SAND2012-8689P

Water Power Program.

Sandia National Laboratories

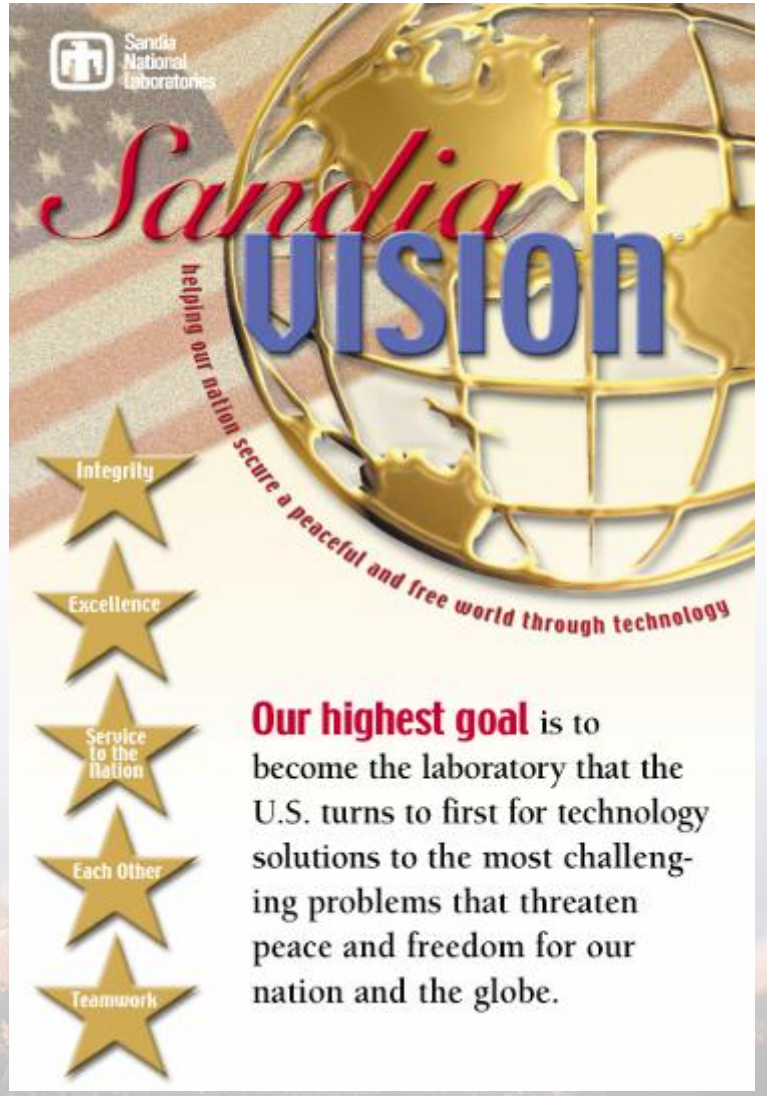
October 22nd, 2012

Prepared for WavEC

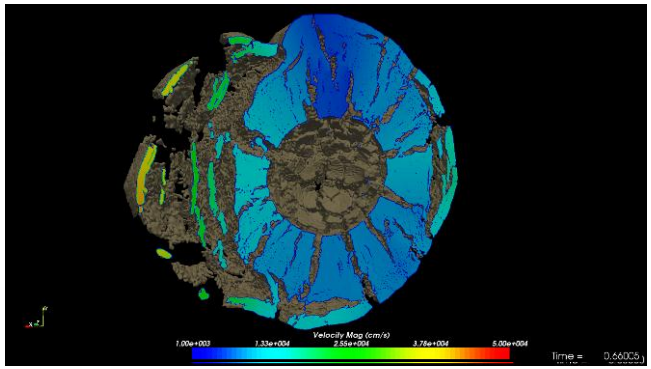
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Our Business: National Security

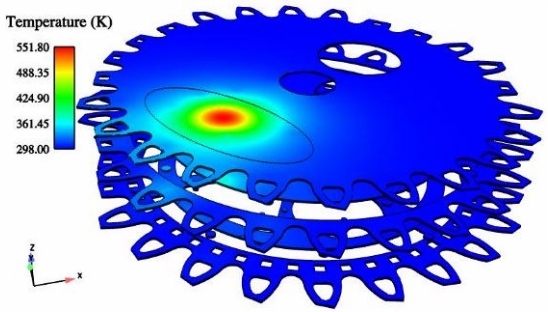
- Broad mission in developing science and technology applications to meet our rapidly changing, complex national security challenges
- Safety, security and reliability of our nation's nuclear weapon stockpile



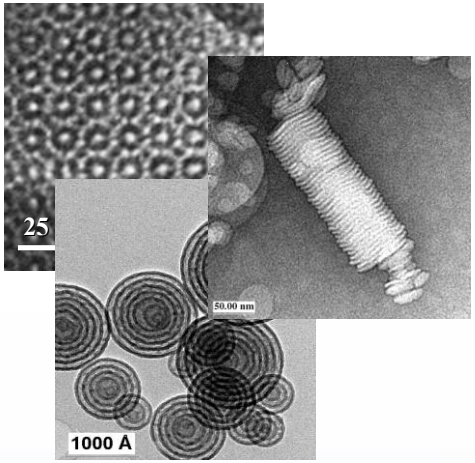
Our Mission Focus Relies on Strong Science and Engineering



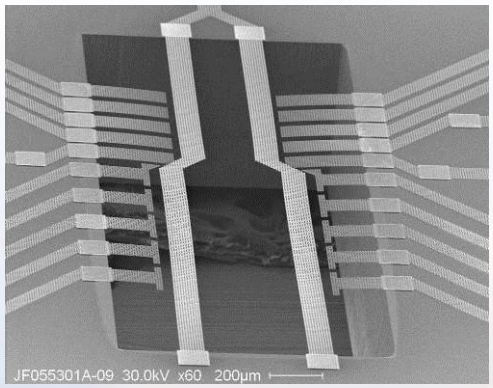
Computational and Information sciences



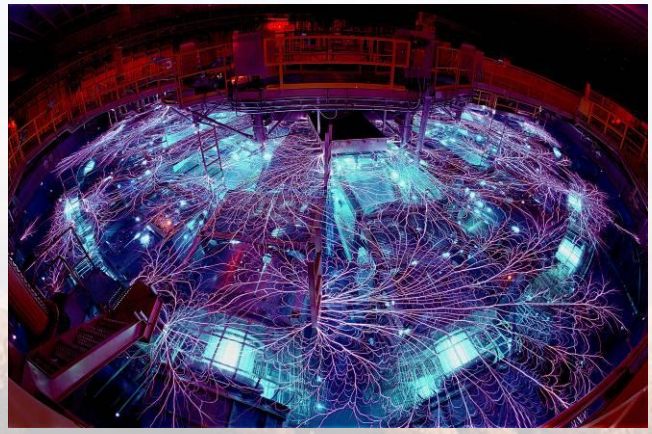
Engineering Sciences



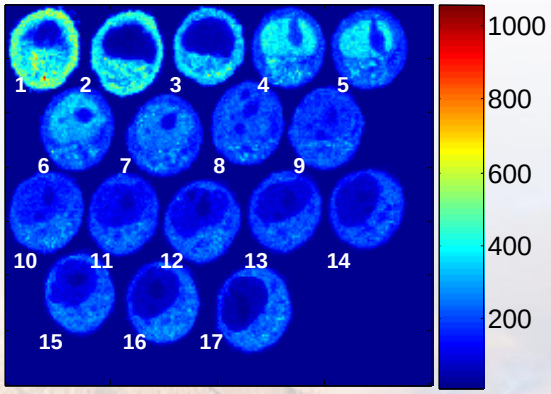
Materials Science and Technology



Microelectronics and Photonics



Pulsed Power



Bioscience

National Nuclear Security Administration

Sandia National Laboratories

Distributed Facilities

Albuquerque,
New Mexico

Kauai Test Facility,
Hawaii

Tonopah Test Range,
Nevada

Yucca Mountain,
Nevada

WIPP, New Mexico

Pantex, Texas

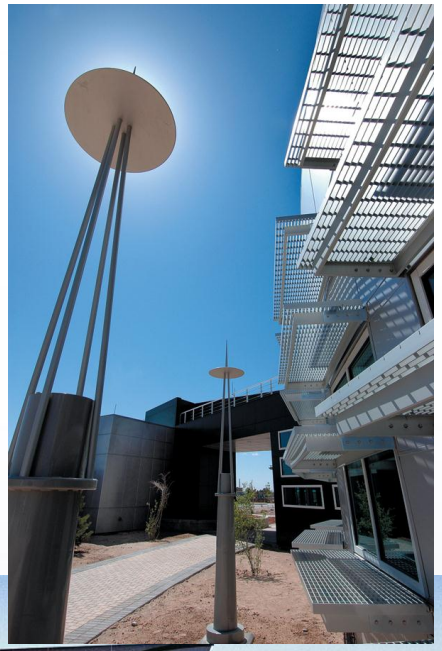
Livermore, California

Sandia

Sandia National Laboratories

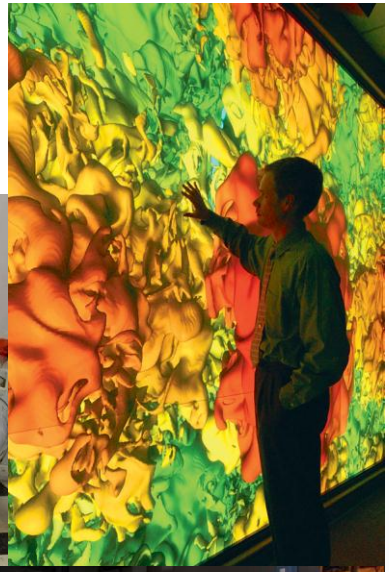
Unparalleled Large-Scale Facilities and Test Capabilities

