International Standards Development for Marine and Hydrokinetic Renewable Energy

DOE Award # DE-FG36-09GO19009.A000

Neil Rondorf, Principle Investigator

Awardee: Science Applications International Corporation

Team Members: Oregon Wave Energy Trust and Maine Maritime Academy

Final Report on Technical Status

DOE/GO19009-1

October 2010

EXECUTIVE SUMMARY: SOW

Statement of Work Summary [and current status]

- Promote and Support US involvement in International Electro-technical Commission Technical Committee 114 (IEC TC-114) – to develop standards for marine and hydrokinetic renewable energy [Ongoing under new DOE/NREL contract]
- Recruit subject matter experts for membership in the US delegation for TC-114 and support travel by key US industry experts to international working group and technical meetings [Completed and Ongoing under new contract]
- Provide a final status to DOE and industry stakeholders that summarizes the IEC standards development process, international power measurement, identification, and systems engineering and integration standards for marine and hydrokinetic renewable energy, and provides standards guidance to industry [Completed]
- Provide a semi-annual newsletter for public outreach and education on the development and description of these standards [Completed and Ongoing under new contract]

EXECUTIVE SUMMARY: Criteria for Success

- Establish US credibility and economic parity with European and Asian Counterparts through increased US participation in standards development
  - Determine critical staffing needs to support the IEC standards
  - DOE funding for US involvement managed by the US TAG
- Report to DOE
  - Status of the IEC standards development effort
  - Provide guidance to industry members
- Perform outreach to inform the public of the progress of the TC114 committee
- Recruit industry / government / academia to staff the US Mirror Committees (MCs)

EXECUTIVE SUMMARY: Work Plan

Promote US participation in the IEC TC-114 effort to develop hydrokinetic (wave, current, and tidal power) energy standards. DOE funds (with SAIC matching funds) supported the following activities:

- Recruitment of US industry experts and coordination of US contributions to IEC PT 62600 series standards for "Marine Energy – Wave, Tidal, and Other Water Current Converters" as follows:
  - PT 62600-1: Terminology (Phil Beauchamp - MC Chair)
  - PT 62600-2: Design Requirements for Marine Energy Systems (C. Smith - PT Chair, R. Williams - MC Chair)
  - PT 62600-10: Assessment of Mooring Systems for Marine Energy Converters (J. Shelton - MC Chair)
  - PT 62600-100 - Part 100: Assessment of Performance of Wave Energy Converters in Open Sea (D. Tietje - PT Chair, Mike Raftery - MC Chair)
  - PT 62600-101: Wave energy resource assessment and characterization (P. Lenee-Bluhm - MC Chair)
  - PT 62600-200 - Part 200: The Assessment of Performance of Tidal Energy Converters (J. Colby - MC Chair)
  - PT 62600-201: Tidal energy resource assessment and characterization (K. Haas - MC Chair)
  - AHG-1 – Power Quality (Allan Chertok, Benjamin Beste - MC Members)
- Funding travel expenses for selected experts to attend IEC TC-114 project team meetings, technical advisory group meetings, and other related events
- Completion of a framework for measuring performance of current and tidal energy scale models
- Completion of a regulatory framework and cumulative effects report for wave energy devices
- Publication / dissemination of US TAG TC-114 activities to stakeholders and the public

CONCLUSIONS AND RECOMMENDATIONS

- Offer TAG services to DOE as a source of information and advice – a “sounding board” to verify the veracity and importance of marine renewable energy issues.
- Continue to recruit/support 2-3 SMEs per PT and 4-5 SMEs per US Mirror Committee - including two new PTs expected to form in 2012
- Assess environmental questions associated with standards
- Address critical interfaces between:
  - Devices
  - Cables
  - Power grids
- Assess active Water Power Programs on their requirements for new standards
- Establish a strategy for market acceptance and implementation of published standards
- Participate in developing additional standards required as industry progresses, such as underwater junctions and field electrical management schemes
- Pursue follow-on funding to sustain US TAG and ongoing/new PT participation, continue SME support, and pursue new objectives

Project Team (PT) Organization and Status

IEC Technical Committee (TC) 114

SAIC

From Science to Solutions

PT 62600-1 Terminology

- Three US members on Project Team (PT)
  - Philip Beauchamp (GE)
  - Sean O'Neill (Foundation for Ocean Renewables)
  - E. David Tietje (SAIC)
- Lead Country: Canada
- Other member countries
  - Denmark
  - Germany
  - Great Britain
  - Ireland
  - US A

PT 62600-1 Terminology

- PT 62600-1 formed in February 2009
- PT 62600-1 "Terminology" Draft Technical Specification (DTS) is issued and approved.
- The TS is scheduled for release in February 2012
- PT 62600-1 will be disbanded after the TS is issued

PT 62600-2 Design requirements for marine energy systems

- Six US members on PT
  - Madasamy Arockiasamy (Florida Atlantic University)
  - Roger Bagbey (Cardinal Engineering)
  - Eric Greene (Eric Greene Associates)
  - Robert Paasch (Oregon State University)
  - Rick Williams (SAIC)
  - Ye Li (NREL)
- Lead Country: USA (Charles Smith, Convener)
- Other member countries
  - Canada
  - Denmark
  - Germany
  - Great Britain
  - Ireland
  - South Korea

PT 62600-2 Design requirements for marine energy systems

- PT 62600-2 formed in August 2009
- PT 62600-2 “Design requirements for marine energy systems” is working toward a January 2012 release date for the 1st committee draft specification
- The Draft TS release is tentatively scheduled for January 2013

From Science to Solutions

PT 62600-10 Assessment of mooring system for marine energy converters

- Two US members on PT
  - Rick Driscoll (NREL)
  - John Shelton (Delmar Systems)
- Lead Country: South Korea
- Other member countries
  - Canada
  - Denmark
  - Great Britain
  - Japan
  - USA

PT 62600-10 Assessment of mooring system for marine energy converters

- PT 62600-10, the latest TC-114 Project Team, formed in March 2011
- PT 62600-10 “Assessment of mooring system for marine energy converters” first committee draft TS is expected in March 2012
- The forecast publication date for TS is June 2013

Energy | Environment | National Security | Health | Critical Infrastructure

SAIC From Science to Solutions

PT 62600-100 Power performance assessment of electricity producing wave energy converters

- Two US members on PT
  - Michael Raftery (Stevens Institute)
  - Neil Rondorf (SAIC)
- Lead Country: USA (E. David Tietje, Convener)
- Other member countries
  - Canada
  - Denmark
  - Great Britain
  - Japan
  - New Zealand
  - Spain
  - China
  - Germany
  - Ireland
  - Sweden
  - Norway
  - South Korea

PT 62600-100 Power performance assessment of electricity producing wave energy converters

- PT 62600-100 formed in August 2008
- PT 62600-100 "Power performance assessment of electricity producing wave energy converters" is currently in 2nd committee draft stage.
- Draft TS is expected in June 2012

Energy | Environment | National Security | Health | Critical Infrastructure

SAIC From Science to Solutions

PT 62600-101 Wave energy resource assessment and characterization

- One US member on PT
  - Pukha Lenee-Bluhm (Columbia Power Technologies)
- Lead Country: Great Britain
- Other member countries
  - Canada
  - Denmark
  - Germany
  - Ireland
  - Japan
  - South Korea
  - Spain
  - USA

PT 62600-101 Wave energy resource assessment and characterization

- PT 62600-101 formed in September 2009
- PT 62600-101 “Wave energy resource assessment and characterization” is currently up for vote in committee draft stage
- Draft TS is due in May 2012

PT 62600-200 Power performance assessment of electricity producing tidal energy converters

- Three US members on PT
  - Jonathan Colby (Verdant Power)
  - Dean Corren (Verdant Power)
  - Jarlath McEntee (Ocean Renewable Energy Co.)
- Lead Country: Great Britain
- Other member countries
  - Canada
  - Germany
  - Japan
  - South Korea
  - USA
  - Denmark
  - Ireland
  - New Zealand
  - Spain

PT 62600-200 Power performance assessment of electricity producing tidal energy converters

- PT 62600-200 formed in July 2009
- PT 62600-200 “Power performance assessment of electricity producing tidal energy converters” is currently in 1st committee draft, 2nd committee draft in work
- PT is requesting vote approval to use: International Hydrographic Organization (2008), IHO standards for hydrographic surveys special publication No. 44. 5th Edition as normative reference

PT 62600-201 Tidal energy resource assessment and characterization

- One US member on PT
  - Kevin Hass (Georgia Tech)
- Lead Country: Great Britain
- Other member countries
  - Canada
  - Germany
  - Japan
  - Spain
  - Denmark
  - Ireland
  - South Korea
  - USA

From Science to Solutions

PT 62600-201 Tidal energy resource assessment and characterization

- PT 62600-201 formed in September 2009
- PT 62600-201 “Tidal energy resource assessment and characterization” is currently up for vote in committee draft stage
- Draft TS is expected in May 2012

AHG 1 Power quality

- No US members on Ad Hoc Group (AHG)
- Two US members on US Mirror Committee
  - Allan Chertok (Magnecon)
  - Benjamin Beste (Alaska Power & Telephone)
- Lead Country: Canada
- Other member countries
  - France
  - Great Britain
  - Ireland
  - South Korea
  - Spain

SAIC From Science to Solutions

AHG 1 Power quality

- AHG 1 is awaiting a vote on a proposed new work package – for possible formation of a new PT.
- Vote closing date is 27 January 2012.
- If the AHG 1 work package is approved:
  - the new PT is expected to form by March 2012
  - the scheduled completion date for first committee draft is October 2013
  - the tentative scheduled completion date for the TS is October 2015

PT Technology Gaps and Information Needs

IEC Technical Committee (TC) 114

From Science to Solutions

PT 62600-2: Design Requirements for Marine Energy Systems
Technology Gaps and Information Needs

- Need developer input on design condition and engineering firm experience in designing offshore platforms
- Defining extreme condition scenarios
- Need more shadow committee members from offshore technology industries
- Implementation of Load and Resistance Factor Design (LRFD) vs. Working Stress Design (WSD)
- Application of current offshore standards and rules
- Uniform application of LRFD
- Defining design loads
- Need expert input for materials section of TS, for effects of corrosion and fatigue

PT 62600-100: Assessment of Performance of Wave Energy Converters in Open Sea
Technology Gaps and Information Needs

- Methodology on the calculation of direction wave energy
  - Two methods under consideration
  - Soliciting input from WEC developers
- Normalization of the power output
  - Reduce the affect of the weight height squared in the power matrix
  - Decision on best method to use the capture length
- Presentation of the power matrix
- Additional work to be considered
  - Error analysis – include discussion of errors with each clause
  - Certification of the transfer functions
- Transfer Function Protocol to predict wave energy at different locations in the test site
  - Unique transfer function needed for each test site due to differences in bathymetry, interaction between wave measurement instrumentation and Wave Energy Converter, and cost impact on the instrumentation of the test site
- Provide a validation methodology for transfer function to increase confidence – rather than specify a transfer function

PT 62600-101 Wave Resource Characterization and Assessment
Technology Gaps and Information Needs

- Quantifying relationship between years of data and uncertainty of results. For reliable estimates of WEC power production, it is essential that the uncertainty of the estimated resource be understood
- Balance between measured data and modeled data
- Scales for assessment and associated resolution, uncertainty and reported quantities
- Possible inclusion of time domain analysis
- How to quantify uncertainty in a wave resource estimate that is based on X years of data?
  - Inter-annual variability of resource is considerable
  - Wave climate may not be stationary (climate change)
  - There is a cost associated with acquiring and analyzing data
- How best to characterize a sea state to estimate recoverable energy?
  - Is analysis in the frequency domain sufficient?
  - Can bimodal seas be accurately characterized without partitioning?
  - Is directionally resolved wave power a better resource estimate for arrays of WECs?
  - Best: Performance data from variety of full-scale devices
  - Good: Modeling diverse device morphologies in simulations of real seas.

