FINAL TECHNICAL REPORT

Project Title: THOR's Power Method for Hydrokinetic Devices

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Principle Investigator: Turner Hunt, President, th@turnerhuntocean.com, 513-527-4924
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Working Partners: Virginia Polytechnic University (Virginia Tech)
Cost-Sharing Partners: Turner Hunt Ocean Renewable, LLC (THOR, LLC)

DOE Project Team: DOE HQ Program Manager – Jose Zayas
DOE Field Contract Officer – Pamela Brodie

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List of Acronyms

ROC-Flume Re-circulating Ocean Current Water Flume

TPM THOR's Power Method, a breakthrough power control method that can provide dramatic increases to the capacity factor over and above existing marine hydrokinetic (MHK) devices. TPM represents a constant speed, variable depth operational method that continually locates the ocean current turbine at a depth at which the rated power of the generator is routinely achieved. Variable depth operation is achieved by using various vertical force effectors, including ballast tanks for variable weight, a hydrodynamic wing for variable lift or down force and drag flaps for variable vehicle drag forces.

TRL3 Technology Readiness Level #3, generally defined as analytical and theoretical proof of concept, including analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.

TRL4 Technology Readiness Level #4, generally defined as scaled component and/or small scale validation in laboratory environment, including basic technological components that are integrated to establish that they will work together.

MHK Marine Hydrokinetic Energy

ROCT Renewable Ocean Current Turbine

SMNREC Southeast Marine National Renewable Energy Center at Florida Atlantic University

NCF Net Capacity Factor (numerator = kilowatt hours produced, denominator = maximum possible kilowatts that could have been produced over the same time period)

OCS Outer Continental Shelf
BOEMRE US Bureau of Ocean Energy Management and Enforcement
FERC US Federal Energy Regulatory Commission

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(i) Executive Summary

The overall purpose and objective of "THOR's Power Method for Hydrokinetic Devices" was twofold; (i) in a controlled laboratory environment, test, demonstrate and validate a breakthrough power control method (THOR's Power Method, or TPM) that can provide dramatic increases to the capacity factor over and above existing marine hydrokinetic (MHK) devices and (ii) advance THOR LLC's ocean current turbine technology from TRL3 to TRL4. To achieve these two primary objectives, a 40 foot long, 7 foot deep open channel re-circulating ocean current flume, or ROC-Flume, was constructed to simulate unidirectional sheered ocean current water flows. Along with the ROC-Flume, a model of THOR LLC's ocean current turbine, or ROCT, was also constructed, instrumented and configured to operate in the ROC-Flume to obtain the experimental data necessary to validate TPM.

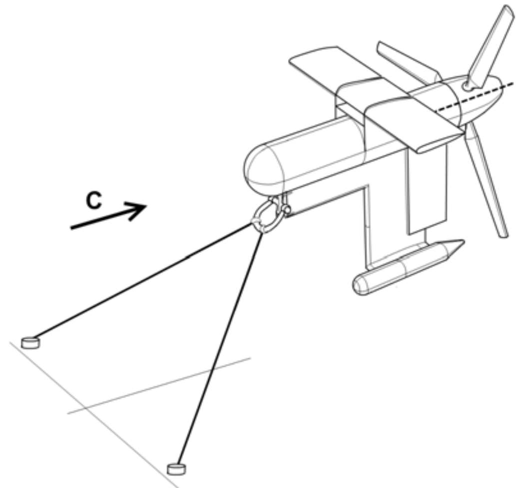
Current day state of the art power regulation and control is achieved by often complex variable rotor blade pitch operation. Conversely, TPM represents a constant speed, variable depth operational method that uses a fixed pitch rotor and continually relocates the ocean current turbine to a depth at which the rated speed, and hence the rated power of the generator is routinely achieved. Variable depth operation is achieved by using various vertical force effectors, including ballast tanks for variable weight, a hydrodynamic wing for variable lift or down force and drag flaps for variable vehicle drag forces which convert to variable lift as coupled by the upstream anchored tethered mooring system. Further, on onboard electronic control system with feedback sensors was implemented on the ROCT to cause these vertical force effectors to act in a coordinated manner to automatically control the depth of the ROCT in response to varying water speed and sheer conditions presented by the programmable flow condition ROC-Flume.

The project achieved the flowing results:

(a) Successfully designed, built and operated the ROC-Flume measuring 40 feet long, 9 feet wide and 7 feet deep. A flume water speed and sheer condition control system computer and software were implemented that produced water speeds up to 6 ft/s in the test section with sheer profiles ranging from 0.2 ft/s to 0.6 ft/s water speed reduction per foot of depth change in the main test section. The ROC-flume computer control system was able to change flow conditions in the test section over any preset period of time and any combination of speed and sheer condition.
(b) Successfully designed, built and operated a scale model ROCT with a rotor diameter of 32 inches which was coupled to an onboard 100 watt electrical generator. The ROCT was equipped with an onboard electronic control system with depth and water speed feedback sensors and an algorithmic logic controller to cause three vertical force effectors, including a ballast tank, wing and flaps, to act in a coordinated manner to automatically control the depth of the ROCT.
(c) Successfully operated the scale model ROCT in the ROC-Flume and documented electrical generator energy yield outputs for various operational schemes, including the aforementioned TPM.
(d) Successfully demonstrated that operation of the ROCT in accordance with the TPM operational concept was feasible. The ROCT was able to maintain near constant rated power output from the onboard electrical generator throughout a variety of water speed and sheer conditions as presented by the ROC-flume in the test section. Near constant rated power output in variable water current flows was achieved using only the three vertical force effectors. Variable rotor blade pitch was not used to achieve said near constant rated power output.

Recommendations for future investigations include (i) increasing the scale of the ocean current turbine to a rotor diameter of at least several meters (ii) pushing the ocean current turbine to greater depths to aid in component development in the presence of greater pressures and (iii) refining the automatic variable depth control system to include surfacing of the vehicle for maintenance or other purposes.

THOR, LLC is using the results and experience from this project to progress the commercial viability of the ROCT to a larger scale with a meaningful power output in the 100s of kilowatts. THOR is working closely with the Southeast National Marine Renewable Energy Center at Florida Atlantic University to deploy a real world proof of concept model.

