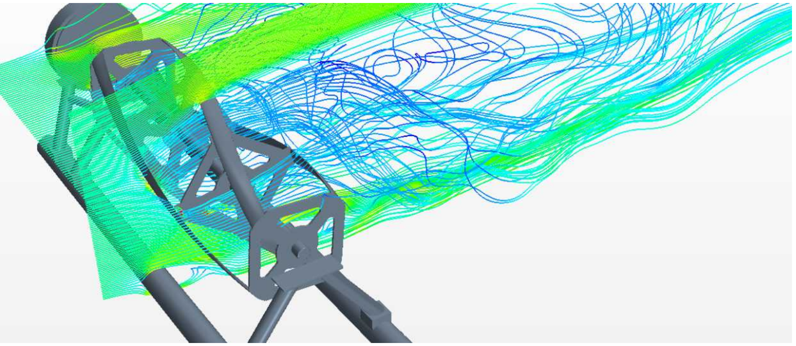
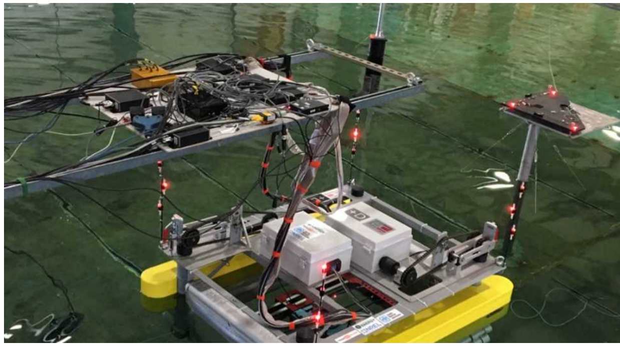
SAND2016-5552PE

Exceptional service in the national interest

Sandia National Laboratories





Sandia Water Power

Peter H. Kobos, Ph.D.

Water Power Department Manager

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

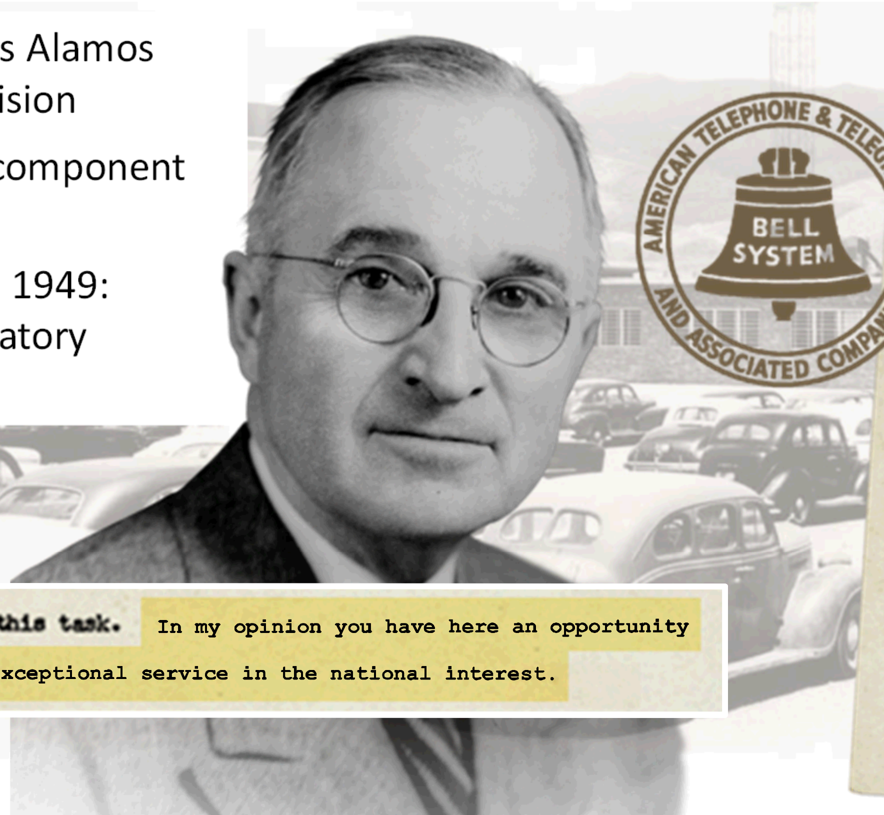
Sandia National Laboratories

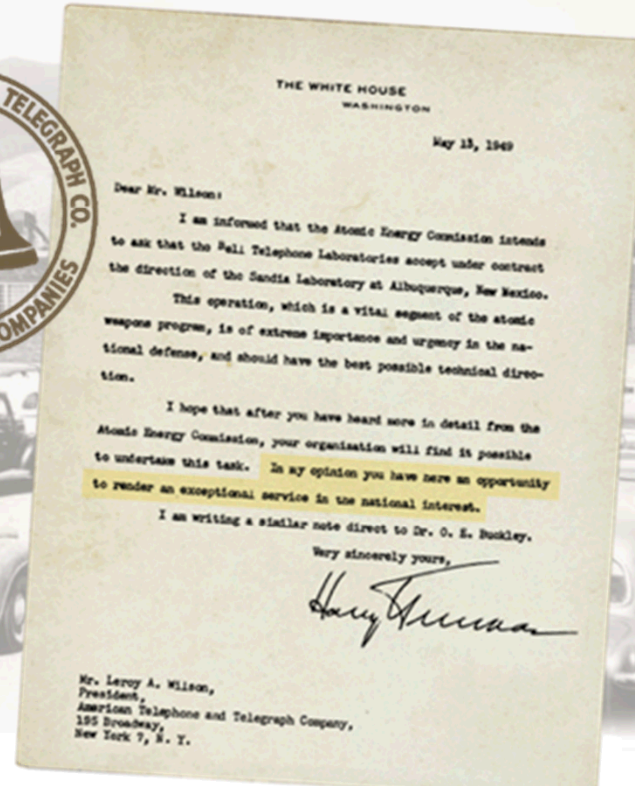
SANDIA NATIONAL LABS

Sandia's History

Exceptional service in the national interest

- July 1945: Los Alamos creates Z Division
- Nonnuclear component engineering
- November 1, 1949: Sandia Laboratory established





THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

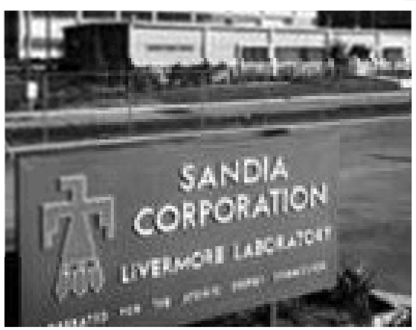
I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.



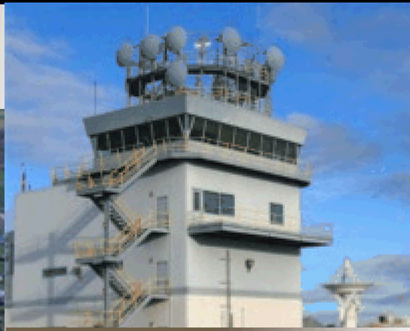
Sandia Sites

Albuquerque, New Mexico

Livermore, California

Kauai, Hawaii

Pantex Plant, Amarillo, Texas



Waste Isolation Pilot Plant, Carlsbad, New Mexico

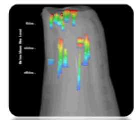
Tonopah, Nevada

History of Sandia Energy Programs

Sandia was born as a nuclear weapons engineering laboratory with deep science and engineering competencies

Energy crisis of the 1970s spawned the beginning of significant energy work

Strategic Petroleum Reserve -geologically characterizing salt domes to host oil storage caverns



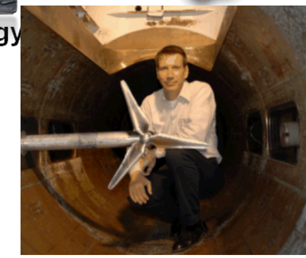
DOE's Tech Transfer Initiative was established by Congress in 1991

Advent Solar

Energy Policy Act of 2005

CRF & Cummins partner on their newest diesel engine

Joint BioEnergy Institute



Water Power Program

1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2007 | 2009 | 2010

Our core NW competencies enabled us to take on additional large national security challenges

Vertical-axis Wind Turbine

NRC cask certification studies & core melt studies

Solar Tower opens

Combustion Research Facility (CRF) opens to researchers

Distributed Energy Technology Laboratory (DETL) to integrate emerging energy technologies into new and existing electricity infrastructures

Power grid reliability study

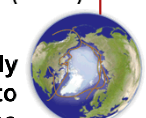
SunCatcher™ partnership with Stirling Energy Systems

Sunshine to Petrol Pilot Test

Large-scale pool fire tests of liquefied natural gas (LNG) on water

Consortium for Advanced Simulation of Light Water Reactors (CASL)

Climate study uncertainties to economies



Combustion Research Computation and Visualization (CRCV) opens

- **Unofficial start: 2008 support to Verdant Power**
- **New U.S. DOE water power program in 2009**
- **Leveraged existing Sandia capabilities**

Sandia National Laboratories

Land-Based Wind

Wind/Water Tech.

