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OCEAN STREAM POWER GENERATION
Unlocking a Source of Vast, Continuous, Renewable Energy

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ABSTRACT
This paper presents the challenges of harnessing the immense continuous kinetic energy of the flowing ocean currents. This kinetic energy has been known for centuries, but to date, no economical installation has been established that provides a continuous renewable power source to a land based power grid system. Discussed are the actions that have been taken to develop a submerged ocean system with a workable propeller. A completed scale model performance test was carried out in the sea making this system a technical readiness level TRL 7. The paper identifies some of the obvious high kinetic energy ocean locations near populated shore lines that make continuous renewable energy possible and practical.

INTRODUCTION
Flowing water contains vast amounts of kinetic energy. Energy from flowing rivers has been harnessed for centuries to become the most used source of renewable energy. Currently, flowing water accounts for approximately three-fourths of the world's renewable power generation, primarily in the form of hydrodynamic dams. Other forms of renewable energy like wave, tidal, osmotic, and ocean thermal energy conversion systems are also being installed. A major source of continual renewable energy also exists in the ocean streams, but this energy remains more allusive.

Early mariners recorded and took advantage of ocean surface currents. One of the largest and strongest ocean streams lies off the East Coast of the United States. It was named "The Gulf Stream" by Benjamin Franklin on his famous map, which he produced in 1770. In 2012, the Southeast National Marine Renewable Energy Center at Florida Atlantic University estimated gross potential of the Florida current to be 200 GW [1]. Even if only a small portion is accessible, at 40% net efficiency the resulting amount of energy is enough to meet a vast portion of Florida's electricity demands [2]. Ocean stream currents flow in all of the earth's oceans, reaching the coastlines of every major continent. If the energy contained in these streams were harnessed and converted into electric power, the impact on the world's energy profile could be revolutionary. Despite the known vast constant renewable energy, there are currently no working power generation systems installed anywhere in the world that utilize this renewable energy nor are there adequate testing facilities for full or near scale devices that are grid connected.

OCEAN STREAMS
The earth's rotation causes a deflection of surface ocean currents known as the Coriolis Effect resulting in a clockwise rotation in the northern hemisphere and a counterclockwise rotation in the southern hemisphere. Other forces also influence the flow of ocean streams. Warm waters nearer the equator cool

as they move northward and sink from the higher density, whereas water flowing southward tends to rise as its temperature increases. Changes in salinity increase or decrease the water's density, and thus create sinking or rising tendencies. Continents and islands redirect the flow of ocean streams as the blocking land mass funnels currents into constricted areas, increasing the velocity of the stream. Since the earth's rotation is a major influence on ocean stream behavior, most of the "near land" ocean confluences are located on the western side of the oceans.

The strongest continuous ocean streams are located over deep water where the boundary layer effects of the stationary ocean floor do not impede the strong-flowing sea water near the surface. Although these streams are slow-flowing, they impose heavy forces on items located in their path. This is good for transfer of kinetic energy, but it is a design challenge for structures and impeller designs placed in this flowing sea water.

In open oceans, the flow is in a stream. The kinetic power density or energy of a flowing stream is described by the following equation:

$$\Phi = \tfrac{1}{2} \rho v^3 \quad \textbf{X A}$$

ϕ = Energy

ρ = Density of a flowing stream

υ = Velocity of flowing stream

A = Area affected or sweep area

A change in this flowing velocity yields the kinetic energy. It is important to note the energy is a cubic function of the velocity. The strongest continuous large open sea water ocean current is the Gulf Stream with a velocity that can range up to of 2.1 meter/second (7 feet/sec or 4.1 Knots).