	 THOR Energy Group's Open Channel Re-Circulating Ocean Current Flume looking from the test section toward the motor thruster array. Water current flows right to left in the photo. The onlooker is peering through the test section's observation window. Maximum Water speeds can reach 2.5 m/s and the water depth speed profile can be tailored as desired to simulate various flow conditions, including reverse.
Fig. i1. THOR's ROCT configured for TPM	Fig. i2. THOR's ROC-Flume

(1) Introduction

THOR's Power Method, and its validation, is the primary objective of this research effort. Therefore, this introduction includes a brief description of TPM and its energy yield implications.

THOR's Power Method of energy is a method of operating a tethered ocean current turbine developed by THOR LLC that uses a constant speed, variable depth control method, versus the conventional constant depth, variable speed method. Ocean currents exhibit an inverse velocity shear profile or decreasing speed with increasing depth and THOR's Power Method exploits this speed gradient and causes the ocean current turbine to adjust depth as ocean current speeds change to continually track and recapture the depth at which rated power is always output from the generator ("rated power depth"). Shown in Fig 1.1 are two accepted methods for estimating capacity factor. The conventional constant depth method shown at the top of Fig. 1.1 uses a turbines' power curve across the speed range in step 1a including selections for cut-in, rated and cut-out speeds and matches that to the frequency of occurrence of ocean current speeds as determined from historical resource data in step 1b to calculate a net capacity factor ("NCF"). THOR LLC's calculations using this conventional method indicate NCFs' in the "high fifties", a value that is also confirmed by other references, which list 57%[5].

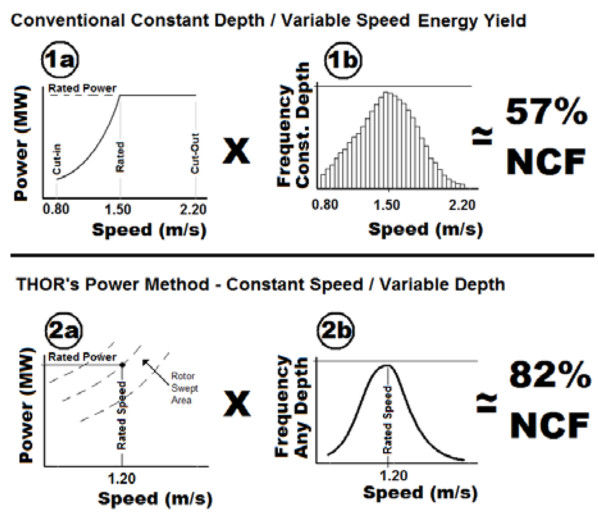


Fig. 1.1 Capacity Factor Calculation

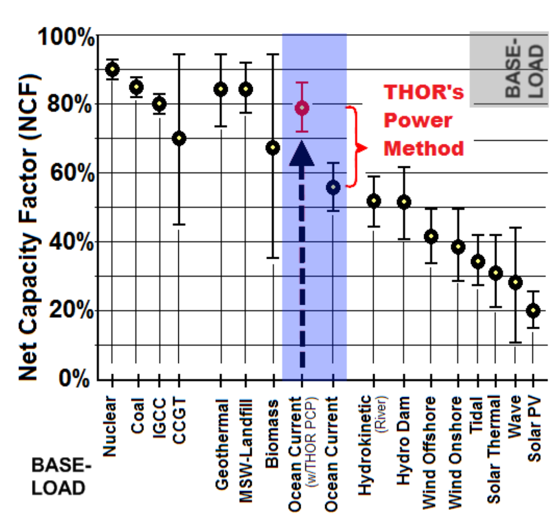


Fig. 1.2 THOR's Leap in NCF vs. Other Fuel Type NCFs (from NREL and DOE)[4]

Conversely, the bottom of Fig. 1.1 uses the turbines' rated speed in step 2a (that speed that produces rated power or nameplate power output) and matches that to the percentage of time that the rated speed occurs anywhere in the vertical water column in step 2b to calculate a NCF of approximately 82% for THOR's Power Method. THOR LLC engaged well known renewable energy engineering firm Garrad Hassan & Partners Ltd. to perform an energy yield analysis ("The GH Analysis") [1] using the ADCP data from reference 6 and further employing THOR's Power Method. The GH Analysis[1] is attached as Appendix A. The validation, testing and demonstration of THOR's Power Method is the primary focus of this research report.

The implication of TPM relative to other energy sources is illustrated using reference 4. Figure 1.2 was constructed to depict THOR's leap in NCF from an already respectable 55-60% range to the 75-85% capacity factor range. This increase in NCF represents an approximate (82-57)/57 = 44% increase over conventional methods, moving the ocean current "fuel type" into the base-load performance range.

To test, demonstrate and validate TPM, this project built a scale model ROCT (Fig. 1.3) and subjected it to a programmable inverse velocity shear flow gradient that mimics the real world velocity shear gradient found in the Gulf Stream and similar ocean currents.

In addition, the ROC-flume shown in Fig. 1.4 was built to generate time variant inverse velocity shear profile water currents upstream of the test section area. THOR's ROCT scale model was moored in the test section. A schematic of the laboratory setup is shown in Fig. 1.5. THOR's ROCT scale model was equipped with a fully functioning control system with inputs from a variety of sensors and control authority over a variable buoyancy ballast tank, a variable incidence hydrodynamic wing, variable deflection split drag flaps. The ROCT rotor drives an actual installed 100 watt generator, the power output from which will provide one of the feedback parameters for operation using TPM.

The ROC-flume was programmed to create inverse velocity shear profile current flows closely resembling real world ocean current flow behavior based on acoustic Doppler current profile (ADCP) data acquired near the core of the Gulf Stream in the Southern Florida Straits[6]. THOR's ROCT scale model executed TPM, along with other operational methods, under the authority of the onboard control system, sensor inputs and control surfaces. THOR's ROCT was systematically and methodically tested in all modes of operation in the ROC-flume. Part of the control system logic and implementation was provided by the involvement of Virginia Polytechnic Institute and State University's ("Virginia Tech") department of Aerospace and Ocean Engineering.