- Technology Development Paradigm
- Turbine Hub and Blade Design (Tidal/Current)
- Field Testing/Data Acquisition
- Aero/Hydro-acoustics

Wind Technologies

- Inflow Modeling
- Tower Designs
- Blade Designs
- Aero-elastic Modeling

Core Competencies

- Materials/Coatings
- Sensors
- Manufacturing
- Reliability
- System Integration
- Lab/Field Testing

Water Power MHK

Marine Technologies

- Hydrodynamics
- Anchoring/Mooring
- Sediment Transport
- Water Use Optimization
- Environmental Analysis
- Materials & Coatings

Offshore Wind

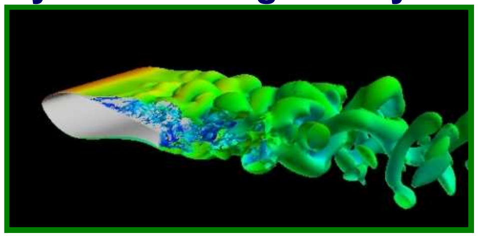
MARINE HYDRO-KINETICS

Industry and Public support

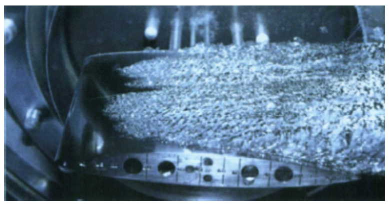
SNL MHK Research Focus Areas

Sandia National Laboratories

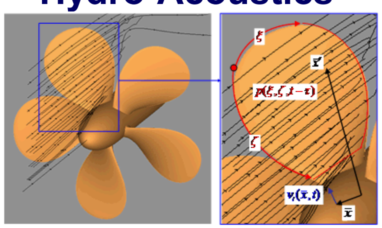
Hydrofoil Design/Analysis



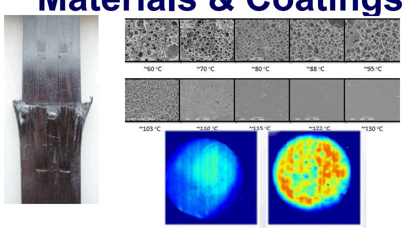
Cavitation



Hydro-Acoustics



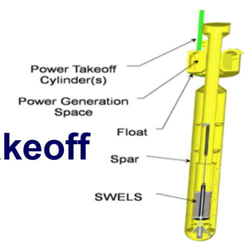
Materials & Coatings



Performance Modeling

Rotor Design & Testing

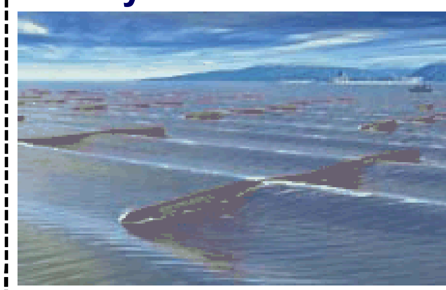
Power Takeoff Testing

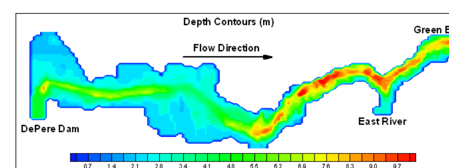


Columbia Power 1/15th Scale Test (OSU)

Water Tunnel (PSU/ARL)

Coupled Device Array and Environmental Analysis





SNL EFDC

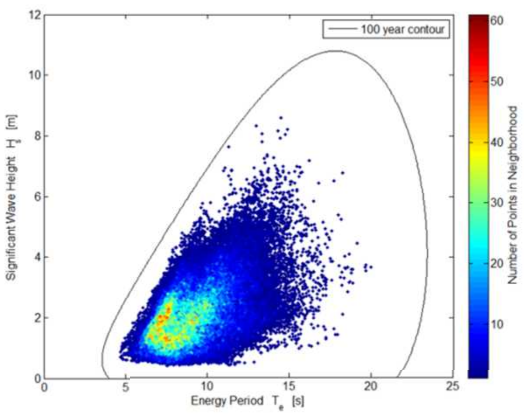
Technology Development Cycle

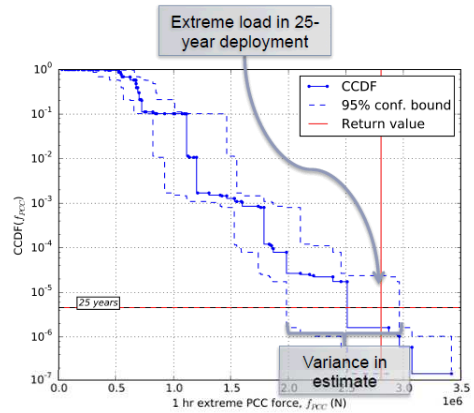
Components | Sub-systems | System Testing | Deployment

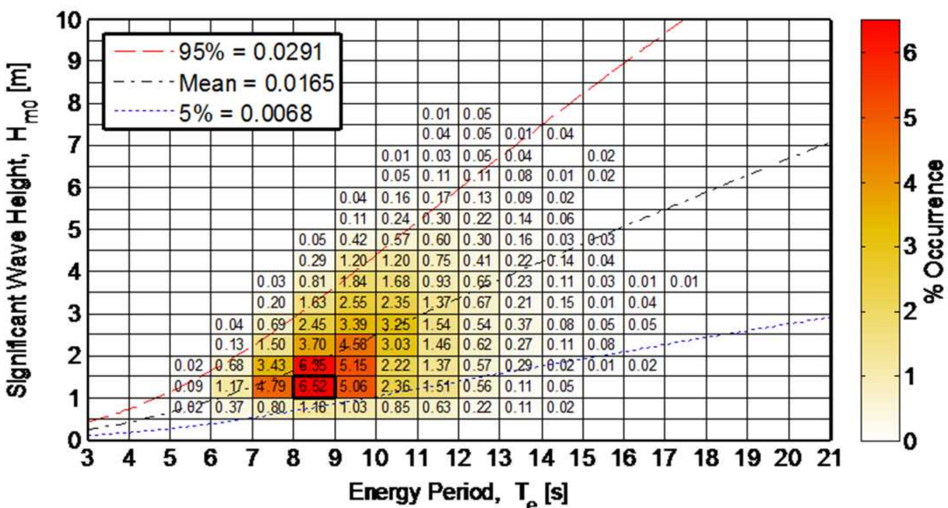
Sandia's Unique Capabilities/Facilities: Dealing with extremes