PT 62600-200: The Assessment of Performance of Tidal Energy Converters
Technology Gaps and Information Needs

- The following task areas were identified as needing significant work:
  - Power Measurements
  - ADCP Deployment
  - AEP/Availability/Up time
  - Measurement Period/Convergence
  - Wave/Turbulence
  - Yawing/Flow Misalignment
  - Blockage
- 3 to 4 international members needed per Task Group above
- Continue to develop Mirror (Shadow) Committees from National Committees to support PT efforts

PT 62600-201: Tidal Resource Characterization and Assessment
Technology Gaps and Information Needs

- Resource Assessment requirements will change depending on the project stage. Early work will generalize the amount of power available, and as a project develops, assessments will become more focused (i.e., for placement of turbine field and monitoring requirements)
- Questionable unknowns exist when using remote sensing (satellite data) combined with Bathymetry data to model available energy at a site
  - Model is large area, low resolution, can be prone to errors
  - ADCP data is small area, high resolution and generally accepted
  - Cost vs. benefits must be considered/defined
  - Requirements are dependent on the stage of the design cycle for the project
- Amount of data points and type of data required are dependant on project status
  - Must account for random events during measurements e.g. Tsunamis, Hurricanes, El Nino
  - Must agree on minimum timeframe of measurement, one lunar cycle is agreed as minimum
  - Cost vs. benefits must be defined for spatial resolution
- What about turbulence effects at a site?
  - Impossible to fully model turbulence and its effects
  - Various methods: Turbulence closure method (Mixing coefficients), Roughness, Manning N
  - Difficult, but possible to measure turbulence effects. Must determine cost vs. benefits
- How should stakeholders affected by the resource assessment be determined?
  - Barriers to navigation
  - Possible unavailability of a region during testing
  - Other uses for that area may be delayed

SAIC OCEAN TECHNOLOGY DIVISION
INTERNATIONAL STANDARDS DEVELOPMENT FOR MARINE AND HYDROKINETIC RENEWABLE ENERGY

DOE Award # DE-FG-09GO19009.A000
Recipient: Science Applications International Corporation

Federal Energy Regulatory Commission (FERC) Licensing Requirements For Traditional, Integrated and Alternative Licensing Processes For Wave Energy Converters (WEC)

Prepared for:
U.S. Department of Energy

Prepared by:

Jason Busch
Oregon Wave Energy Trust
Portland, Oregon

and

Science Applications International Corporation
Ocean Technology Division
26279 Twelve Trees Lane, Suite B
Poulsbo, Washington 98370

March 2010
Document Number DOE/GO19009-2

May | 10

The MHK Regulatory Framework and Cumulative Effects

Emerging Concepts and Best Practices

Prepared by Pacific Energy Ventures and Steve Bartell
on behalf of the Oregon Wave Energy Trust

Report #: DOE/ GO19009-2

Table of Contents

1. Introduction

1.1 Integrated Licensing Process (ILP)

Overview of ILP Pre-filing Steps

Applicant Files Pre-application Document (PAD) with Notice of Intent to File License Application

- PAD brings together all existing, relevant, and reasonably available information about the project and its effects on resources; and
- PAD also includes a well-defined process plan that sets the schedule for developing the license application and a list of preliminary studies and issues.

FERC Conducts Scoping

- The purposes of scoping is to identify and refine issues, discuss existing information, explore information gaps, and finalize the process plan; and
- Stakeholders discuss the issues and provide study requests.

Applicant Files Proposed Study Plan

- Applicant holds a meeting(s) to discuss the proposed study plan and informally resolve study disagreements;
- Applicant files revised study plan;
- Director of the Office of Energy Projects approves the revised study plan with any modifications after considering all information in the record;
- Agencies with mandatory conditioning authority may request the use of a formal dispute resolution process;
- Applicant conducts the studies as approved;
- Applicant files preliminary licensing proposal with the Commission, agencies, and public for comment;
- Applicant files final license application with the Commission and provides copies to agencies, tribes, and the public; and

- After the application is filed, the Commission has defined time frames to prepare and issue its environmental analysis pursuant to National Environmental Policy Act.

1.2 Traditional Licensing Process

1.2.1. First Stage

- Applicant issues notice of intent, preliminary application document, request to use TLP, and newspaper notice;
- Commission approves use of TLP;
- Applicant conducts joint agency/public meeting and site visit;
- Resource agencies and tribes provide written comments; and
- Agencies, tribes, or applicant request dispute resolution on studies with the Commission.

1.2.2. Second Stage

- Applicant completes reasonable and necessary studies o Applicant provides draft application and study results to resource agencies and tribes;
- Resource agencies and tribes comment on draft application; and
- Applicant conducts meeting if substantive disagreements exist.

1.2.3. Third Stage

- Applicant files final application with Commission and sends copies to agencies and tribes.

2. Alternative Licensing Process

As part of the alternative licensing process, an applicant can:

- Tailor the pre-filing consultation process to the circumstances of each case;
- Combine into a single process the pre-filing consultation process and environmental review processes under the National Environmental Policy Act and other statutes; and
- Allow for preparation of a preliminary draft environmental assessment by an applicant or an environmental impact statement by a contractor chosen by the Commission and funded by the applicant.

	Integrated Licensing Process (ILP)	Traditional Licensing Process (TLP)	Alternative Licensing Process (ALP)
Consultation w/ Resource Agencies and Indian Tribes	Integrated	Paper driven	Collaborative
FERC Staff Involvement	- Pre-filing; beginning at filing of NOI- Early and sustained throughout process	- Post Application filing	- Pre-filing - Early involvement on requested basis
Deadlines	- Defined deadlines for all participants throughout the process, including FERC	- Pre-filing - some deadlines for participants - Post-filing - defined deadlines for participants	- Pre-filing - deadlines defined by collaborative group - Post-filing - defined deadlines for participants
Study Plan Development	- Developed through study plan meetings - Plan approved by FERC	- Developed by applicant based on early agency and tribal recommendations - No FERC involvement	- Developed by collaborative group - FERC staff assist as resources allow
Study Dispute Resolution	- Informal dispute resolution available to all participants - Formal dispute resolution available to agencies w/ mandatory conditioning authority. Three-member panel technical recommendation on study dispute - OEP Director opinion binding on applicant	- FERC study dispute resolution available upon request - OEP Director issues advisory opinion	- FERC study dispute resolution available upon request - OEP Director issues advisory opinion
Application	- Preliminary licensing proposal or draft application and final application include Exhibit E that has form and contents of an EA	- Draft and final application include Exhibit E	- Draft and final application with applicant prepared EA or third-party EIS
Additional Information Requests	- Available to participants before filing of application - No additional info requests after application filed	- Available to participants after filing of Application	- Available to participants primarily before filing of application - Post-filing requests available but should be limited due to collaborative approach
Timing of Resource Agency Terms and Conditions	- Preliminary terms and conditions filed 30 to 60 days after REA notice - Modified terms and conditions 60 days after comments on draft NEPA document	- Preliminary terms and conditions filed 60 days after REA notice - Schedule for final terms and conditions	- Preliminary terms and conditions filed 60 days after REA notice - Schedule for final terms and conditions

2. FERC Preliminary Permit

Before seeking a license from the Federal Energy Regulatory Commission (FERC), a project proponent has the option of first applying for a preliminary permit. A preliminary permit, issued for up to three years, maintains priority to apply for a license on that site while the permit holder determines the project's feasibility, consults with stakeholders, performs baseline studies and prepares to apply for a license.

http://www.ferc.gov/industries/hydropower/gen-info/licensing/pre-permits.asp [17]

A preliminary permit does not authorize construction or operation of a facility. Once the preliminary permit has been granted, permit holders must submit reports containing specific information, including a schedule of activities and target dates, and periodic reports on the status of its studies.

Formal consultation is not required when applying for a Preliminary Permit. However, anyone may submit comments or a motion to intervene in accordance with the requirements of Rules of Practice and Procedure.[18]The Commission will consider all comments filed in making its decision whether or not to issue a preliminary permit, but only those who file a motion to intervene in accordance with the Commission's Rules may become a party to the proceeding. Any comments or motions to intervene should be received within 60 days from the issuance date of the notice of the preliminary permit application, unless otherwise specified in notice.

Primary Legal Authority: *§ 4(f) of the FPA* authorizes FERC to issue preliminary permits for the purpose of enabling prospective applicants for a hydropower license to secure the data and prepare the materials that must accompany an application for a hydrokinetic license. Additional responsibilities given to FERC under the EPAct of 2005 stipulate that FERC regulate the transmission and wholesale sales of electricity in interstate commerce; monitor and investigate energy markets; and oversee environmental matters related to hydroelectric projects and major electricity policy initiatives

3. Federal Hydroelectric License

Pursuant to the Federal Power Act (FPA), advanced water power projects must be licensed by FERC. A Federal Hydroelectric License, which may be issued for a term of up to 50-years

http://www.ferc.gov/industries/hydropower/gen-info/handbooks/licensing_handbook.pdf [19],

gives the licensee authority to construct and operate a hydroelectric project. FERC has three primary licensing processes: Integrated Licensing Process (ILP), the default, Traditional Licensing Process (TLP), and Alternative Licensing Process (ALP).[20]Consultation periods and procedures will vary depending on the type of process used and the size and scope of the project. Each of the licensing processes will entail a substantial level of consultation. For an explanation of the differences between these processes, please refer to FERC's "Licensing Handbook."

Project proponents interested in a short-term license to test new technologies may request to use the *Hydrokinetic Pilot Project Licensing Process.* Criteria for pilot projects generally include the following: 1) small; 2) short-term; 3) not located in sensitive areas; 4) removable and able to be shut down on short notice; and 5) able to be decommissioned with site restoration at end of license term. Pilot projects are generally intended for testing technology devices and studying sites. The purpose of the expedited licensing process for pilot projects is to provide an opportunity to prove the emerging technology devices, determine appropriate sites, and gather information on environmental and other effects of the devices. For additional information, see FERC's *Hydrokinetic Pilot Project Criteria and Draft Application Checklist.*

http://www.ferc.gov/industries/hydropower/indus-act/hydrokinetics/pdf/pilot_project.pdf

FERC's extensive licensing system provides the framework through which many other local, state, tribal, and federal approvals may be obtained. Additionally, the FPA requires license applicants to obtain lands or other rights needed to construct, operate, and maintain the hydroelectric project, and applicants must provide evidence of compliance with state and local requirements before implementing an action authorized by a FERC license.