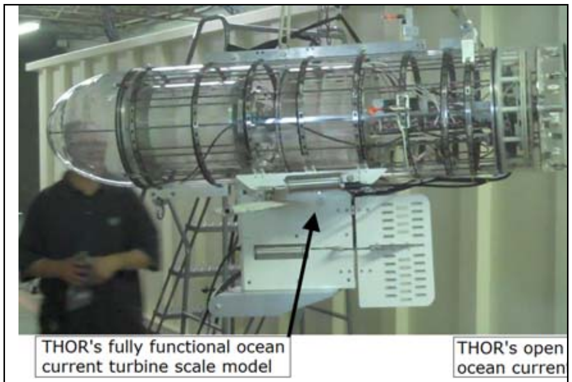


Fig. 1.3 THOR's Scale ROCT

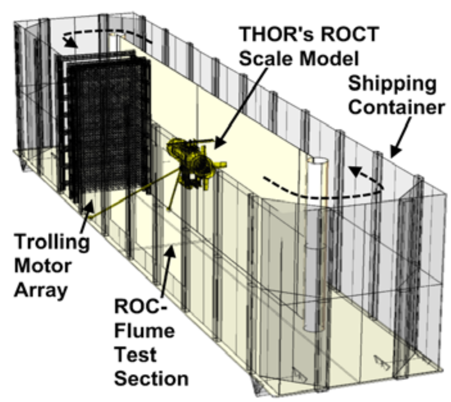


Fig. 1.4 Re-Circulating Ocean Current "ROC"-Flume with THOR's ROCT scale model moored in test section

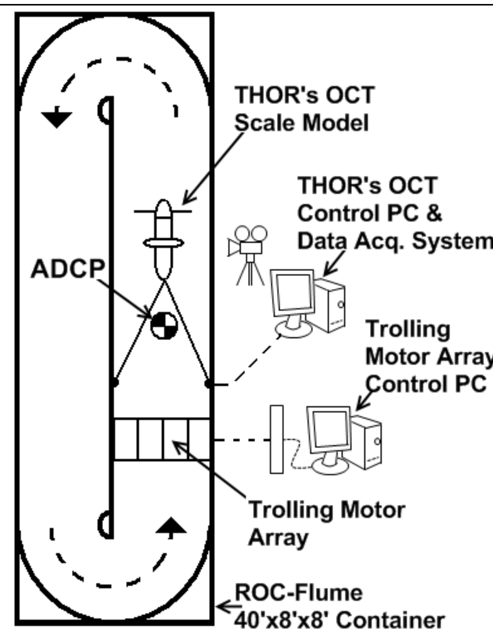


Fig. 1.5 THOR's Laboratory Setup

(2) Background

Variable blade pitch power regulation schemes are the state of the art in power generation for devices that employ a propeller or rotor like energy transducer that converts the kinetic energy of a moving fluid into useable electrical energy. Such variable pitch power regulation schemes basically "dump" or shed power above the devices rated speed (the fluid speed at which rated or design power occurs) by pitching the rotor blades about their longitudinal axis to a less efficient angle of attack. On the one hand, the rotor blade swept area is made as large as possible to capture and yield as much energy at low fluid speeds and as a result must protect itself against being overwhelmed with energy and too much power capture at high fluid speeds (power increases with the cube of the speed and devices can get overwhelmed quickly as fluid speed increases). Mechanical integrity of the power drive train (i.e. gear box, if any) and/or avoiding too much power through the generator is of primary concern at high fluid speeds as such conditions might lead to gearbox failure or "blowing out or frying" the generator. Since the generator and its rotor are geographically fixed, the design of the device must be compromised to accept whatever fluid flow conditions are present at the fixed geographic location.

However, if the generator and its rotor can be periodically geographically relocated to a different location where the rated speed of the device is always present, the design of the device, its rotor and generator need not be compromised as in the conventional sense. Periodic geographic relocation is exactly what TPM achieves by repositioning the device in depth to that depth at which the rated fluid speed occurs – thereby producing rated power from the generator for prolonged periods – and hence dramatic increases to the net capacity factor.

The personnel executing this project have a demonstrated track record of advancing innovation and technology in the areas of renewable energy, aircraft design, control system development, autonomous underwater vehicles and other relevant areas. Brief biographies of each team participant are provided below.

J. Turner Hunt, with THOR LLC, is President of Turner Hunt Ocean Renewable LLC (THOR LLC) as well as the parent of THOR LLC, Vision Energy LLC, a wind power development and operations company based in Cincinnati, Ohio. Turner began his career as an aerospace engineer working for the McDonnell Douglas Corp. in the advanced aircraft design division as an aeronautical engineer after two years of part time employment as a Master's student in the University of Kansas machine shop. Turner lead a team of multidisciplinary engineers on many conceptual design studies at MacAir involving a variety of missions, including hypersonic intercept, long range reconnaissance and fighter/attack. Several of the concepts lead to extensive wind tunnel test programs in facilities at NASA Langley and in McDonnell's Lambert field low speed tunnel. Turner later worked on the F/A-18 Hornet and F-15 Strike Eagle full production aircraft programs while at McDonnell. Turner has founded or been involved with companies in real estate development, software programming, internet/networking services, and wind power development. With Vision Energy, Turner is involved with the development, acquisition, permitting, financing, construction, power marketing and operations of wind farms both in the development stage as well as two existing wind farms developed and now partly owned and operated by Vision totaling 280 megawatts, which include 187 GE 1.5MW wind turbines. Turner has been directly involved in the development of over 1,500MW of wind power projects now currently in operation in the Midwestern US. Turner received a B.S. and M.S. degree in aerospace engineering from the University of Kansas.

Russ Rommé, with THOR LLC, has a diverse background with both the private sector and federal government. Mr. Rommé has extensive experience in project management, interdisciplinary alternative energy planning, wildlife biology, National Environmental Policy Act compliance, and interagency coordination in eastern, Midwestern, and western states. Russ earned numerous awards from the U.S. Department of Agriculture, US Department of the Interior, and the US. Army for large-scale planning efforts, NEPA analyses, and complex Endangered Species Act compliance efforts. Russ has 20 years experience performing complex programmatic and project-specific planning efforts for numerous agencies, including the Federal Aviation Administration, US Air Force, U.S. Army, The National Guard, State Departments of Transportation, U.S. Forest Service, U.S. Bureau of Land Management, and the Department of Justice. Mr. Rommé led a team including numerous NEPA contractors and Pentagon specialists in developing the programmatic approach for analysis of cumulative effects in what the U.S. Army termed their "most complex EIS ever." He has participated in the administrative and legal defense of numerous planning analyses, and is developing patents for an innovative water purification technology. Russ earned a BS in Natural Resources Management for the Ohio State University in 1984.