Sandia National Laboratories

Probabilistic methods for predicting extreme design loads

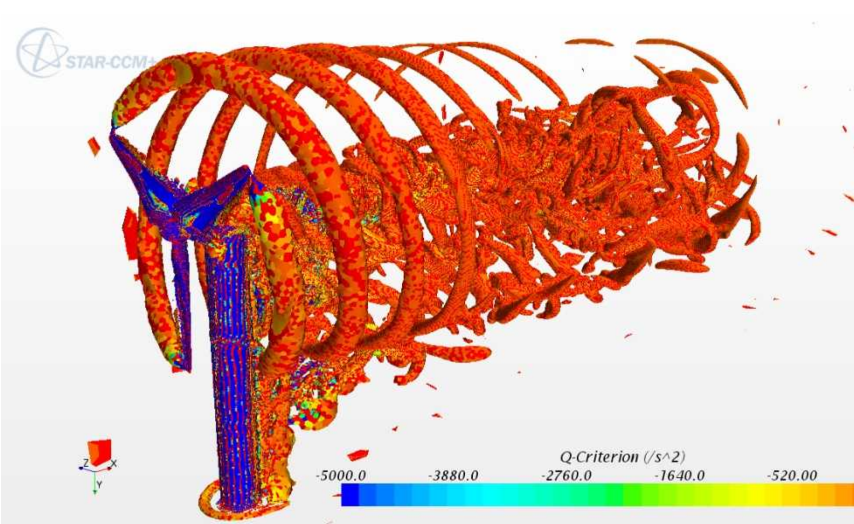


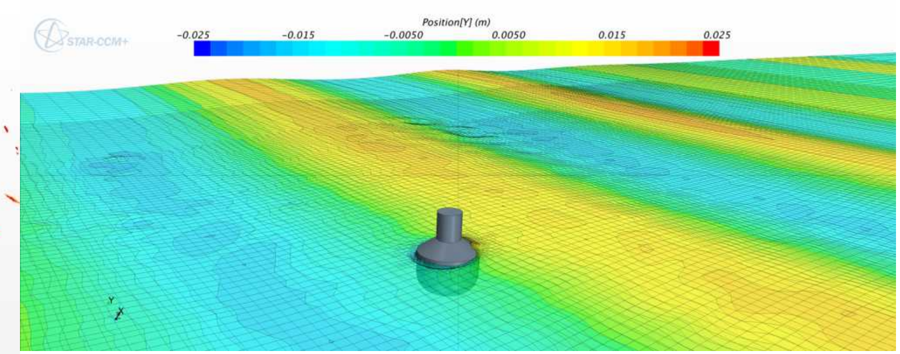


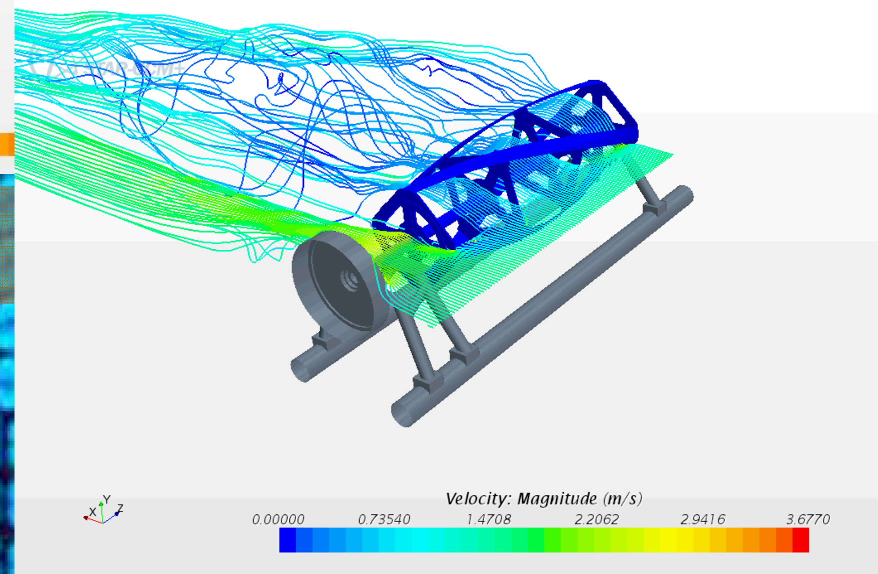


Sandia's Unique Capabilities/Facilities: Dealing with extremes

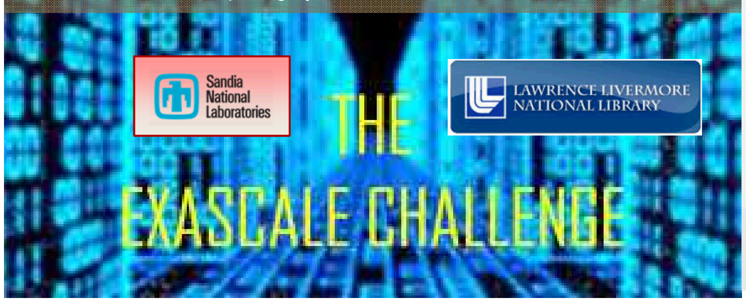
High fidelity modeling of fluid and structural dynamics, fluid-structure-interaction







XPRESS (eXascale Programming Environment and System Software) - operating system and associated components that will enable exascale computing by 2020.



Reference Models

Accomplishment: Developed 6 public domain designs incorporating:

- Power performance models
- Structural models
- Anchor and Mooring Design
- Economic Model
- PTO Design
- O&M / Installation
- Permitting & Environment

Released report on four of the completed designs highlighting the philosophy behind Levelized Cost of Energy (LCOE) derivation and experimental verification.

Objective: Obtain baseline performance and Cost Of Energy (COE) estimates for a variety of Marine Hydro-Kinetic (MHK) devices.

Project Impact:

- All reference models are public domain serving broader stakeholder needs
- Process of obtaining COE facilitates knowledge / modeling tool gaps that the industry is facing thus allowing DOE to target their research dollars effectively
- The creation of independent and experimentally verified COE across multiple device architectures legitimizes the comparison

Current Work:

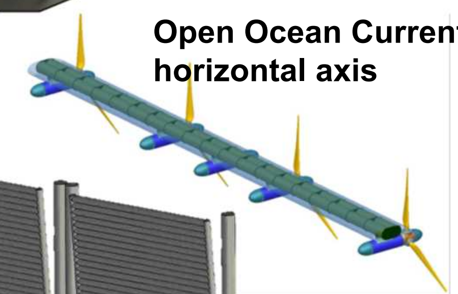
Work to disseminate:

- Project reports
- Reference model designs
- Data from scaled model studies
- COE model spreadsheets
- Release of RM5 and RM6 information

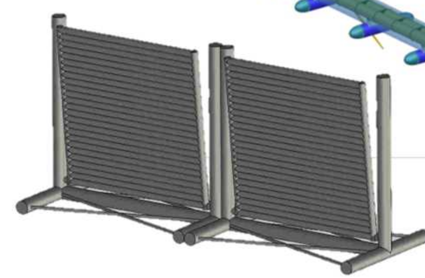
Tidal Turbine horizontal axis

River Turbine vertical axis

Point Absorber dual absorber

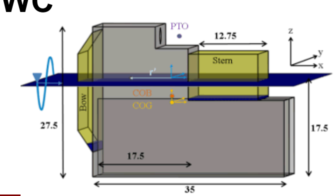


Open Ocean Current horizontal axis



Floating Surge Pitching Flaps

Floating OWC BBDB



Technical Support of MHK Technology Industry Support

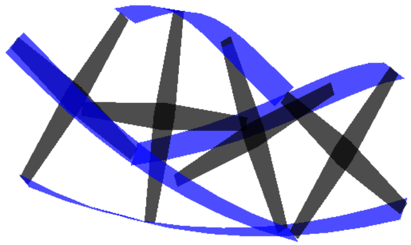
CACTUS (Code for Axial and Cross-flow Turbine Simulation) to perform a preliminary design-space search to evaluate rotor design hydrodynamic (power) performance.

The numerical modeling test matrix considered the following parameters:

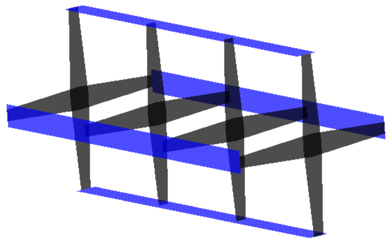
- rotor geometry (helical vs. straight blade),
- the number of struts used to support the blades,
- the solidity of the rotor (based on the number of blades and the chord-to-radius ratio).

