SAND2013-2565P

Wave Energy Converters:

Designing and Modeling a Successful Device

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UNM Mechanical Engineering Seminar

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Sandia Water Power Overview

Technology Assessment: Reference Model Project

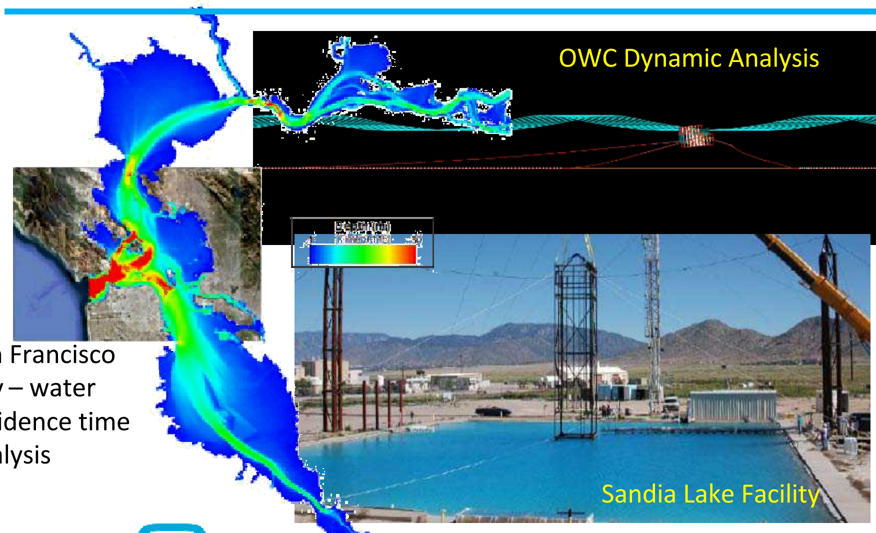
- Goal: obtain baseline Cost Of Energy (COE) estimates for a variety of Marine Hydro-Kinetic (MHK) devices.

Technology Development: Modeling Tools & Advanced Materials

- Modeling Tools: predict power performance of MHK devices
- Advanced Materials: evaluate new corrosion resistant and antifouling material coatings

Market Acceleration: Environmental Impact

- SNL-EFDC: MHK –capable environmental circulation and array performance code
- SNL-SWAN: tool to evaluate environmental effects of WEC arrays

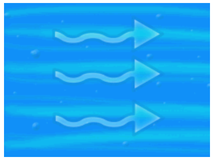


San Francisco Bay – water residence time analysis

Unique Capabilities

- SEAWOLF laboratory/field oscillatory-flow sediment transport testing
- Sandia Lake Facility – potential for large scale wave testing
- Ability to leverage defense spending on fundamental sciences: controls, hydrodynamics, aerodynamics, experimentation, etc.

Marine Hydrokinetic (MHK) Devices

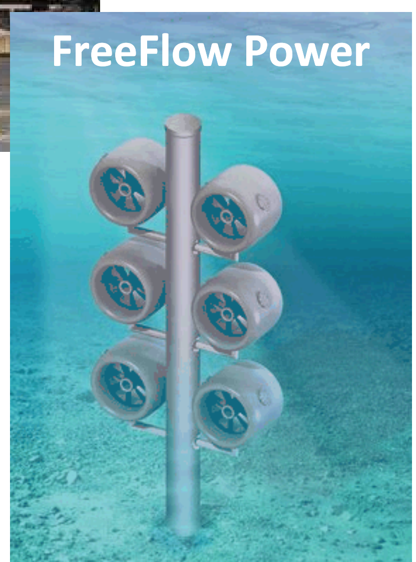


ORPC TidGen

CPT SeaRay

OPT Power Buoy

Verdant



FreeFlow Power

Resolute Marine Energy

Ocean Energy BBDB

Pelamis

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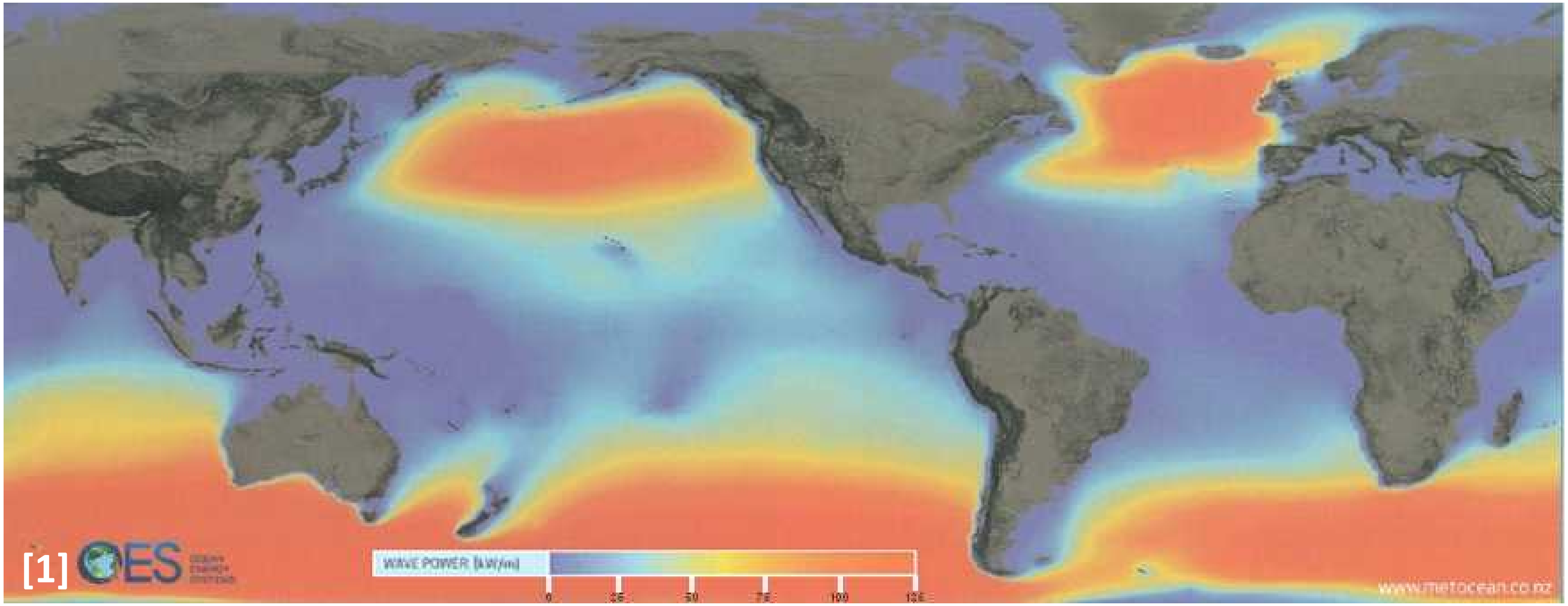
Ocean Wave Resource



Globally [2]

- **3.4 TW (29,400 TWh/yr)**

United States [3]

- **300GW (2,640 TWh/yr)**
  - West Coast (WA, OR, CA): 67 GW (590 TWh/yr)
  - Hawaii: 15 GW (130 TWh/yr)
  - East Coast (NC thru ME): 23 GW (200 TWh/yr)
  - Alaska (Pacific Ocean): 155 GW (1,360 TWh/yr).

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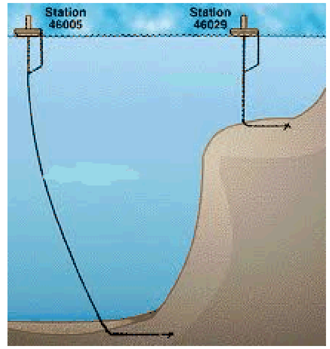
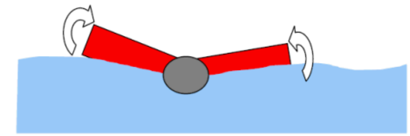
WEC Types [4]

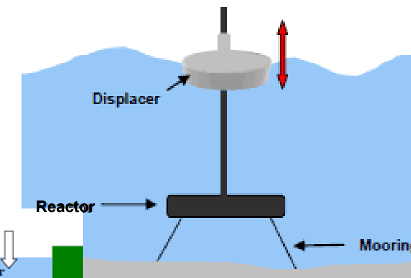
Water Depth

- Shore-Mounted.
- Near-Shore.
- Offshore.



Wave Activated Bodies

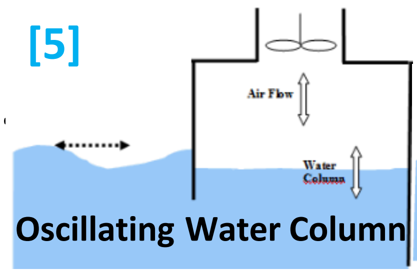


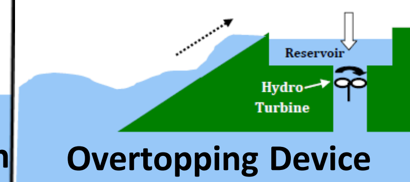


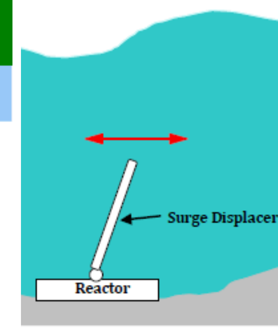
Conversion mechanism

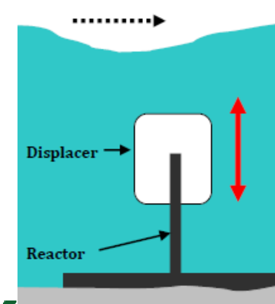
- Oscillating Water Column (OWC).
- Overtopping Device (OTD)
- Wave Activated Body (WAB)

[5]





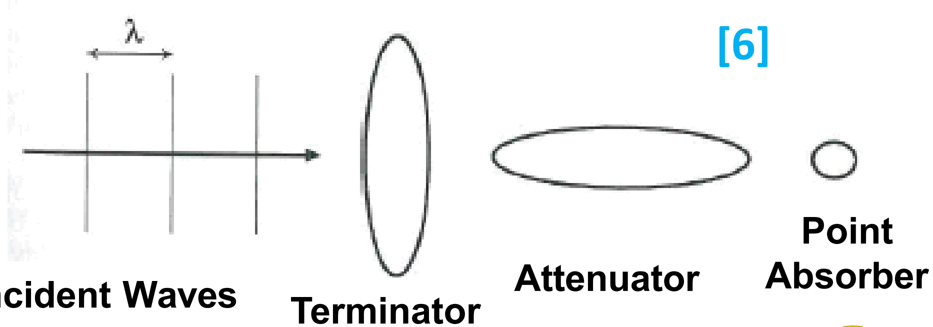




Directional dependence

- Point Absorber
- Terminator
- Attenuator

[6]



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WEC Classification

Placement in the water column

- Surface expression or submerged

Buoyancy

- Neutrally buoyant or ± buoyancy

Mooring & Anchoring Type

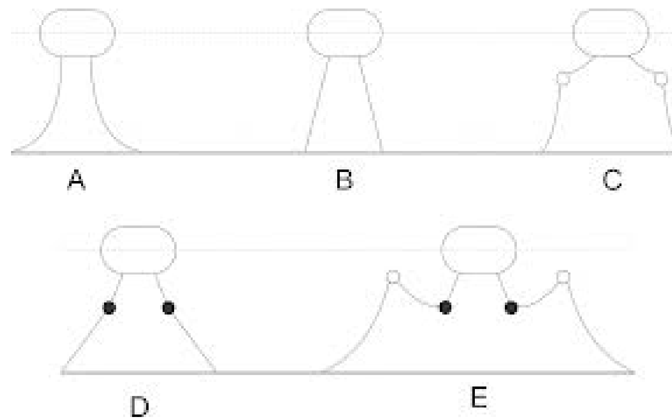
- Number of legs, slack or taut, presence of subsurface floats, anchor type, watch circle radius