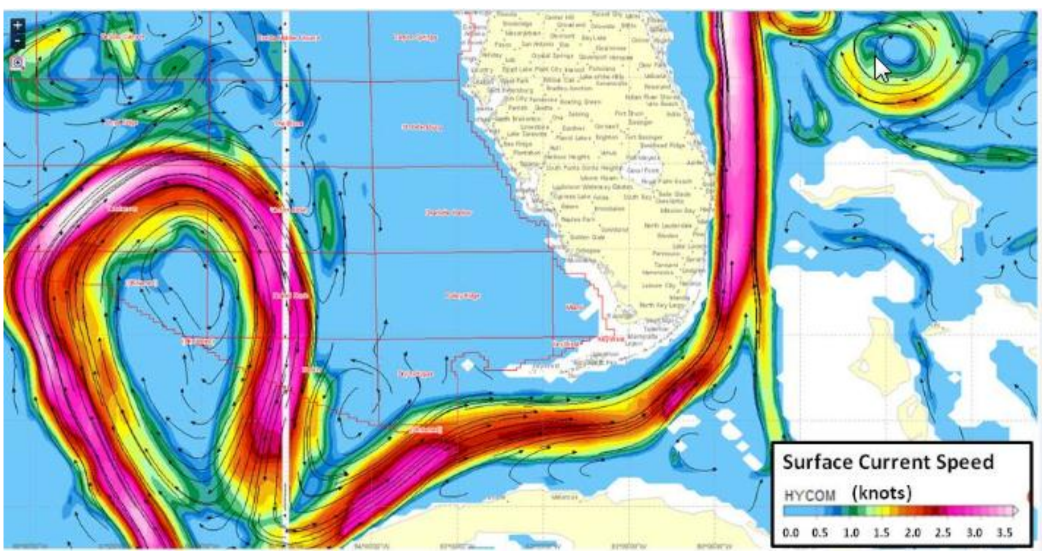

Figure 1: April 1, 2014 HYCOM Loop Current in the Gulf and Gulf Stream East of Florida [3]

In this Gulf Stream data capture (Figure 1), some surface current speeds measured over 3.5 knots with much of the surface current in the range of 3 knots. The main loop Current in the Gulf of Mexico has no land boundary constraints and is free to break off currents that travel through the Gulf of Mexico as smaller loop currents.

Because seawater is 880 times denser than air, these ocean streams have the kinetic energy equal to hurricane force winds. Just like the wind, without dams, seawater will be diverted to bypass structures in the stream. This limits the amount of energy transfer possible as defined by the Betz Theory limit of 59.3% of the existing kinetic energy (Figure 2). If a structure blocks too much of the flowing stream, the stream will divert. If it does not block enough of the stream, the energy is not captured. From Betz Theory we know the maximum energy efficiency is at a blockage of 1/3 of the flow past the propeller.

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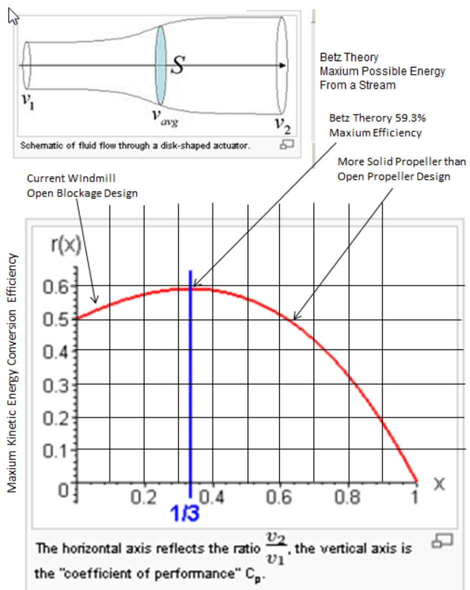

Figure 2: Betz Theory [4]
Maximum Possible Energy from a Stream

DESIGN CHALLENGES

There are unique design challenges to efficiently capture ocean stream kinetic energy with negligible environmental impact to the sea environment. Unlike wind and tidal renewable energy, strong deep water ocean streams don't reverse direction. The energy conversion needs to be efficient. The structure must withstand strong water forces which creates a challenge to design a turbine that converts the kinetic energy out of the flowing water. Structures must also survive fatigue vibration and vortex induced vibrations. All of these challenges need to be met in an environmentally efficient manner that is not cost prohibitive. It is critical that structures in the open ocean must not adversely affect the surrounding environment. In deep-water applications, grounded structures are cost prohibitive. Thus, like the oil industry, the design will need to be some form of floating structure. If a horizontal propeller system is used, it must be large enough to deliver a significant amount of power to the grid onshore. One 13.7 meter (45 foot) propeller placed in an ocean stream flowing at 2.1 meter/second (7 feet/sec) will deliver 296 kW with a 40% kinetic energy efficient propeller. Ten – four propeller structures in an area will generate over 10 MW of continuous power.

Large propellers are a major design problem due to the extreme weight and structural forces encountered in the flowing water. Hydrodynamic propellers used on large, ocean-going ships are massive. They are typically cast metal and surface-machined. These are designed for performance with the changes in rotational speeds for good thrust to the ship. They are also made with materials that are able to survive the rugged, corrosive, erosional ocean environment. These design parameters make a significant size propeller expensive and extremely heavy.