Objective:

- Evaluate for higher power performance in future ORPC turbine designs
- Enhance the next generation of MHK systems to compete in the market
- Increase rapidly advanced of technologies to commercialization
    - comprehensive analysis and optimization of MHK technologies



CACTUS model of ORPC TidGen™ turbine



CACTUS model of straight blade turbine

Future Work: Perform detailed evaluation of the ORPC TidGen™ rotor hydrodynamic and structural performance and assess viability of an alternative straight-blade rotor design for improved economic performance.

Ocean Renewable Power Company (ORPC) TidGen Turbine

SYSTEMS ENGINEERING AND MODELING EXAMPLES

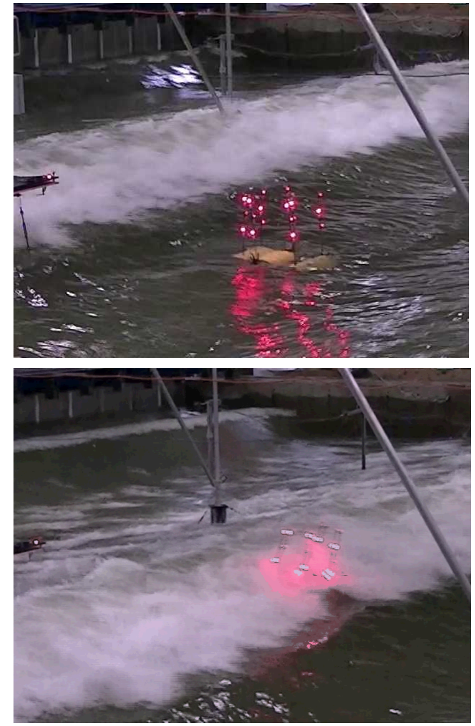
Extreme Conditions Modeling

The Extreme Conditions Modeling (ECM) project will expand capabilities in analyzing the survivability of Wave Energy Converters

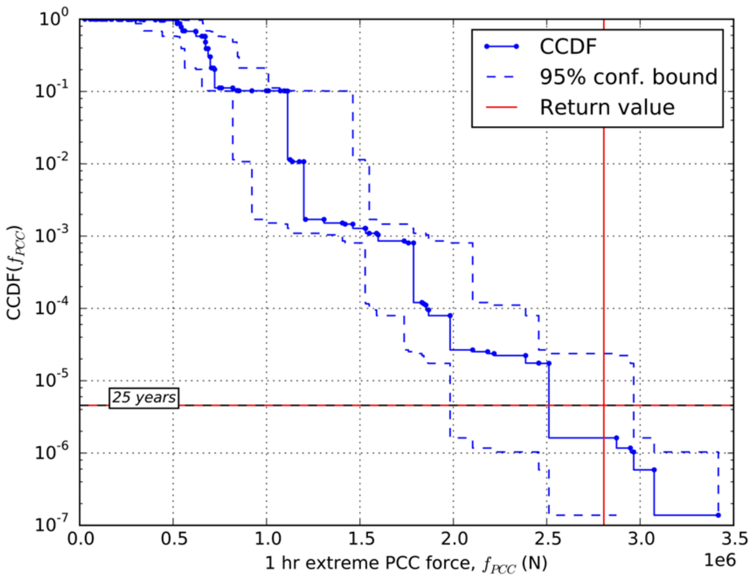
WECs must be designed to respond to ocean waves,

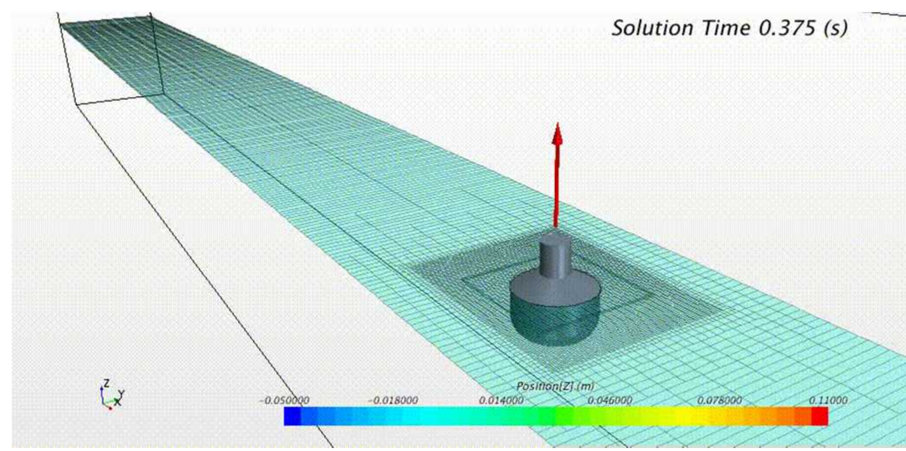
Objective:

- Improve best-practices for design response analysis of WECs
- Develop and study numerical modeling, empirical modeling and analysis methods to better predict design responses in WECs



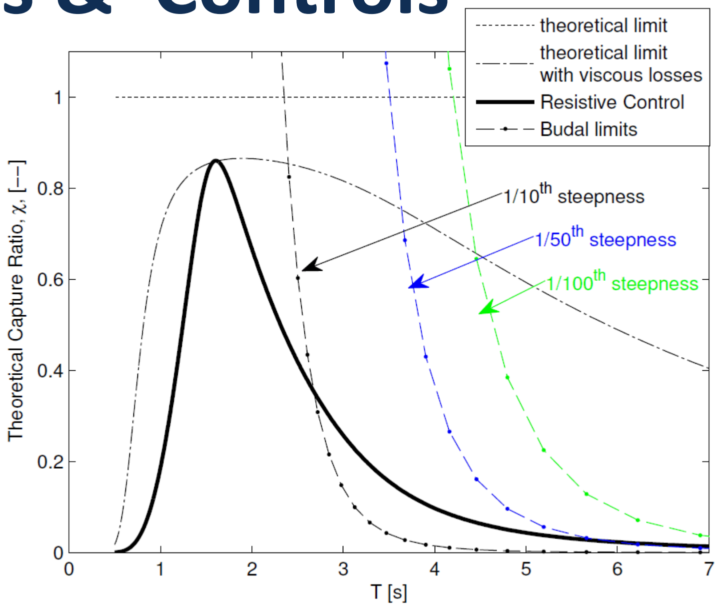
Images courtesy of Columbia Power



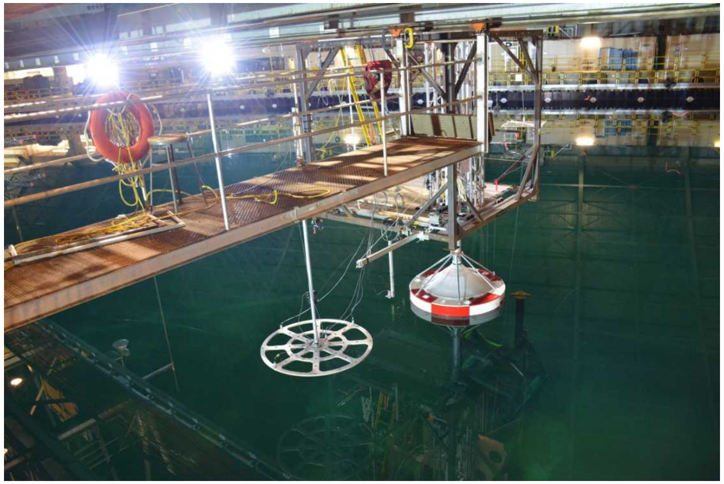


Advanced WEC Dynamics & Controls

- Advanced control strategies alter the dynamics of a WEC to increase energy absorption over a broader range of wave frequencies
- Numerous studies have shown large benefits of more advanced control of WECs (e.g., Hals et al. showed **330% absorption increase**)
- To-date, most studies rely on significant simplifications and assumptions
    - Availability of incoming wave foreknowledge
    - 1-DOF motion
    - Linear or perfectly know hydrodynamics
    - No sensor noise
    - Unlimited actuator performance



Project goal: accelerate/support usage of advanced WEC control by developers



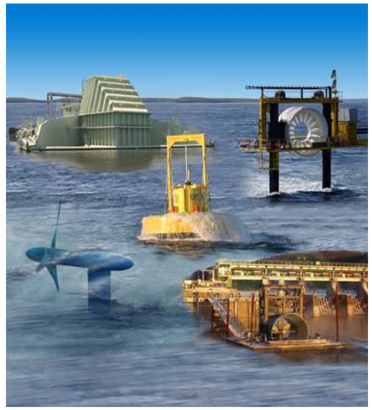
Wave tank testing at Naval Surface Warfare Center, Carderock Division (NSWCCD) Maneuvering and Seakeeping (MASK) basin.