4. Clean Water Act § 404 Permit

Enacted to conserve and restore the quality of the nation's waterways, §404 of the Clean Water Act (CWA) requires authorization for dredge and fill activities for activities in waters of the U.S., including certain wetlands. The 404 permit program is administered jointly by EPA and the U.S. Army Corps of Engineers (ACOE). The ACOE handles the actual issuance of permits, and it determines whether a particular area of land is a wetland or water of the U.S. The ACOE also has primary responsibility for ensuring compliance with permit conditions, although EPA plays a role in compliance and enforcement.

The ACOE can authorize dredge and fill activities with a standard individual permit, a letter-of-permission, a nationwide permit, or a regional permit. Based on the level of impacts associated with a proposed project, the ACOE will make a determination on what type of permit review and authorization is appropriate. Authorizations expire within 2-5 years from the date of issuance; however, they may be renewed if the ACOE is notified at least one month prior to expiration. Depending on the scope of the project and construction methods, certain activities associated with advanced water power renewable energy projects (e.g., transmission cables) may require a §404 permit.

In its application review, the ACOE will consult with federal and state agencies, to evaluate potential impacts, such as effects on fish and wildlife, water quality, navigation, historic, cultural, scenic and recreational values, and economics. The inter-agency consultation process also involves review and negotiations to identify conservation measures that can help protect and mitigate potential effects. Before issuing a decision on a Standard Individual Permit, the ACOE will provide a 15 to 30 day public notice period. Also, the ACOE must provide notice of and opportunity for public hearings before issuing a permit.

If a project could affect a threatened or endangered species or its critical habitat, then the ACOE must consult with the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (FWS) before issuing an authorization. Additionally, the project applicant may be required to submit a Biological Evaluation[25].

5. Rivers and Harbors Act § 10 Permit

In order to prohibit the obstruction or alteration of navigable waters, any structures or activities (e.g., anchoring cables, aids to navigation) occurring in or affecting the navigable waters of the U.S., including the Territorial Seas and the Outer Continental Shelf[26], are subject to authorization by the ACOE. The ACOE can authorize activities by a standard individual permit, letter-of-permission, nationwide permit, or regional permit.

Based on the level of impacts associated with a proposed project, the ACOE will make a determination on what type of permit is needed. For example, Aids to Navigation may be authorized by a nationwide permit if they are approved by and installed in accordance with requirements of the U.S. Coast Guard. (33 CFR 330.5(a)(1)). However, if the ACOE can exercise its authority through mandatory FPA §4(e) conditions to the license, it is possible that structures and activities that are part of a project authorized by a FERC license may not require a § 10 Permit.

If a project may affect threatened or endangered species (or their designated critical habitat), then the ACOE must consult with NMFS and FWS before making a permit decision; additionally, permit applicants will be required to submit a Biological Evaluation describing the species in the area, the impact the project may have on the species or its critical habitat, and measures that can be taken to minimize impacts. Before issuing a decision on a Standard Individual Permit, the ACOE will provide a 15 to 30 day public notice period. Also, the ACOE must provide notice of and opportunity for public hearings before issuing a permit.

6. Private Aids to Navigation Permit

Because advanced water power technology devices are located in the marine environment, these projects will need to comply with U.S. navigation standards. Before deploying any structure, the owner/operator must apply for U.S. Coast Guard (USCG) authorization to properly mark the structure, and navigation aids require prior ACOE permit approval for the work being done. Navigation aids for marine renewable energy projects will be installed and maintained by the project owner/operator (not by the USCG), which classifies the markings as *Private Aids to Navigation (PATON).*

In order to establish PATON markings in waters regulated by the federal government, it is mandatory to obtain either a permit or letter of no objection. The approved markings are required to remain in place until the structure is removed, or otherwise directed by the Coast Guard District Commander.

http://www.uscg.mil/d13/dpw/docs/PATONGuide12Jul06.pdf

Action Agency Requirements for Federal Permits & Licenses

Summary Table Authorization	Primary Legal Authority	Lead Agency	Participating Agencies	Anticipated Process Time
NEPA Documentation (EA/EIS)	National Environmental Policy Act	FERC *for grid connected,* ACOE *for non-grid connected*	Relevant federal, state and local agencies	2-6 months EA, 1yr EIS[29]
§7 ESA Consultation[30]	Endangered Species Act	NMFS, USFWS	FERC, ACOE, USCG, NMFS	135+ days[31]
Marine Mammal Consultation	Marine Mammal Protection Act	NMFS & USFWS	None specified	120 days or 6-24 months[32]
Essential Fish Habitat Consultation	Magnuson-Stevens Act	NMFS	Regional Fisheries Management Council	30-60 days[33]
Fish and Wildlife License Conditions	Fish and Wildlife Coordination Act	USFWS, NMFS	State resource agencies	Varies
Migratory Bird Consultation	Migratory Bird Treaty Act	USFWS	FERC, ACOE, state resource agencies	Varies
§106 NHPA Consultation	National Historic Preservation Act	SHPO/THPO	ACHP, FERC, ACOE	At least 30 days for each stage of consultation[34]

7. National Environmental Policy Act

The National Environmental Policy Act (NEPA) was enacted to ensure that federal agencies evaluate the potential environmental impacts of a proposed action and reasonable alternatives to those actions *before* authorizing the action. NEPA provides a framework to identify and assess environmental effects and reasonable alternatives to the proposed actions. The federal action agency, which is the agency issuing the license, lease or permit, is expected to utilize alternatives and/or mitigation to avoid or minimize impacts so that the purpose and need for the proposed action is accomplished in a manner that does not result in significant environmental effects.

The federal action agency documents the NEPA process by first determining that either 1) the proposed action is categorically excluded from detailed environmental review, or 2) the proposed activity requires a detailed environmental review and documentation containing information about the proposed project, alternatives considered, and likely environmental effects. If a categorical exclusion does not apply, then the federal agency prepares either an Environmental Assessment[35](EA) or an Environmental Impact Statement (EIS). Whether an EA or an EIS is prepared depends on the quantity and complexity of the issues identified during the scoping period.

If substantial issues are not identified in the scoping period, agency staff will prepare an EA indicating that project is not likely to have significant effects, along with a Finding of No Significant Impact (FONSI). If substantial issues are identified, the agency will prepare an EIS [36]. In some cases, the action agency may tier its NEPA document off a prior EIS or a programmatic EIS. Additionally, the federal NEPA process may be coordinated with state environmental review processes conducted for state permitting and leasing determinations.

Stakeholder consultation usually involves government agencies and the public. Government agencies participate as either the action agency or a cooperating agency. The federal action agency is responsible for executing the NEPA process and for documenting its evaluation. Any federal, state, tribal or local agency having expertise with respect to a particular environmental issue or jurisdiction by law may participate in the NEPA process as a cooperating agency. Cooperating agencies assist the action agency by participating in the scoping process, developing information and preparing environmental analyses on issues with which the cooperating agency has special expertise. However, cooperating agencies are precluded from intervening in the proceeding.

Members of the public (individuals or organizations) and agencies that are not cooperators can participate in the NEPA process by consulting during study development and data interpretation, providing comments on the licensing application, participating in scoping of issues, filing of recommendations and conditions, and reviewing and commenting on the draft EA or EIS. The action agency must take into consideration all comments received from the public and other parties on the NEPA documents during the comment period.

8. Endangered Species Act §7 Consultation

The Endangered Species Act (ESA) is a federal statute designed to protect and conserve endangered and threatened fish, marine mammals, turtles, wildlife, and plant species and their habitats. The ESA is administered together by the "Services." NMFS administers consultations that pertain to marine and anadromous species, and FWS administers consultations that pertain to terrestrial and freshwater species. Pursuant to § 7(a)(2) of the ESA, federal action agencies are obligated to consult with the appropriate Service whenever the proposed action may affect a listed species. The purpose of this consultation is to assist the federal agency in ensuring that the proposed action and its related activities do not jeopardize any threatened or endangered species and/or their critical habitats.

License and permit applicants are encouraged to document and implement a due diligence process that includes impact avoidance, minimization, enhancement, monitoring, and adaptive management to address unforeseen impacts to endangered and threatened species and their critical habitats. FERC applicants are required to include a discussion of the status or results of informal or formal consultation in their license application. Generally, an applicant will prepare a draft biological assessment [39] (BA) under the supervision of the action agency[40] and in cooperation with the Service. Once complete, the applicant will submit the BA to the action agency (e.g., FERC, ACOE) for its adoption and submission to the Service. Under the FERC licensing process, FERC's NEPA documentation includes an ESA section that serves as the final BA to the Service. Any additional consultation after this is FERC's responsibility.

If the action agency determines from the BA that the proposed action is not likely to have adverse impacts *and* the Service concurs with this determination, then the consultation process is complete. However, if the Service does not concur with such determination, or if the action agency determines that the proposed action is likely to adversely impact an ESA-listed species or its critical habitat, then the action agency must initiate formal consultation. To initiate formal consultation, a written request must be submitted to the Service.

During formal consultation, the Service develops a "jeopardy analysis" and uses this analysis to make informed decisions about the action's effects. If the Service's analysis concludes that the proposed project is not likely to jeopardize the species and/or its critical habitat, then the Service will issue a "no jeopardy" biological opinion (BO), along with an Incidental Take Statement (ITS) detailing the amount and extent of expected incidental take, and terms and conditions that the applicant and the action agency must take to minimize impacts. If the Service's analysis concludes that the proposed project is likely to jeopardize the species and/or adversely impact its critical habitat, then the Service will issue a "jeopardy" BO, including any "reasonable and prudent alternatives" ("RPAs") to the action that would prevent adverse impacts. [42]Issuance of the BO concludes formal consultation.

9. Marine Mammal Protection Act

The Marine Mammal Protection Act (MMPA) makes it illegal "take" any marine mammal without prior authorization from NMFS. "Take" is defined as harassing, hunting, capturing, or killing, or attempting to harass, hunt, capture, or kill any marine mammal.[44] Authorizations may be granted to conduct scientific research, such as conducting surveys of abundance to determine habitat use during preliminary baseline studies, or for incidental taking by disturbance or injury during construction, installation, and operation of a new wave energy facility.[45]Additionally, for marine mammals listed under the ESA, an MMPA authorization must be issued in order for an Incidental Take Statement to be valid.

The MMPA includes two authorization processes: an *Incidental Harassment Authorization (IHA)* and a *Letter of Authorization (LOA).* Each of these authorizations provides for the incidental, but not intentional, take of small numbers of marine mammals while engaging in a specified activity (other than commercial fishing), provided that NMFS finds that the take will have a negligible impact on the species.

The issuance of MMPA permits and authorizations is a public process that may involve notice and comment rulemaking and is subject to NEPA. As such, NMFS will perform a NEPA review when issuing an authorization for marine mammal take. If NMFS believes the lead federal agency's NEPA document sufficiently analyzes marine mammal issues, then it may decide that a Categorical Exclusion is appropriate and simply adopt the federal agency's NEPA document. Otherwise, NMFS will prepare its own NEPA document for the issuance of the MMPA permit. An *Incidental Harassment Authorization (IHA)* authorizes harassment to marine mammals from short-term activities as long as impacts on the species or stock are negligible. An IHA is only valid for up to one year, but it may be renewed prior to expiring. An IHA is generally issued if the proposed activities do not hold potential for serious injury or mortality, or if the potential for serious injury or mortality can be negated through mitigation. Monitoring and reporting is required to comply with an IHA.

http://www.nmfs.noaa.gov/pr/permits/incidental.htm

A *Letter of Authorization (LOA),* valid for up to five years, is generally issued if the potential for serious injury and/or mortalities exists and there are no mitigating measurements that could be taken to prevent this form of take from occurring. An LOA authorizes the harassment, injury or mortality of a marine mammal as long as impacts on the species' annual rates of recruitment or survival are negligible.