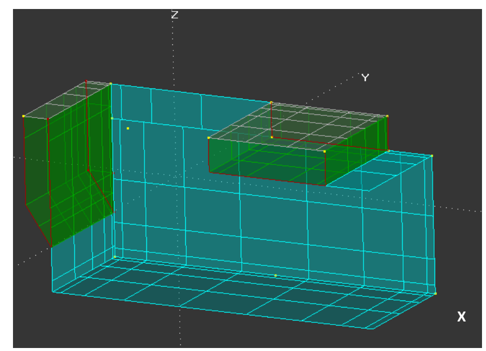
Symmetry

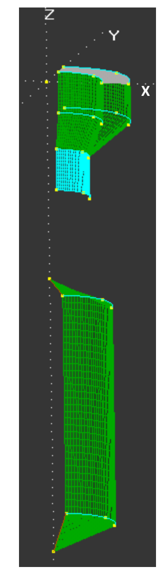
- Identifies directional dependence & manufacturing constraints

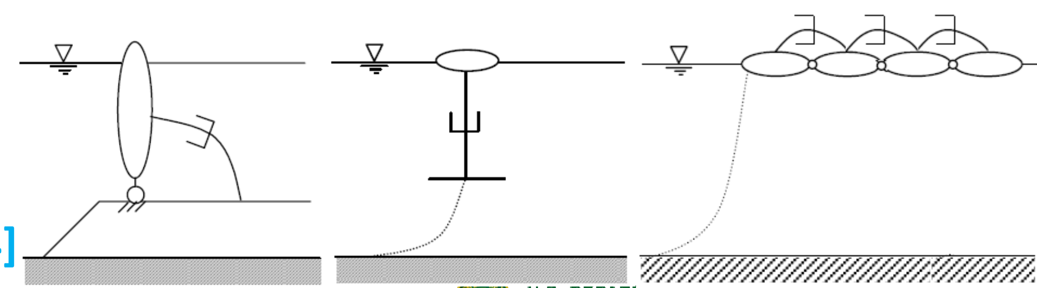
Number of bodies

- Identifies complexity and indicates: PTO reference and deployment depth range









[4]

WEC Classification

Primary oscillation directions

- Identifies primary excitation mode and indicates maximum theoretical energy capture (along with directional dependence)

Drivetrain Type

- Component of power conversion that converts motions of WEC into mechanical power.

Drivetrain reference

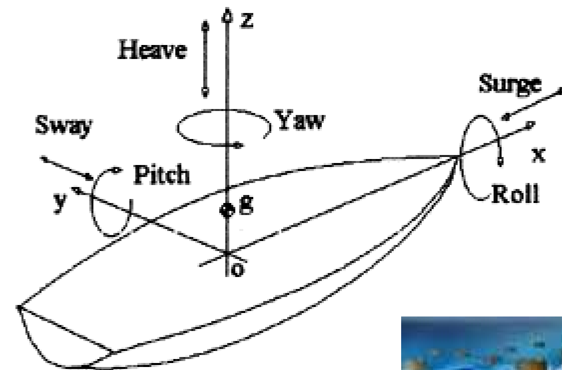
- Identifies reference through which power conversion happens and indicates deployment depth range

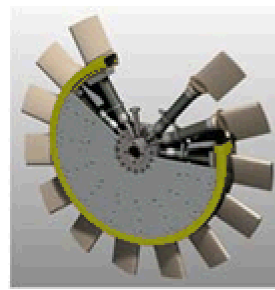
Oscillation constraint

- Identifies maximum extension of the drivetrain components if present

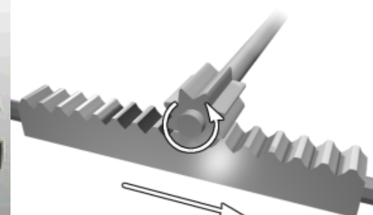
Survival strategy

- Identifies how the device will survive large waves that could potentially damage the drivetrain

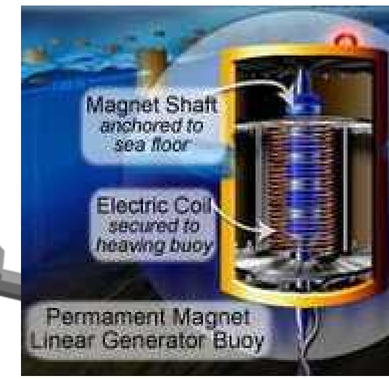




Air Turbine

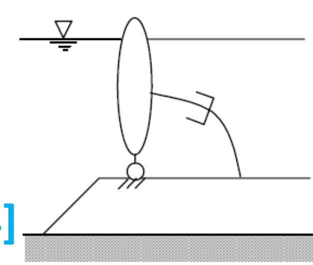


Mechanical: rack & pinion

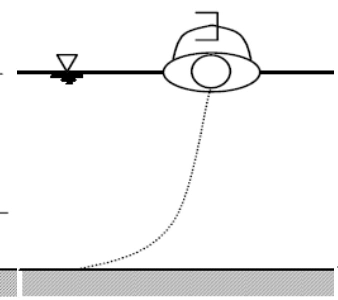


Linear Generator (drivetrain & generator)

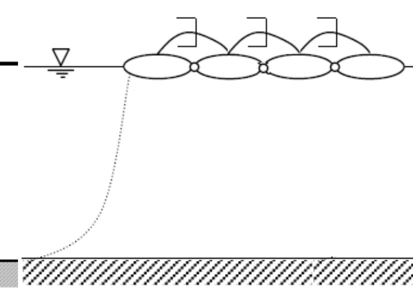
[4]



Ground

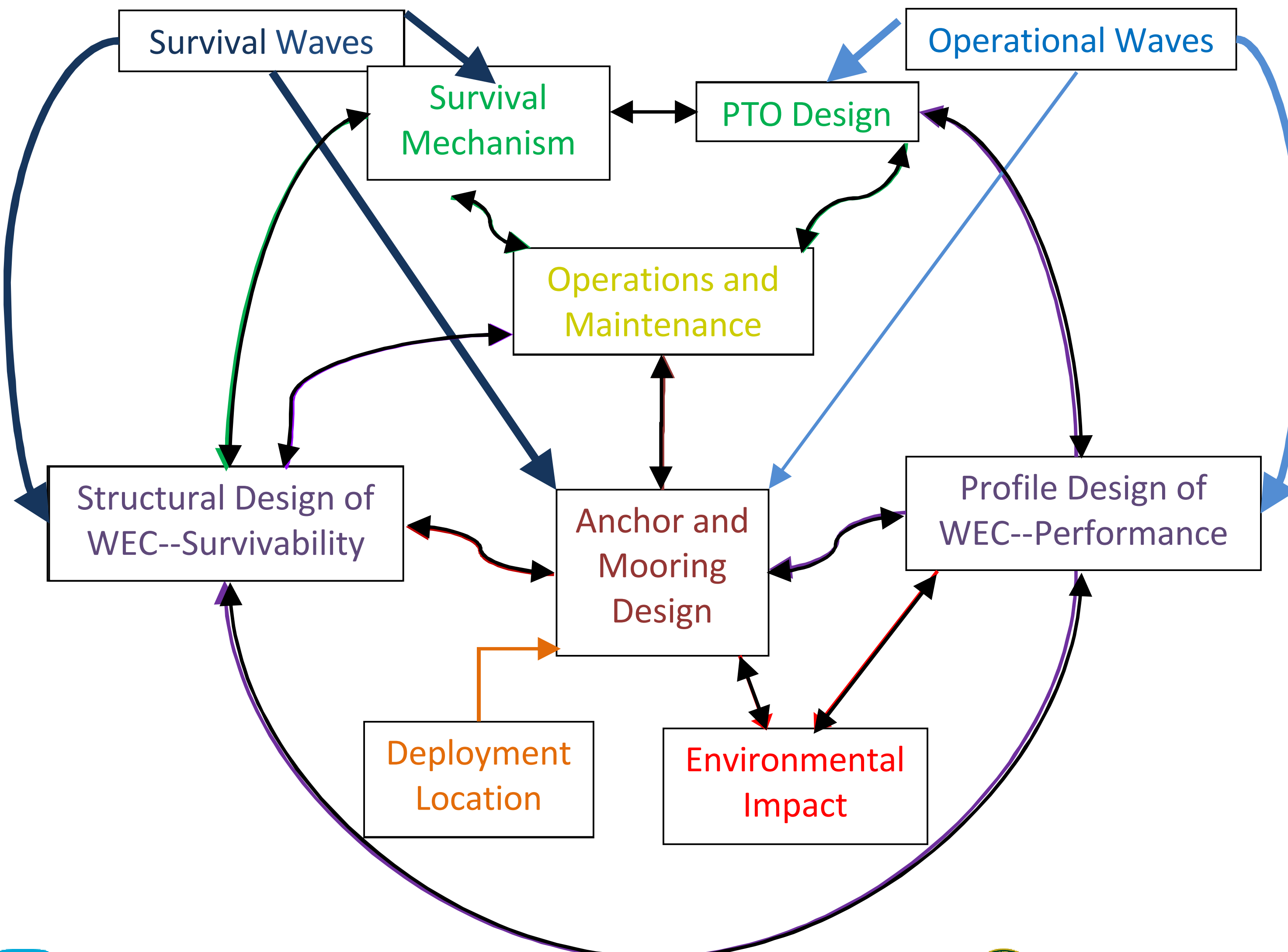


Self – inertia



Self – reacting bodies

WEC Design

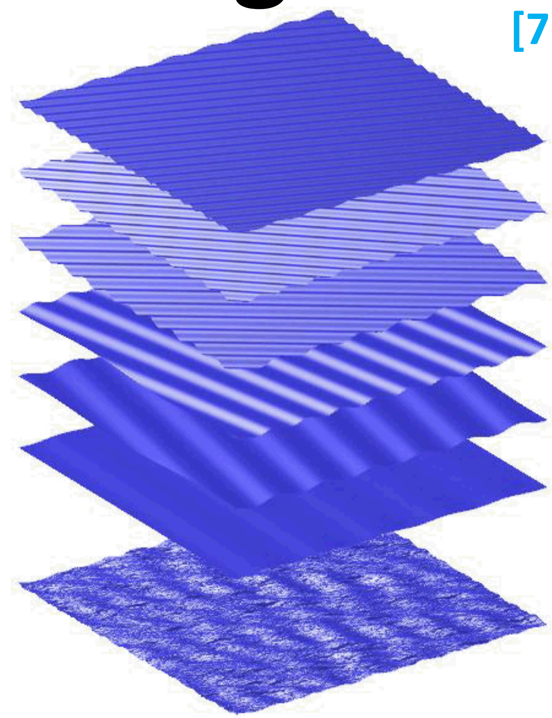

Survival Waves
Operational Waves
Survival Mechanism
PTO Design
Operations and Maintenance
Structural Design of WEC--Survivability
Anchor and Mooring Design
Profile Design of WEC--Performance
Deployment Location
Environmental Impact

Wave Climate Modeling

Modeling Ocean Waves

- **Superposition of harmonic waves**
  - Distinct frequencies, amplitudes, and incident directions.
- **Wave Spectra**
  - Represent distribution of energy content as a function of frequency and direction.
  - Use standard distributions to describe waves in different parts of the world.

[7]



Linear Wave Theory Assumptions

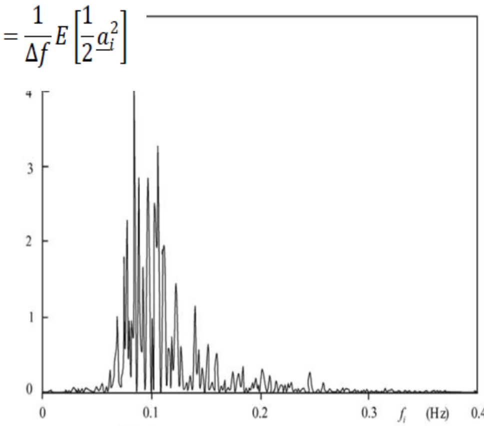
- **Velocity potential formulation**
  - Small amplitude motion, incompressible, inviscid & irrotational flow
- **Satisfies the Laplace Equation**

$$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0$$

  - Meets bottom boundary condition (no flow),
  - dynamic free surface boundary condition (no pressure discontinuity at surface), and
  - kinematic free surface boundary condition (no velocity discontinuity at surface)
- **Dispersion relation**
  - Establishes relationship between wave period and wave length

$$\eta(x,y,t) = \sum_i a_i \cos(k_i(x\cos\theta_i + y\sin\theta_i) - 2\pi f_i t + \phi_i)$$

$$S(f_i) = \frac{1}{\Delta f} E\left[\frac{1}{2} a_i^2\right]$$



Wave Climate Modeling

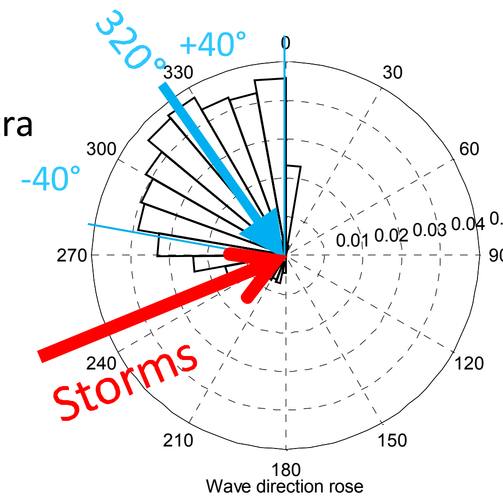
Ocean Climate

- **Temporally, spatially, and energetically diverse.**
  - Deployment climate is described by spectra type, along with significant wave height correlated to energy period and the peak direction.