The wind turbine industry has gone through many generations of propellers. Currently, large three-bladed, open-structure propellers are typically used because they work successfully throughout the working wind envelope and have fewer blade fatigue failure problems than other configurations that were tried (figure 4)[5]. Looking at the old west windmills for water wells, they had blockage of over the maximum energy convergence of 1/3, but they were also designed for maximum torque to turn a gearbox that powered a rod up and down to pump water out of the water well.

Figure 3: Typical West Texas Windmill Design

Figure 4: Three Blade Wind Generator

If used in the sea, this large three blade wind propeller design would have extreme forces on the blades. There is an additional major design consideration of cavitation that must be taken into account for a deepwater application. Cavitation first starts at the outer ends of the propeller [6]. This is when vapor pressure voids are created and then collapse causing destructive micro jet velocities that are destructive to the surface of the propeller. The larger the propeller, the greater the challenges to construct for an ocean application using known materials. Yet, large propellers are necessary to capture the slow-moving kinetic energy of flowing sea water efficiently. Maybe a new propeller design is needed if there is to be an economical solution to renewable ocean stream energy conversion.

FIN-RING PROPELLER DESIGN

The Ocean Stream Power Generation (OSPG) concept presents a unique set of requirements for a unique propeller configuration. In particular, the OSPG propeller must be low speed, low RPM, high torque tolerant and compatible with long term operation below the seawater.

The objective of the propeller design is to develop a configuration that is:

Efficient: Commercial success of the OSPG is strongly influenced by the amount of power generated and the cost to install the device to generate the power. An efficient propeller will produce more power and lower the overall cost of each kW-hr.

Fish Friendly: Environmental concerns are important for acceptance of the device. The propeller should be compatible with marine life that may be encountered at the operating depth.

Fabrication Friendly: The ocean currents that are suitable for an OSPG application occur in a variety of locations throughout the world, including locations with minimal industrial capability and infrastructure. A propeller that can be fabricated locally using local labor has advantages.

Structurally Sound: The propeller should be robust, rugged and structurally designed for operating loads and environment that includes long periods of submergence.

Low cost: The cost of the propeller per kW-hr produced will factor significantly in the overall OSPG economics.

A unique Fin-ring propeller may meet these needs. The fin-ring propeller with its distinctive configuration currently cannot be precisely modeled using mainstream software. A full, three-dimensional computational fluid dynamics program could be used to model the ring propeller precisely, but the engineering and software expense is not justified compared to the testing budget. In addition, the fluid flow for the full scale device will include both laminar and turbulent regions which increase the complexity of the computational analysis and reduces the accuracy of the results.

The hydrodynamic performance of the propeller is a function of the fluid properties (density and viscosity), stream velocity and propeller geometry. The propeller geometry is characterized by:

1. Cross section shape (flat plate with camber for ring propeller, airfoil shape for conventional propeller)
2. Width at each radial station
3. Pitch angle at each radial station

One important parameter for fluid dynamics is the Reynolds number:

$$R = \rho UL/\mu$$

Where:
R = Reynolds number
ρ = Fluid density

U = Stream velocity
L = Characteristic length scale
μ = Viscosity

The Reynolds number characterizes the relative importance of inertial forces and viscous forces in the fluid flow, and most importantly for offshore generation determines whether the flow is expected to be laminar (typically $R < 10^4$) or turbulent (typically $R > 5 \times 10^6$).

The Reynolds number for full scale offshore generation is expected to be on the order of 2×10^6 which implies that the flow will transition from laminar to turbulent as it flows through the propeller. The transition creates additional complexity in predicting the propeller performance because the transition location will impact key parameters like maximum lift and lift-to-drag ratio.

Reynolds number sensitivity was selected from computer programs, but testing will be important for final validation of the selection.

To solve these challenges, Anadarko designed a fin-ring propeller that targets operating rotational speed of a set frequency power from a flowing ocean current. This patented [7] propeller has outer rings that direct the water flow and provides a protective ring that would keep fish from being struck by the outer fins of the propeller. The fin-ring design reduces the effects of cavitation by directing the flow with the rings inside the propeller. There is no tip of a fin to experience cavitation. These rings act like the curved tips of the newer air-plane wings that improve efficiency of lift and drag.