The applicant initiates the LOA process by submitting an application for small take authorization. The appropriate Service must publish notice of the proposed regulation and its findings in the Federal Register, in newspapers, through appropriate electronic media, and in the coastal areas that may be affected by the activity. The public will have up to 30 days to submit comments on the proposal.

The Service will then prescribe regulations setting forth permissible take methods to ensure the least practicable adverse impacts on the species or stock and its habitat, the availability of the species or stock for subsistence uses, and appropriate monitoring and reporting. Once the regulations are promulgated, the Service may issue an LOA to the project proponent based on a determination that the level of take will be consistent with the findings made for the total take allowable under the regulations. The Service will publish notice of the LOA in the Federal Register within 30 days of its issuance.

10. Essential Fish Habitat Consultation

One of the primary purposes of the Magnuson-Stevens Fishery and Conservation Act (MSA) is to promote the protection of essential fish habitat (EFH). EFH can consist of both the water column and the underlying surface (e.g. seafloor) of a particular area. Certain properties of the water column such as temperature, nutrients, or salinity are essential to various species. Areas designated as EFH are essential to the long-term survival and health of managed fisheries, and include those habitats that support the different life stages of each managed species.[46] EFH encompasses those habitats necessary to ensure healthy fisheries now and in the future. §305(b)(2) of the MSA mandates that federal agencies consult with the Secretary of Commerce on all actions, proposed actions, authorized, funded, or undertaken by the agency, that may adversely affect EFH.

Federal agencies (e.g., FERC, ACOE) must consult with NMFS with respect to any Essential Fish Habitat (EFH) that may be affected by the proposed project that the federal agency is authorizing. NMFS strongly encourages federal agencies to streamline the consultation process by consolidating, where appropriate, environmental review procedures required by other statutes such as NEPA, ESA, Fish and Wildlife Coordination Act, Clean Water Act, and Federal Power Act.

http://www.nmfs.noaa.gov/habitat/habitatprotection/pdf/efh/EFH%20Consultation%20Guidance%20v1-1.pdf

Once consultation is complete NMFS will provide *Conservation Recommendations* to the project proponent. If NMFS finds that the proposed project would adversely impact any EFH, then it will recommend measures to be taken (by the federal agency or the project proponent) to mitigate, reduce, or eliminate impacts the EFH. Federal agencies are required to submit a description of the intended conservation measures, as well as their reasons for not implementing any of NMFS' recommendations (if applicable). EFH Consultation Guidance is available at:

http://www.nmfs.noaa.gov/habitat/habitatprotection/pdf/efh/EFH%20Consultation%20Guidance%20v1-1.pdf

An applicant for a FERC license is required to document any EFH that may be affected by a proposed project in the EA or EIS that accompanies the FERC license application. Additionally, if EFH consultation does occur the EA or EIS will also include the following:

i. Description of any EFH that may be affected
ii. Summary of the consultation process
iii. *Conservation Recommendations* provided by NMFS (or the applicable fishery management council)
iv. Conclusions with respect to adoption of the recommended conservation measures

11. Fish & Wildlife Coordination Act

The FWCA requires all federal action agencies to consult with and give strong consideration to the views of the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, and state wildlife agencies regarding the fish and wildlife impacts of projects that propose to alter a body of water. Federal agencies must consult with relevant state and federal natural resource agencies to insure that the construction, maintenance, and operation of a facility is in accordance with the FWCA so as to prevent the loss or damage to fish or wildlife resources. Further, pursuant to *§ 10(j) of the FPA*, when issuing a hydroelectric license, FERC must include measures to protect fish and wildlife resources and to mitigate damages to those resources that may be affected by a project. These measures are based on recommendations from the NMFS, FWS, and state fish and wildlife agencies.[49] A FERC license application must include a summary of the recommendations, a discussion of how the applicant addressed the recommendations, and an explanation of how the application complies with § 10(j).

12. Migratory Bird Treaty Act

Migratory birds in North America are an international resource, with numerous species breeding throughout the United States and Canada. In the fall of each year, these birds migrate south to winter in the USA, Mexico, and Central and South America. The original Migratory Bird Treaty Act of 1918 (MBTA) implemented the 1916 Convention between the U.S. and Great Britain (for Canada) for the protection of migratory birds. Later amendments to the Migratory Bird Treaty Act implemented treaties between the U.S. and Mexico, the U.S. and Japan, and the U.S. and Russia.

It is important to address potential migratory bird impacts at the early stages of project planning as the potential impacts may be fairly complex. For example, corridors needed for transmission lines could fragment habitats and create flight hazards to migratory birds, and maintaining those corridors with herbicides may cause adverse effects to plants and wildlife.

FWS encourages applicants to document and implement a due diligence process that account for migratory bird impacts, including impact avoidance, minimization, enhancement, monitoring, and adaptive management commitments to address unforeseen impacts to migratory birds.

http://www.fws.gov/migratorybird

13. National Historic Preservation Act §106 Consultation

The National Historic Preservation Act (NHPA) requires federal action agencies, which are those federal agencies that issue licenses, leases and/or permits, to identify and assess the effects of its actions or actions it authorizes on historic resources. The NHPA also requires federal action agencies (e.g., FERC, ACOE) to afford the Advisory Council on Historic Preservation (ACHP) a reasonable opportunity to comment on the proposed action. Federal action agencies must consult with appropriate state and local officials, including State Historic Preservation Office (SHPO), Tribal Historic Preservation Office (THPO), Indian tribes, and members of the public to consider their views and concerns about historic preservation issues when making final project decisions. The SHPO or THPO will act as the lead agency in the consultation process. There are three stages of formal consultation with defined time frames; however, FERC includes NHPA analysis in its NEPA documentation, so the timeframes of the consultation stages are not necessarily formally followed. The federal action agency will seek concurrence from the SHPO or the ACHP at each stage.

Initiation of Consultation (60 days)- First, the action agency initiates a 30 day consultation period with other relevant agencies to identity the Area of Potential Effect (APE) and to determine if any historic resources exist within the APE that are listed or eligible for listing in the National Register. [51]Concurrence on project APE is then sought from SHPO, Tribal governments, and other agencies involved. If it is determined that no historic properties are present or that present properties will not be affected, then the action agency notifies SHPO. If SHPO does not object within 30 days, then § 106 consultation concludes.

Assessment of Adverse Effects (60 days)- If the action agency concedes that the action will affect historic properties (or those eligible for listing), then the action agency consults with SHPO and Indian tribes to assess what effect the project would have on the historic properties. Concurrence on determination of effects is sought from SHPO and tribes, who have 30 days to respond to the finding. If there is no response to a determination of effects, then the § 106 consultation concludes. If the SHPO or a Tribe objects and the action agency cannot resolve the objection, then the action agency forwards the objection to the ACHP, which can provide its opinion.

Resolution of Adverse Effects (60 days)- If the action agency concedes that the project will have adverse effects, then the action agency must consult with SHPO and tribes on mitigation measures to protect or mitigate the effects on the historic properties. If the parties agree, they can incorporate those measures into a Memorandum of Agreement (MOA)[52]between the action federal agency and SHPO. If the effects of the project on historic properties cannot be fully assessed before the action agency approves the project, consultation may result in a Programmatic Agreement (PA) between the SHPO and the action agency (e.g., FERC).
In situations where FERC is the federal action agency for a proposed project, FERC typically incorporates the PA (or MOA) into the project license, which defines the APE and requires the licensee to develop and implement a Historic Properties Management Plan [53](HPMP) to resolve all identified adverse effects, as well as any other necessary mitigation measures. If the action agency and SHPO are unable to agree on how to resolve adverse effects, then the ACHP will make recommendations.

SAIC OCEAN TECHNOLOGY DIVISION
INTERNATIONAL STANDARDS DEVELOPMENT FOR MARINE AND HYDROKINETIC RENEWABLE ENERGY

DOE Award # DE-FG-09GO19009.A000
Recipient: Science Applications International Corporation

Hydrokinetic Turbines: Power Performance Measurements of Electricity Producing Hydrokinetic Turbines: Laboratory Scale Models

Prepared for:
U.S. Department of Energy

Prepared by:

Dr. Richard Kimball
Maine Maritime Academy
Castine Maine 03290

and

Science Applications International Corporation
Ocean Technology Division
26279 Twelve Trees Lane, Suite B
Poulsbo, Washington 98370

March 2010

Document Number: DOE/GO19009-3

Table of Contents

1 Forward

The purpose of this document is to provide a framework for the development of testing and performance reporting standards for laboratory scale models of hydrokinetic turbines. This document references standards and guidelines published for turbo-machines in similar fields such as marine propulsion and wind energy. The document develops a proposed system of turbine classification and develops a proposed framework of non-dimensional performance parameters and test formats relevant to the reporting of basic performance of hydrokinetic turbines. The document also reviews current turbine design practices as well as giving guidelines for the testing of laboratory scale model hydrokinetic turbines in tow tanks, water tunnels and water flumes.

Hydrokinetic turbines are machines which extract energy from the kinetic energy in a free stream of flowing water. Many natural energy sites occur which can utilize this form of energy extraction including river run, tidal flow and ocean currents. This energy form is site specific and requires a source of fast moving water. Such sites exist in tidal flows of estuarine bay systems, fast moving river systems and deep ocean current such as the gulf stream. This technology has promise as an energy harvesting technology in such areas as it does not require an impoundment dam to harness the energy of the flow, thereby allowing relatively free migration and navigation of the waterway.

2 Scope

The scope of this document is to provide a draft framework for a standard for the testing of laboratory scale model hydrokinetic turbines in laboratory settings Such models are utilized in the development of commercially deployed hydrokinetic turbines, and are useful for cost effective development and improvement of turbine performance. The use of laboratory scale prototypes to predict and improve the performance of turbo-machines is common practice in similar fields, such as in the design of marine propellers. The use of scale models using the well known science of dimensional analysis can yield accurate predictions of full scale device performance using more cost effective scale models tested in controlled laboratory facilities such as tow tanks and water tunnels.

This document puts forth a proposed methodology for the testing and reporting of data for laboratory scale hydrokinetic energy extraction devices testes in a laboratory setting. The methodology relies upon standard testing practices developed in similar fields such as those published by the International Towing tank Conference (ITTC) for the testing of marine propellers, the International Electrotechnical Commission (IEC) for the testing of wind turbines and other relevant organizations which adopt standards applicable to the field.

A turbine classification system is proposed as part of this document as well as a proposed set of performance parameters, non-dimensional numbers and data reporting formats. Guidelines for the testing of model hydrokinetic turbines in tow tanks, water tunnels and water flumes are also presented.

This document does not address directly the testing of Field Scale prototype as tested in-field, including vessel mounted test beds and in-situ field testing of turbines. It is expected that standards for this type of testing will developed separately from this document. Bedard 2005 is a good reference on field scale testing of hydrokinetic devices.