Dr. Craig Woolsey, with Virginia Tech, received a bachelor's degree in mechanical engineering from Georgia Tech in 1995 and a Ph.D. in mechanical and aerospace engineering from Princeton University in 2001. He is an Associate Fellow of AIAA and a Senior Member of IEEE. In 2002, he was granted the National Science Foundation CAREER award and the Office of Naval Research Young Investigator Program Award. He was named a Virginia Tech College of Engineering Faculty Fellow in 2003. Since the Fall of 2006, Dr. Woolsey has served as the inaugural director of the Virginia Center for Autonomous Systems (www.unmanned.vt.edu), a Virginia Tech ICTAS/College of Engineering Research Center. In 2007, he was awarded the Ralph Teetor Educational Award from the Society of Automotive Engineers.

THOR LLC's past research has focused mainly on advancing THOR's ROCT and THOR's Power Method to a technology readiness level of TRL3. The past research projects of the individuals listed above are quite considerable, with the most relevant including aircraft scale model wind tunnel testing projects to underwater autonomous vehicle control. Additional and relevant past research projects are listed in the résumé section of this proposal in each individual resume.

(3) Results and Discussion

Variable Energy Output by Depth Change: Figure 3.1 presents results of ROC-flume run #65 thru 69 in which water speed and the change of water speed with depth were held constant in the flume's test section and the ROCT scale model power output from the onboard generator was varied by changing the depth of the ROCT using the onboard ballast tank and hydrodynamic wing to alter the vertical forces acting on the ROCT. Water speeds ranged from about 4 ft/s at 2 feet of depth down to about 2 ft/s at 5 feet of depth. The ROCT recorded about 35 watts from the generator at about 3 ½ feet of depth and increased energy output to about 50 watts as the ROCT ascended near the surface. During ROC-flume runs 65-69, the ROCT model operator was able to input or "tell" the model via its onboard control system an energy output level maintain and the scale model ROCT was able to automatically pump water in or out of its ballast tank and/or vary the hydroplane wing angle of attack to alter vertical forces to ascend or descend to the appropriate depth at which the commanded power level was maintained.

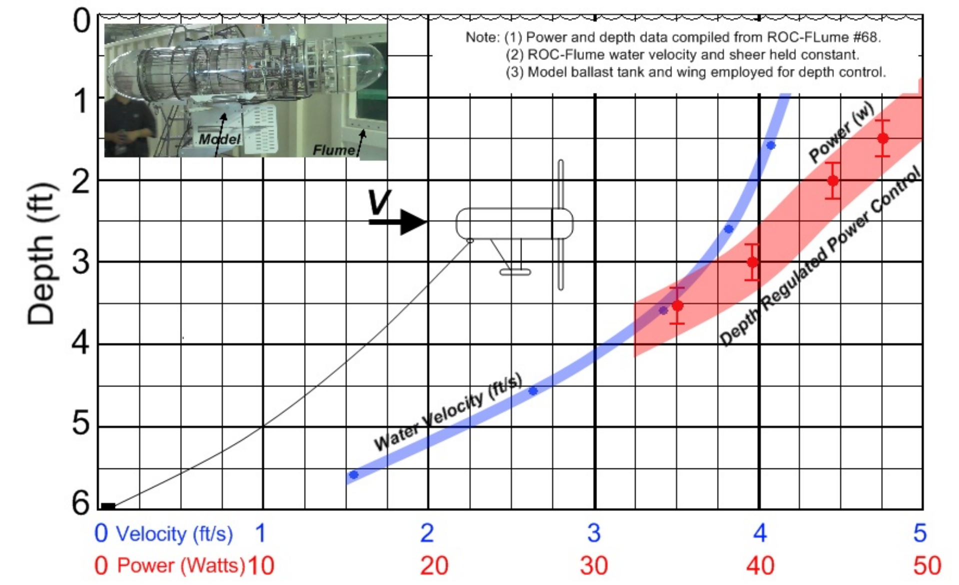


Fig. 3.1 – Results of ROC-flume runs 65-69 for constant flow conditions

Constant Energy Output by Depth Change: Figure 3.2 presents results of ROC-flume run #65 thru 69 in which water speed and the change of water speed with depth were varied to the maximum extents of the ROC-flume's capabilities. The scale model ROCT automatic control system was commanded to output a constant 35 watts of power regardless of the flow speeds and sheer in the test section area. The ROCT was able to automatically comply with the 35 watt request at depths ranging from about 1.5 feet (the minimum depth at which the rotor tip would break the

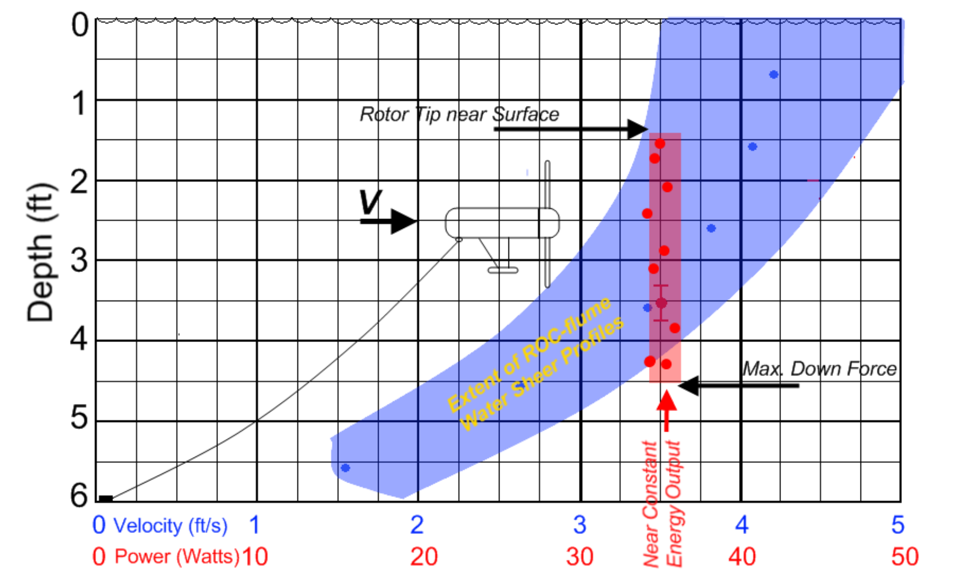


Fig. 3.2 – Constant Power Output Results of ROC-flume runs 65-69 for various water flow conditions

surface) and 4.5 feet of depth where the ballast tank was completely full and the hydrodynamic was at maximum negative angle of attack.