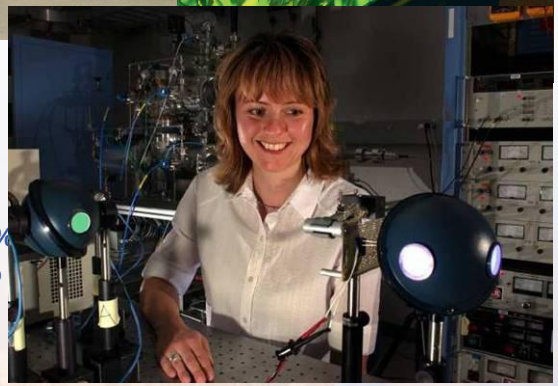
- User facilities
- Designated national capabilities
- Z-Machine and radiation effects
- Real-life physical test ranges

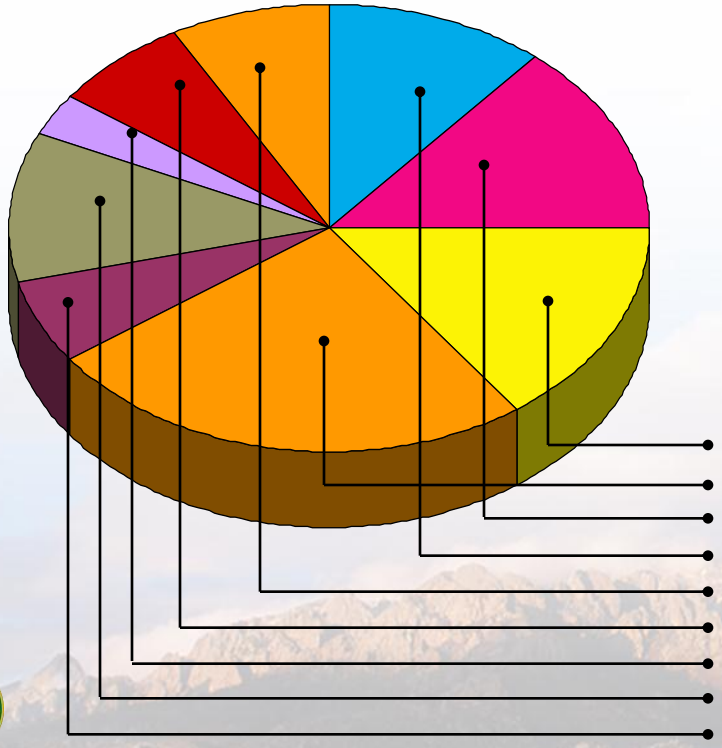


Highly Skilled Workforce

- More than 8,600 full-time employees
- More than 1,500 PhDs and 2,700 MS/MAs
  - 2,200 on-site contractors
  - $2.7 billion FY08 total bud







Mechanical Engineering - 16%
Electrical Engineering - 22%
Other Engineering - 15%
Other Science - 6 %
Physics - 6%
Chemistry - 6%
Math - 2%
Computing - 16%
Other Fields - 6 %

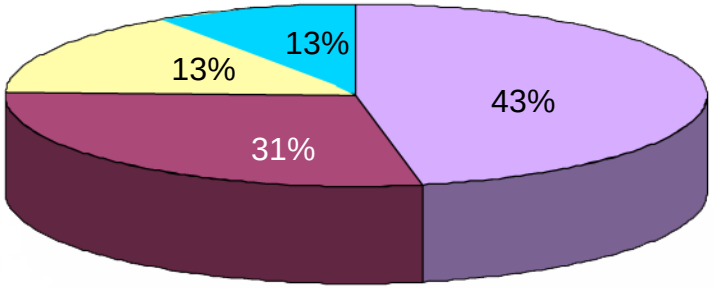
Sandia National Laboratories

People and Budget

(As of October 15, 2010)

- On-site workforce: 11,677
- Regular employees: 8,607
- Gross payroll: ~$898.7 million

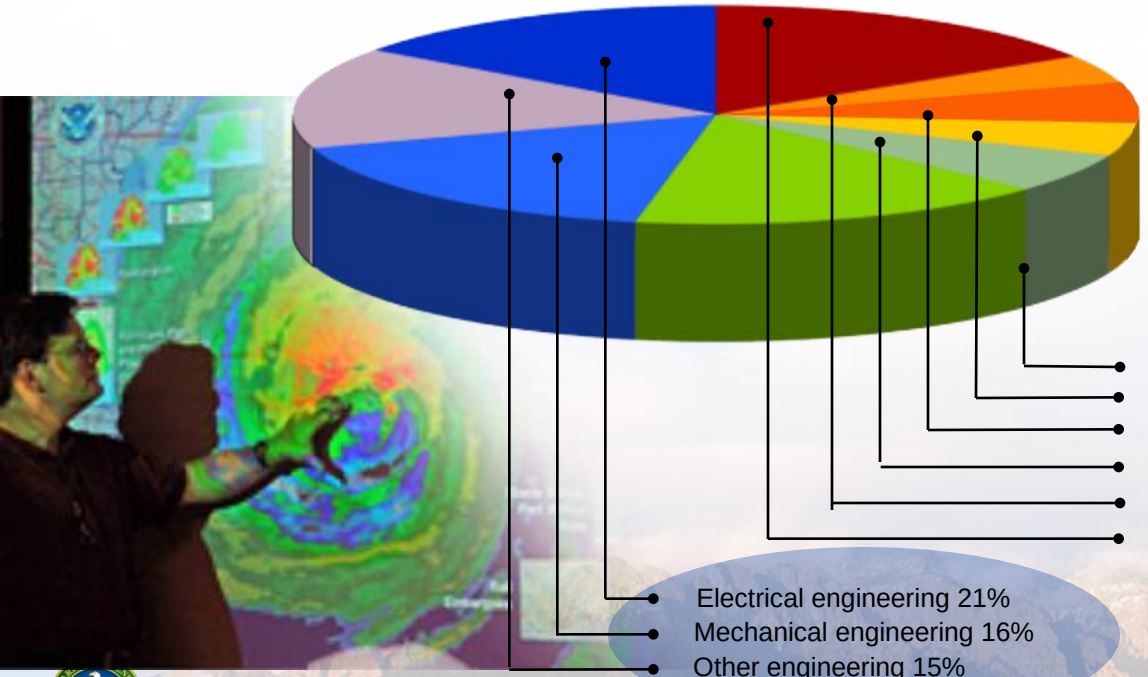
FY10 operating revenue
$2.3 billion



(Operating Budget)

- Nuclear Weapons
- Defense Systems & Assessments
- Energy, Climate, & Infrastructure Security
- International, Homeland, and Nuclear Security

Technical staff (4,277) by discipline:



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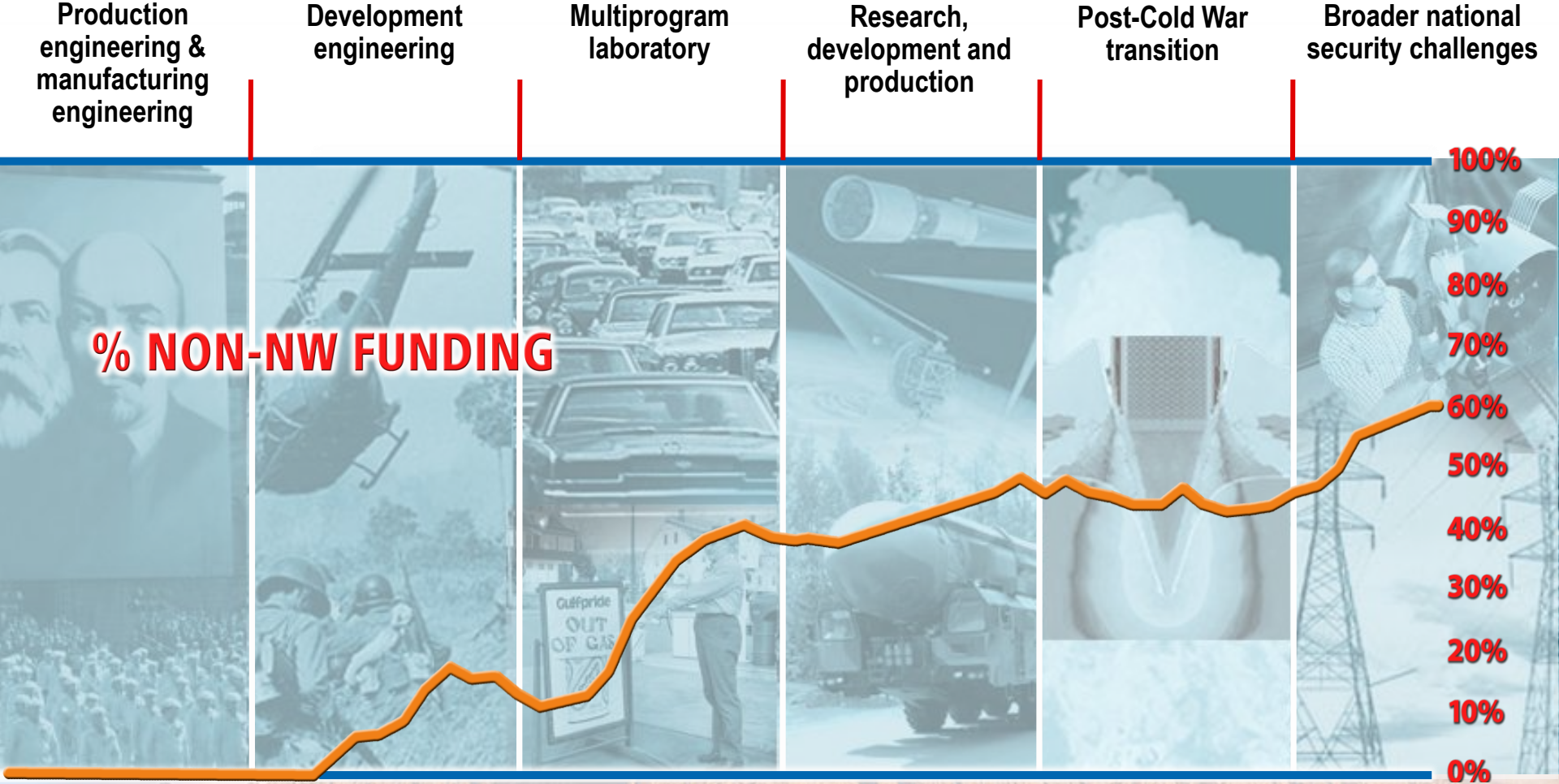
The Mission Has Evolved for Decades