This document addresses only the testing of single hydrokinetic devices testing in a uniform inflow for the purpose of characterizing the power producing performance of the turbine itself under these conditions. The performance effects of turbine arrays and sever in-flow turbulence should be addressed in subsequent standards.

3 Normative References

The following referenced documents are utilized in this standards document and contain pertinent information and standards cross-referencing to the application of this standard in practice.

International Electrotechnical Commission, *Standard 61400-12-1 Power performance measurements of electricity producing wind turbines*

International Towing Tank Conference. *ITTC Recommended Procedures and Guidelines 0.0 Rev. 3,* 2005. Specifically the following subsections:

7.5-01-02 *Propeller models*

7.5-02 *Testing and Extrapolation Methods*

7.6 *Control of inspection, measuring and test equipment*

Air Movement and Control Association. *ANSI/AMCA Standard 210-07 Laboratoy Methods of Testing Fans for Certified Aerodynamic Performance Rating,* 2007

4 Definitions

4.1 Rotating Machines

Rotating hydrokinetic turbines refer to turbines by which the main turbine action translates hydrodynamic forces and energy extraction directly to a rotating shaft.

4.2 Rotating Machines With Lifting Surfaces

Any rotating hydrokinetic turbines which utilize blades which create lifting forces (through the generation of circulation) which in turn provide the main action of the turbine in the extraction of power.

4.3 Parallel Axis Machines with Free Tip Lifting Surface blades (Rotating):

Any rotating hydrokinetic turbine which aligns its rotating axis along the direction of the free stream flow which utilizes lifting surfaces which are not contained in a housing or shroud at the blade tips. Examples of such turbines are depicted in figure 1 below, being developed by SMD Hydrovision, Verdant and Marine Current Turbines respectively. To note, the main differentiating feature of these configurations is the methods of providing flow reversal of the turbines.

Figure 1: Examples of Paralles Axis Free tip Turbines (Left to right: SMD Hydrovision, Verdant, Marine Current Technologies)

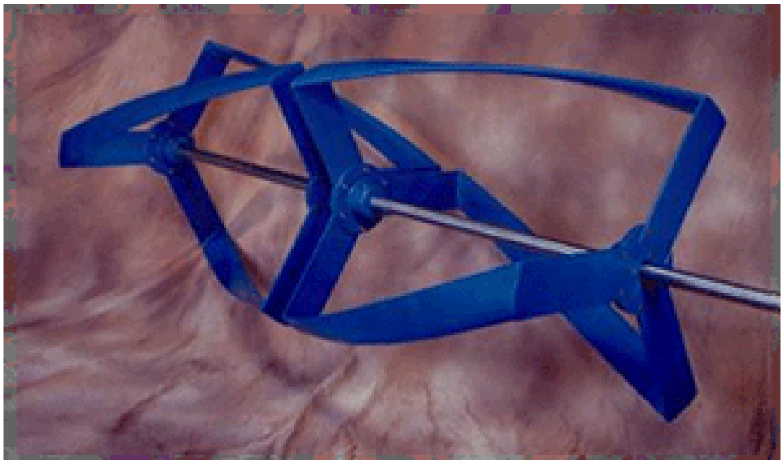
4.4 Parallel Axis Machines with Ducted or enclosed tip Lifting Surface blades (Rotating):

Any rotating hydrokinetic turbine which aligns its rotating axis along the direction of the free stream flow which utilizes lifting surfaces which are contained in a duct or hosing. A duct may be attached to the blades directly or to the housing, but is intended to provide guidance of the flow into the machine and may provide a means to retard blade tip flow recirculation. Such a duct or shroud may act as a nozzle to accelerate the flow or as a diffuser to decelerate the flow. As such the duct is an integral part of the turbine design and is purpose goes beyond supporting and protecting the machine. Figure 2 depicts turbines of this class by OpenHydro and Lunar Energy.

Figure 2: Examples of ducted or shrouded parallel axis lifting surface type turbines (Left to right: OpenHydro turbine being test at EMEC, Lunar Energy turbine)

4.5 Crossflow Axis Machines with Open Frame Lifting Surface blades (Rotating):

Any rotating hydrokinetic turbine which aligns its rotating axis perpendicular to the direction of the free stream flow which utilizes lifting surfaces which are not contained in a housing or shroud encasing the blades. Examples of such turbines are depicted in figure 3 below, showing a Gorlov rotor and Ocean Renewable Powers' SeaGen turbine.



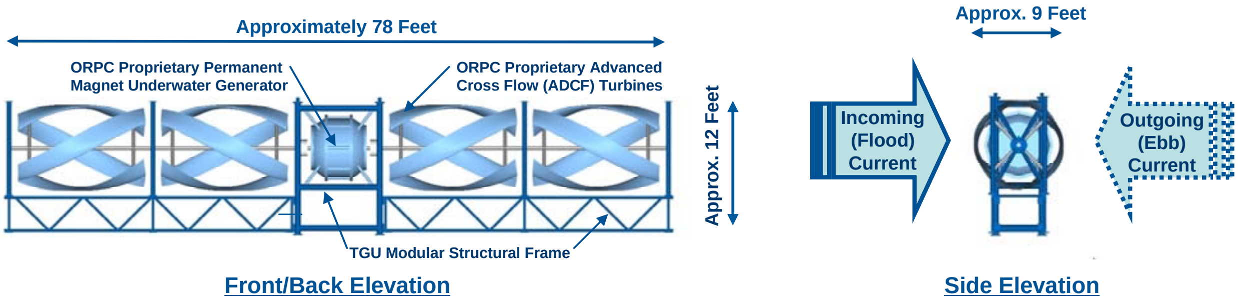


Figure 3: Examples of Open Frame Crossflow turbines using lifting surface blades. (top to bottom: Gorlov rotor, Ocean Renewable Power Seagen rotor)

4.6 Crossflow axis with enclosed lifting surface blades:

Any rotating hydrokinetic turbine which aligns its rotating axis perpendicular to the direction of the free stream flow which utilizes lifting surfaces which are contained in a housing or shroud around the blades. Figure 4 depicts an Example of such a turbine design from Canadian tidal turbines.

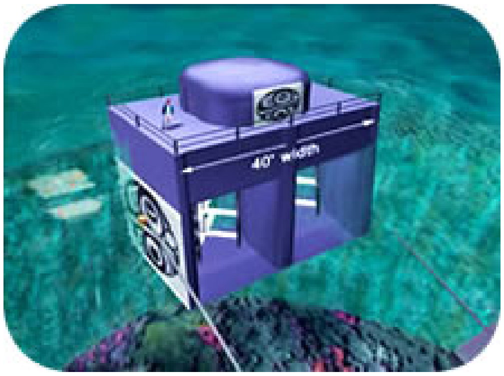


Figure 4: Example of an enclosed frame crossflow turbine with lifting surface blades from Blue Energy

4.7 Crossflow axis machines with drag surface type blades:

These machines utilize blades which act as drag elements. The blades are design such that the blades have lower drag on the return side than the side moving with the stream, thereby creating a differential torque driving the shaft. The Savonius rotor depicted in Figure 5 is an example of this type of machine.

FIGURE 5 TBD

Figure 5: Savonius Rotor – Example of crossflow axis machine with drag surface type blades

4.8 Other Machine Types:

Flapping foil Machines: utilize flapping wing(s) connected to a specialized drive mechanism to convert the flapping action to useful power.

Parallel flow Linear track with lifting surfaces: This type of machine, depicted in Figure 6 is being developed by Atlantis.

FIGURE 6 TBD

Figure 6: The Atlantis Nereus linear track parallel axis free tip turbine

5 Nomenclature

ρ - Fluid density

ω - Rotation rate rad/s

ν - Kinematic Viscosity

λ - Tip Speed Ratio

$\vec{V}$ - Velocity (vector)

U - Inflow or Free stream velocity

q - Velocity magnitude (total)

q_{in} – Local blade inflow velocity magnitude $q_{in} = \sqrt{(U^2 + (\omega R)^2)}$

A - Area

A_f - Turbine Swept Frontal area

$\dot{W}$ - Shaft Power

D - Turbine Diameter

R - Turbine Radius

Re - Reynolds number

$\hat{n}$ - Surface unit normal vector

Cp – Power Coefficient

P - Pressure

Po- Ambient hydrostatic pressure

Patm- Atmospheric pressure at surface

Pv-Fluid vapor pressure

T - Temperature

Q - Torque

Ft – Thrust

N – Rotation rate Rev/s

6 Introduction to Hydrokinetic Turbine Energy Extraction

Hydrokinetic Turbines refer to a class of energy extraction machines, which extract kinetic energy from a free flowing fluid stream. This is as opposed to hydraulic turbine systems which extract energy from the differential head in a water system (i.e. an impoundment dam). Though the use of impoundment dams is an efficient way to capture energy from flowing water sources, the blockage of the water flow systems due to the dam is often an environmental issue for species which would normally migrate through the waterway.

Commercial scale hydrokinetic energy extraction would utilize a field of turbines placed in the higher flow speed areas of the waterway, much like a wind farm below the waters surface. Turbine fields can be configured to allow for the migration of species as well as navigation of vessel over them. Though the turbines, in this configuration, would no longer be a direct impediment to species migration, the presence of the turbines may have a negative impact on species migration through blade impact mortality, noise and other environmental factors, and such potential impact needs study for the particular situation in which the turbine field is placed.

To determine the energy potential of a particular site, typically a transect of the velocities across the stream of a desirable site needs to be obtained or predicted. For example the Electrical Power Research Institute (EPRI) published reports on the assessment of hydrokinetic energy potential at tidal energy sites (Hagerman 2006). The instantaneous kinetic energy flux (i.e. power) flowing through a particular site can be computed using the following relationship:

$$\dot{W} = \oiint_A \frac{1}{2}\rho q^2(\vec{V}\bullet\hat{n})dA$$

Where ρ is the fluid density, q is the magnitude of the velocity vector V and the integration is performed over the cross section of the site of interest.

If the flow is uniform and turbulence free and perpendicular to the to the area cross section then this integral reduces to:

$$\dot{W} = \frac{1}{2}\rho V^3 A$$

Where V is the average stream velocity and A is the area of the cross section.
For a hydrokinetic turbine typically the projected area of the device perpendicular to the flow stream as it sweep though one cycle of motion is considered the reference area for the turbine. The turbine is thought of as acting on a particular area of the flow stream.
Form this turbine area one can estimate how efficiently the device extracts energy by comparing the energy flux through through the turbine projected area without the turbine in place and compare that to the actual energy extracted. This gives a measure of the efficiency of the device and this factor is called the Power Coefficient (CP) of the device.
The power coefficient is thus defined as :

$$CP = \frac{\dot{W}_{actual}}{\frac{1}{2}\rho V^3 A_f}$$

The power coefficient is the typical non-dimensional measurement of performance associated with the efficiency of the turbine to convert the hydrokinetic energy of the fluid into usable energy.

One should recognize that if the flow were completely stopped (ie. all kinetic energy removed) then there is no flow through the turbine and thus the energy extraction would be zero. This indicates that maximum energy extraction will occur with some kinetic energy left in the flow. This gives a theoretical maximum to the power coefficient known as the Betz limit which is CPbetz=0.593 (Betz 1966). For devices with ducts, sometimes called a flow augmenter, the power coefficient for the turbine based on turbine diameter can appear to exceed the Betz limit. However, if the total device area is used, including the duct, rather than the turbine swept area, the Betz limit idea is preserved.