(4) Accomplishments

The project was able to demonstrate and accomplish (i) power regulation via a depth change process (Fig. 3.1) and (ii) constant power output under varying flow conditions (Fig. 3.2). Both of these two accomplishments are integral capabilities of operation according to TPM. Further, the project was able to advance THOR LLC's ocean current turbine technology from TRL3 to TRL4 both in the hardware of the fully functional scale ROCT model as well as the software associated with the automatic control system that enabled constant power output under varying flow conditions.

The project also provided real world data and experience to further lend backup information to the previous conceived THOR Patents (filed as non-provisional patents in May, 2009):

- "Power Control Protocol for a Hydrokinetic Device and an Array Thereof"
- "Pitch, Roll and Drag Stabilization of a Tethered Hydrokinetic Device"
- "Mooring System for a Hydrokinetic Device and an Array Thereof"
- "Self Contained Variable Control Rotor Hub"
- "Flooded Anchoring System and Method of Deployment, and Recovery"

An additional publication was also made possible at the Renewable Energy World Conference in Tampa Florida pm March 8-10, 2011 in Tampa Florida entitled, "Baseload Renewable Ocean Current Energy" and attached as Appendix B.

(5) Conclusions

The project and the accomplishments lead to the flowing conclusions:

Varying Power Output via Depth Change: THOR's ROCT was able to regulate power output from the marine hydrokinetic energy ocean current turbine by simply changing depth, rather than by employing a complex rotor blade pitch regulation scheme.

Constant Power Output via Depth Change: Furthermore, a constant power output was maintained by the ROCT in varying water speed and water sheer flow conditions, again by simply changing the depth of the ROCT using an automatic control system.

Depth Change via Simple Means: The depth of the ROCT was controlled by ballast pumps and a wing – very well known and easily implemented mechanisms.

Power Regulation via Simple Means: The ROCT achieved power regulation and control by ballast pumps and a wing – very well known and easily implemented mechanisms, rather than by employing a complex rotor blade pitch regulation scheme.

With regard to commercialization of a larger scale ROCT, and with the elimination of the complex mechanism of a variable pitch control rotor hub that could operate at great pressure depths of the ocean environment, most if not all of the remaining components are commercially available off the shelf with few or no exceptions. From the PI's standpoint, the real challenges to the deployment and commercialization of this technology reside with the environmental impact and permitting requirements as governed on the United States OCS by FERC and BOEMRE.

Environmental impact and permitting is further complicated by the lack of prior similar facilities that might have similar impacts from which to judge relative effects.

(6) Recommendations

Future research and development should focus on scaling up the technology presented in this report to larger commercial scale ocean current turbines that may approach rotor diameters of 40 to 60 meters (120 to 200 feet in diameter). A 2.0 MW ocean current turbine operating at a rated hub speed of about 1.3 m/s would require a 200 foot rotor diameter rotating at about 3 to 4 rpm. Commercial direct drive wind turbine generators run at about 20 rpm, and a novel 10:1 ratio between the rotor and generator would be required – or other schemes might be developed that used higher speed generators with 100:1 type transmission systems. In any event, Future research and development should focus on gearing and mechanical transmission of power from the rotor to the generator.

With water depths in excess of 1500 feet, anchor deployment and anchor environmental impact should require significant research and development.

(7) References

(1) "Energy Yield Assessment of the THOR Ocean Current Turbine", MD Thomson, C Elkinton, L Gill, RI Rawlinson-Smith, Garrad Hassan & Partners, Ltd., March 2010, A Summary Attached as Appendix A, Pgs 19-20

(2) "High Frequency Radar Compilation and Real Time Data Display for Ocean Surface Currents of the Continental United States", National Oceanographic and Atmospheric Administration NOAA Web Page [http://hfradar.ndbc.noaa.gov/], with supporting data from three sources (i) Univ. of Miami/Rosenstiel School WERA System (ii) Skidaway Inst. of Oceanography WERA System and (iii) UNC CODAR System

(3) "Characterization Study of the Florida Current at 26.11 N. Latitide, 79.50 West Longitude for Ocean Current Power Generation", Robert E. Raye, Master's Thesis, Florida Atlantic University, Boca Raton, Florida, May 2002

(4) "Assumptions to the Annual Energy Outlook 2009", DOE/EIA-0554 and "Inputs to the 20% Wind Report, 2007", by Black and Veatch

(5) "Ocean Renewable Energy's Potential Role in Supplying Future Electrical Energy Needs", Robert Thresher and Walter Musial, Oceanography Magazine, June 2010, pgs. 16-21

(6) Private Data: Acoustic Doppler Current Profiler Data located at LAT 26° 1'30.18"N (26.02505N), LONG 79°50'16.91"W (79.83803W), First Ensemble: 12/7/2007 Last Ensemble: 5/23/2008 w/30 minute sampling intervals, Florida Atlantic University Buoy #0.