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Catastrophic Event Mitigation

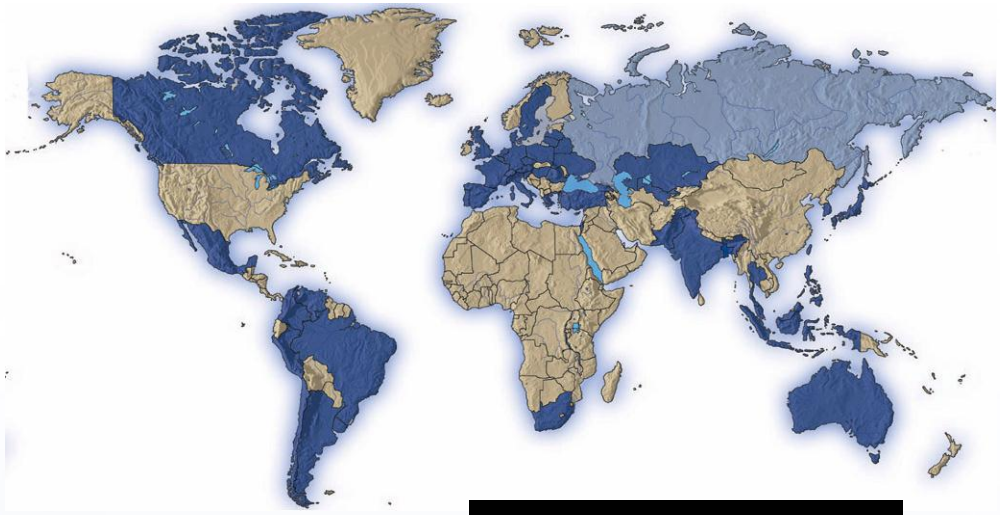
- Chemical and Biological Countermeasures
- Radiological and Nuclear Countermeasures
- Explosives Countermeasures
- Information Analysis
- Red Teaming
- Border and Transportation Security
- Systems Analysis

National Nuclear Security Administration

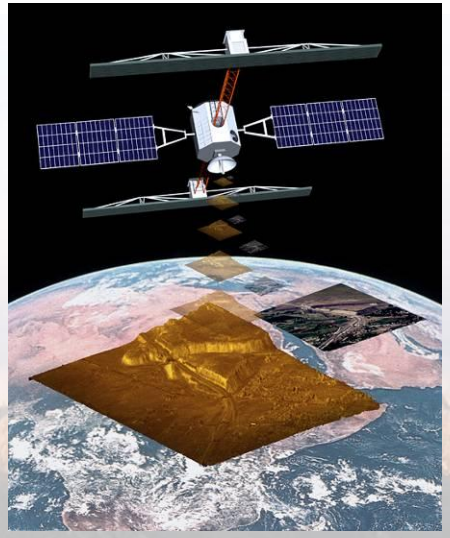
Sandia National Laboratories

Energy, Resources, and Nonproliferation

Making the World a Safer Place



- Technologies for detecting proliferation activities
- Performance and vulnerability assessments
- Monitoring and verification
- Cooperative international security programs
- Physical security



National Nuclear Security Administration

Sandia National Laboratories

Energy, Resources, and Nonproliferation

Energy, Water, and Security Enabled by Science & Technology

- Secure energy supplies for national security
- Clean, abundant and affordable energy
- Water research
- Infrastructure protection

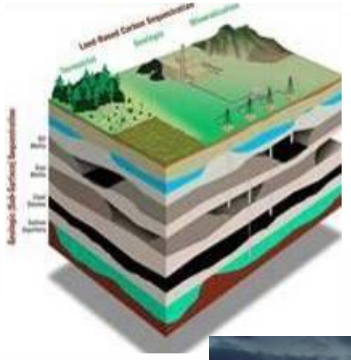
National Nuclear Security Administration

Sandia National Laboratories

Energy Policy Act of 2005

- Encourages Expanded Energy Supplies (Fossil, Renewables, Nuclear and Hydrogen)
- Supports Siting New Nuclear Power Plants
- Enhances Liquefied Natural Gas (LNG) Facility Siting
- Vehicle Efficiency
- Improved Electric Grid Reliability
- Lighting

Energy Futures Program



Develop and Demonstrate Persistent Energy Sources – Electricity and Transportation
Create a Flexible and Enabling Energy Infrastructure
Enhance Energy Storage Capabilities

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Renewable Energy and Storage Activities

- Concentrating Solar Power

- Wind

- Energy Storage

- Geothermal

- Photovoltaics

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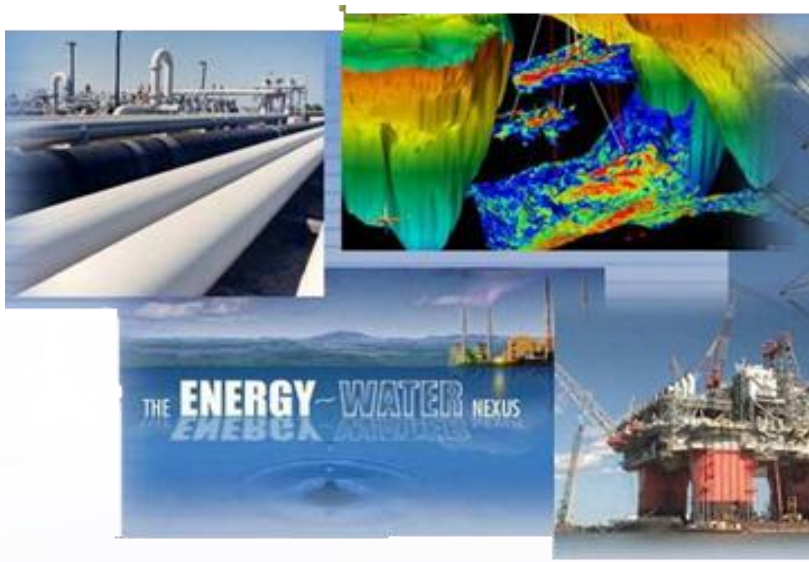
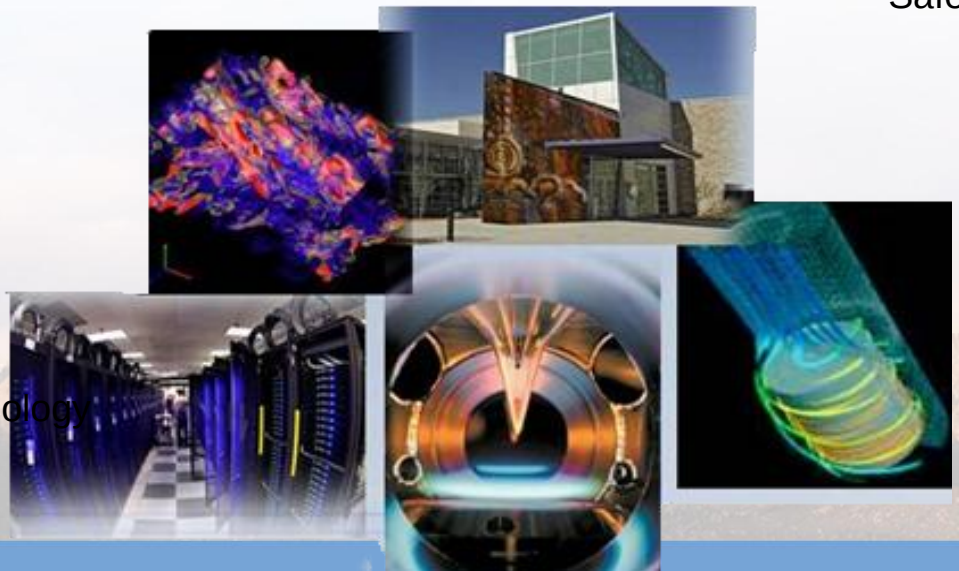
Sandia National Laboratories are Contributing to Our Nation's Energy Future

Energy Supply, Energy Efficiency, and Environmental Stewardship



Safe, Secure, Reliable Energy Supply and Infrastructure



Science and Technology

Sandia National Laboratories

Water Power Program

- **Marine-Hyrdo-Kinetics--MHK**
  - Turbines
  - WECs
  - Reference Models
- **Offshore Wind**
  - Design and Tool Development
  - Structural
  - Regulatory
- **Core Topics**
  - Mooring
  - Sediments
  - Materials
  - Controls