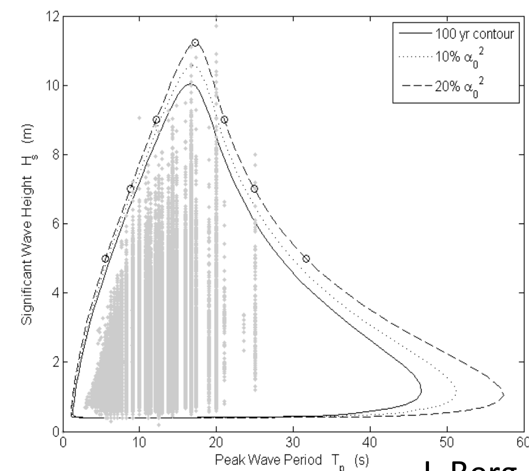
Ocean Wave Measurements

- **Public Sources**
  - National Data Buoy Center (NDBC)
  - Coastal Data Information Program (CDIP)

Directional Wave Rose



Survival Events—
100yr return contour



J. Berg

Joint Probability Distribution of Hs and Tp populated from 15years of measured data.

Significant Wave Height, Hs [m]	Peak Period, Tp [sec]																	
	3.7	**4.7**	**5.7**	**6.7**	**7.7**	**8.7**	**9.7**	**10.7**	**11.7**	**12.7**	**13.7**	**14.7**	**15.7**	**16.7**	**17.7**	**18.7**	**19.7**	**20.7**
0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.75	0.0	0.0	0.002	0.007	0.006	0.010	0.004	0.004	0.0	0.004	0.0	0.007	0.0	0.004	0.0	0.0	0.0	0.0
1.25	0.0	0.002	0.008	0.022	0.015	**0.043**	0.017	0.013	0.003	0.011	0.002	0.012	0.002	0.007	0.0	0.0	0.0	0.0
1.75	0.0	0.0	0.005	0.028	0.017	0.039	0.025	0.023	0.007	0.019	0.002	0.013	0.0	0.005	0.0	0.0	0.0	0.0
2.25	0.0	0.0	0.0	0.014	0.017	0.036	0.020	0.026	0.009	0.025	0.003	0.016	0.0	0.006	0.0	0.0	0.002	0.0
2.75	0.0	0.0	0.0	0.006	0.009	0.036	0.012	0.019	0.008	0.026	0.003	0.018	0.0	0.007	0.0	0.0	0.003	0.0
3.25	0.0	0.0	0.0	0.002	0.004	0.024	0.009	0.012	0.005	0.021	0.003	0.017	0.0	0.006	0.0	0.0	0.002	0.0
3.75	0.0	0.0	0.0	0.0	0.0	0.010	0.007	0.007	0.003	0.014	0.002	0.015	0.0	0.005	0.0	0.0	0.0	0.0
4.25	0.0	0.0	0.0	0.0	0.0	0.004	0.003	0.003	0.002	0.009	0.0	0.012	0.0	0.004	0.0	0.0	0.0	0.0
4.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.002	0.0	0.004	0.0	0.008	0.0	0.004	0.0	0.0	0.0	0.0
5.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.002	0.0	0.005	0.0	0.003	0.0	0.0	0.0	0.0
5.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.002	0.0	0.002	0.0	0.0	0.0	0.0
6.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

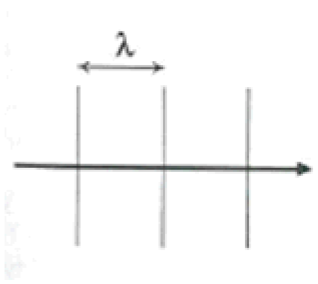
Wave Structure Interaction

Hydrodynamic Forces

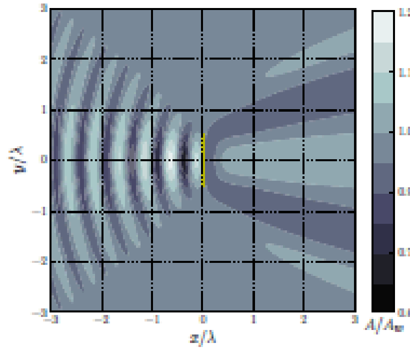
Potential Flow

- **Frequency Domain Response**
  - Superposition of incident, diffracted, and radiated potentials : $\hat{\varphi} = \hat{\varphi}_o + \hat{\varphi}_d + \hat{\varphi}_r$
  - Based on linear wave theory assumptions.

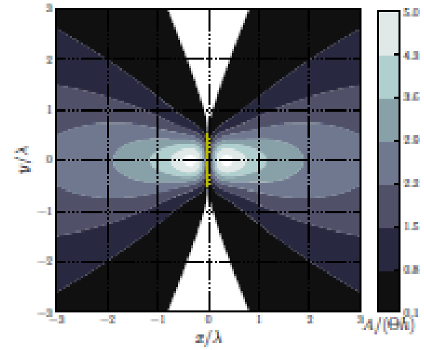
Incident Linear Theory Wave



Diffracted Wave

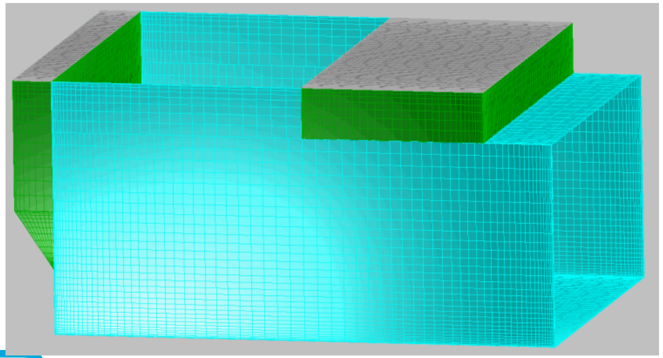


Radiated Wave

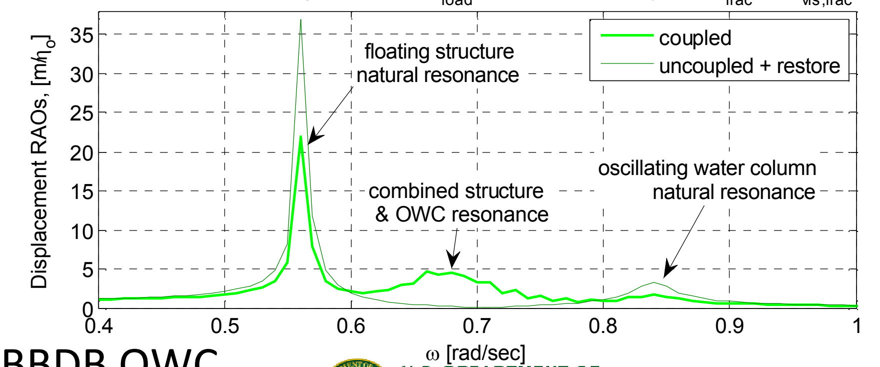


[8]

- **Commercial programs apply potential flow theory using Boundary Element Method (BEM) to obtain the response of a structure to incoming waves**
  - WAMIT, AQWA.



RM6: BBDB OWC



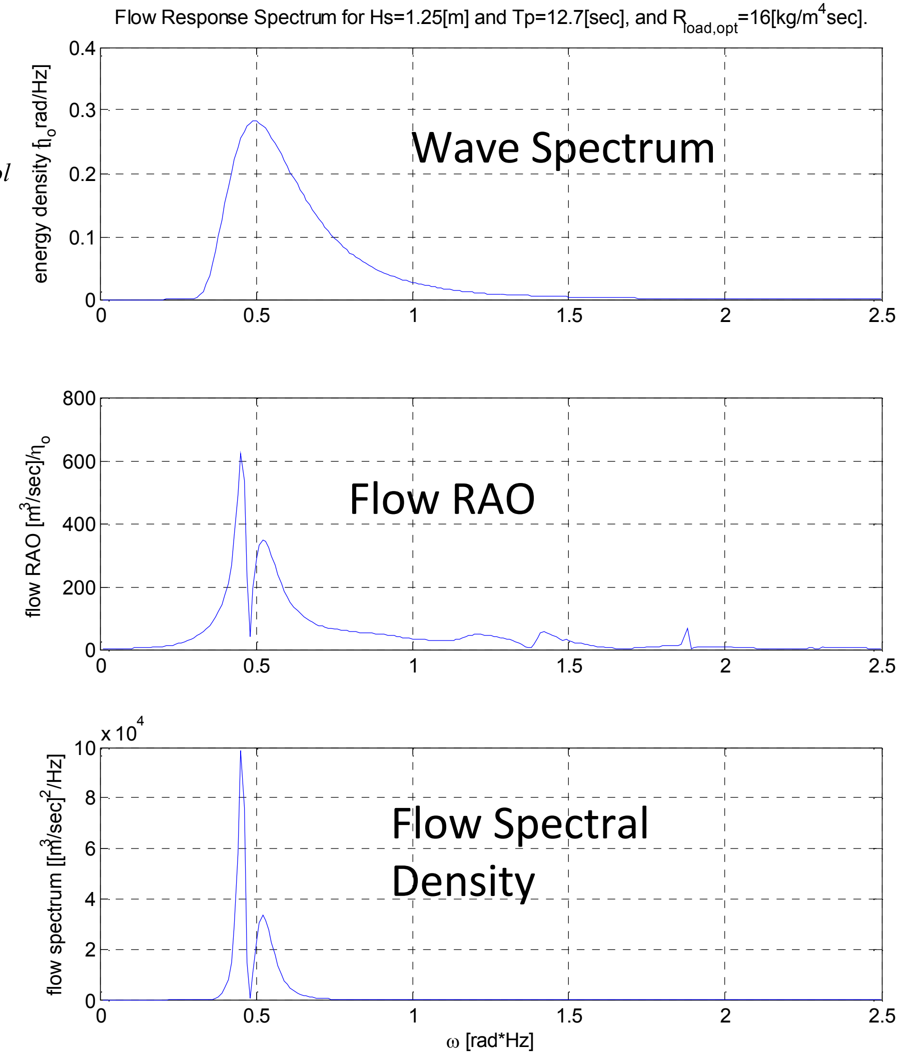
Performance Modeling

Frequency Domain

Equations of motion for a device are derived from governing equation:

$$F_{total} = F_{hydrodynamic} + F_{hydrostatic} + F_{ViscousDamping} + F_{mooring} + F_{Control}$$

- $F_{hydrodynamic}$ **&** $F_{hydrostatic}$ **are found from a potential flow solver, like WAMIT**
- $F_{ViscousDamping}$ **found with aid of CFD, experiment, or targeted RAO response at resonance**
- $F_{Mooring}$ **are found through evaluation of design in OrcaFlex for operational conditions.**
- $F_{Control}$**, the optimal "slow tuning" parameters are found for each sea state**
  - The control parameters are independent of the PTO type at this stage.