At a constant power generation frequency, rotational speed of these propellers can be virtually the same regardless of the ocean stream velocity, creating rotational torque for AC power generation which operates at a fixed frequency.

We decided to make the fin-ring propeller a solid metal material as any voids can be subject to survival problems in long service at deeper ocean submergence. This design can be made at a structural shop using common welding techniques providing for cost effective construction and future maintenance on the propeller.

TESTING THE FIN RING PROPELLER

The University of Michigan Hydrodynamics Lab provided their facilities for testing the fin-ring propeller. They have an open tank test facility that is long enough for stable repeatable operations.

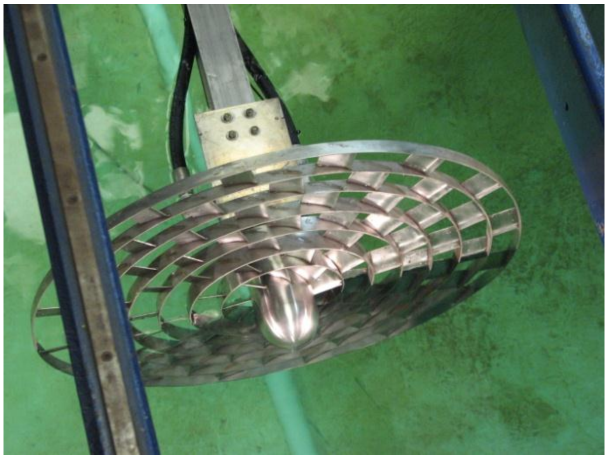

Figure 5: Fin-Ring Propeller

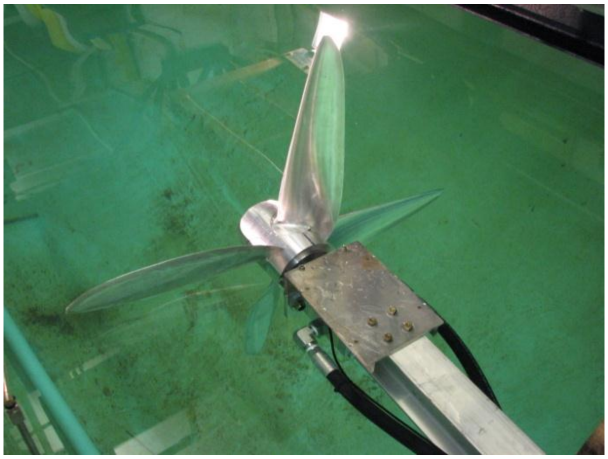

Figure 6: Four Blade Propeller

We constructed a 32 inch (1/10 scale) stainless steel fin-ring propeller and a four blade aluminum propeller for Hydrodynamics Lab testing. This is close to the largest propeller that could be tested at this facility without expecting error from the walls and floor which could significantly affect the results.

This testing design has 7 rings with 88 fins and a solid center hub. The outside fins have 16 fins connecting the rings and then on the inside it drops to 8 fins per ring. This geometric solution was selected in consideration of expected performance of the design and the ease of construction.

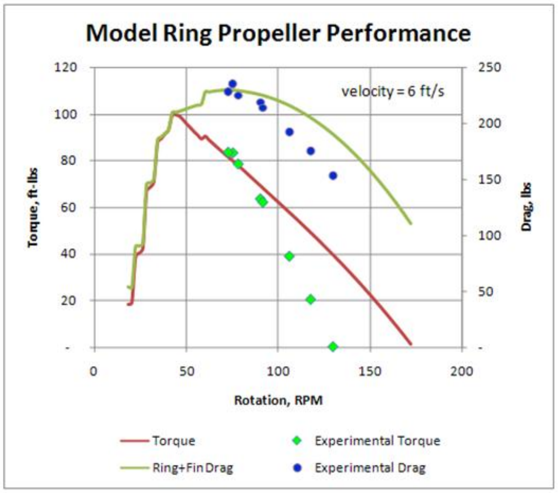

Figure 6: Model Test Results

At the set velocity, the rotational RPMs were adjusted with the resulting drag and torque. The computer design result is a composite of three programs. The experimental measurement is the results of testing. Torque and drag are high at the design speed and drop at higher rotational RPMs.