For many classes of devices a fundamental frequency of the turbine is part of it's design morphology. For example, most turbines spin about and axis at a particular rotation rate. A flapping foil devices flaps at a particular rate. Therefore it is common to use a non-dimensional parameter related to this frequency in classifying the performance. For a rotating turbine this quantity is typically the tip speed ratio, defined as:

$$\lambda = \frac{\omega R}{V}$$

Where ω is the rotation rate of the turbine in rad/sec, R is the maximum radius of the turbine blade and V is the free stream velocity (without turbine present). If the turbine is not a traditional rotating machine the numerator can be replaces with the maximum velocity of the hydrodynamic portion of the machine (maximum blade velocity for example).

7 Classes of Hydrokinetic Turbines

Given that a wide variety of proposed hydrokinetic turbine designs are actively being developed my companies, organizations and entrepreneurs worldwide, a classification system for categorizing the machine types is proposed. The basic parameters for classification include:

1. Rotating vs. Flapping vs. Translating
2. Flow direction relative to rotating axis (crossflow vs. parallel flow)
3. Free blade vs. ducted or enclosed frame
4. Lifting surface vs. drag surface driven
5. Submerged vs. surface piercing of turbine working surfaces

Additional classifications can be applied to:

1. Method of flow reversal (tidal turbines)
2. Method of mooring.
3. Shaft power conversion methods (Electrical, hydraulic etc)

For the purposes of this document, which focuses on laboratory scale model testing of hydrokinetic turbines, the flow reversal method and mooring system classification will not be utilized, though such systems should be included in the testing of such devices if these systems have a significant impact on the performance of the turbine.

8 Overview of Turbine design and analysis theory

8.1 Actuator disk Theory

The most basic theory as applied to turbines and propellers is that of actuator disk theory which idealizes the turbomachine as a thin disc, which provides a uniform pressure jump (or drop for turbines) across the disk in a free stream. There is no swirl included in the theory and inflow is uniform. This theory provides the basic framework for the derivation of the Betz limit, which is the theoretical maximum power extraction that a turbine device can achieve based on its swept frontal area which is Cp=0.593.

A good description of actuator disk theory can be found in Kerwin 2007. The derivation by Betz can be found in Betz 1966.

8.2 Blade element theory and Momentum theory and Multiple Stream Tube Methods

Blade element theory (BET) utilizes two dimensional computational or experimental results of the lift and drag on 2D wing sections to predict the performance of each section of the wing along the blade in a stripwise fashion. Since the overall action of the turbine slows the free stream flow, a correction to the freestream due to the action of the turbine is necessary to correct the inflow and get the proper fluid angle of attach for the wing. This turbine “induced” velocity is typically estimated from a momentum analysis like actuator disc theory or some momentum based theory.

This method of blade design is common for axial flow turbines such as wind turbines and other lightly loaded turbomachines. This method generally lacks treatment of the blades wakes which can influence the velocities on other blades when blade loading is high.

The National Renewable Energy Laboratory (NREL) implement these techniques in many of their wind turbine design codes.

BET coupled with a multistream tube momentum theory originally developed by Strickland (Strickland1975) discretizes the flow domain into stream tubes for which the momentum is balanced between blade forces and fluid momentum in each stream tube.

These techniques were successfully applied to the design of efficient Darrius rotors of low solidity.

In the momentum techniques the momentum correction to predict the propeller induced flow effects are treated is a control volume sense which lose the details of the complex wake formed from the passing blades. In cases of high solidity and/or high blades loading these complex flow wakes are very localized and complex and the smearing of the stream tube type analysis begins to breakdown in accurately predicting blade forces.

8.3 Vortex lattice Theory

The most basic form of vortex lattice theory is that of lifting line theory, which models an axial flow blade set as a set of lifting vortex lines. Though this idealization loses the local blade geometric effects it can accurately model the blade wakes and their interaction with the flow. By combining this discrete blade wake modeling calculation with the blade element theory an accurate calculation of the blade forces can be achieved. Propeller design codes such as MIT’s PLL (Propeller Lifting Line) or OpenProp utilize this technique to successfully design propellers and in the case of OpenProp, axial flow turbines as well.

The key parameter relating the vortex lattice strength to the propeller forces is the circulation strength of the blade vortex system. The lifting line techniques can quickly optimize the blade force distribution to maximize power extraction in the case of a turbine. The blade vorticity is convected into the wake where is follows the local flow. The induced velocities due to all the blade and wake vortices is then computed on the blade to determine the blade flow angles whereby the blade section can be designed using BET techniques. Figure 7 shows the velocity diagram and circulation applied to a single blade radius in the determination of the blade forces. The propeller induced velocities ua* and ut* are computed from the influence of the entire vortex wake system.

Futher details on these methods can be found in Kerwin 2007 and Epps 2009.

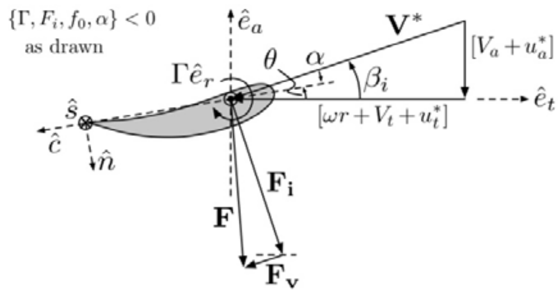


Figure 7: Velocity and force diagram for a lifting line representation of a turbine blade section (Epps2009)

For the case of crossflow turbines, the situation is much more complicated as the blades are changing load as they move and the blade angles are high enough that the blades are in a state of dynamic stall. Vortex wake methods were originally applied to low solidity crossflow turbines successfully by Strickland (Strickland1975), but as blade solidity is increased and dynamic stall is prevalent the accuracy of a lifting line blade is limited. The current state of the art in crossflow turbine modeling is working to model the effect of dynamic stall into the unsteady wake vortex model.

8.4 RANS Analysis

Reynolds Averaged Navier Stokes numerical codes are a common computational fluid dynamic (CFD) technique employed by engineers today. The fluid domain is disctretized and the Navier Stokes equations are solved for each element. Corrections to the element flows and momentum are provided through a averaging the flow and momentum inside the element and applying corrections to these terms due to the fluid turbulence in the form of turbulence models. Therefore the art of getting accurate results from RANS lie in the ability to discretize the fluid domain intelligently and choose an accurate turbulence model for the flow at hand. This type of code is limited to analysis as it solves for the flow around a known geometry. Since it discretizes the flow, the computational time for a solution can be quite long, so care must be taken in the number of cases analyzed. The RANS technique can give some very detailed information about the nature of complex flows that is difficult using the previously described techniques. The technique also by nature can convect a complex flow accurately. Much of the current development in advanced propeller and turbine design is combining the advantages of RANS with the advantages of Boundary element techniques such as the vortex lattice method described previously.

For the case of crossflow turbines, RANS codes are being used to characterize the force on a 2D wing in periodic dynamic stall. This information can be used to develop an accurate BET data set to feed into a vortex lattice model of the turbine and wake, resulting in a computationally efficient turbine design and analysis tool. In this case the RANS code becomes a numerical wind tunnel providing the “empirical” blade data for the Vortex lattice model.

Of course, RANS analysis can and has been used to analyze the performance of turbine at a particular operating conditions. These calculations require great care by the user and the run time can be significant. Many times such detailed analysis is used in the final stage of design verification to check for undesirable flow patterns or blade stresses. The techniques described earlier are often used in the preliminary design and optimization stages of the turbine design.

8.5 Relevance of Turbine Design theory to the testing of model hydrokinetic turbines

An understanding of the design tools and theories used to create and optimize a turbine design is important for the experimenter to understand in regards to the usefulness of the data collected in improving the design. Accurate measurement of the basic performance parameters such as free stream speed, rotation speed and rotor torque is essential information to the designer.

In addition, certain details of the rotor flow and performance can give the designer invaluable insight into accuracy of the design codes. For example, if a position encoder is installed on the rotor then the instantaneous torque can be phase averaged, giving valuable data on the instantaneous forces on the rotor.

9 Testing of Laboratory Scale Hydrokinetic Turbines

9.1 Non-Dimensional Performance Characterization for Hydrokinetic Turbines:

A primary measure of the performance of a hydrokinetic turbine is the turbines power output as a function of its rotation speed and the speed of the free stream. For such purpose it is useful to utilize dimensional analysis to reduce the number of variables necessary to characterize performance. Dimensional analysis also allows the testing of smaller scale prototypes, such as the laboratory scale turbines covered in this document, providing a means to accurately predict the performance of a larger scale machine. The use of dimensional analysis is standard practice in most fields of study which characterize turbomachines. For example, scale model testing of marine propellers is well established and the test procedures are thoroughly documented by ITTC. Hydrokinetic turbines are similar in design and performance to marine propulsion, expecting that hydrokinetic turbines are designed to absorb power from the fluid rather than transmit power into the fluid. Another example of a related field which routinely employ scale models and dimensional analysis is in the area of wind turbine development. In this case the machines are very similar to hydrokinetic machines excepting that they operate in air rather than water (i.e. wind turbines can be considered as aerokinetic turbines). Since hydrokinetic devices fall somewhere amidst marine propellers which operate in a marine environment, and wind turbines which produce power from an air stream rather than water stream, it is rather obvious that similar dimensional analysis techniques be applied to hydrokinetic turbines.

In order to establish the dimensional analysis framework as applied to hydrokinetic turbines a set of relevant non-dimensional numbers needs to be developed. By commonizing the non-dimensional number sets from the wind turbine industry and the marine propeller industry a sufficient set of non-dimensional numbers can be proposed which apply to hydrokinetic turbines and preserve the historical usage of the numbers from their respective parent fields. From this basis the following set of non-dimensional numbers are proposed as a basic set of performance variables used to describe the key performance parameters of hydrokinetic turbines:

Proposed Basic non- dimensionalizing parameters for rotating turbines:

Basic Fluid Properties:

Density: ρ
Vapor pressure (temp. dependant): Pv
Temperature: T
Ambient hydrostatic pressure: Po

Basic Kinematic Properties

Free Stream Speed(Mean) : U
Turbine rotational speed N Rev/s or ω rad/s

Turbine Geometric Properties:

Turbine diameter: D or radius: R
Turbine frontal swept area: A_f
Blade number: Z
Blade planform area A_p
Blade span: s
Blade chordlength: c
Proposed Non-dimensional number set related to the performance of hydrokinetic machines

Tip Speed Ratio: $\lambda = \frac{\omega R}{V}$

Power Coefficient: $CP = \frac{\dot{W}_{actual}}{\frac{1}{2}\rho V^3 A_{turb}}$

Thrust coefficient $Ct = \frac{Ft}{\frac{1}{2}\rho Vo^2 A_f}$

Torque Coefficient $Kq = \frac{Q}{\rho N^2 D^5}$

Reynolds number: (Blade): $\mathrm{Re} = \frac{q_{in} c}{\nu}$

Blade Solidity : $S = \frac{Z A_p}{A_f}$

Cavitation number: $\sigma = \frac{Po - Pv}{\frac{1}{2}\rho Vo^2}$

In some cases, ambiguity arises in the use of certain symbols utilized in specific related fields. In cases such as this the symbol is chosen such that the symbol proposed symbol set is unambiguous. Blade number, for example often uses the symbol N in the wind turbine field, but N is also a common symbol for rotation speed. Therefore, the symbol Z, which is used n the marine propulsion field was chosen to avoid ambiguity with symbols for rotation speed.