RM6: BBDB OWC

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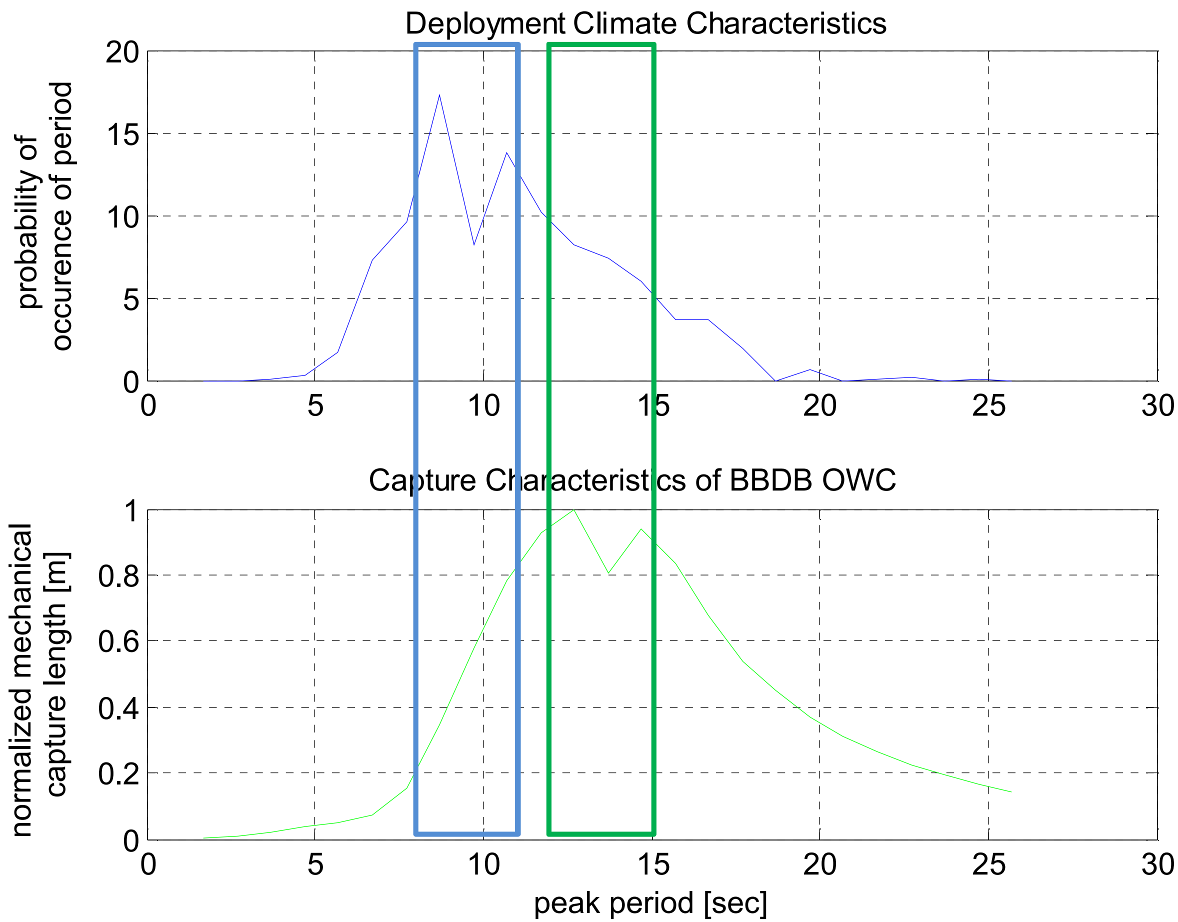
Performance Model Outcome

- The average power for each sea state is found through

$$\langle \mathrm{P} \rangle = R_{control} \int_{0}^{\infty} |u|^2 S(\omega) d\omega$$

- Evaluating a design can be aided by comparing the deployment characteristics to the device capture characteristics.
- Goal is to match the device design to the deployment location.



Most Probable Periods in Climate

Largest Capture Length by Device

Anchor and Mooring Modeling

Mooring Design Driven by Survival Waves

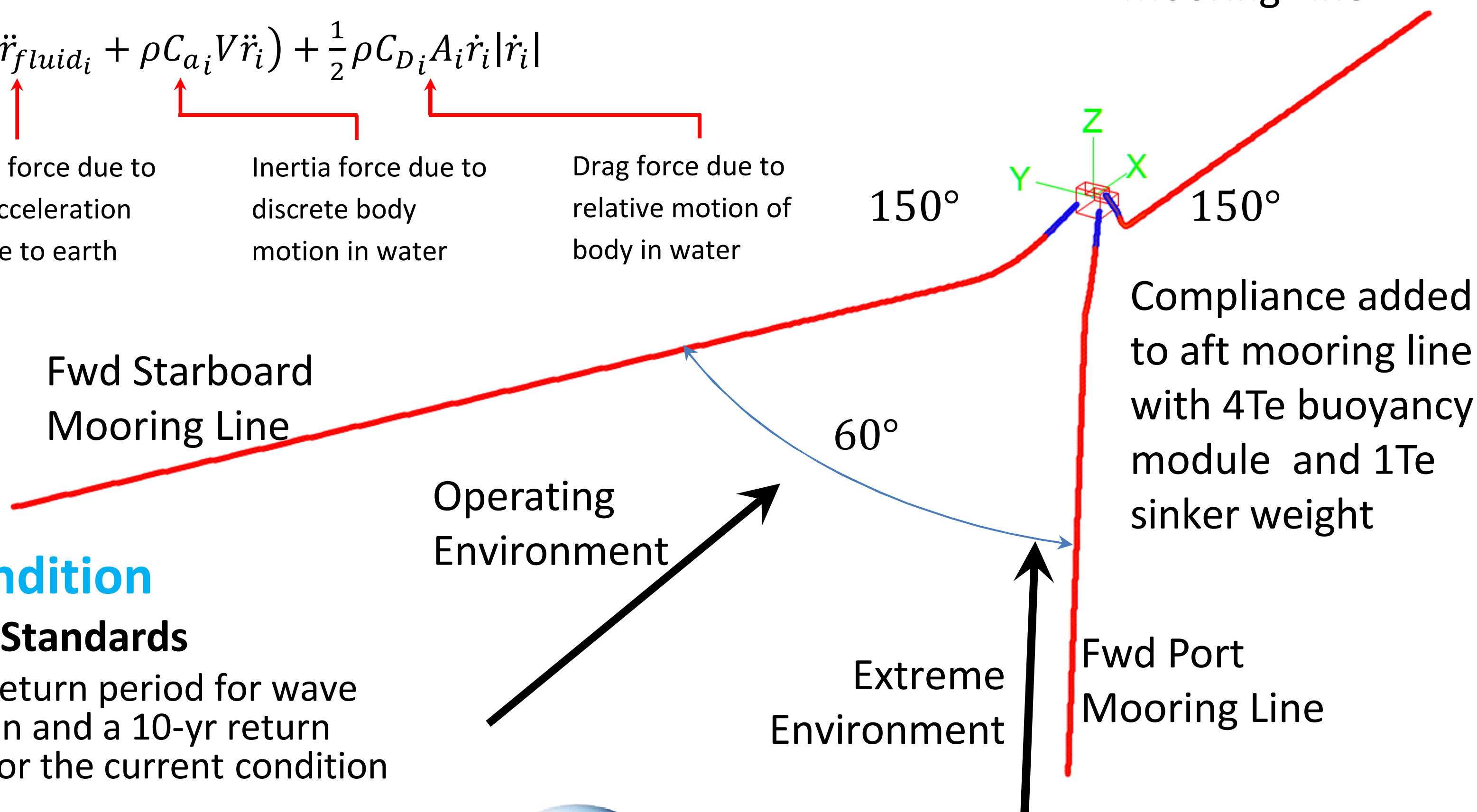
- **Potential Flow is NOT a valid method to predict dynamics**
- **Morison Eq. is a valid approach to predict dynamics**
  - $f_i = f_{inertial_i} + f_{drag_i}$

$$= \left(\rho V \ddot{r}_{fluid_i} + \rho C_{a_i} V \ddot{r}_i\right) + \frac{1}{2}\rho C_{D_i} A_i \dot{r}_i |\dot{r}_i|$$

Inertia force due to fluid acceleration relative to earth

Inertia force due to discrete body motion in water

Drag force due to relative motion of body in water



Survival Condition

- **Apply DNV Standards**
  - 100-yr return period for wave condition and a 10-yr return period for the current condition

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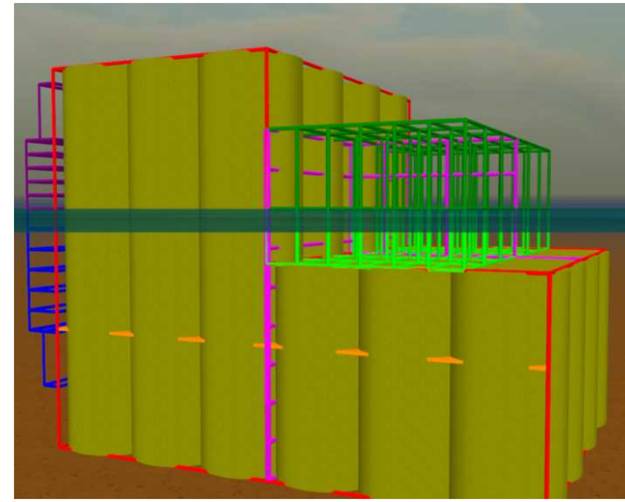
Anchor and Mooring Modeling

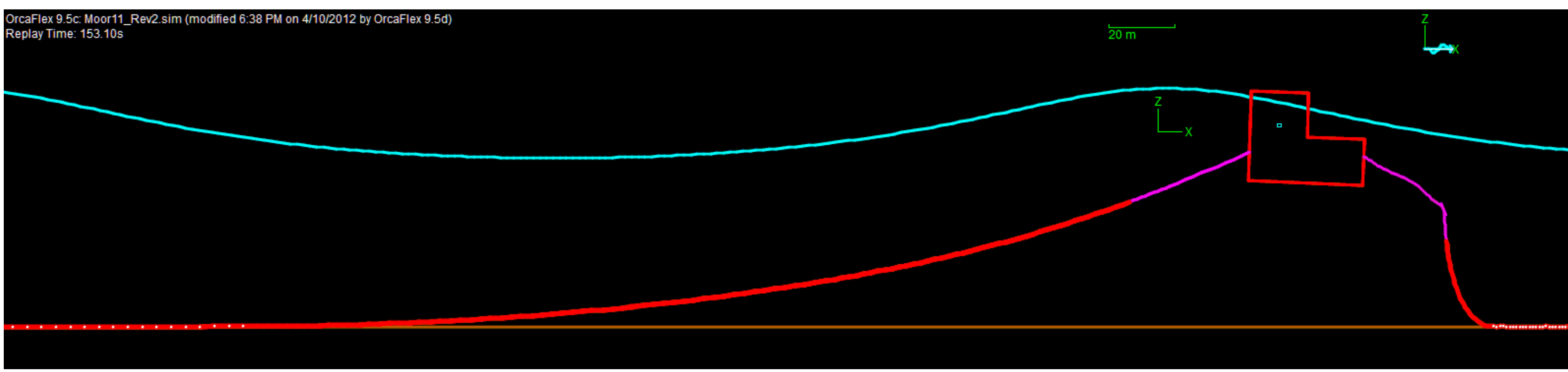
OrcaFlex

- **3D time domain solution of equations of motion for bodies subjected to hydrodynamic loads**
  - Hydrodynamic loads calculated using extended formulation of Morison’s equation.