The fin-ring propeller efficiency is 39.7% at 9 rpms. The fin-ring propeller had a narrow performance band of >90% of peak power between 7 to 12 rpm. The four blade hydrodynamic propeller was 43.8% efficient at 9 rpm with the same test conditions.

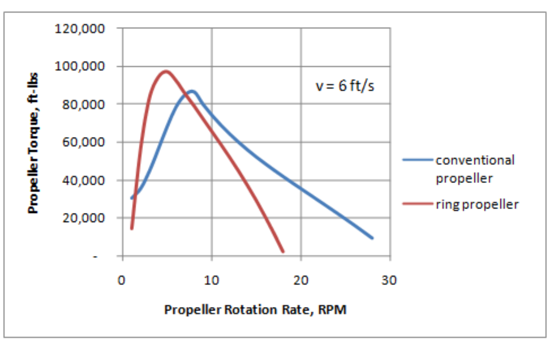

Figure 7: Torque at Speeds

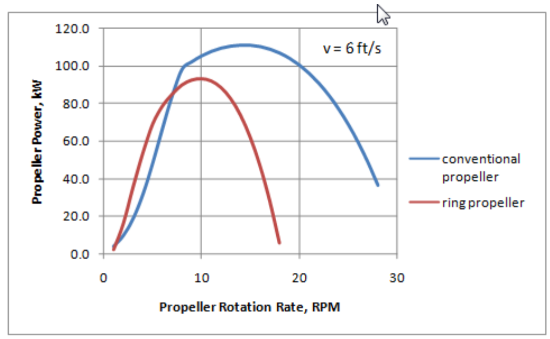

Figure 8: Power at Speeds

Figure 8 shows test results at 6 ft/sec for conventional four blade propeller vs the fin-ring. At low rpms, the fin-ring propeller had higher torque. Also the fin-ring propeller has a vastly slower stall speed. The fin-ring propeller would turn and generate at .8 ft/sec where the conventional propeller took almost 2 ft/sec to start generating. This is signification in ocean current areas with varying flow rates.

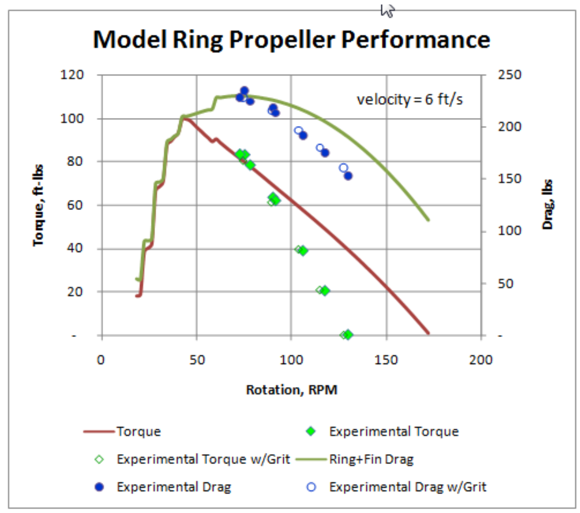

Figure 9: Test with Turbulence Grit

Tests were done with Grit applied to the back side of the propeller. The fin-ring propeller did not have degradation in performance, but the four blade propeller lost 14% efficiency. This will be important if there is any marine growth on the propellers. West Texas wind farms have special water blasters to clean off grasshopper remains from the blades to keep from losing performance.

The angle of attack was changed by 5 degrees and the results of peak power were within 4% of the original.

PROTOTYPE DEMONSTRATION IN AN OPERATIONAL ENVIRONMENT:

Since there are no grid-connected test facilities for testing ocean stream power generation equipment, we built a prototype structure to pull behind a boat at different speeds in the open sea. This will mimic the flow of the ocean sea water in possible future installation areas. To mimic the mooring system that will be attached to the ocean floor, we used a clump weight to pull the prototype from below.

The generation system incorporates a floating support structure similar in construction to those used by navigational buoys and deep water oil rigs. It will be designed to operate stably in water depth of 60 to 152 meters (200-500 feet) below the surface. This water depth accesses strong ocean streams and is below light penetration, thus suppressing marine growth and the associated fish feeding activity while also remaining below the deepest ocean going ship draft.
Operating in the deeper water protects the ocean stream power system from surface weather events such as hurricanes and typhoons that are prevalent in warm water ocean current locations. A permanently installed structure will be anchored to the ocean bed and would utilize subsea umbilical power cables for power delivery and controls back to the coastal land power grid. The structure will be designed to surface periodically for maintenance and repairs. Hurricanes and typhoons are surface weather events.
In 2012, Hurricane Sandy passed through east of Florida in the warm Gulf Stream waters. At 300 meters (984 feet) down, an ADCP positioned in the deeper Gulf Stream water showed no deep water effects from Hurricane Sandy [8].