(7) The THOR Patents (filed as non-provisional patents in May, 2010):
- "Power Control Protocol for a Hydrokinetic Device and an Array Thereof"
- "Pitch, Roll and Drag Stabilization of a Tethered Hydrokinetic Device"
- "Mooring System for a Hydrokinetic Device and an Array Thereof"
- "Self Contained Variable Control Rotor Hub"
- "Flooded Anchoring System and Method of Deployment, and Recovery"

(8) Assessment of Power Purchase Agreement Between Delmarva Power and BlueWater Wind Delaware LLC, Public Service Commission of the State of Delaware, PSC Docket Number 06-241

(9) "The Gulf Stream as a Graded River", R.M. Pratt, Woods Hole Oceanographic Institution, Published by the American Society of Limnology and Oceanography,

Vol. 11 (1), 1966, pgs. 60-67

(10) "Wind Turbines, Fundamentals, Technologies, Application, Economics", Erich Hau, Springer Science and Business Media, 2nd Edition, 2006

Appendix – A
Garrad Hassan THOR Energy Yield Report - Summary and Condensed Version

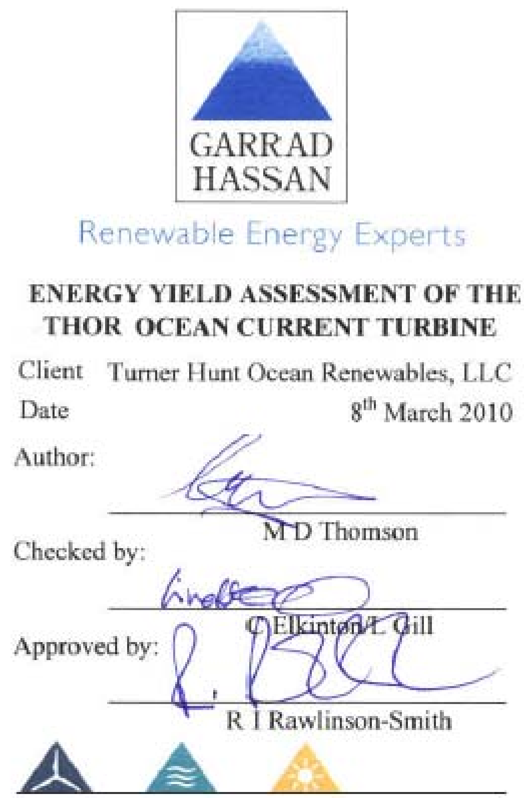

GARRAD HASSAN
Renewable Energy Experts
ENERGY YIELD ASSESSMENT OF THE THOR OCEAN CURRENT TURBINE
Client Turner Hunt Ocean Renewables, LLC
Date 8th March 2010
Author: M D Thomson
Checked by: C Elkinton/L Gill
Approved by: R I Rawlinson-Smith

Figure A.1 GL Garrad Hassan Cover Page

A1) Introduction - Turner Hunt Ocean Renewables, LLC (THOR) are developing a variable buoyancy tethered Ocean Current Turbine (OCT) to extract energy from the currents found within the Gulf Stream. THOR have acquired ADCP data from a location 17 miles east of the coast of Miami, USA. The aim of the work reported here is to provide THOR with an independent assessment of the expected energy yield of a single OCT device operating in the currents measured by the ADCP. This document has been prepared pursuant to the GH proposal 104295/BP/01 Issue B dated 5th Nov 2009 and provides a description of the work undertaken by GH.

A2) Scope of work - The work involved the following tasks: (A) Checking the quality of the ADCP data; (B) Writing scripts to perform the analysis, including (B.1) The rotor averaged root mean cubed flow speed (incident flow), (B.2) Frequency analysis, (B.3) Time domain analysis, (C) Produce data characterization analysis plots, including: (C.1) Data quality visualization, (C.2) Distribution of flow speed occurrence as a function of depth, (C.3) Spread of normalized depth profiles, (C.4) Averaged depth profiles per datum speed bin, (C.5) Time series of operating hub height for 3 rotor averaged rated flow speeds, (C.6) Occurrence of the required ascent/descent rates, (C.7) Distribution of incident flow speeds within depth range, (C.8) Distribution of hub height depths at rated speeds; (D) Energy yield analysis, (D.1) Evaluate energy yield based on ADCP data, (D.2) Losses will be reported in a gross-to-net table, (D.3) A comparison of the energy yield using the time and frequency (statistical) domain methods, (E) Uncertainty analysis, including the Review of density variation effects.

A3) Description of the monitoring equipment - An Acoustic Doppler Current Profiler (ADCP) was deployed at the site to measure the flow speeds through the water column. The location was 26.02505° N and 79.83803° W and the period of the measurement was from 7th December 2007 to 23rd May 2008. An RDI Long Ranger ADCP tether-mounted instrument was used in approximately 350 meters of water depth.

A4) Description of the THOR Technology - The THOR technology consists of a tethered variable depth horizontal axial flow turbine which operates at constant speed. In order to achieve optimum power, the operating depth of the turbine is adjusted to seek an incident flow speed (rated flow speed) which yields the rated power level. The turbine operating depth varies with changes to the rotor thrust force. To control the operating depth and seek the rated flow speed, variable buoyancy and lifting surfaces are used.

A5) Energy Yield Prediction - Main assumptions and operating philosophy:

- The device actively seeks power, changing depth to maintain power at the rated point, thus peak electrical rating is always assumed, provided it is within the operating depth range.
- The operating hub height depth range of the turbine was set between 5 metres plus half the rotor diameter and 230 meters from the surface.
- A maximum ascent/descent rate of 5 ft/min was used.
- The electrical rating of the device is 1MW.
- The device will cut out if the minimum or maximum depth range is exceeded.
- Power generation will only resume once the rated speed reappears.

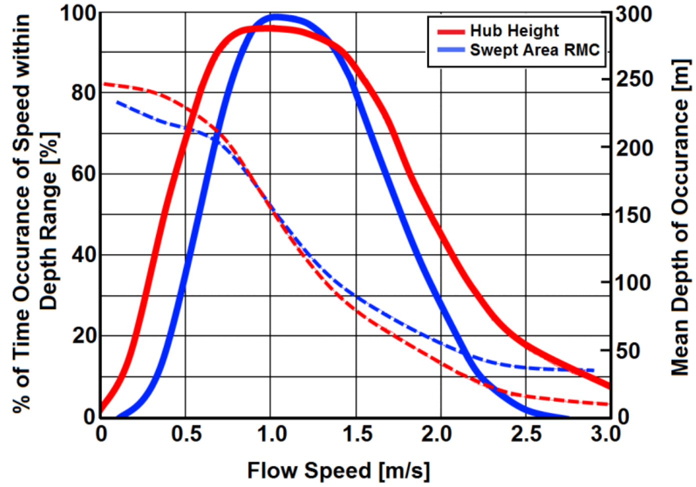


Figure A.2 ADCP Data Statistical Percent Time Occurrence of Speed Within Depth Range (30m to 230m Depth Range)