Discretization Methodology

- **Model rigid structure as an array of 6-DOF discrete bodies to capture**
  - Buoyancy distribution
  - Hydrodynamic characteristics that account for inertial and viscous effects
- **Rotational response controlled by distribution and density of discrete bodies.**



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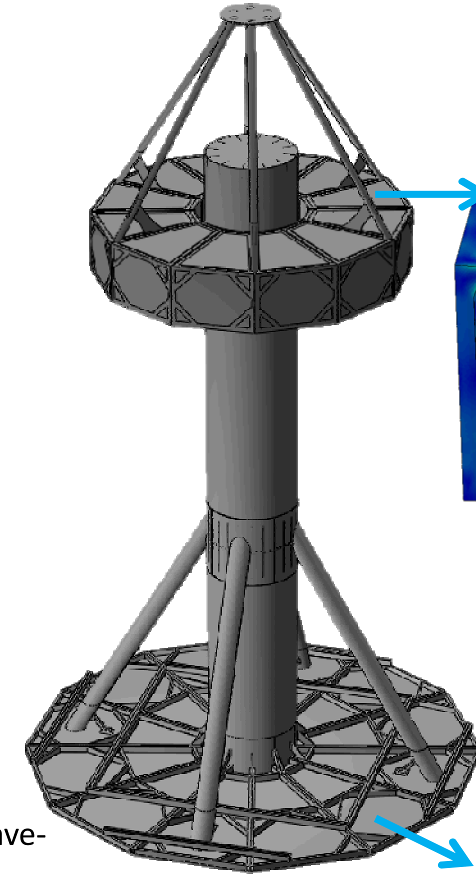
Structural Modeling

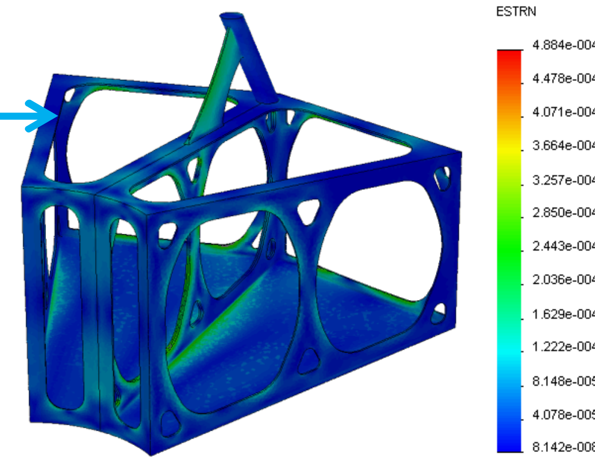
Initial Design

- **Use Standards to estimate structural requirements**
  - Survival conditions drive structural design
  - Use conservative estimates of load to generate baseline design
- **Determine Basic Properties**
  - Center of Gravity & Center of Buoyancy
  - Moments of Inertia
  - Required Ballast
  - Expected natural resonances
- **Select Baseline Materials**
  - A36 steel is often used in marine environments

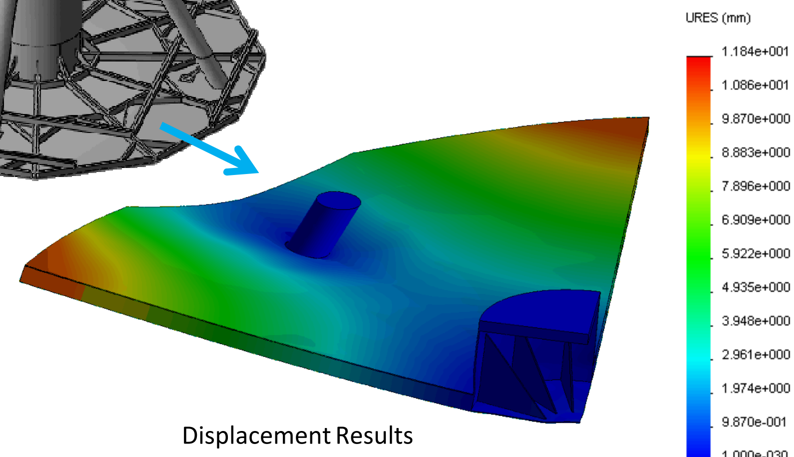
Structural Integrity

- **Refine Design**
  - Add appropriate supports while minimizing required material
  - Obtain higher accuracy loading estimates from wave-structure modeling tools
- **Finite Element Analysis (FEA)**
  - Ensure design meets required Factors of Safety (FOS) for provided loads
- **Consider manufacturing constraints**
  - Designs requiring metal cutting and welding not only offer points of failure but also increase expense





Strain Results (98% Accurate)



Displacement Results
(Deformation Scale 179.16)

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Power Conversion Chain Modeling

Designing PTO, must balance:

Large variability's:

- **Across the entire deployment climate.**
- **Within a particular sea state—average vs. peak values.**

Single vs. Multiple Drivetrains

- **Added redundancy can increase WEC availability but may adversely effect cost or efficiencies**

Drivetrain & Generator sizes

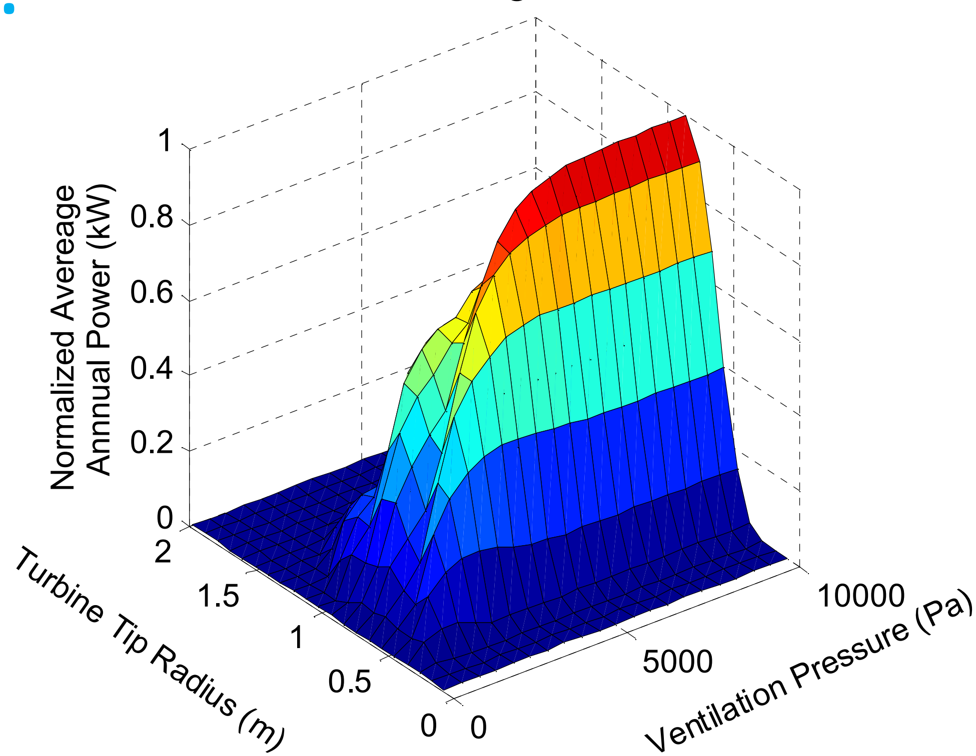
- **Must be optimized for the climate variability**

Power Conversion Efficiency

Power Conversion serviceability and reliability

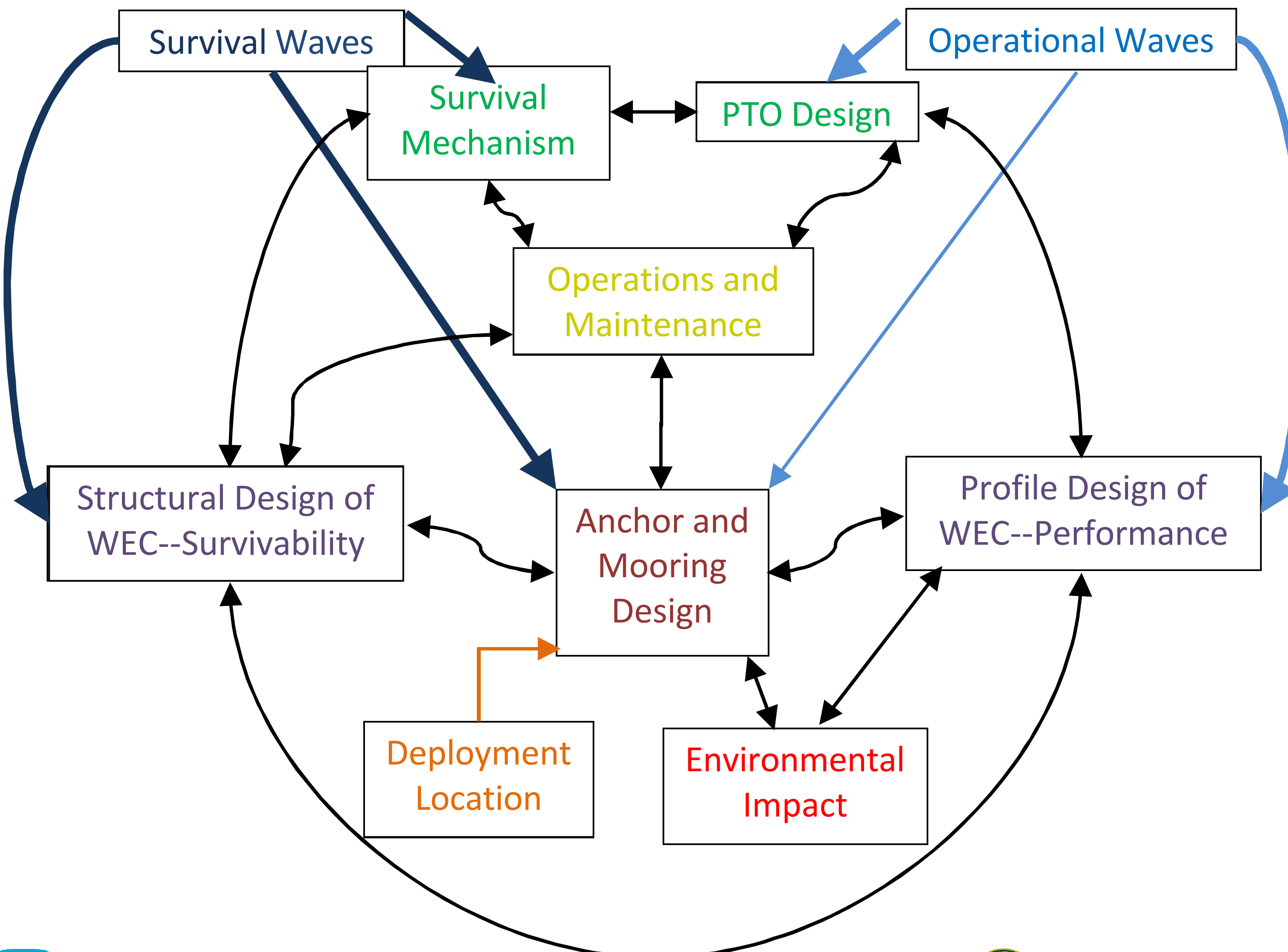
- **The drivetrain, generator, and other subcomponents are the most likely to fail: need to really consider O&M for this subsystem**

Normalized Average Annual Power



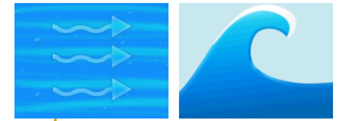
ARL in collaboration with SNL has been developing an optimization code to optimize average annual electrical power for various Well's Turbines for RM6 (BBDB OWC)

WEC Design


Survival Waves
Operational Waves
Survival Mechanism
PTO Design
Operations and Maintenance
Structural Design of WEC--Survivability
Anchor and Mooring Design
Profile Design of WEC--Performance
Deployment Location
Environmental Impact