- http://energy.sandia.gov/

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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

Marine Technologies

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

Water Power MHK

Offshore Wind

Sandia National Laboratories

Marine Hydro-Kinetic

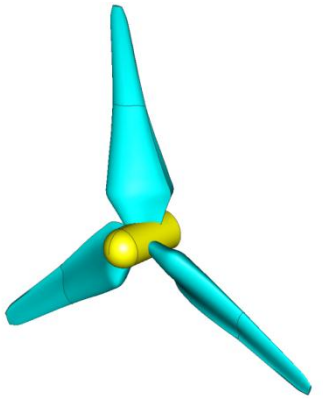
Turbines

WECs

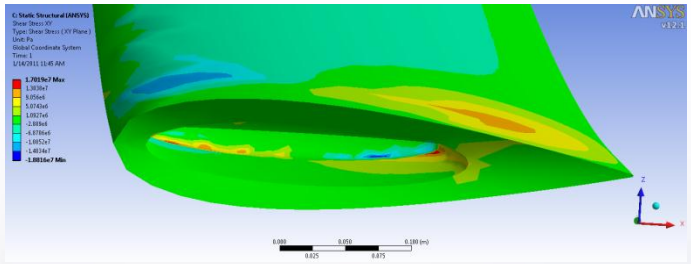
Reference Model

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Hydro-Turbine Design



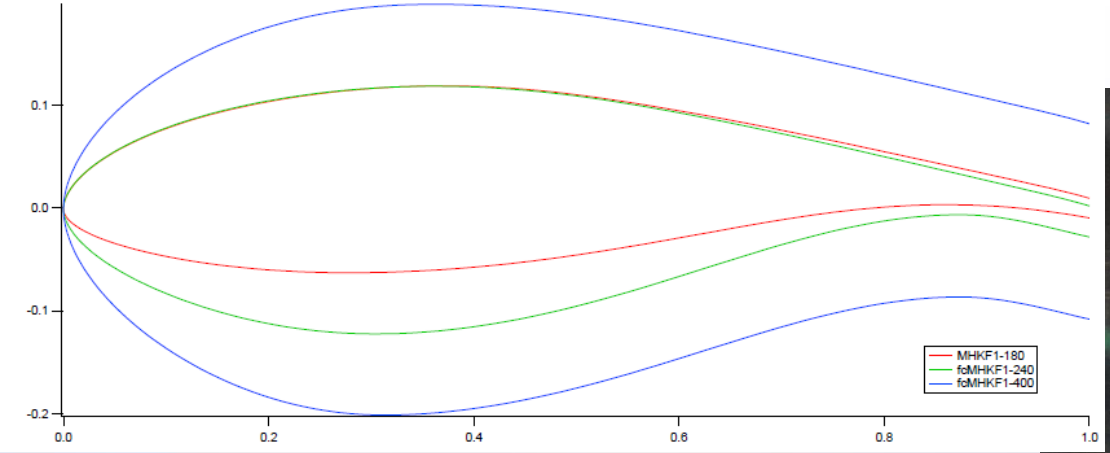
- **Unique resource and physics compared to wind**
  - Density
  - Optimal performance for site characteristics
  - Soiling, erosion, biofouling, animal/debris strike
  - Cavitation
  - Noise

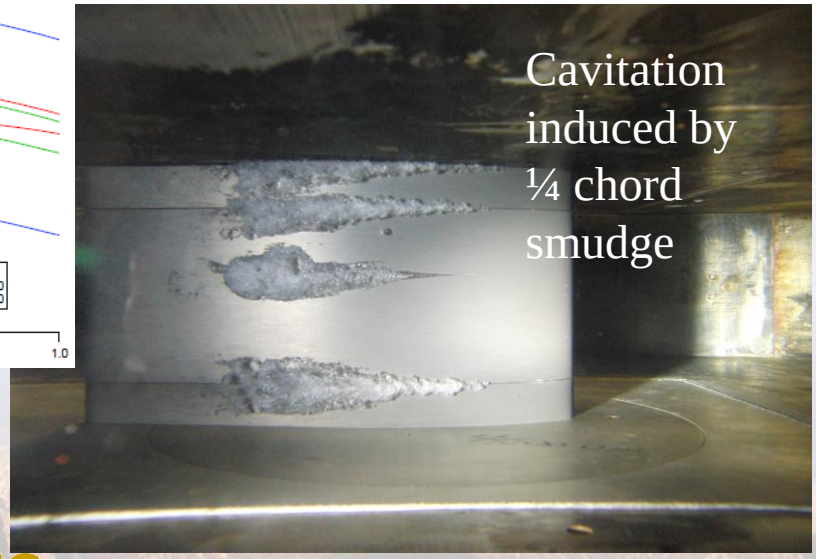


- **Design process**
  - New hydrofoil family
  - Optimization of rotor for strength and performance
  - Stress and hydrodynamic analyses
  - Acoustic predictions

Foil design

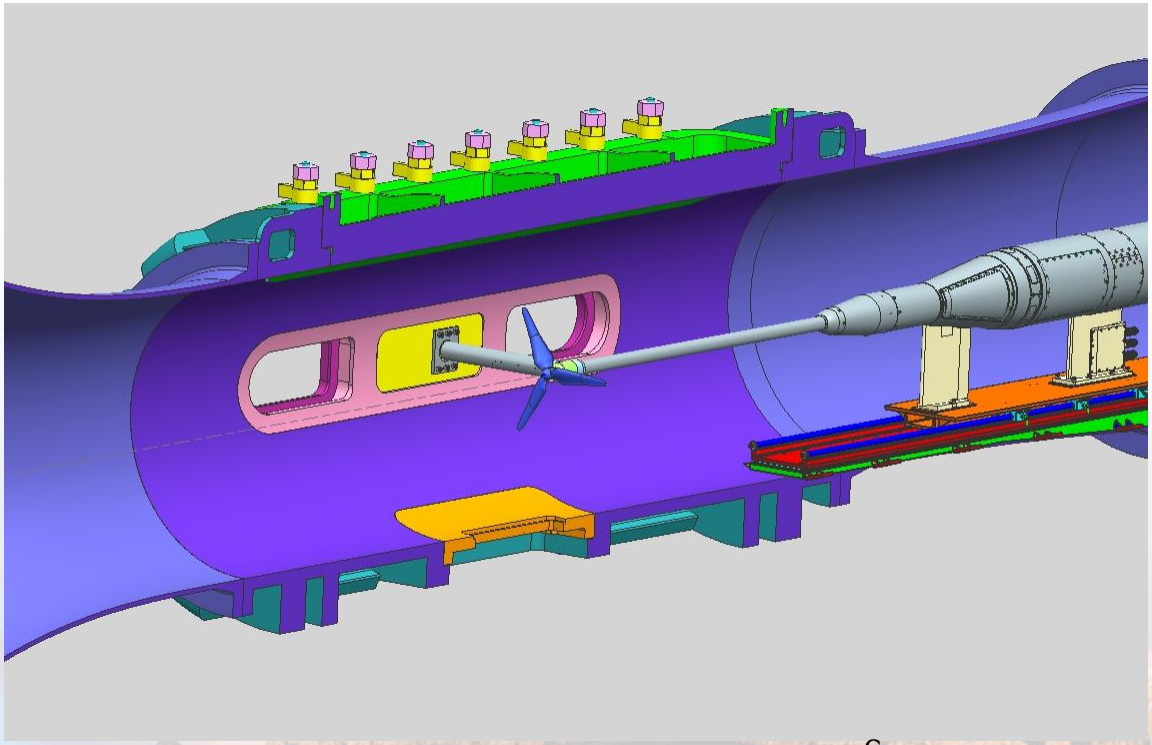
- **Collaboration with UC Davis to design a hydrofoil family**
  - Increased turbine performance
  - Reduced susceptibility to soiling
  - Reduced trailing edge vibration and shedding (anti-singing)