Rated Power (MW)	1.0	1.0	1.0
Rated Flow Speed (m/s)	**1.0**	**1.2**	**1.4**
Rotor Diameter (m)	74.3	56.5	44.9
Number of Turbines	1	1	1
% Time Speed Occur	98.5	97.8	91.0
% Rates > 5 ft/min	1.8	1.5	1.0
Gross Output (GWh)	4.0	3.9	3.6
Losses:			
Ascent/Descent	98.5	99.0	99.2
Electrical Efficiency	95.0	95.0	95.0
All Other Losses	100.0	100.0	100.0
Net Output (GWh)	3.73	3.66	3.36
Net Capacity Factor (%)*	**92.9**	**91.1**	**83.5**
* P-50 NCF			

Table A.1 Results of Energy Yield Analysis, Including Only Losses as Listed

A6) Conclusions - Long range ADCP data has been analysed to inform the energy yield analysis of the THOR OCT technology. The ADCP data was quality checked and bad data was replaced with interpolated fits. The depth flow speed profiles showed that below the top 25 metres the flow speed reduction with depth was generally linear. Three different turbines with varying rated flow speed were analysed. The percentage time in operation was evaluated in both the time and frequency domain, yielding different results. The time domain estimates of energy yield over the measurement period are presented, along with standard error which was evaluated via an uncertainty analysis.

HYDRO WIND HYDROGEN GEOTHERMAL BIOMASS SOLAR
RENEWABLE ENERGY WORLD CONFERENCE & EXPO NORTH AMERICA
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THE ONE EVENT FOR **RENEWABLE** CONNECTIONS

THOR ENERGY GROUP

Base-Load Renewable Ocean Current Energy

Author: Turner Hunt
THOR, LLC (Turner Hunt Ocean Renewable, LLC)

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co-located event Photovoltaics CONFERENCE & EXPO WORLD

Company

- Turner Hunt Ocean Renewable, LLC (THOR, LLC)
- Formed in 2007 and based in Cincinnati, Ohio
- Hydrokinetic Energy – Ocean Currents
- 5 US Patents Filed and International Patents Pending
- THOR LLC – 5 Employees
- Recent Dept. of Energy Grant, W&WPP Marine-Hydrokinetic 2010 FOA
- Parent of THOR LLC is Vision Energy LLC
- Vision Energy LLC is a Wind Power Development Company with wind farms under development in mid-west USA. Vision has developed or now owns, operates or sold over 1,500 MWs of operational wind farms in Illinois, Indiana, Michigan and Ohio
- www.turnerhuntocean.com

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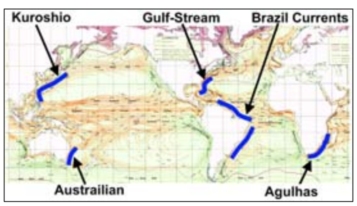
Ocean Currents Worldwide

- Ocean Current Energy is the 'Other Hydrokinetic' Not Tidal, Not Wave, Not River
- Ocean Currents exhibit and 'inverse velocity sheer' (slower speed with deep depth)
- Public/Private ADCP & CODAR data is available for energy yield analysis studies



- Sea floor depths to 500 meters
- Flow speeds from 0.80-2.5 m/s
- Flow direction +/- 30 deg.
- Flow active to 250m depths
- Core does not meander
- "Rivers in the Ocean"

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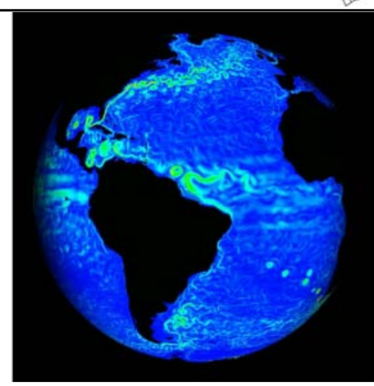
Atlantic Ocean Currents



Courtesy NASA-Science on a Sphere

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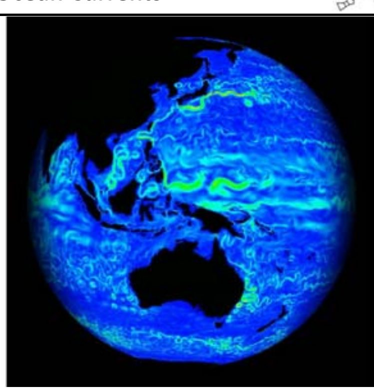
Pacific Ocean Currents



Courtesy NASA-Science on a Sphere

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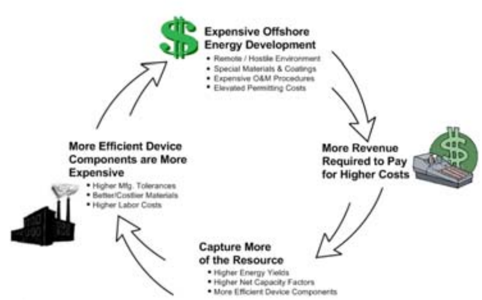
Problem: Offshore Cost Spiral



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Break the Cost Spiral

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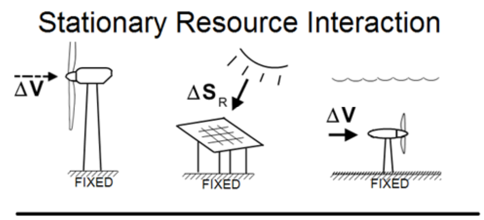
THOR's Power Method



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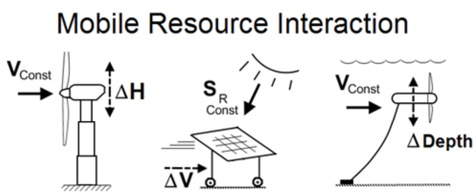
THOR's Power Method



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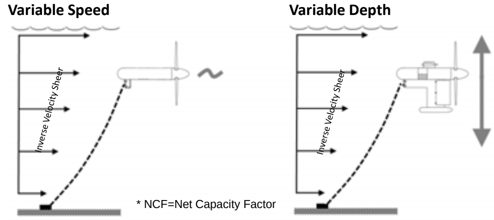
THOR's Power Method