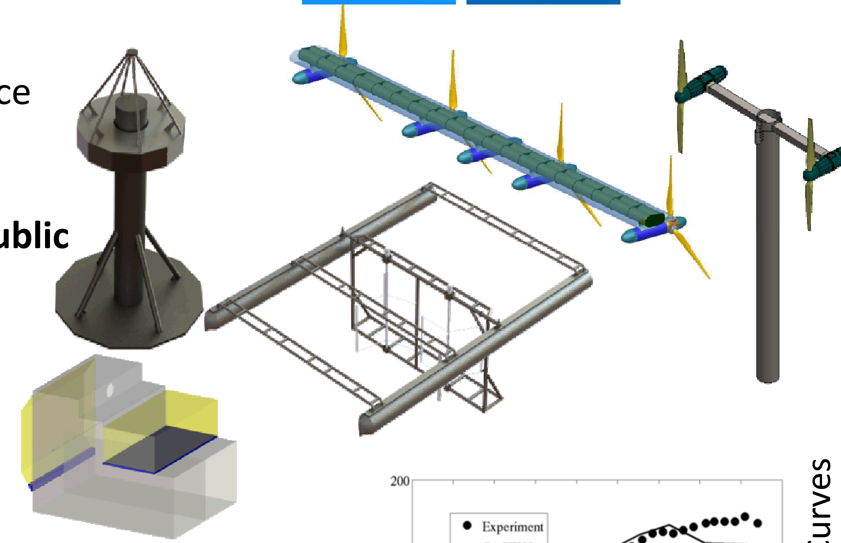
SAMPLEING OF SNL’S WORK IN WATER POWER

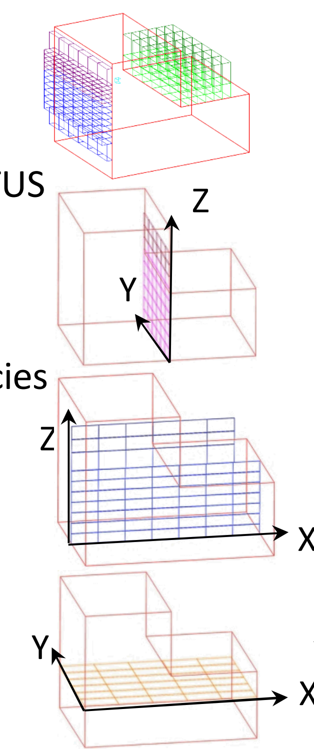
Reference Model

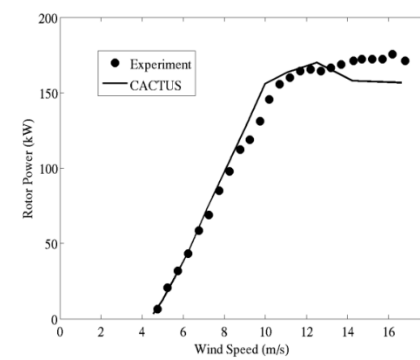


PI: Neary

- **Summary**
  - Multi-Lab collaborative effort to obtain **baseline** performance and Cost Of Energy (**COE**) estimates for a variety of Marine Hydro-Kinetic (MHK) devices.
  - Method to achieve cost of energy estimates is to develop **public domain designs** incorporating the following:
    - •Power performance models
    - •Structural models
    - •Anchor and mooring design
    - •Economic Model
    - •PTO Design
    - •O&M / Installation
    - •Permitting & Environment
  - Designs are intended to be conservative, robust, and **experimentally verified**.
- **SNL Developed Tools**
  - **Performance Models**—WEC: developed 3-dimen model capable of handling 7DOF in Matlab, FEC: developed CACTUS
  - **Survival Model**—developed methodology to utilize a Morison's Eq. approach to model extreme conditions
  - **Structural Sizing Tool**—developed tool that determines weight, ballast, COG & COB locations, and natural frequencies
  - **PTO Sizing Tool**—developed Turbine sizing tool
- **SNL Utilized Tools**
  - **Hydrodynamics**—WAMIT / AQWA / Fluent
  - **Mooring**—OrcaFlex / AQWA Moor
  - **Structural Integrity**—ANSYS / SolidWorks
- **Partners:** PNNL, ARL, NREL, ORNL

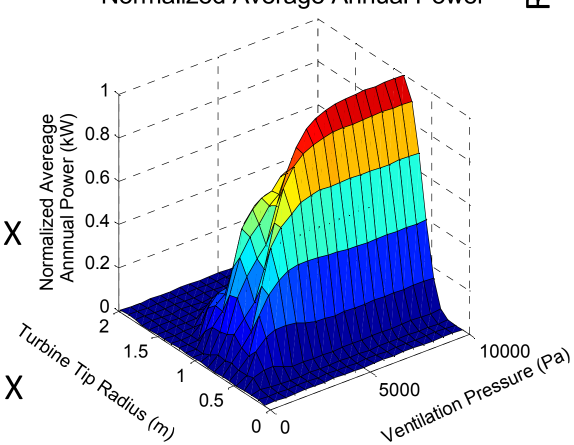






Normalized Average Annual Power

Rotor Performance Curves



SNL-SWAN: WEC Array Performance and Optimization

PI: Ruehl

Summary/Impact

- SNL is developing a new modeling tool, **SNL-SWAN**, by modifying the SWAN source code to include a **WEC Module** that accounts for **wave height- and frequency-dependent** energy extraction of WECs

Tools

- SWAN – Simulating WAves Nearshore is an **open source** third-generation wave model developed at Delft University of Technology that solves the **spectral wave action balance equation**.

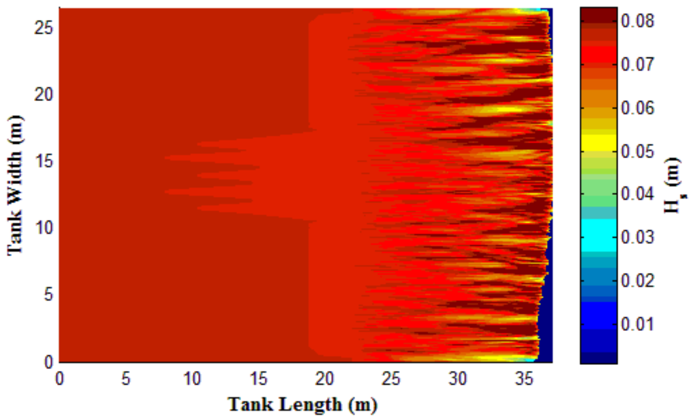
Accomplishments

- FY12: SWAN **Sensitivity analysis** in the **OSU Tsunami Basin** model domain, modeled the **CPT experiments** (see figures)

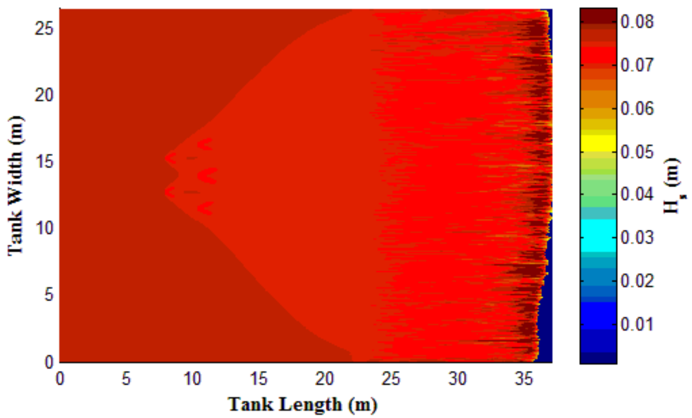
Partners:

- Coast and Harbor Engineering (C&H), Columbia Power Technologies (CPT), Oregon State University (OSU), Sea Engineering Inc. (SEI)

SWAN Tsunami Basin Model for 5 WEC Array



Hs = 0.0758 [m], Tp = 1.82 [s], Unidirectional Waves, Obstacle Transmission = 0 (aka 100% Absorption)



Hs = 0.0758 [m], Tp = 1.82 [s], Directionally Spread Waves (DSPR=4), Obstacle Transmission = 0 (aka 100% Absorption)

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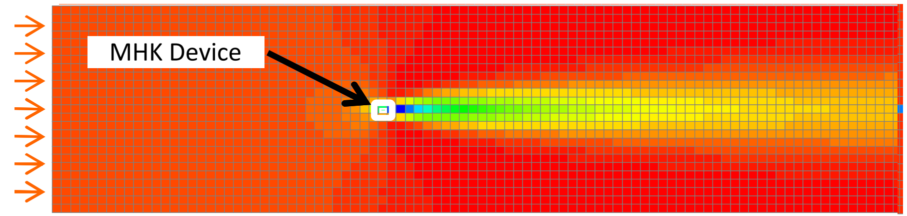
SNL-EFDC: FEC Array Performance and Optimization

PI: Roberts

Summary/LCOE Impact

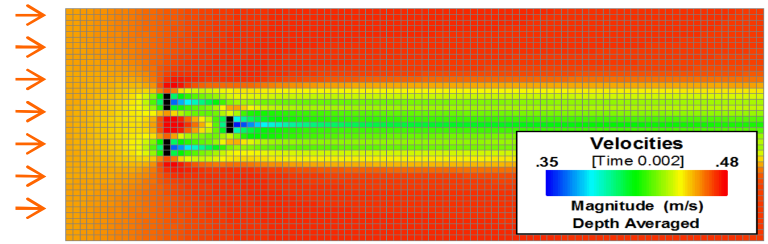
- Refine and apply **SNL-EFDC:** a tool for **balancing** MHK-turbine energy harvest **efficiency and environmental effects.**
- **Maximize power** and **minimize** potentially harmful **environmental effects**
- Accurately modeling MHK-turbines addresses **performance and environmental concerns** about large-scale development.



Treats MHK-turbine device as a momentum sink and source of turbulent kinetic energy and its dissipation rate

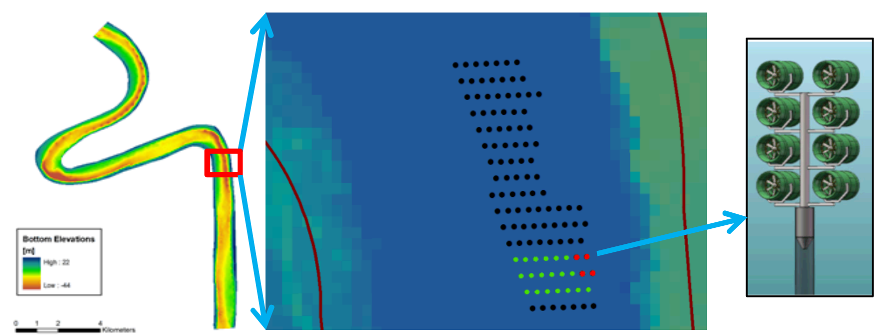
Accomplishments

- Modified EFDC source code to include **CEC module** that treats CECs as momentum sink and source/dissipation of TKE.
- SNL-EFDC validation with flume data
- SNL-EFDC application – Mississippi River, LA
  - Investigated **performance, flood hazard, and sedimentation** concerns for 12, 132, 534 CEC arrays (FFP)



Tools

- EFDC – Environmental Fluid Dynamics Code (RANS)
- Originally Developed by the EPA for Clean Water Act
- **SNL-EFDC** – adds **MHK-turbine module** and advanced **sediment transport routines**.



Partners:

- Ocean Renewable Power Company (ORPC)
- Argonne National Lab (ANL)
- University of Maine (UM)
- Sea Engineering Inc. (SEI)

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Blade Strike Analysis
(Collaboration with PNNL)

PI: Jepsen

Summary/LCOE Impact

- **Regulatory Driver:** Little is known about blade strike on marine mammals.
- **Simulate strike events** to characterize potential **impact to marine mammals**.
  - Consider multiple turbine designs and mammal types.

Background

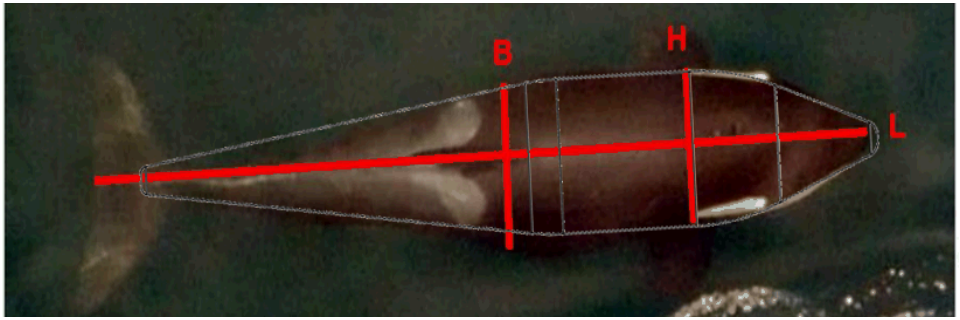
- SNL defines **turbine properties & simulates strike** to determine dynamic impact.
  - Use 3 impact velocities within turbine operating conditions for deformation trends.
- PNNL defines **mammal properties** and **tissue response** based on simulated deformation.