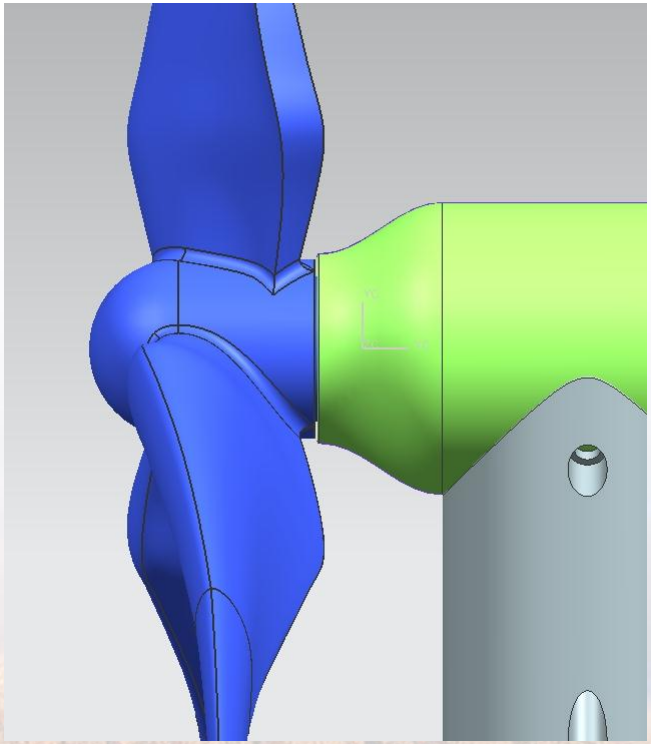




PSU ARL 48” Tunnel Test

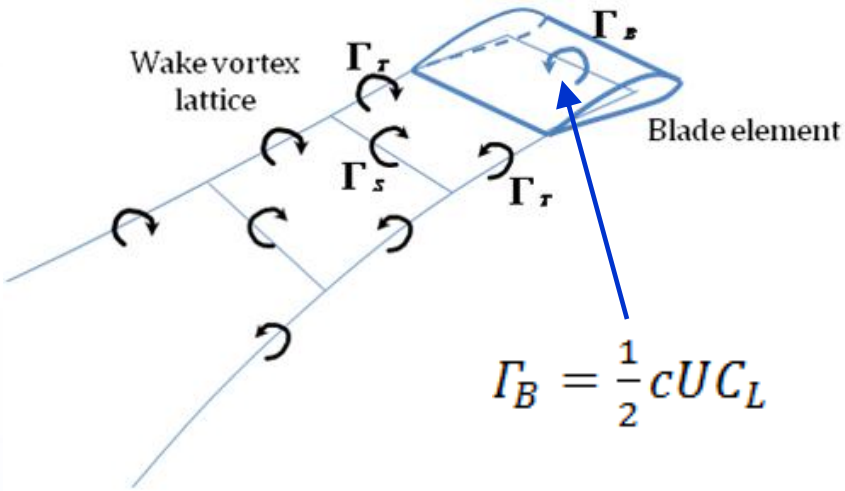
- **Test planned for October, 2012**
  - Load cell, torque/thrust, pressure, acoustic, LDV
  - On-design test, max 7 m/s @ 900 rpm

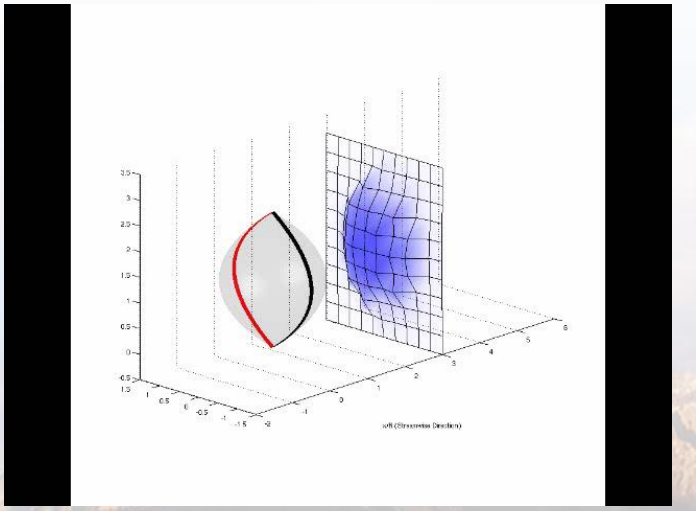




E. Johnson &
M. Barone

Code for Axial and Cross-flow TUrbine Simulation





- Blades represented as “lifting lines”, divided into blade elements
- Blade forces determined from foil data input
- Rotor wake represented with vortex elements
- Initial model of support drag is included
- Time-domain simulation

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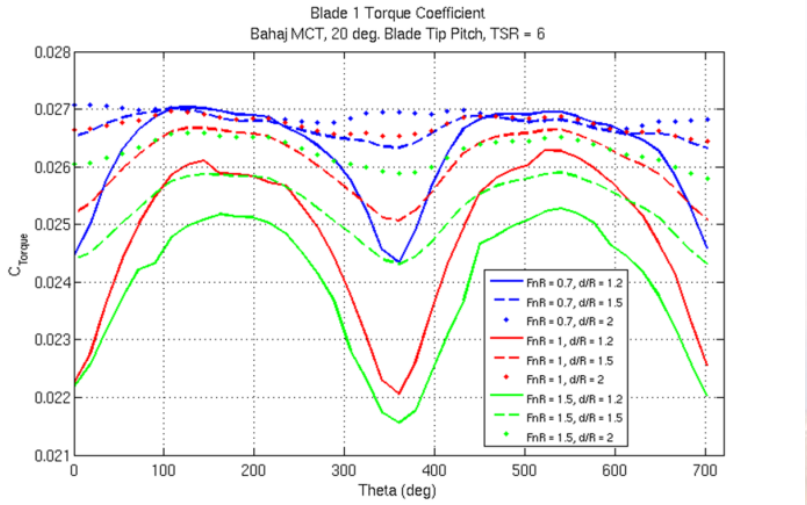
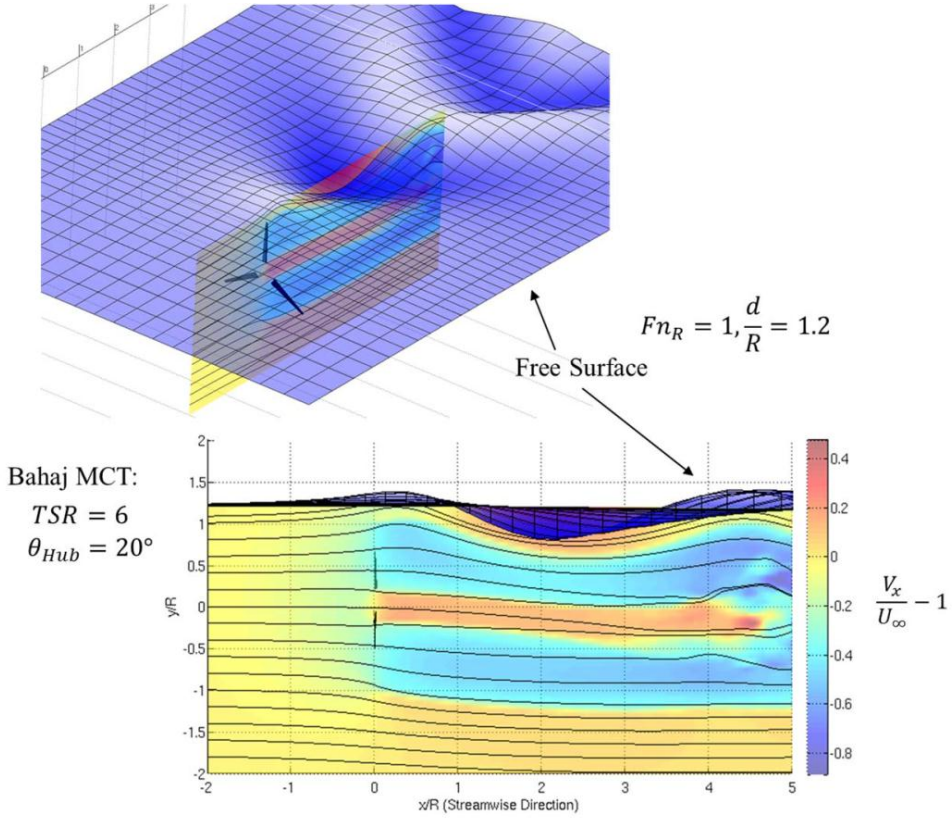
Free Surface and Dynamic Stall

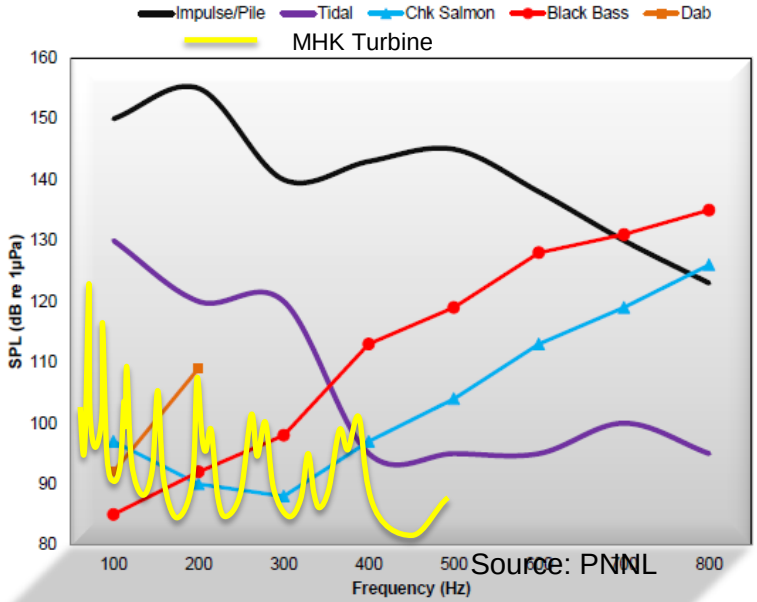
- Free surface results compared well to Kelvin wave theory
- Beddoes – Leishman dynamic stall model



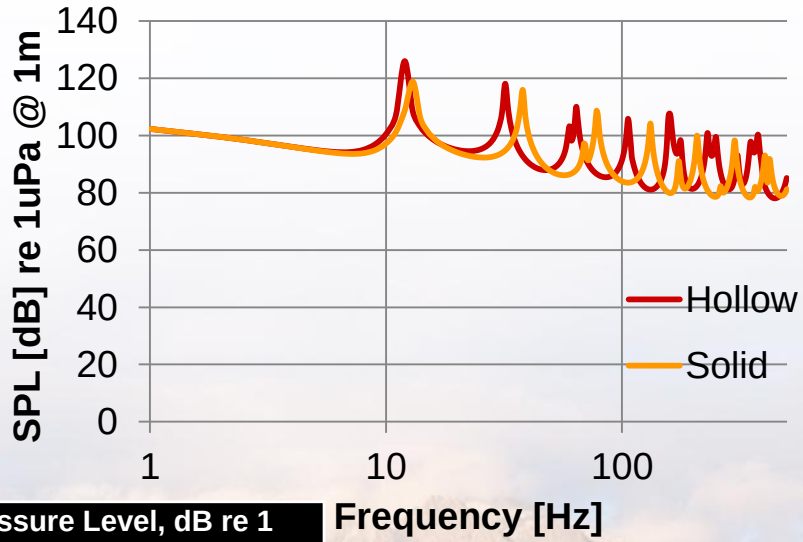


MHK Turbine Acoustic Analysis

- **Requires RANS+ to calculate integrated values**
  - Friction velocity, displacement thickness, etc.
- **With PSU-ARL's CHAMP framework, looked at a traditionally designed blade**
- **Does not include generator or tower noise**
- **Numerical analyses to be compared against September tunnel tests**