9.2 Performance Metrics for Hydrokinetic Turbines

The basic metric for the determination of performance of a hydrokinetic turbine is the power coefficient curve. This curve plots the measured power coefficient for the machine against the tip speed ratio and serves document the measured power extraction capability of the machine. Figure 8 shows the non-dimensional power curve for a typical axial flow rotor as a function of tip speed ratio, indicating that maximum power conversion occurs at a tip speed ratio of about 5.5.

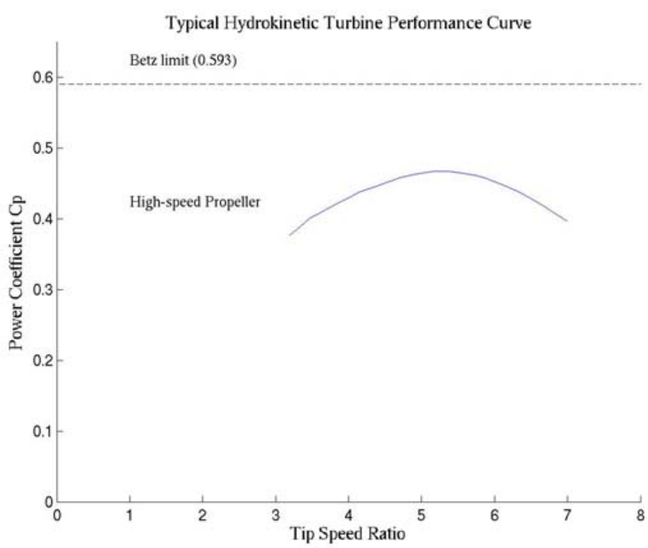


Figure 8: Non-dimensional Power Curve for a typical Axial flow Turbine

The power coefficient curve represents a non-dimensional representation of rotor performance for all scales if the blade Reynolds number is sufficiently high to ensure turbulent flow over the blade surfaces. For blades of typical roughness the viscous friction coefficient for the surface is fairly constant over a wide range of Reynolds numbers. For designs in which blade stall is inherent (as with many Darrius rotors and Savonius style rotors, unless the stall or blade separation point is very sharp and well defined, the performance could have significant Reynolds number dependency. The typical method for testing for this Reynolds number dependency is to test the rotor at a variety of free stream speeds. Figure 9 shows the raw dimensional data for a Darrius rotor test in a tow tank at three test speeds.

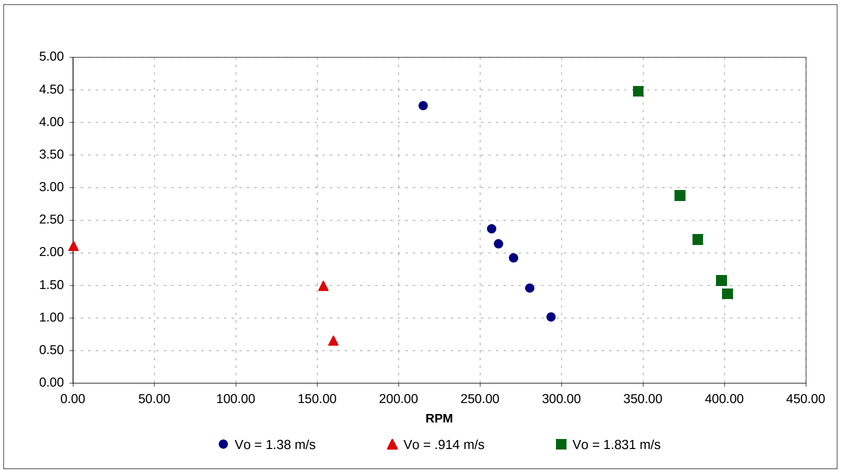


Figure 9: Dimensional performance data of an axial turbine at three test speeds

When all the data is plotted in non-dimensional form as in figure 10, all but the lower speed data collapses to a single line. This indicates that the higher speed data has reached a state of Reynolds number independence .

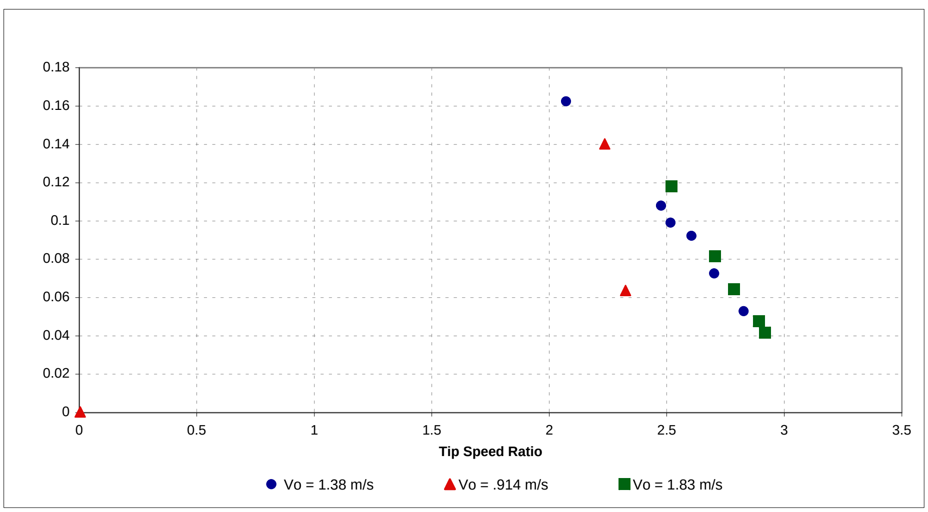


Figure 10: Non-dimensional plot of an axial turbine power curve showing Reynolds number independence of the higher speed data.

The non-dimensional power curve serves not only as a useful representation of the basic performance of the machine. If the data curves for a variety of types of machines is superimposed on this plot, what arises is a performance map which indicates ideal operating ranges for different classes of machines. If enough data exists, then a Pareto frontier can be developed to estimate the limit of power coefficient as a function of tip speed ratio. Figure 11 show a preliminary version of such a map first presented by Kahn et al. To this curve can be added the theoretical limits of predicted performance including the Betz limit and the ideal performance of a single axial flow turbine. From this single plot merges a very useful insight into the design of high performance of hydrokinetic machines. This map also serves as a good way to compare the different technologies in one key area, power extraction capability.

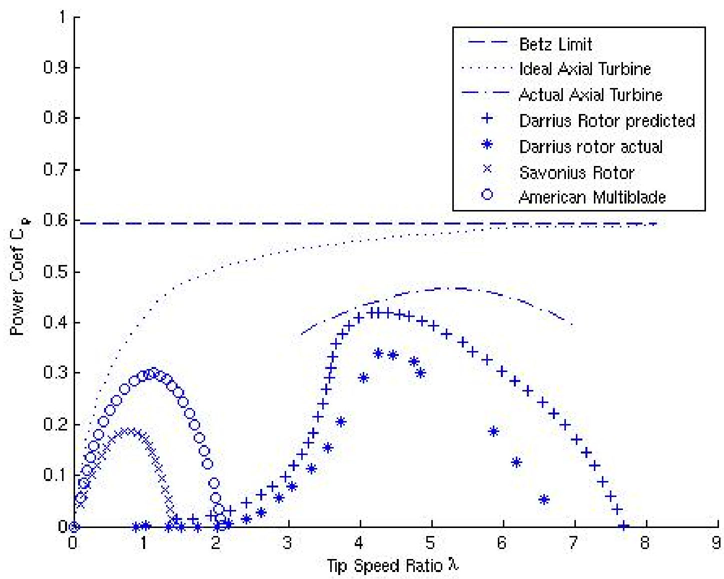


Figure 11: Power curve map showing results of various turbine types and ideal limits From Kahn et al. and Epps et al.

The map of figure 11 shows that both axial flow turbines and crossflow turbines achieve fairly high power coefficients at tip speed ratios of about 4-7. The plot also shows that Savonius style rotors reach maximum power coefficient at tip speed ratios of less than one.

The high blade solidity American wind turbine rotor reaches decent performance at low tip speed ratio (about 1.2).

9.3 Testing in Tow Tanks

For testing laboratory scale hydrokinetic turbine models, tow tanks are often utilized. Instrumentation, calibration and design guidelines for the proper operation and setup of tow tanks can be found in the ITTC standards cited prior. Specifically, for a proper test of a hydrokinetic turbine the tow tank must possess the following basic capabilities:

- Accurate carriage speed control
- Accurate measurement of the rotor rotation rate
- Accurate measurement of the rotor torque or shaft power
- A means of controlling the shaft load (through a brake or generator for example)

Carriage speed control is a typical feature of all tow tanks and the addition of a rotary speed measurement device to the turbine is usually straight forward. Shaft torque and power is usually the most difficult instrument to install and calibrate. Rotary shaft torques sensors offer direct measurement of torque but requires complicated slip rings or telemetry equipment. It is most common to mount the power absorbing dynamometer on gimbals and measure the reaction torque of the entire turbine/dyno/generator unit.

Figure 12 shows tow tank hydrokinetic test devices for both axial flow and crossflow turbines. In both cases, the turbine power is transmitted to a shaft above the waterline through a chain drive and the secondary shaft contains a gimbaled generator, which absorbs the power generated by the turbine. A load cell is place in a motor arm bracket between the motor gimbal and the carriage frame, which measure the shaft torque on the secondary shafts. These systems are run without a rotor attached to get a calibration tier of the torque due to the residual bearing and chain losses in the system. This tare torque is then added to the measured torque to properly credit the rotor with overcoming the residual losses in the test system.

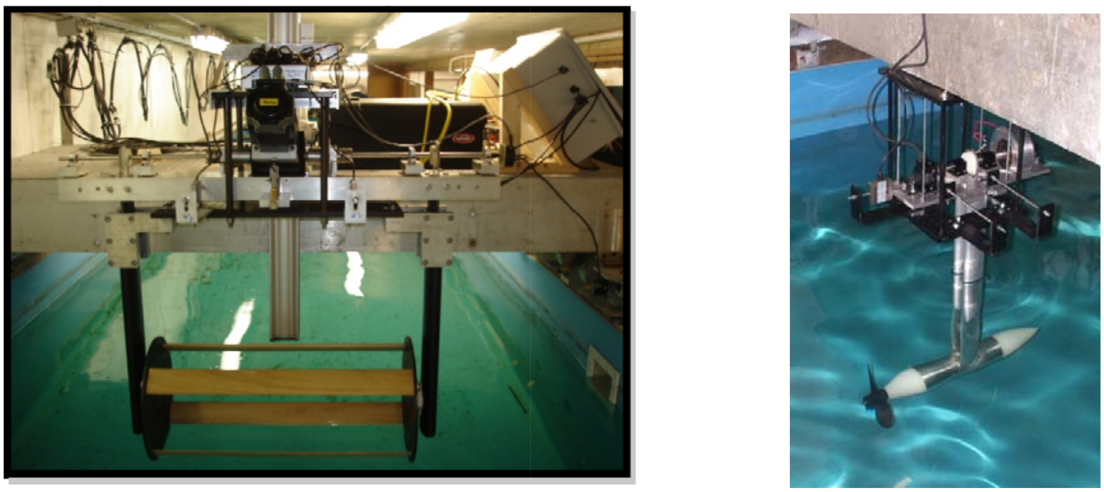


Figure 12: Test platforms for testing Crossflow and Axial flow hydrokinetic turbines in a tow tank.