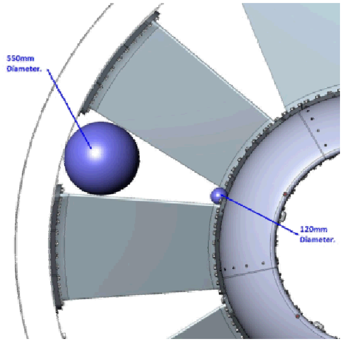
Tools

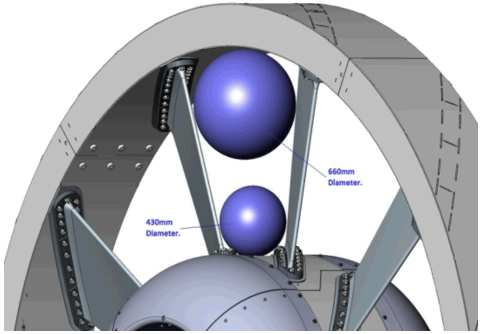
- **PRESTO- SNL weapons code** for L/E analysis of high solid deformation events.
- **RM designs and performance models**

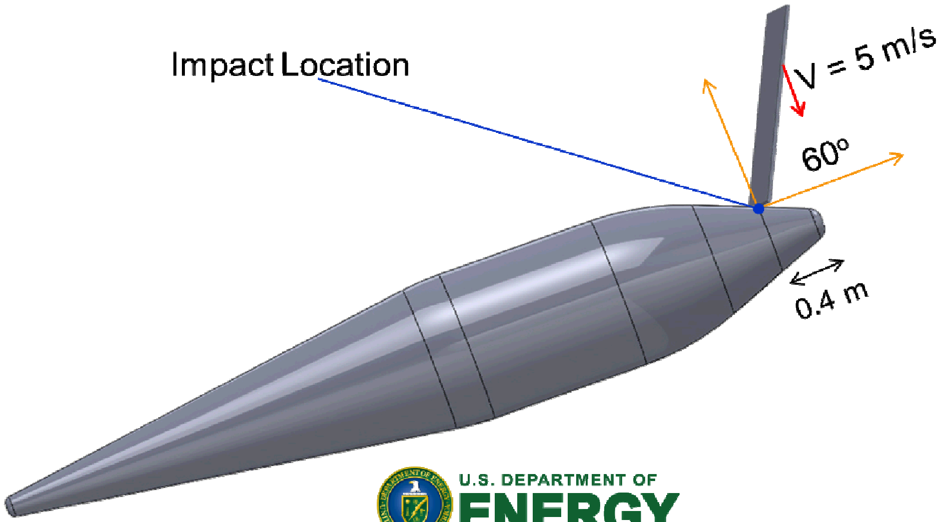
Partners

- Pacific Northwest National Lab









Pacific Northwest NATIONAL LABORATORY

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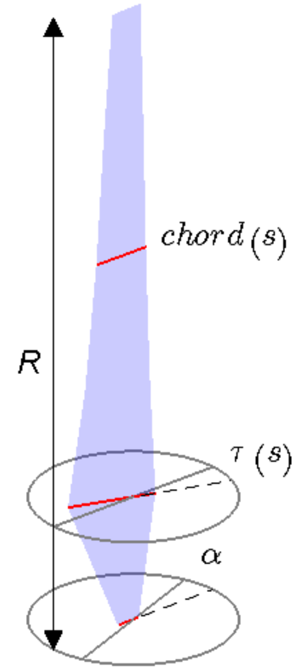
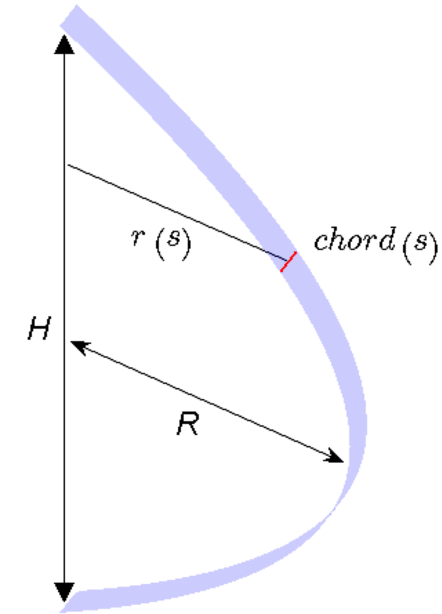
CACTUS: Code for Axial and Cross-flow TUrbine Simulation

PI: Barone

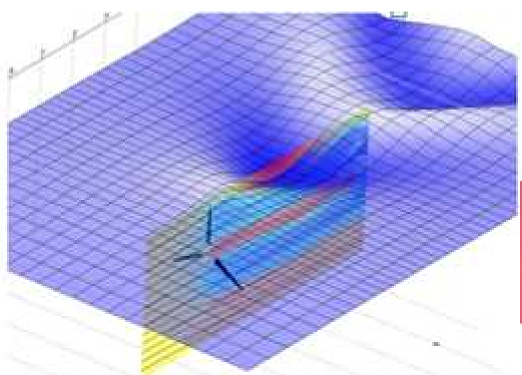
- ## LCOE Impact
  - Open-Source, publicly available, Validated, & Rapid run-times: Coded in Fortran95, compiled in Linux, Windows, & OSX
  - **Performance:** power predictions for generalized rotor geometry
  - **Structural:** unsteady hydrodynamic load estimates for generalized rotor geometry
  - Solves for wake profile without the need for high-fidelity CFD
- ## Tool Capabilities
  - Generalized Axial and Cross-Flow Turbine designs, including struts and joints
  - Time Domain Simulation
  - Blades represented as lifting lines with forces determined from input foil data
  - Rotor wake represented with vortex elements
  - Drag from support struts can be included
  - Free surface effects included
  - Dynamic Stall model included

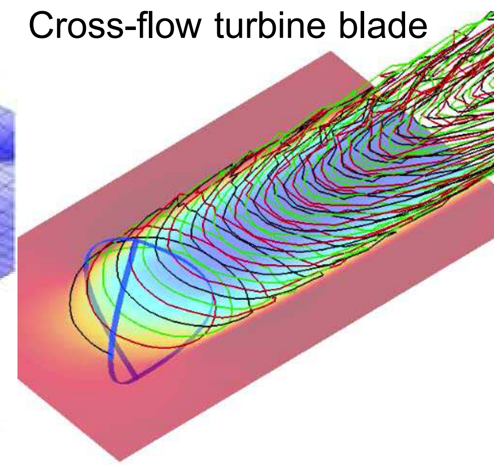


Axial turbine blade



Cross-flow turbine blade





Code Development: Matt, Erick Johnson, & Jon Murray

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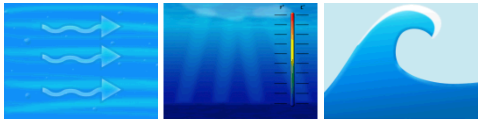
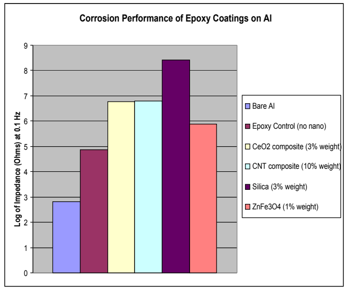
Materials & Coatings



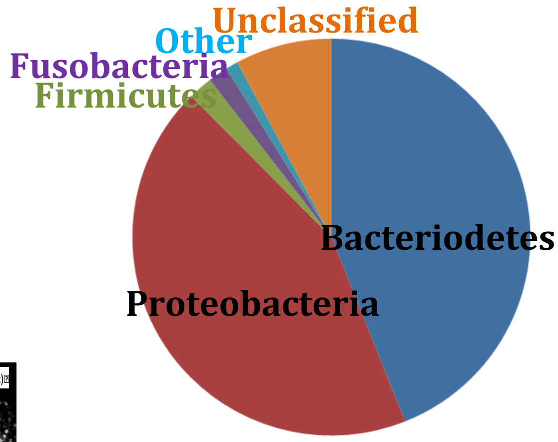
PI: Hernandez-Sanchez

- **Summary**
  - Novel Coating Synthesis
  - Biofouling Testing
  - Corrosion and Reliability Testing
  - Composite Fabrication and Performance Testing
  - Material Environmental Impact
- **LCOE Impact**
  - **Development Cycle, Performance, Reliability, Survivability, O&M:** impacted by materials & coatings selected for component/structure
  - **Industrial Assessment:** impact of material choices to be analyzed and integrated into program
  - **Repository of Expertise**: ability to direct industry to proven technologies
- **Accomplishments**
  - Novel antifouling & anticorrosion coatings with significant performance
  - Significant Industry Involvement
  - Testing salt water effects on composites
  - Ocean correlated laboratory testing
  - ONRL: No acute Toxicity on Zwitterionic coating
- **Partners:** BYU, MSU, NDSU, ORNL

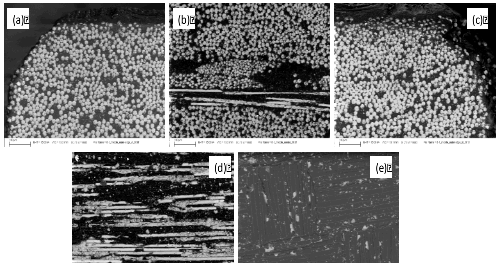
Corrosion Studies

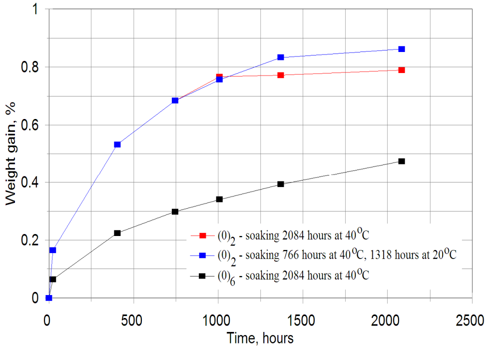


Biofilm Characterization on Verdant Power Systems Deployed in East River

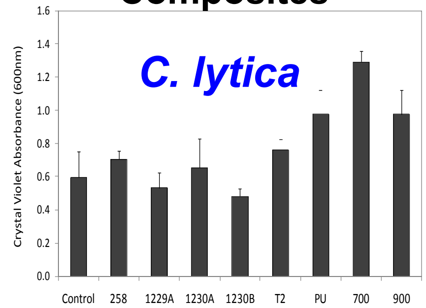


Salt Water Effects on Composites





Biofilm Testing of Owens-Corning Composites



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Sediment Transport, Scour, and Foundation Impact Analysis

PI: Roberts

Summary/LCOE Impact

- Develop **public domain methods/tools** for assessing wind farm and ecosystem risk from **ocean forces** & **sediment mobilization**
- **Reduce Siting Risk** and Uncertainty
- **Reduce time and costs associated with permitting**

Focus Areas/Background

- Pre- and post-installation analysis of sediment mobility and effect of underwater structures
- Fine-scale scour analysis
- SEAWOLF – sediment testing for model calibration and validation

Tools

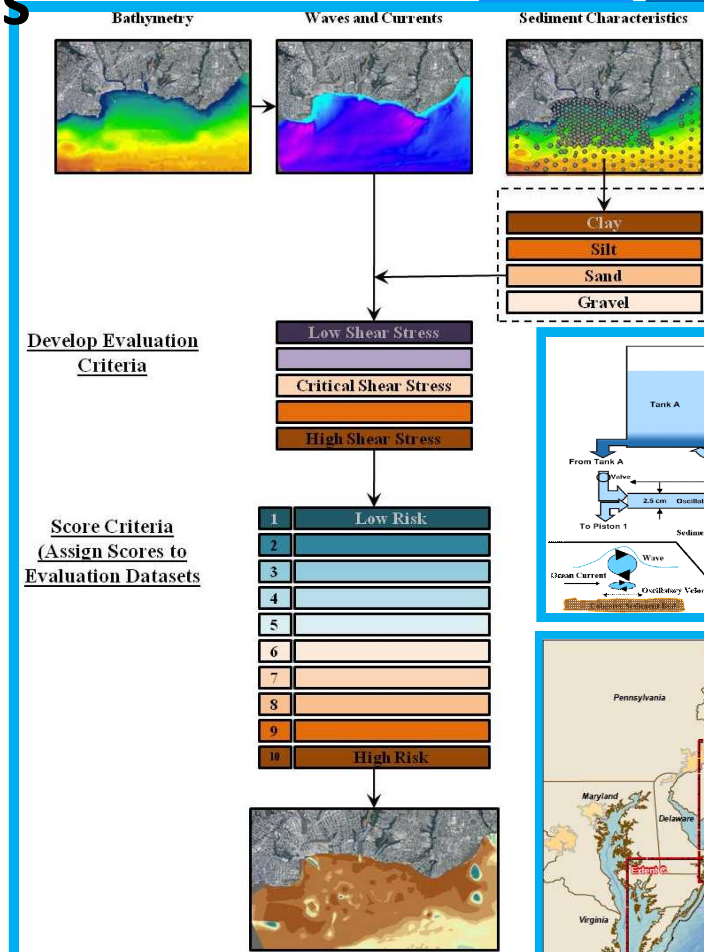
- SNL-EFDC (unique code for macro-scale studies)
- Fluent (commercial code)
- SEAWOLF mobile erosion test facility