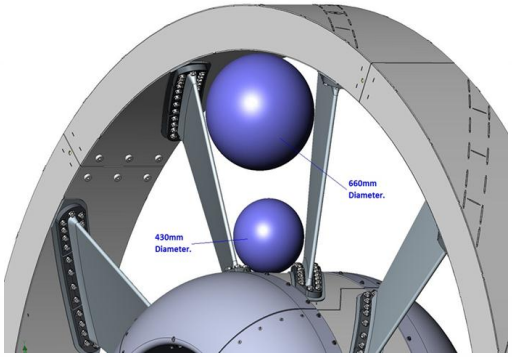
Source: PNNL

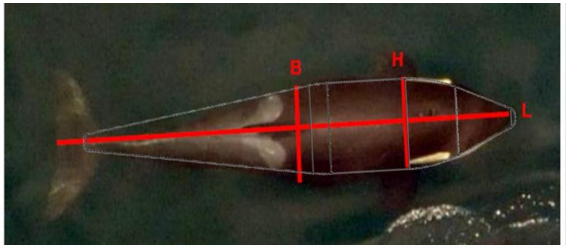


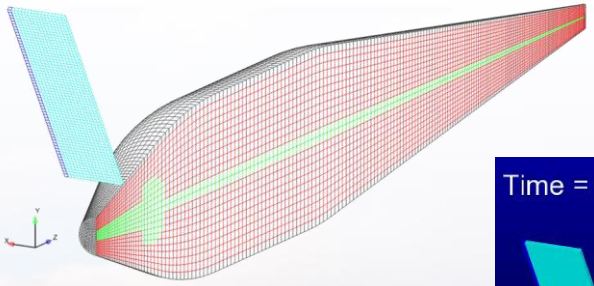
Sound Pressure Level, dB re 1 µPa² at 1 m integrated from 0 Hz to 500 Hz			
	LE	TE	LE&TE
Hollow	127.8	112.1	128.0
Solid	122.9	111.3	123.3

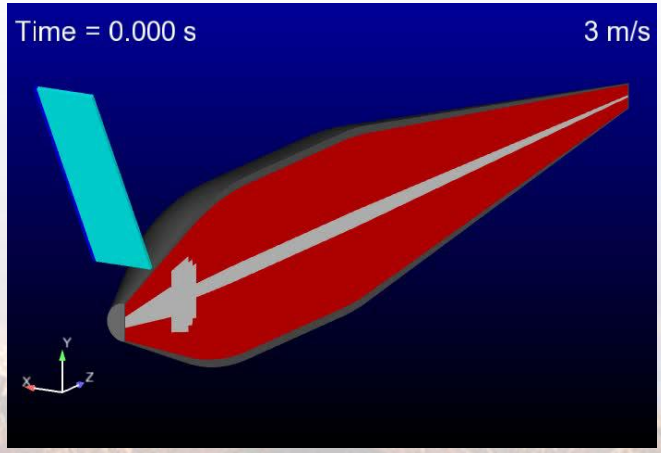
MHK Interactions with Marine Mammals

- **Analysis of Blade Strike for a ducted turbine on an adult Southern Resident Killer Whale**
  - Used basic geometry and tissue material properties for the whale
  - Used Sandia structural dynamics code to model a free body impact
- **Results showed minor bruising with no significant tissue damage for worst case impact scenario**









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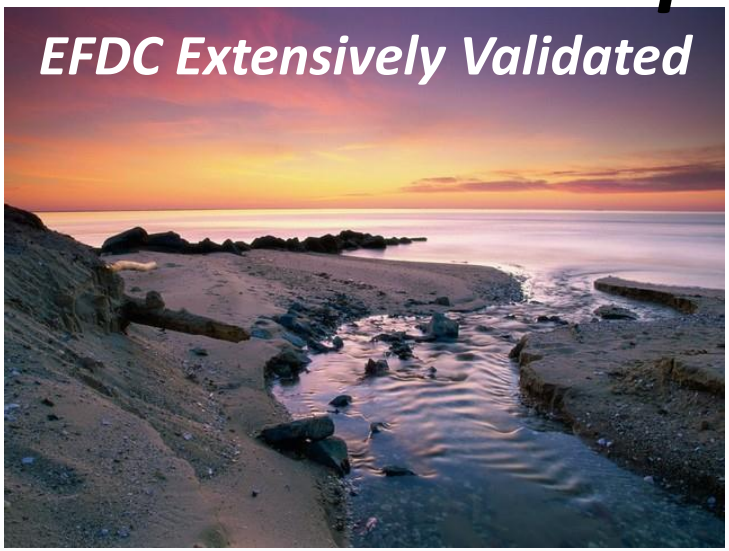
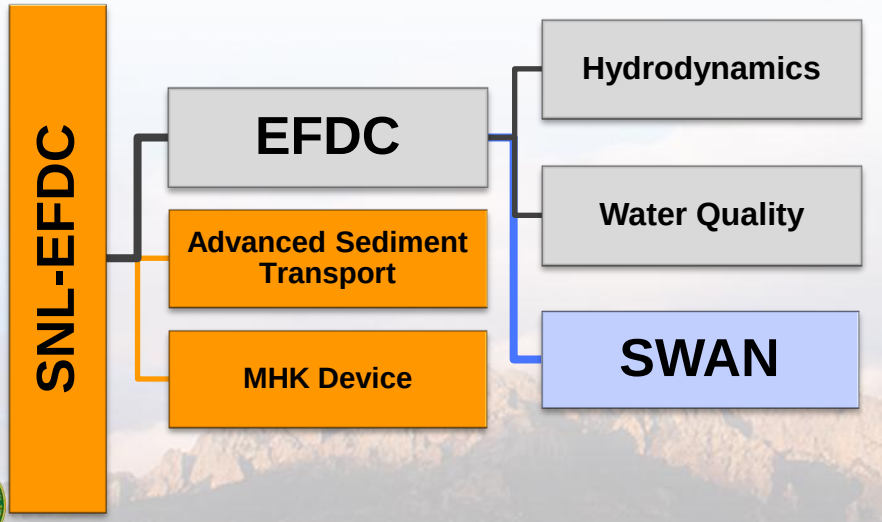
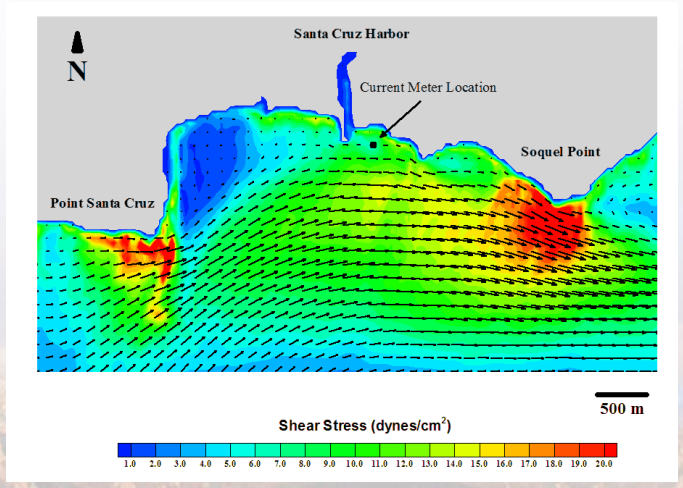
SNL-Environmental Fluid Dynamics Code: Flow and Transport

- **EPA open-source code**
  - Curvilinear orthogonal grid
  - Coupled-equation solution
    - Mass conservation
    - Momentum conservation
    - *K-ε conservation*
    - Temperature transport
    - Salinity transport
    - Dye transport