Conventional Method:
Constant Depth
Variable Speed

THOR's Power Method:
Constant Speed
Variable Depth



* NCF=Net Capacity Factor

57% NCF

Pitch Regulated Power Control = Variable Partial Power
Constant Depth 50m to 80m
Variable Speed approx. 0.8 – 2.4 m/s
Vertical Rates Approx. = 0
Variable Anchor Loads
Variable Mooring Line Tensions

85% NCF

Depth Regulated Power Control = Constant Rated Power
Depths 30m to 200m
Constant Speed approx. 1.2 m/s
Vertical Rates < 10 fpm
Constant Anchor Loads
Constant Mooring Line Tensions

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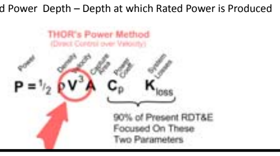
THOR's Power Method

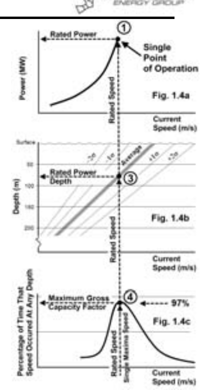
Constant Speed / Variable Depth Operation
- Not Constant Depth / Variable Speed

Depth Regulated Power Control
- Not Blade Pitch Regulated Power Control
- Ascent / Descent Rates less than 6 feet per minute (6 fpm)
- Power Feedback to Track & Recapture the 'Rated Power Depth'

Significant Increase in the Net Capacity Factor
- Relocate to Place Where More Fuel Exists
- Rated Speed Depth – Depth at which Rated Speed Occurs
- More Concerned with Relocating the Device
- Less Concerned with Device Component Efficiency

Only Moderate Efficient Components Required
- Relocate to Place Where 'Even More' Fuel Exists
- Rated Power Depth – Depth at which Rated Power is Produced





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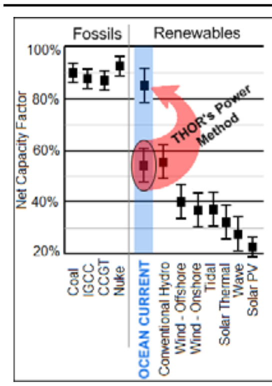
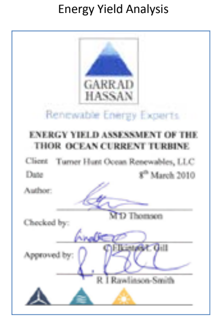
Capacity Factor by Fuel Type



3rd Party Independent
Energy Yield Analysis



GARRAD HASSAN

Renewable Energy Experts

ENERGY YIELD ASSESSMENT OF THE THOR OCEAN CURRENT TURBINE

Client: Turner Hunt Ocean Renewables, LLC

Date: 8th March 2010

Author: M D Thomson

Checked by: C Elizabeth Gill

Approved by: R I Rawlinson-Smith

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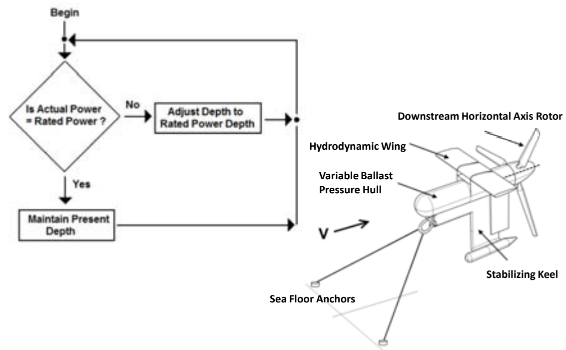
THOR's Power Method

Power Control and Power Feedback



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Other Ocean Current Devices

Florida Atlantic Univ. Concept Device

Aquantis Twin Rotor C-Plane

Cyclocean Ducted Rotor

Florida Hydro

Constant Depth Variable Speed Devices

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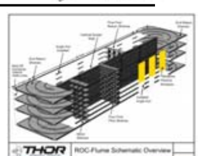
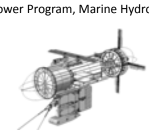
THOR's ROC-Flume / DoE Grant

- Primary Project Objectives – Validate THOR's Power Method and perfect scale model control system software
- Unique Hydrodynamic Testing Facility - Re-Circulating Open Channel Water Flume (40'L x 9'W x 8'D)
- 32 Individually Programmable/Controllable Thruster Motor Array with Control Feedback from ADCP and Pitot Tube Array
- Time Variant Inverse Velocity Sheer Profile Water Currents in the Test Section – Programmable Changing Currents for Hours
- Turbulence Simulation by 'Pulsing' the Thruster Motors above/below Mean Water Current Speed
- Funded in part by a Grant from Dept. of Energy Wind & Water Power Program, Marine Hydrokinetic 2010 FOA





THOR's Scale Model #1

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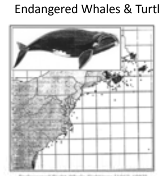
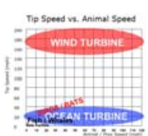
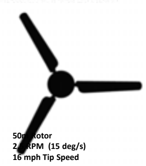
Environmental Considerations

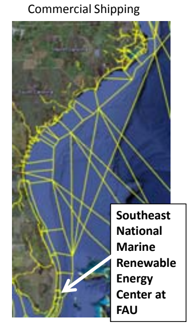
Endangered Whales & Turtles







Recreational Boating
Commercial Shipping



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Summary

- Ocean Current Energy can provide base-load renewable energy with net capacity factors above 80%
- Ocean Current Energy can be more consistent, more efficient and more cost effective (TBD) than conventional impoundment dam hydroelectric power
- Operating using THOR's Power Method can de-couple cost/capacity factor dependence leading to lower cost more efficient devices - thus leading to lower cost of energy
- THOR was recent recipient of US Dept. of Energy Grant to demonstrate the benefits of THOR's Power Method with a unique re-circulating open channel water flume during 2011
- The Gulfstream off of the Southeastern United States could supply over 60 GW of base load renewable ocean current energy to the entire eastern seaboard

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