Accomplishments

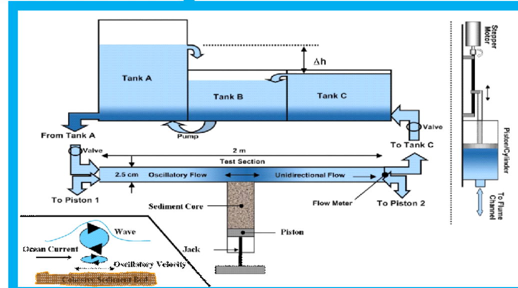
- Draft Sediment Stability Guidance Document
- Beta version of sediment stability mapping tool

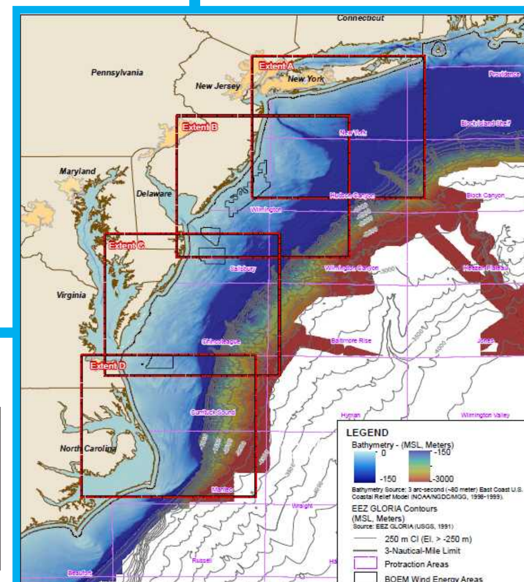
Partners:

- **Technical:** Fugro and Sea Engineering
- **Advisory:** MMI, Alpine, Fisherman's, Global Marine, Mott McDonald, Prysmian



SEAWOLF Flume





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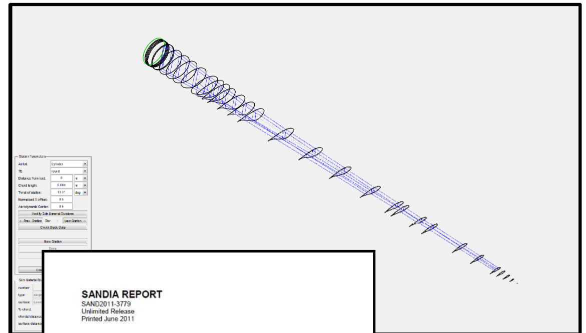
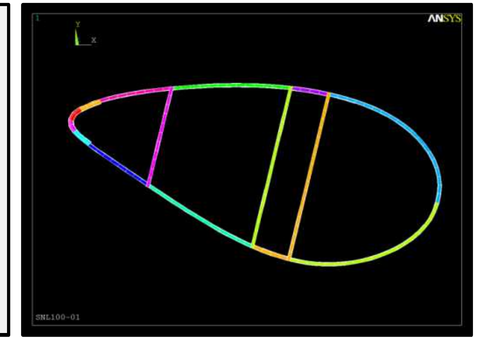
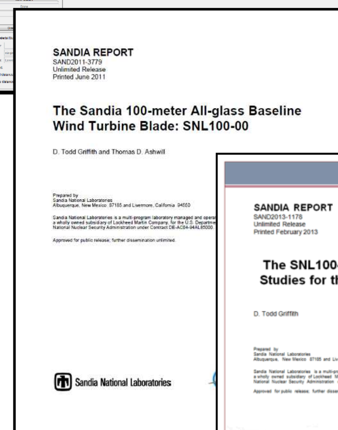
Large Offshore Rotor Development

PI: Griffith

- **Summary/LCOE Impact**
  - Advanced large blade design studies aimed to **reduce technology risk**; enable cost-effective large rotors
  - **Public domain blade project**
- **Objectives/Focus Areas**
  - Identify trends and challenges
  - **Detailed 100-meter reference designs**
  - **Targeted follow-on studies**: **advanced concepts, materials**, flutter, manufacturing cost trends, **thick airfoils**, CFD
- **Products**
  - Design reports
  - 100-m blade and 13.2 MW turbine reference models
  - **http://largeoffshorerotor.sandia.gov**
- **Partners:**
  - **None funded, 40+ users, ECN, Altair, Bristol, Stuttgart**



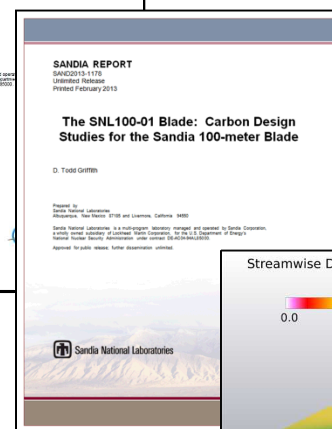



SANDIA REPORT
SAND2011-3779
Unlimited Release
Printed June 2011

The Sandia 100-meter All-glass Baseline Wind Turbine Blade: SNL100-00

D. Todd Griffith and Thomas D. Ashwill

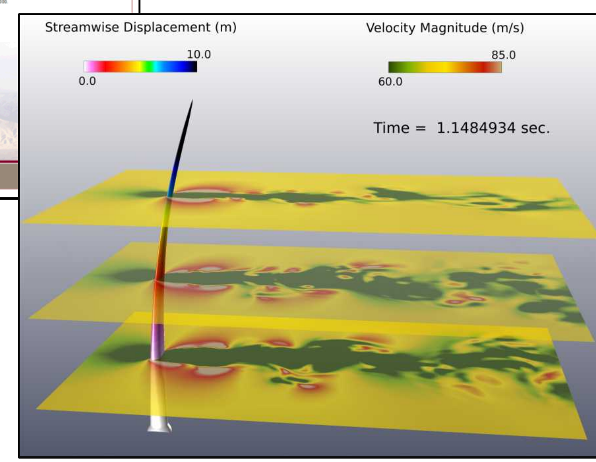
Sandia National Laboratories

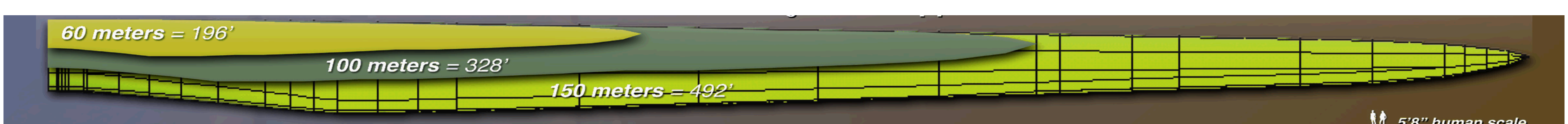

SANDIA REPORT
SAND2013-1178
Unlimited Release
Printed February 2013

The SNL100-01 Blade: Carbon Design Studies for the Sandia 100-meter Blade

D. Todd Griffith

Sandia National Laboratories





Innovative Offshore Vertical-Axis Wind Turbine Rotors (FOA)

PI: Paquette & Griffith

- **Summary/LCOE Impact**
  - This project focuses on the development of a deepwater, offshore VAWT design to explore possible LCOE benefits
  - This includes optimization of the rotor in response to higher balance of station and O&M costs associated with the offshore environment
  - Goal is to achieve a *transformative* LCOE reduction for deepwater offshore wind
- **Background/Current Focus**
  - Historical VAWT Expertise (1970s to 1990s)
  - Current focus on VAWT Aero-Hydro-Elastic Design Code development and Preliminary Design Studies
- **Tools**
  - Legacy Codes and Experimental Measurements
  - New VAWT-specific aero-hydro-servo-elastic code with variable fidelity
  - VAWT-specific airfoils, manufacturing methods, and platforms
- **Partners:**

tpi

A&M

DNV

1865 THE UNIVERSITY OF MAINE

TU Delft

STATE

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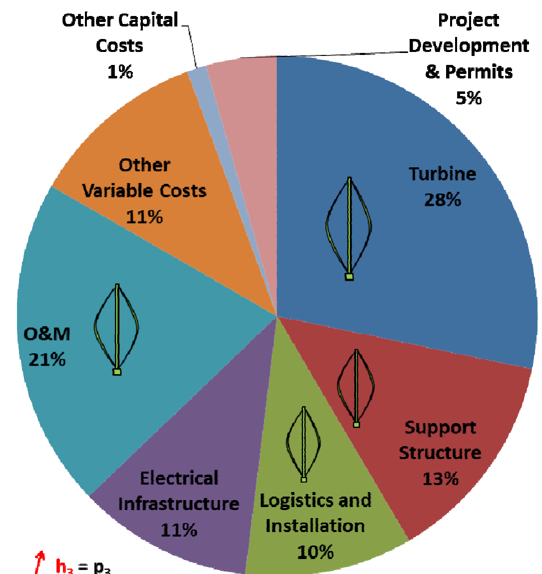
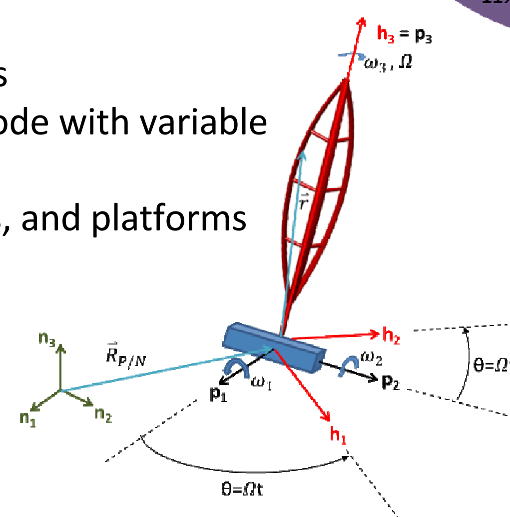
Offshore System Cost with Potential VAWT Impacts





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Rich Jepsen:		rajepse@sandia.gov

References

[1] Ocean Energy Systems and Met Ocean Solutions, Ltd., "An International Vision for Ocean Energy." International Energy Agency.

[2] G. Mørk, S. Barstow, A. Kabuth, and M. T. Pontes, "Assessing the global wave energy potential," in *29th International Conference on Ocean, Offshore Mechanics and Artic Engineering*, 2010.

[3] Electric Power Research Institute, "Mapping and Assessment of the United States Ocean Wave Energy Resource," EPRI Technical Report 1024637, Dec. 2011.

[4] Harris, R.E., Johanning, L., and Wolfram, J., "Mooring systems for wave energy converters: A review of design issues and choices," in *Marec2004*, 2004.

[5] HMRC-UCC, "Dynamic Characteristics of Wave and Tidal Energy Converters and a Recommended Structure for Development of a Generic Model for Grid Connection," OES-IEA Document No: T0321, Jul. 2010.

[6] J. Cruz, Ed., *Ocean Wave Energy*. Springer-Verlag Berlin Heidelberg: Springer.

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[8] R. Gomes, M. Lopes, J. Henriques, L. Gato, and A. Falcão, "A Study on the Wave Energy Conversion by Submerged Bottom-hinged Plates," in *Proceedings of the 9th European Wave and Tidal Energy Conference*, Southampton England, 2011.

[9] D. Bull and P. Jacob, "Methodology for creating nonaxisymmetric WECs to screen mooring designs using a Morison Equation approach," in *OCEANS '12. "Harnessing the Power of the Ocean". Proceedings*, Hampton Roads, VA, 2012, pp. 1 –9

In general all non-referenced pictures not produced by personal or collaborative work were goggled and can be easily found.

Thank you.

Diana Bull dlbull@sandia.gov
Sandia National Laboratories.
March 29th, 2013.

UNM Mechanical Engineering Seminar

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