ADVANCED MATERIALS AND COATINGS FOR MHK

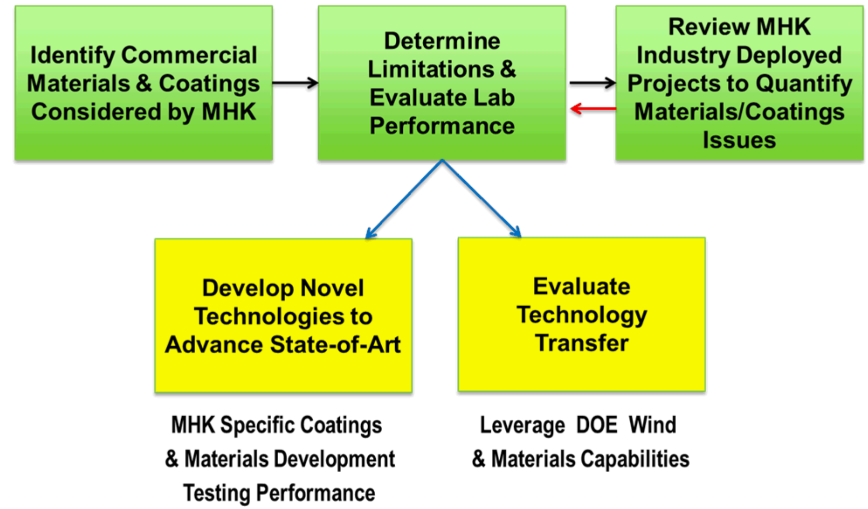
Advanced Materials for Marine Hydrokinetic (MHK) Technology

Purpose:

Sandia's Water Power Technologies Advanced Materials Program conducts applied research and provides guidance on Materials & Coatings to enable viability, lower the cost of energy (COE), and accelerate commercialization of marine and hydrokinetic technology (MHK).



Procedure:



Early Program Addressed:

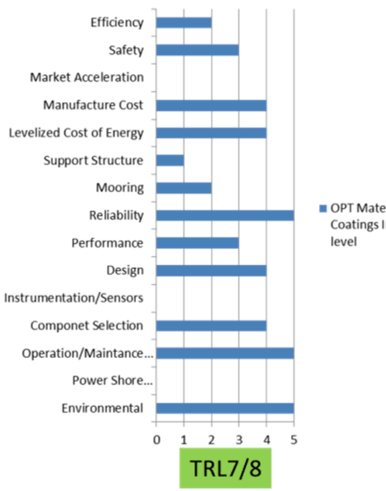
- Industrial Survey on Materials & Coatings Needs
- Development & Characterization of MHK Specific Protective Coatings
- Toxicity Testing of New Coatings
- Performance Testing on Wind Composites
- Materials Reliability–FBG sensors
- Initial Assessment of Underwater NDI Monitoring (meeting with Phoenix International)
- Meeting with Naval Research Laboratories–Arthur Webb on Coatings
- Meeting with International Marine Coatings
- MHK Composites Workshop

Future Program to Address:

- Removing Uncertainty & Barriers of using Composites (Industry Directed)
- Leverage Coatings Research & Library
- Understand Materials & Coatings Impact on MHK Manufacture, O&M, Reliability, Safety, Cost
- Support MHK Developers on Their Deployments

MHK Advanced Materials & Coatings

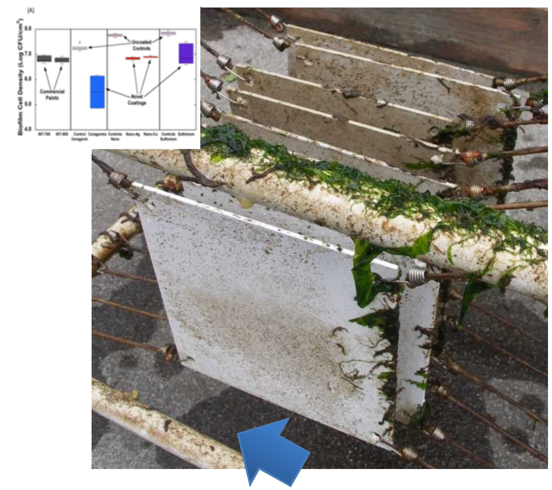
MHK Industrial Review



Water Power Materials Science & Engineering

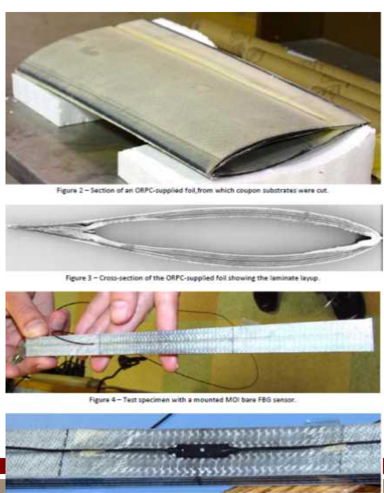
PNNL Marine Science Laboratory

Protective Coatings

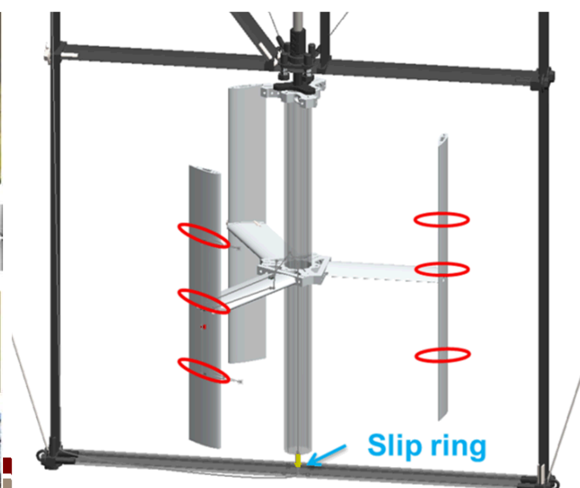


PNNL Open Water Testing

Materials Reliability: SHM Monitoring (FBG)

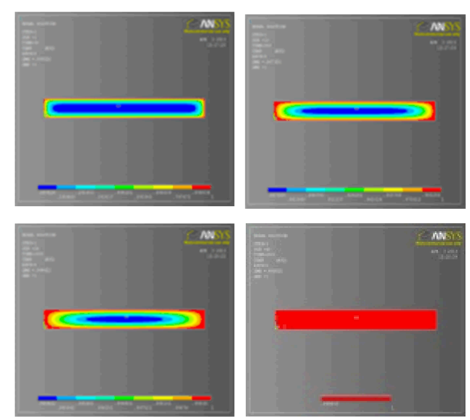


ORPC/MSU



UNH

MHK Composite Performance



MSU

TRANSITION:
DR. BERNIE HERNANDEZ-SANCHEZ

THANK YOU

Additional Sandia MHK Capabilities

BACKUP SLIDES

WEC Device Modeling, WEC-Sim

SNL and NREL worked together to jointly develop an alpha version of WEC-Sim used to model the RM3 WEC design, a two-body heaving point absorber.