Figure 10: String test of one of the four generation pods prior to installation into the prototype.

Figure 11: 1/5 Scale Propeller (2.43 Meter) built in a welding shop in Houston, Texas

OPEN SEA WATER TESTING

Following the initial test, we built a 1/5th scale system with four fin-ring propellers. This was tested as a fully functional support submerged generation structure in the Gulf of Mexico by pulling it with a boat to simulate various ocean stream velocities (Figure 12). The structure held stable during test operations. Power was generated at 60 Hz and fed back to the boat at levels exceeding the expected generation power for the speeds. The structure was controlled with a local PLC and communicated back to the boat prior to testing in the Gulf of Mexico.

Figure 12: Four propeller fin-ring system onshore

Figure 13: Four propeller fin-ring system prior to submerged testing in the Gulf of Mexico

PERFORMANCE TEST RESULTS

The four 2.44 meter (8 feet) fin-ring propeller system was deployed behind a boat with an anchor weight simulating the departure angle of an ocean anchor. The unit was pulled at varying speeds to simulate different ocean currents. The structure had stable motion and the pair of propellers generated equal power levels back to the boat appropriate to the ocean current. Power generated was slightly over the anticipated 40% propeller efficiency level at the various velocities and was repeatable at different speeds.

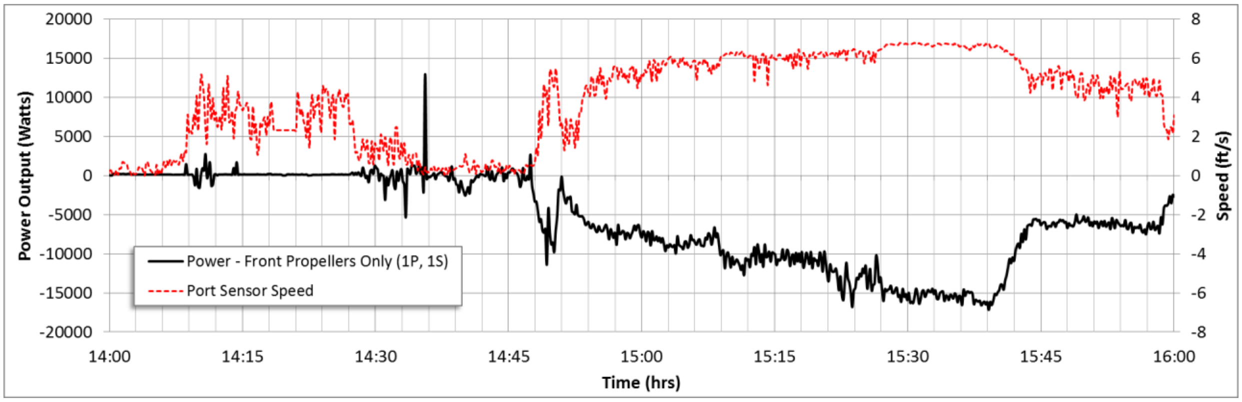

Figure 14: Front Propeller (1P & 1S) Power Test. Propeller efficiency is 40% with mechanical losses.

Using the port speed sensor and total power data, 6 feet/sec should generate 11.8 kW at 40% efficiency. The output was constant at 11 kW, not accounting for generator losses or gear box losses. At 6.7 feet/sec, the two 8 foot propellers should generate about 16.4 kW. The total power is about 16 kW indicating the propeller is right at 40% efficiency including mechanical losses. After 15:45 hours, the boat was slowed down and the power was repeated as expected.

Should a system generate slightly more power than a similar one propeller test? This is a two propeller system in the same area. All structures in the same area affect each other. Sea water must flow past all the structures in the area, creating a slight increase in pressure around the area, thus generating a slightly increased power that is the same tunnel effect experienced when wind circulates around large buildings. Even with a moderate, winds around some downtown buildings can gust, creating noticeable wind turbulence when you walk around buildings.