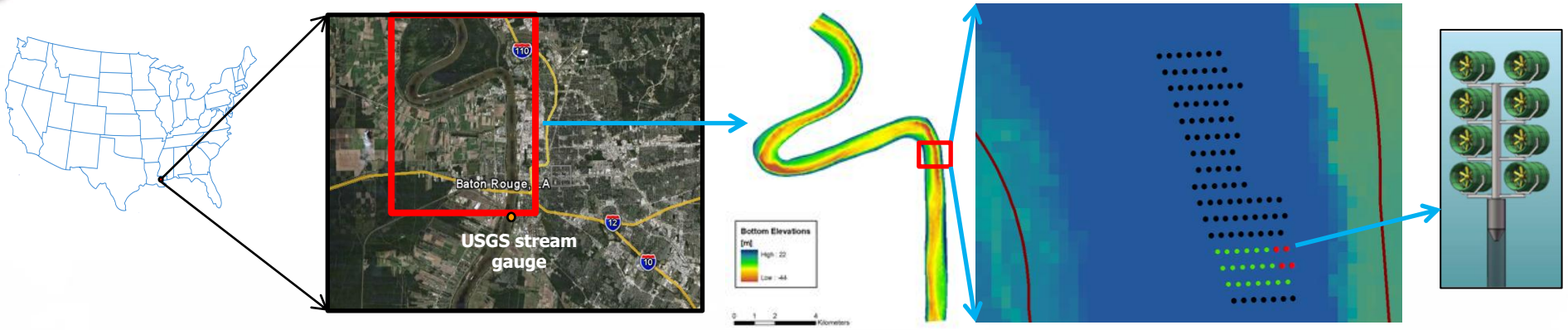




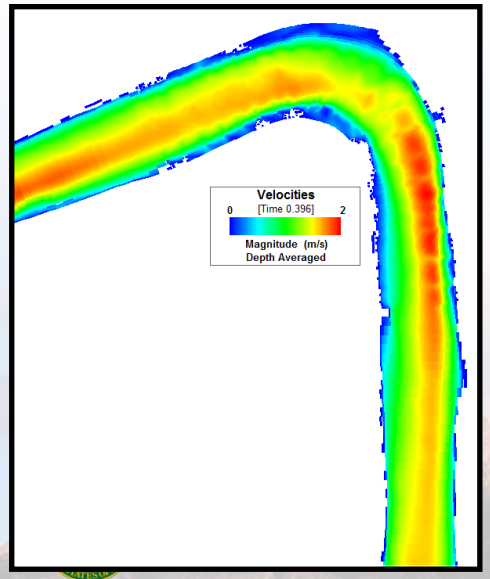
J. Barco &
J. Roberts

Demonstration Sites

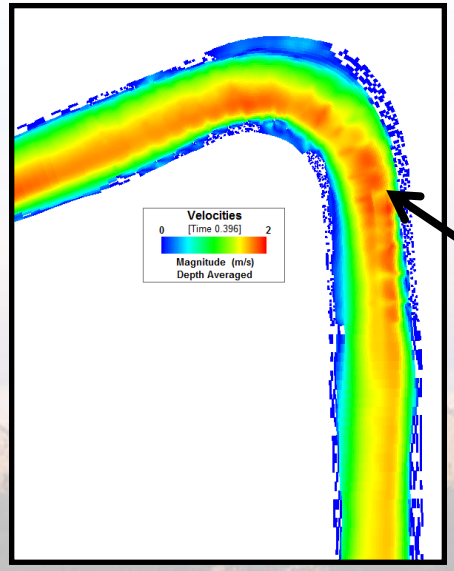
Scotlandville Bend, Mississippi River, Louisiana



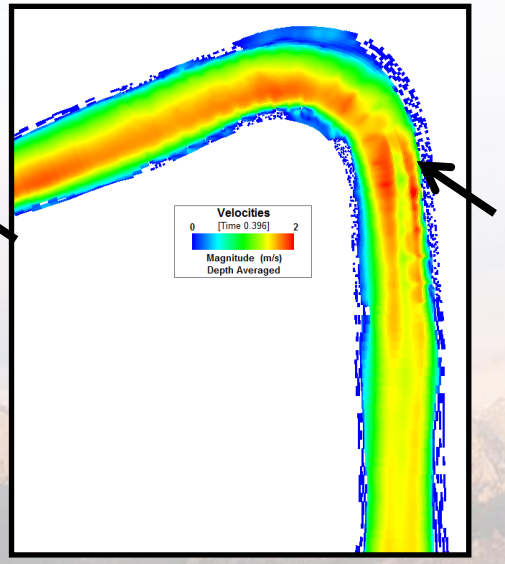
Simulated depth-averaged velocities without turbine array



~ Hub height velocities with 23-pilings (112 MHK-turbines)



~ Hub height velocities with 112-pilings (534 MHK-turbines)



- Evaluation of potential changes to the hydrodynamics in a real system using SNL-EFDC
- Field velocities showed decreasing velocities through the MHK array as energy is generated, turbulence introduced, and flow obstructed
- Modeling/scenario analysis can assist cost-effective planning of MHK technology

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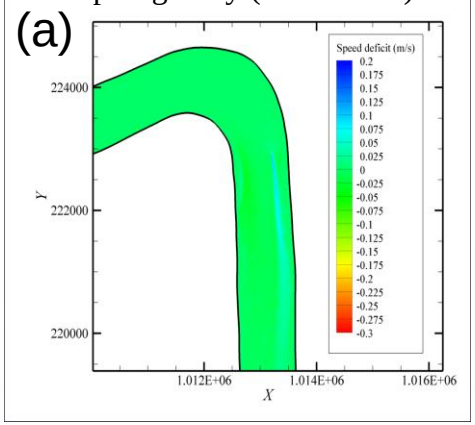
J. Roberts

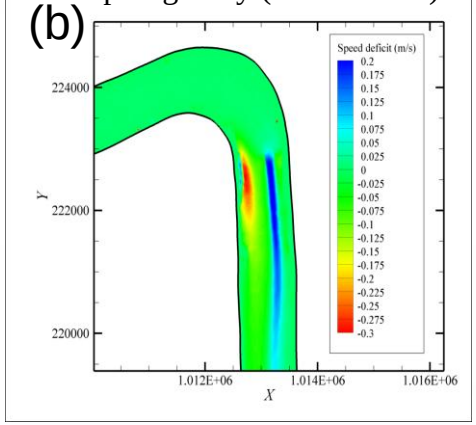
Demonstration Sites

Scotlandville Bend, Mississippi River, Louisiana

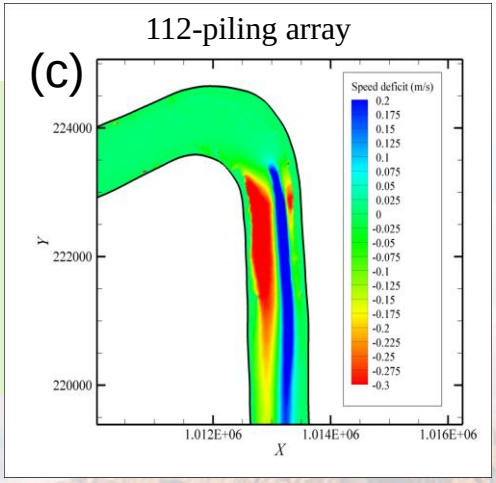
4-piling array (12 turbines)



23-piling array (112 turbines)

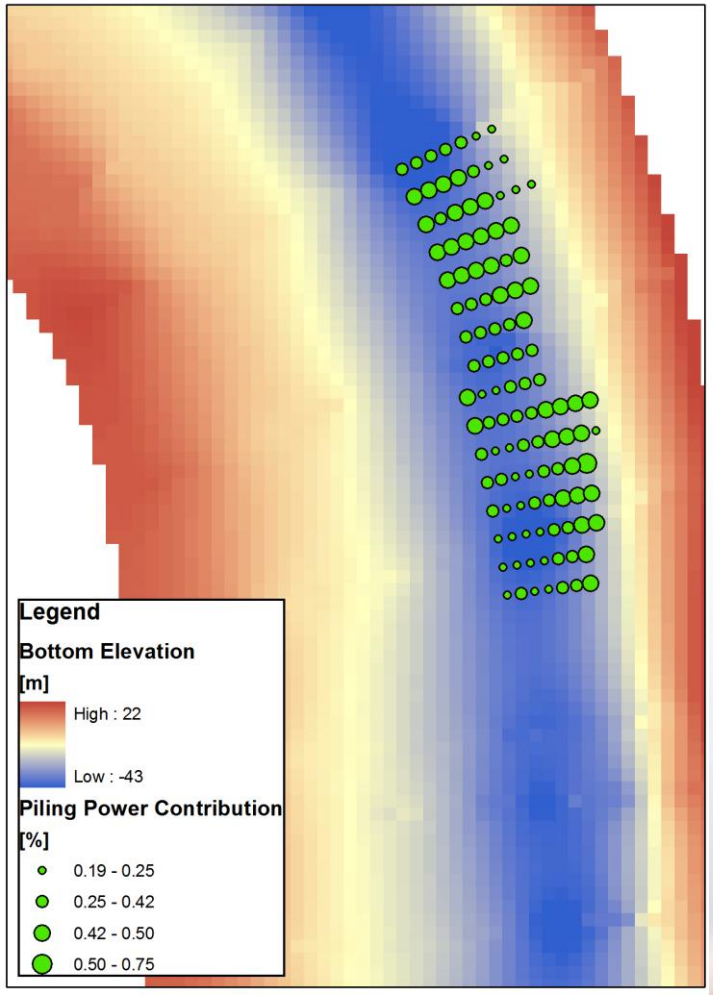


112-piling array



The 4-piling array shows smaller velocities differences, while 112-piling shows the highest differences

The contribution of power in each piling is mainly driven by the flow velocities, number of pairs of turbines and flow piling blockage