Objective:

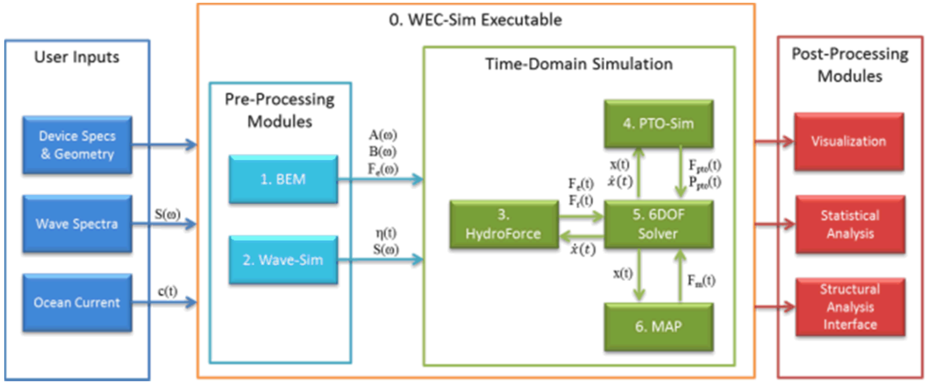
The long term objective, develop a cost effective suite of open source code modules containing a computer aided engineering tool for the development and optimization of wave energy conversion devices.

Project Impact:

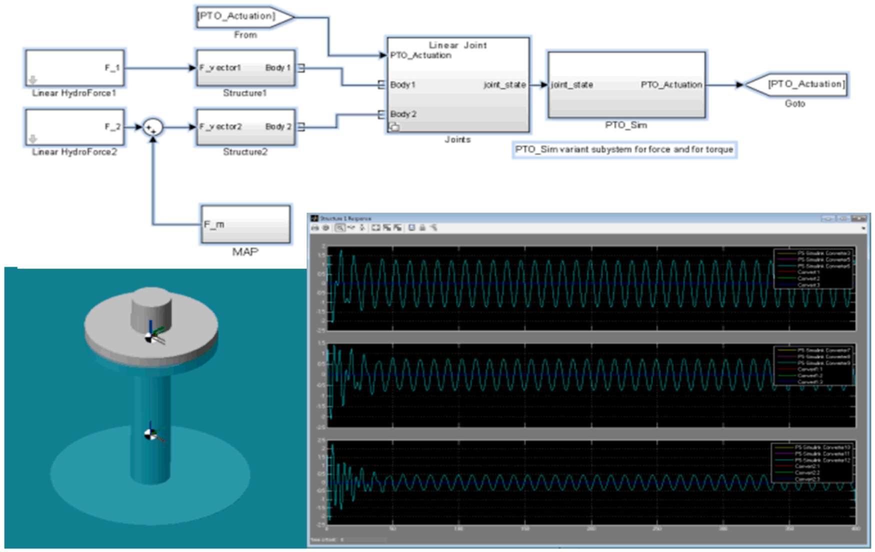
- WEC-Sim will provide the wave energy community a low cost alternative to commercial WEC modeling tools
- Allow early stage developers to optimize their design using the easily customizable open source code.

Future Work:

- SNL and NREL will work together to perform verification of WEC-Sim through a code-to-code comparison to the commercial codes WaveDyn and AQWA.
- Numerical model results will also be compared to experimental data, and a Beta version of WEC-Sim has been released.

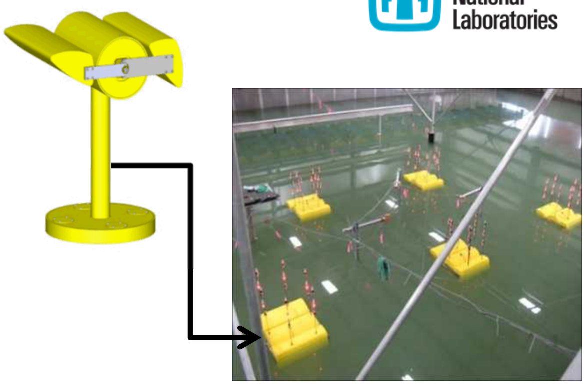


WEC-Sim Module Structure



WEC-Sim Implementation in SimMechanics

Wave Array Performance and Optimization



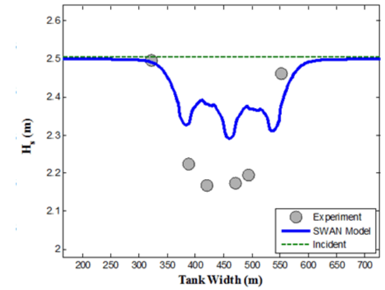
OSU Wave Farm Tank Tests

Accomplishment:

Development of SNL-SWAN, a version of the spectral code SWAN (Simulating Waves Nearshore), to include a WEC Module by implementing a WEC Module that imports WEC power performance in the form of a relative capture width (RCW) curve or a power matrix.

Objective:

- The SNL-SWAN WEC Module incorporates frequency- and directional-dependent energy extraction terms that better model Wave Energy Converters (WECs).
- Validation of SNL-SWAN will based on the Oregon State University (OSU) Tsunami Basin array power performance data collected from the OSU wave tank tests.



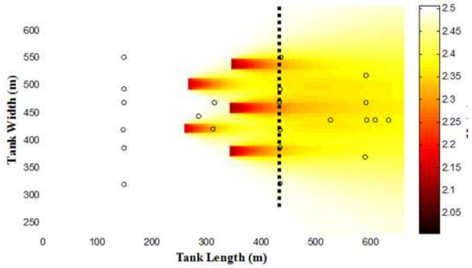
SNL-SWAN Experimental, Numerical Comparison

Project Impact:

SNL-SWAN will provide a fast solving array modeling tool, allowing developers to perform preliminary array layout optimization and determine potential environmental impacts of deploying wave farms.

Future Work:

SNL will continue to perform comparison to experimental data from the Oregon State Tsunami Wave basin array tests. A Beta version will be released in FY14.



RCW based WEC power absorption

SWAN Application - Wave Modeling for Far-field Environmental Effects

SNL-SWAN includes a WEC Module capable of modeling the energy extraction of WECs via three methods:

- Baseline SWAN's obstacle formulation
- A WEC's relative capture width (RCW) curve
- A WEC's power matrix.

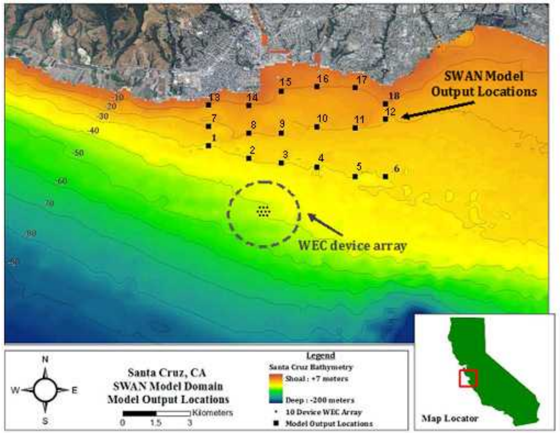
Incorporated eight different WEC device types, four array sizes, and three device spacing's into the validated Monterey Bay model domain at three different locations and performed sensitivity analysis of wave propagation and obstruction parameters.

Objective: To accelerate environmentally responsible deployment of WEC devices through the development and application of WEC friendly wave propagation models to assess the environmental effects created by changes in wave climates resulting from deployment of WEC arrays in the ocean.