For modern tow tanks it is recommended that a high speed data acquisition system be utilized to collect the carriage speed, rotor speed and torque data. One major issue with forces and torques measured in a tow tank is that the data is notoriously noisy due to the vibrations of the carriage as the device is being tested. Figure 13 shows a typical raw dataset of both carriage speed and shaft torque during a run. The torque data is very noisy and requires the average torque to be properly filtered from the run. Typically the data rate for such test is recommended at 1 kHz or higher. One should take care to examine the raw data for data clipping, which can happen if the vibration forces exceed the limit for the data acquisition range limit. In this case the recorded signal will not exceed the range which will result in a false average which is lower than it should be.

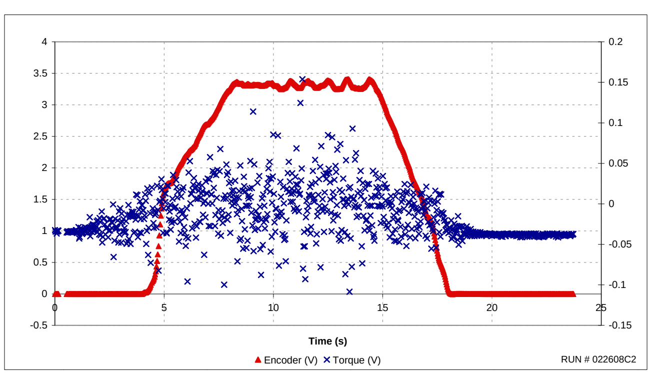


Figure 13: Typical Raw tow tank data showing carriage speed sensor (red) and rotor torque (blue). The torque data falling in the steady speed range is averaged to get the mean torque with the rotor at speed.

For devices which do not self start at the test speed and additional problem with the power absorption system arises. A four quadrant generator control system can be incorporated to effectively test such devices. This system consists of a stepper motor with controller and a power resistor. The controller is commanded to maintain rotor RPM for the run. As the device gains speed on the carriage, the device may start producing power, whereby the controller will dump the generated power to the power resistor. This type of test control scheme results in very high quality and high fidelity data as it can handle the rotor running in both power absorbing and power producing mode.

Rotor sizing and free surface effects;

The size of the test rotor relative to the size of the tow tank cross section is an important parameter when designing a test setup. Since most hydrokinetic devices will be placed in bounded channel flows, it is best if one can achieve geometric similitude with the field scale situation. In practice however, this will rarely be achieved. The ITTC guidelines offer good guidelines on the size of models relative to the width and depth of the tow tank but these do not directly apply to the testing of hydrokinetic turbines and is an area for which a standard needs to be developed. For tests currently being conducted in tow tanks, turbine models are being testing up to about 1/3 of the tank depth in vertical scale and up to 1/3 of the tank width for the horizontal scale. For example the Darrius rotor test rig shown in figure 12 has dimensions of 30 inches wide by 14 inches in diameter and is being tested in a tow tank 96 inches wide by 46 inches deep, giving a frontal swept area of about 10% of the cross sectional area of the tow tank. The rotor is tested with the centerline at mid-depth, giving it about 1 rotor diameter of distance to both the bottom and the free surface.

9.4 Testing in Water Tunnels and Water Flumes

Testing in tunnels and flumes has one main advantage in the testing of hydrokinetic devices, given that the flow speed is continuous for long duration. The basic data set required for the generation is performance curves is the same as that for tow tank models, excepting that carriage speed would be replaced with tunnel mean free stream speed. The requirements for accurate measurement of rotation rate and torque or power absorbed are the same and the same recommendations apply for data acquisition and control as were discussed previously.

Figure 14 shows the schematic of the water tunnel housed at the Massachusetts Institute of Technology showing the layout of a typical water tunnel. It has a test section of 0.5m by 0.5m in cross section and is about 1.2m long. The tunnel can achieve test speed of 10 m/s. Upstream of the test section a series of flow straighteners and screens are installed to eliminate swirl and reduce turbulence in the test section. A drive pump in the bottom of the tunnel is used to generate the flow speed. A controlled vacuum can be drawn on the tunnel which is useful in the determination of cavitation inception and cavitation breakdown for the test turbine.

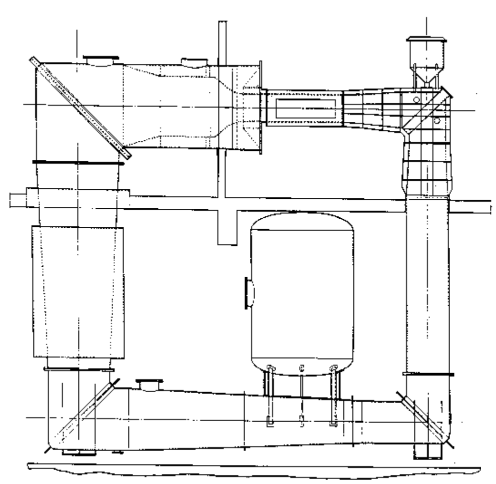


Figure 14: Schematic of MIT's Water Tunnel

Regarding the general design of water tunnels a good reference standard for the design of nozzles, test section and flow screens is given by The Air Movement and Control Association (AMCA) publication 210-07. This document is intended for the testing of air moving fans but applies equally well to water tunnels and the testing of hydrokinetic turbines.

Since a tunnel or flume generates the free stream flow through its piping system and the model is held fixed in a test section, the turbulence generated by the tunnel system is of concern. Generally a tunnel free stream turbulence intensity of about 2% of free stream velocity is considered a turbulence level acceptable for the testing of propellers and should suffice for the testing of hydrokinetic devices. Also the flow uniformity in the turbine test area should be measured and held to 1% of the freestream. The parameters of free stream non-uniformity and turbulence intensity are typically characterized for a test tunnel and should be included with the reporting of performance test data of a hydrokinetic turbine model.

The size of typical water tunnel model frontal swept area runs about 1/4 to 1/5 of the tunnel cross sectional area. For example, in the MIT water tunnel a propeller of 0.25 to 0.3m are routinely tested with good results. ITTC gives some guidelines for tunnel wall corrections which should be applied the performance data, but these corrections are typically on the order of 1-2% of the measurement. These corrections are derived using the method of images and give a first order correction for the performance of the device in an infinite fluid when tested in a confined channel.

Cavitation measurements:

The use of a closed water tunnel with vacuum control allows one to conduct tests on the cavitation performance of the turbine. This is done by running the turbine at the desired operating point and placing a strobe light in the tunnel window to “freeze” the motion of the blades. then the pressure in the tunnel is slowly lowered until cavitation is observed on the blades of the turbine and this ambient pressure is recorded. This cavitation inception point can be non-dimensionalized using the cavitation number. To get the cavtation breakdown point for a propeller the pressure is lowered further until the thrust of the propeller drops by more than 2 %. For a hydrokinetic turbine, it is recommended that the definition for cavitation breakdown be modified to be a reduction in the power coefficient by more that 2% at a given tip speed ratio. In addition to the measurement of cavitation pressure points, photographs of the cavitation pattern are typically taken at various cavitation levels. It should be noted that nucleation seeding is required for accurate representation of cavitation is a seaway. Artificial seed particles may need to be added to the tunnel if the water is highly filtered.

Additional testing suited to water tunnels and flumes:

Since the flow speed can be held constant for long durations, water tunnels and flumes lend themselves well to flow survey measurements including pitot tube surveys, laser Doppler velocimetry surveys (LDV) and Particle imaging velocimetry measurements. The latter two methods require lasers to penetrate the tunnel water and typical require laser quality windows be in place on the tunnel test section walls. These sophisticated test procedures are beyond the scope of this document excepting that these test procedures require accurate measurement and control of the operating point which utilize the same measurement and control equipment utilized to generate the basic performance data for the hydrokinetic turbine.

10 Conclusions and Recommendations

In conclusion of this document the authors have:

- Presented a comprehensive review of standards developed in related fields which are recommended to be adopted as cross reference material in a hydrokinetic turbine test standard
- Provided a review of the basic design methodologies being used to design Hydrokinetic turbines and how the laboratory scale test data contributes to that design process.
- A proposed system to classify the wide range of hydrokinetic turbines being developed worldwide, based on their hydrodynamic and geometric configuration.
- Proposed a framework for basic non-dimensional parameters needed to describe the hydrodynamic performance of hydrokinetic turbines
- Presented a proposed framework for the basic hydrodynamic performance test format, namely in the form of the non-dimensional power curve plotting power coefficient vs. tip speed ratio.
- Presented proposed guidelines for the testing of hydrokinetic turbine models in tow tanks, water tunnels and water flumes.

It is the hope of the authors that the information in this document will help guide the hydrokinetic turbine community toward a sensible and comprehensive standard that can aid in the development of this fledgling industry.

11 Bibliography

(a) Bedard, R.; *Survey and Characterization tidal In-Stream EnergyConversion (TiSEC) Devices EPRI Report EPRI-TP-004-NA, Electrical Power Research Institute 2005*

(b) Betz, A. (1966) *Introduction to the Theory of Flow Machines.* (D. G. Randall, Trans.) Oxford: Pergamon Press

(c) Khan, M.J. Iqbal, M.T. Quaicoe, J.E."Design considerations of a Straight Bladed Darrieus Rotor for River Current Turbines", 2006 IEEE symposium on Industrial Electronics, July 2006

(d) Epps, B.P, Stanway, M.J. Kimball, R.W.: *OpenProp:An Open-source Design Tool for Propellers and Turbines:* Propellers and Shafting Conference, Society of Naval Architects and Marine Engineers, September 2009

(e) Hagerman, G. Polagye, B , Bedard, R. , Previsic, M.:*Method for estimating Tidal Current Energy Resources and Pwer Production by Tidal In-Stream Energy Conversion (TISEC) Devices:* Report #: EPRI-TP-001 NA Rev.3; Electric Power Research Institute, 2006

(f) Kerwin, J.E.; *Hydrofoils and Propellers;* MIT Course 2.23 notes 2007

(g) Strickland, J.H.; *The Darrius Turbine: A Performance Prediction Model using Multiple Stream Tubes:*Sandia Laboratory Report 75-0431 October 1975

(h) Swift, R. :Assessment of Performance of Tidal Energy Systems; Marine Renewable Energy Guides, European Marine Energy Centre 2009

(i) ITTC Recommended Guidelines and Procedures; International Towing Tank Conference, Refer to Register document 0.0 Revision 3 2005 for complete of documents

(j) IEC Document 61400-12-1 *Wind Turbines, Power performance measurements of electricity producing wind turbines;*International Electrotechnical Commission 2005

(k) Air Movement and Control Association. ANSI/AMCA Standard 210-07 *Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating*, 2007