1.25 | 939119 | 92.4% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| > | 1.25 | to | 1.50 | 37294 | 3.7% | <= 1.50 | 976413 | 96.1% |
| > | 1.50 | to | 1.75 | 18886 | 1.9% | <= 1.75 | 995299 | 97.9% |
| > | 1.75 | to | 2.00 | 10119 | 1.0% | <= 2.00 | 1005418 | 98.9% |
| > | 2.00 | to | 2.25 | 5408 | 0.5% | <= 2.25 | 1010826 | 99.5% |
| > | 2.25 | to | 2.50 | 2944 | 0.3% | <= 2.50 | 1013770 | 99.7% |
| > | 2.50 | | | 2597 | 0.3% | | | |

**Channel Discharge (cms)**

|  |  |  |  |
|---|---|---|---|
| Minimum value | 0.00 |  |  |
| Maximum value | 212683.20 |  | Std Deviation |
| Average value | 179.14 |  | 1059.95438 |
| If the value is: | **179.14** | 89% | of the values are equal to or lower |
|  |  | 11% | of the values are higher |



|  |  |
|---|---|
| Data values | 1,016,367 |
| Error values | 0 |
| Bin Size | 200 |
| Number of bins | 21 |

|  |  |  |  | Frequencies: |  | Cumulative Frequencies: |  |  |
|---|---|---|---|---|---|---|---|---|
| < | 200.00 |  |  | 913439 | 89.9% | < 200.00 | 913439 | 89.9% |
| >= | 200.00 | to | 400.00 | 32623 | 3.2% | <= 400.00 | 946062 | 93.1% |
| > | 400.00 | to | 600.00 | 13433 | 1.3% | <= 600.00 | 959495 | 94.4% |
| > | 600.00 | to | 800.00 | 9213 | 0.9% | <= 800.00 | 968708 | 95.3% |
| > | 800.00 | to | 1000.00 | 10556 | 1.0% | <= 1000.00 | 979264 | 96.3% |
| > | 1000.00 | to | 1200.00 | 7464 | 0.7% | <= 1200.00 | 986728 | 97.1% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| > | 1200.00 | to | 1400.00 | 4456 | 0.4% | <= 1400.00 | 991184 | 97.5% |
| > | 1400.00 | to | 1600.00 | 3115 | 0.3% | <= 1600.00 | 994299 | 97.8% |
| > | 1600.00 | to | 1800.00 | 2305 | 0.2% | <= 1800.00 | 996604 | 98.1% |
| > | 1800.00 | to | 2000.00 | 1997 | 0.2% | <= 2000.00 | 998601 | 98.3% |
| > | 2000.00 | to | 2200.00 | 1573 | 0.2% | <= 2200.00 | 1000174 | 98.4% |
| > | 2200.00 | to | 2400.00 | 1239 | 0.1% | <= 2400.00 | 1001413 | 98.5% |
| > | 2400.00 | to | 2600.00 | 1088 | 0.1% | <= 2600.00 | 1002501 | 98.6% |
| > | 2600.00 | to | 2800.00 | 915 | 0.1% | <= 2800.00 | 1003416 | 98.7% |
| > | 2800.00 | to | 3000.00 | 827 | 0.1% | <= 3000.00 | 1004243 | 98.8% |
| > | 3000.00 | to | 3200.00 | 728 | 0.1% | <= 3200.00 | 1004971 | 98.9% |
| > | 3200.00 | to | 3400.00 | 762 | 0.1% | <= 3400.00 | 1005733 | 99.0% |
| > | 3400.00 | to | 3600.00 | 576 | 0.1% | <= 3600.00 | 1006309 | 99.0% |
| > | 3600.00 | to | 3800.00 | 558 | 0.1% | <= 3800.00 | 1006867 | 99.1% |
| > | 3800.00 | to | 4000.00 | 473 | 0.0% | <= 4000.00 | 1007340 | 99.1% |
| > | 4000.00 | | | 9027 | 0.9% | | | |

### Column Headings and Definitions from USGS Streamflow Database

| **Tab-separated Output Column Name** | **Formatted Table Output Column Name** | **Description** |
|---|---|---|
| agency_cd | Not Included | agency code |
| site_no | Not Included | site number |
| measurement_nu | Meas.Number | measurement number |
| measurement_dt | Date/Time | date of measurement (format = MMDDYYYY or Month/Day/Year. The user has options for the data output format) |
| party_nm | Who | an indication of who made the measurement and is usually populated with a pair of initials separated with a slash |
| discharge_va | Streamflow | the computed discharge in cubic feet per second (cfs) |
| gage_height_va | Gage Height | gage height as shown on the inside staff gage at the site or read off the recorder inside the gage house in feet |
| current_rating_nu | Rating No. | The number of the rating used to calculate the streamflow from the gage height |
| shift_adj_va | Shift Adj. | The current shift being applied to the rating (feet) |
| diff_from_rating_pc | % Diff. | The percent difference between the measurement and the rating with the shift applied |
| gage_va_change | GH Change | The amount the gage height changed while the measurement was being made in feet |
| gage_va_time | Meas. Duration | The amount of time elapsed while the measurement was being made in decimal hours |
| measured_rating_diff | Meas.Rated | measurement rating codes that denote the relative quality of the measurement |
| control_type_cd | Control | condition of the rating control at the time of the measurement |

| | | |
|---|---|---|
| discharge_cd | Flow Adjust. Code | The adjustment code for the measured discharge |
| chan_nu | Channel Number | The channel number |
| chan_name | Channel Name | The channel name |
| meas_type | Measurement Type | The channel measurement type |
| streamflow_method | Streamflow Method | The channel discharge measurement method |
| velocity_method | Velocity Method | The channel velocity measurement method |
| chan_discharge | Channel Flow | The channel discharge in cubic feet per second |
| chan_width | Channel Width | The channel width in feet |
| chan_velocity | Channel Velocity | The mean velocity in feet per second |
| chan_area | Channel Area | The channel area in square feet |
| chan_stability | Channel Stability | The stability of the channel material |
| chan_material | Channel Material | The channel material |
| chan_evenness | Channel Evenness | The channel evenness from bank to bank |
| long_vel_desc | Long. Vel. Desc. | The longitudinal velocity description |
| horz_vel_desc | Horz. Vel. Desc. | The horizontal velocity description |
| vert_vel_desc | Vert. Vel. Desc. | The vertical velocity description |
| chan_loc_cd | Channel Loc. Code | The channel location code |
| chan_loc_dist | Channel Loc. Dist. | The channel location distance |