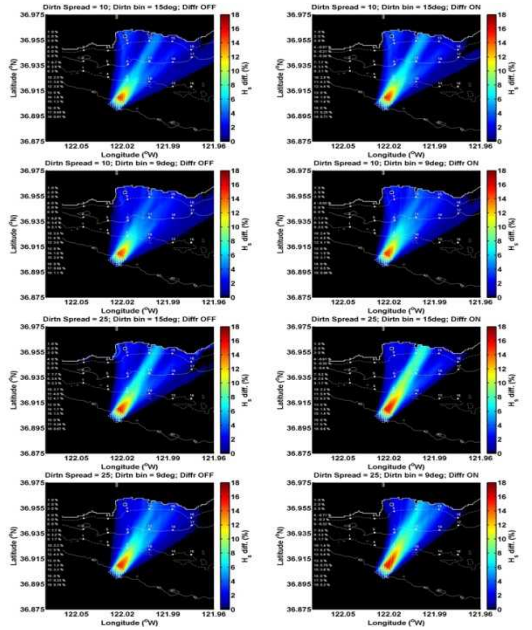
Project Impact:

This project fulfills an industry wide need for development and application of wave propagation models to

- Accurately inform developers and regulators about site-specific available wave power and realistic generation potential based on quantifiable environmental effects.
- The modeling tools will accelerate deployment of early generation devices and arrays through enhanced site planning and evaluation
- Improve DOE WWPP's modeling capability for assessing wave energy resources and environmental impacts.



SNL-SWAN model domain with example 10-WEC array



SNL-SWAN % difference in H_s with and without a WEC array

Open Source and Outreach for Current and Tidal Turbine Models

Sandia National Laboratories

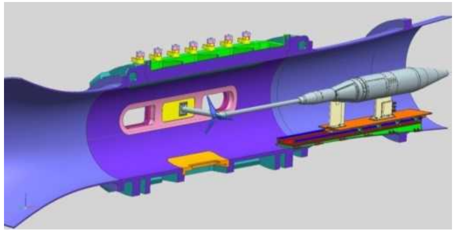
CACTUS code User's Manual has been developed and released.

The model was validated with data collected for a 1:8.7 scale model of the Sandia axial-flow turbine at the Applied Research Laboratory (ARL) at Penn State University.

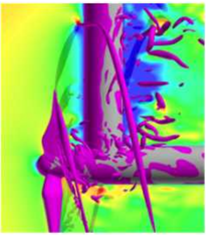
Objective: Improve MHK industry modeling capabilities for hydrokinetic turbine design and analysis and provide developers and researchers an open source CACTUS model that incorporates techniques unique to a single package and allows for rapid design turnaround.

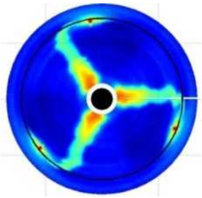
Project Impact: This simulation capability will improve the performance of the next generation of axial-flow and cross-flow hydrokinetic turbines. Many researchers and industry developers are actively using this code.

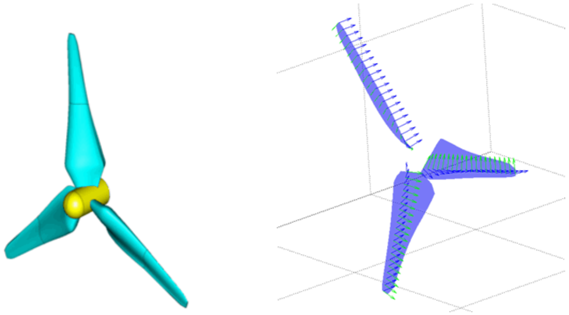
Future Work: Experimental performance data collected from scaled model testing of the Reference Model 2 cross-flow turbine at The St. Anthony Falls Laboratory Main Channel, at the University of Minnesota, will be used to evaluate CACTUS model performance simulating a cross-flow hydrokinetic turbine.



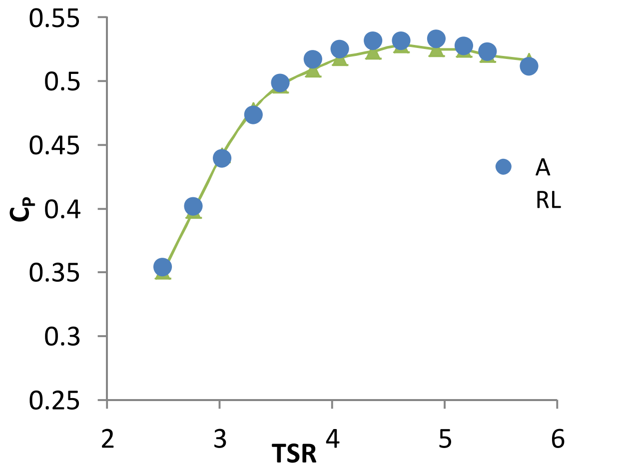
Experimental set-up at ARL water tunnel





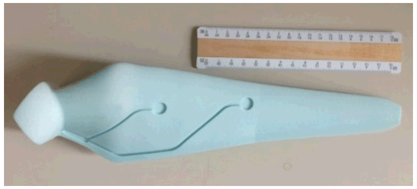


Sandia hydrokinetic turbine (left) and CACTUS model of turbine (right)



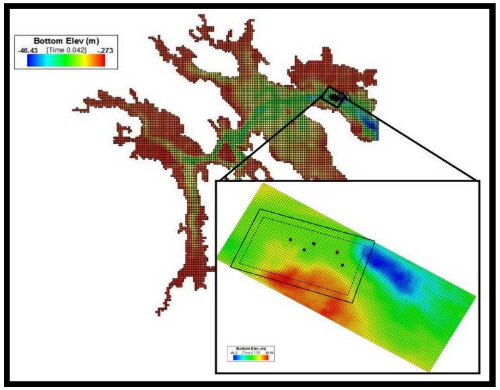
CACTUS predicted power curve (green) compared to experimental measurements from ARL

Rapid prototype foil showing location of strain gages



MHK Device Performance Modeling and Analysis

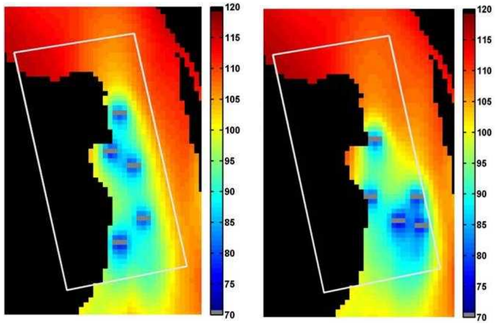
- Developed a current energy converter (CEC) array optimization framework
  - Designed to determine optimal device placement to maximize array performance and minimize potential environmental effects.
- Developed a refined grid SNL-EFDC model domain
  - Encompassing Ocean Renewable Power Company test site in Cobscook Bay, ME and applied the array optimization methodology over a 29-day period.
- The SNL-EFDC optimized arrangement of the proposed 5 CEC array showed nearly 20% increase in power production



Cobscook Bay, ME regional and local model domains

Objective:

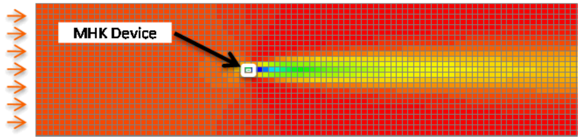
- To reduce cost of energy through strategic deployment of MHK devices
- Enhance and apply simulation tools to investigate optimal array spacing



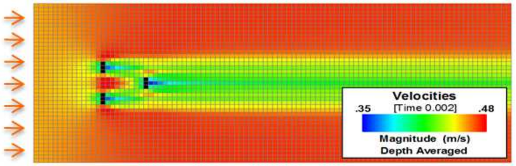
Preliminary (left) and optimized (right) 5-CEC arrays

Project Impact:

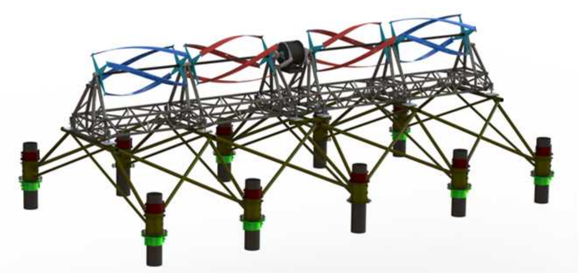
- Application of SNL-EFDC at key industry sites will help maximize power and minimize potential environmental effects. (Sediment Transport)
- Mature the simulation modeling to become more highly technically defensible
- Increase confidence in its use as it becomes the industry standard tool.