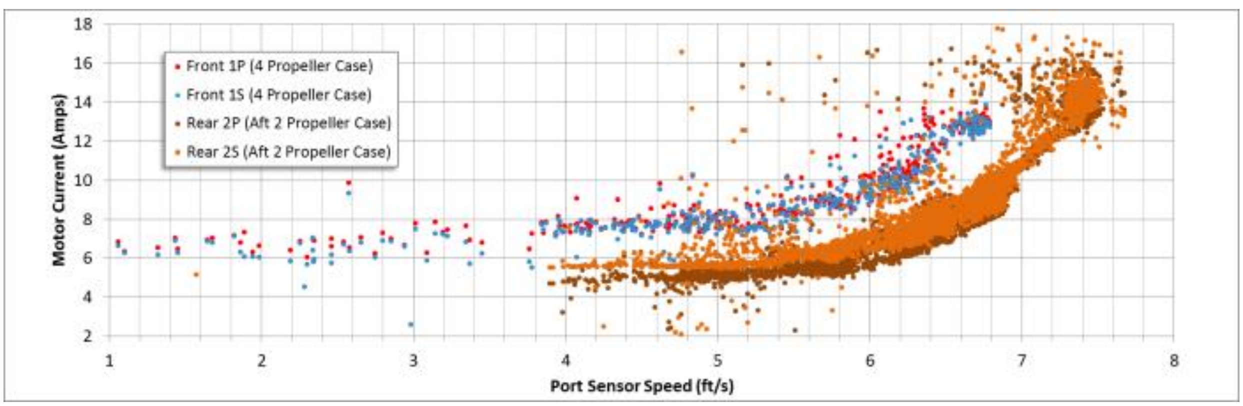

Figure 15: Test data for Forward, Aft, Port and Starboard positioned propellers

Test data for forward and aft propellers (Figure 15), the front two propellers generated considerably more power than the aft two propellers at the same port sensor speed. The conclusion is the turbulence from structures in front of the propellers affect efficiency of the propellers. Next generation designs would only install front propellers.

TECHNICAL READINESS LEVEL (TRL)

The U.S. Department of Defense and NASA have a technical readiness level for determining the status of potential projects. At this writing, The Ocean Stream Power Generation Project is classified TRL 7 (*System prototyping demonstration in an operational environment.*) [9]. A working unit permanently installed in the flowing ocean current ,connected and generating power back to the onshore power grid is classified as TRL 9 *(Actual system "mission proven" through successful mission operations*.) Currently, there is no available test facility connected to a power grid anywhere in the world for this type of renewable kinetic energy.

THE NEED FOR CONTINUOUS RENEWABLE ENERGY

A dependable renewable energy source that is continuous will stabilize a power grid, allowing for uninterrupted power without the need for large-scale energy storage. Reliable power would mitigate the need for emergency capital for stand-by equipment dedicated to short term peak needs. The driving forces of these flowing ocean streams are continuous in areas of deeper waters and ideal for certain coastal applications.

The Gulf Stream has been studied ever since it was first mapped by Benjamin Franklin in 1770 and is the strongest large ocean current. The Kuroshio Current is the 2^{nd} strongest and is getting heightened attention as a potential resource as Japan researches way to replace the Fukushima nuclear power plant.

On islands with limited energy resources, ocean streams could be the primary source of the continuous renewable energy needed to attract tourism and increase the quality of life for inhabitants.. Having power all the time would give communities the ability to distribute power at low use times to accommodate high use facilities such as desalination plants, electric car charging stations, etc.

CONCLUSION

As more global demands are placed on power generation, this viable solution is within reach for coastal populations around the world. The process needed to capture and convert this perpetual kinetic energy from the flowing ocean has been known for 100s of years. With an innovative approach, energy can be unlocked resulting in the safe, efficient, environmentally responsible generation of a huge amount of power. Clean renewable continuous energy could make a paradigm shift in coastal communities with a proportional, scalable, out of sight, out of mind, power all the time operation.

ACKNOWLEDGEMENTS

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VITAE

William D Bolin, PE (S'73) received his BSEE from The University of Texas at Arlington in 1973.Working 36 years in the Oil and Gas Industry, William is Distinguished Engineering Advisor – Worldwide Projects with Anadarko Petroleum Corporation. Of his patents, he holds three in energy conversion including the Water Current Power Generation System. With the PCIC-IEEE, he has been production subcommittee chairman and multiple times an author at the PCIC-IEEE with two papers making transaction status with IAS/IEEE. He is a professional Engineer in Texas.