SNL-EFDC simulation of single turbine in a test flume



Simulation of actuator disk array in a test flume

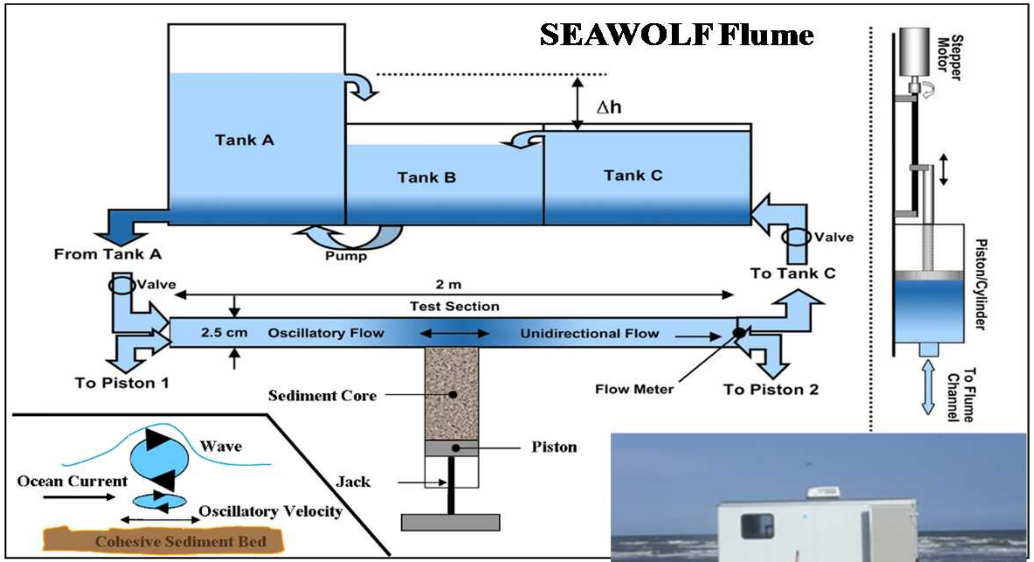


Schematic of the ORPC TideGen^{TM} turbine.

Sediment Field Measurements & Dynamics Lab

ASSET and SEAWOLF Flumes

- Mobile for onsite measurements
- Simulate extreme events
- Measures
  - Erosion rate
  - Critical shear stress
  - Transport mode
  - Stratification
  - Cohesive properties



Sediment Dynamics Laboratory

Acoustics

Finalized acoustic signature predictions for 5-m diameter, 3-bladed, horizontal axis reference current energy conversion device using a proprietary BEM model.

Completed initial validation of the BEM model against test data for flow and noise generation of a scaled model of a similar CEC device to the one described above.

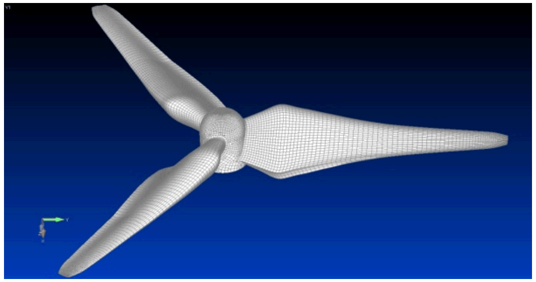
Objective:

- To accelerate environmentally responsible deployment of MHK devices by developing MHK-specific acoustic simulation tools to predict device operational noise enabling quieter designs.

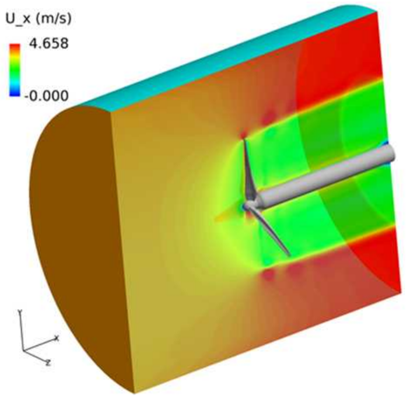
Project Impact:

- Provide easily accessible open source acoustic tools that will enable the MHK industry to predict CEC noise generation in advance of deployment
- Helping the industry design MHK devices and array layouts that minimize environmental effects created by MHK acoustics.

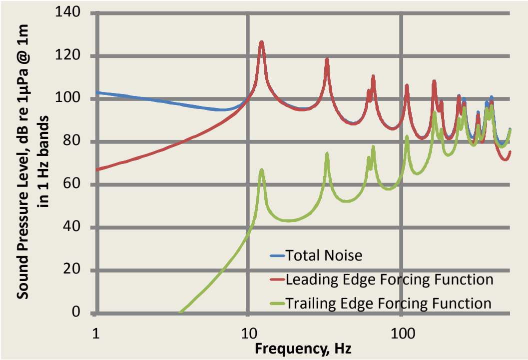
Future Work: Develop methodologies and open source tool sets to predict CEC noise generation and general MHK noise propagation in the marine environment.



Finite element mesh of reference CEC turbine



Flow computational domain with axial velocity contour



Predicted sound pressure levels from reference CEC turbine

Performance Testing for Hydrokinetic Canal Effects

Sandia National Laboratories

Hydrokinetic (HK) electricity generation from canals shows potential to support local electricity needs with minimal regulatory or capital investment vs. conventional hydropower. However,

- Effects of HK on water operations in canals not well understood
- No experience full-scale *in-situ* testing of HK devices in canals

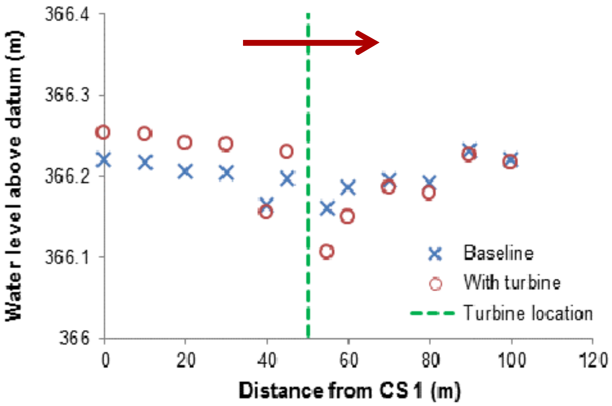
Objective:

- Enable stakeholders to accurately quantify HK turbine performance and effects on water operations in canals
- Product: Best practice manuals for HK device performance characterization and quantifying effects to water operations

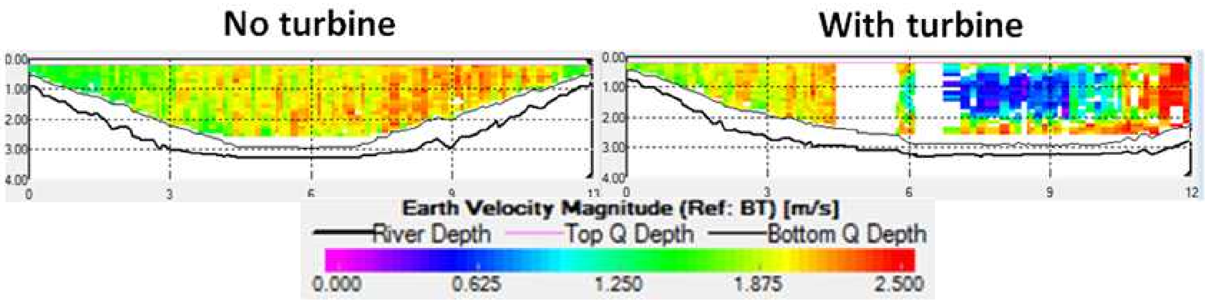
Study site near Pomona, WA

Performance testing and analysis

- Field measurements
  - Water levels
  - Inflow and wake velocities
  - Turbulence
  - Thrust and torque
- Analysis of all flow field measurements around device
- Develop performance curves



Water level differences along canal



Velocity magnitude downstream turbine utilizing Acoustic Doppler Current Profiler