Marine Hydro-Kinetic

Turbines

WECs

Reference Model

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

National Nuclear Security Administration

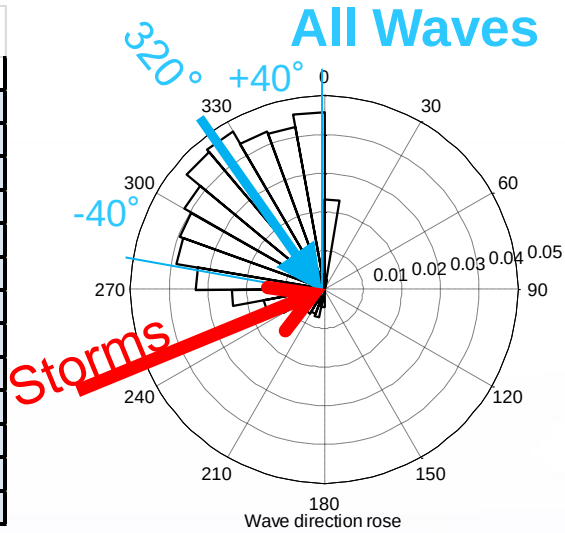
Sandia National Laboratories

D. Bull &
J. Berg

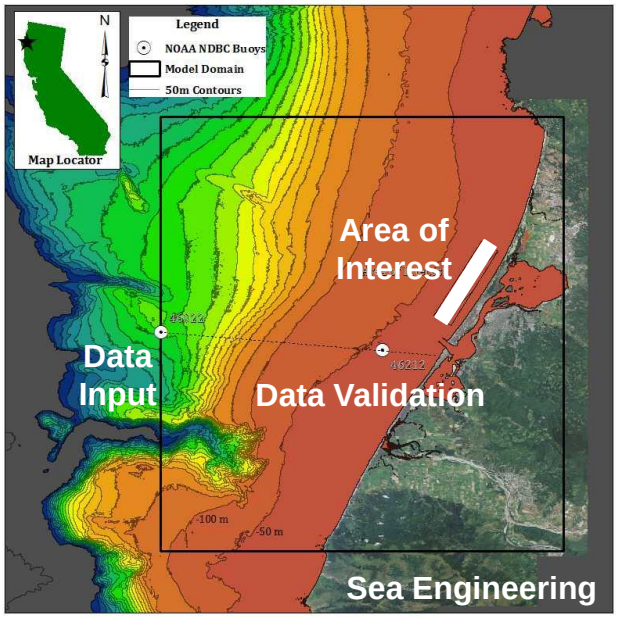
Deployment Climates

Operational Climate

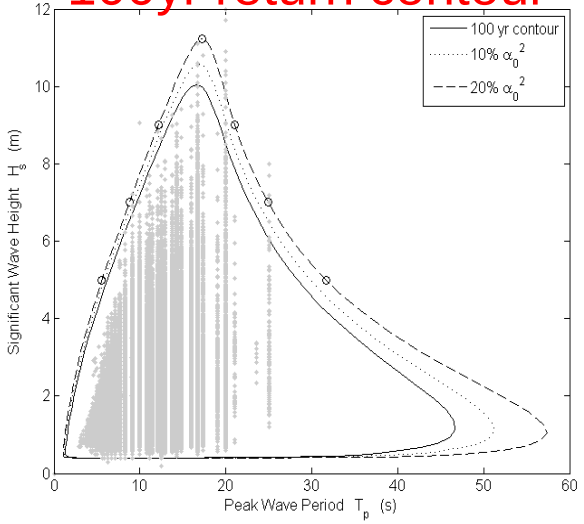
Significant Wave Height, Hs [m] \ Peak Period, Tp [sec]	4.7	5.7	6.7	7.7	8.7	9.7	10.7	11.7	12.7	13.7	14.7	15.7	16.7	17.7
0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.75	0.0	0.002	0.007	0.006	0.010	0.004	0.004	0.0	0.004	0.0	0.007	0.0	0.004	0.0
1.25	0.002	0.008	0.022	0.015	**0.043**	0.017	0.013	0.003	0.011	0.002	0.012	0.002	0.007	0.0
1.75	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
2.25	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
2.75	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
3.25	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
3.75	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
4.25	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
4.75	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
5.25	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
5.75	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
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



- **Suite of codes capable of defining operational and survival climates from historical data.**
- **SWAN modeling capabilities**



Survival Events—100yr return contour



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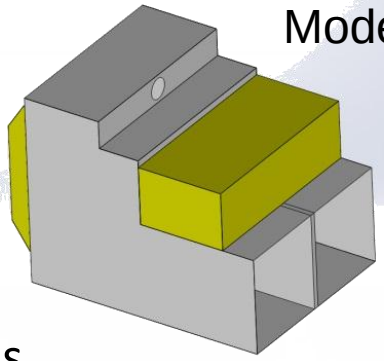
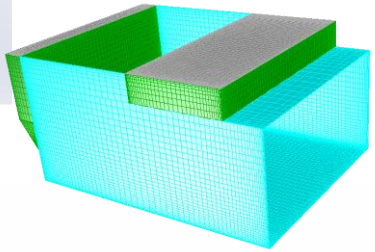
WEC Design

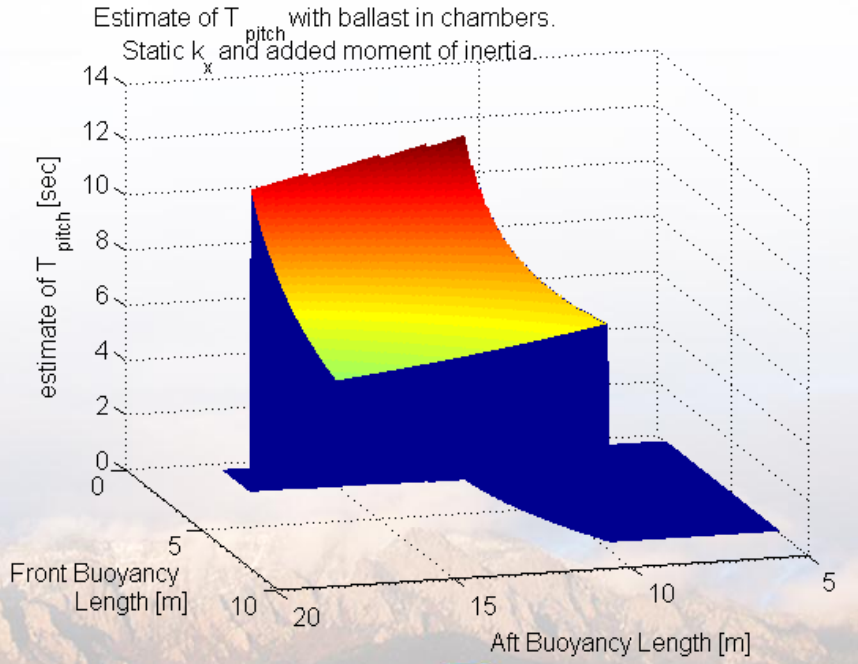
- **Experience modeling multiple devices**
  - Intermediate & shallow water depths
  - Single and multiple bodies
  - Free-surface expression devices
  - Distinct archetypes: moving bodies and oscillating water columns
- **Hydrodynamic and structural design capabilities**
- **Natural resonance optimization**

3-D CAD Models



Panelized Models for WAMIT/AQWA





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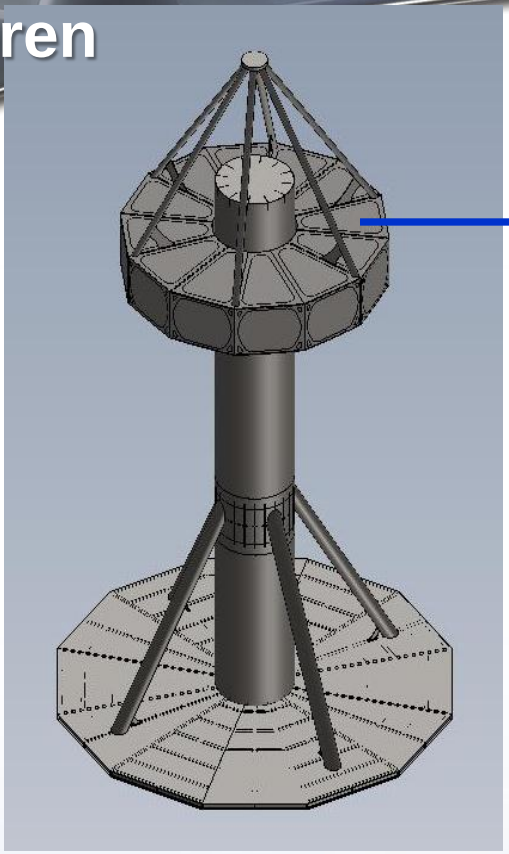
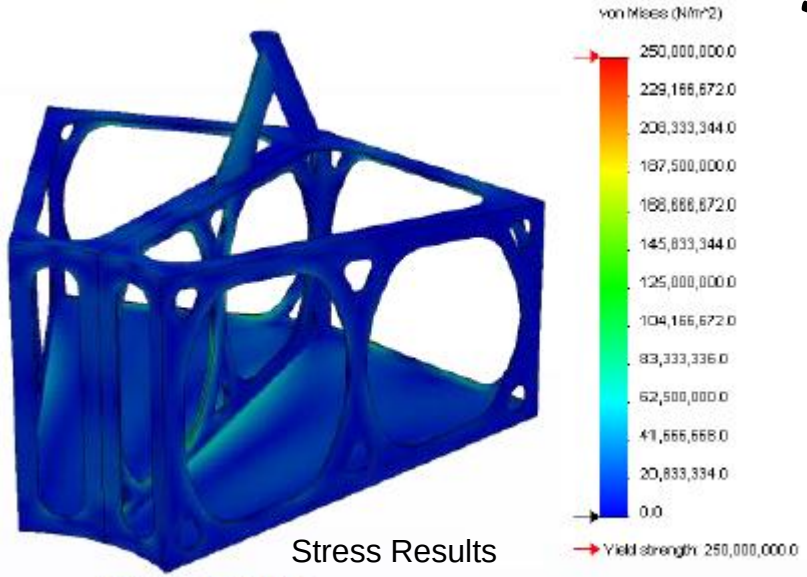
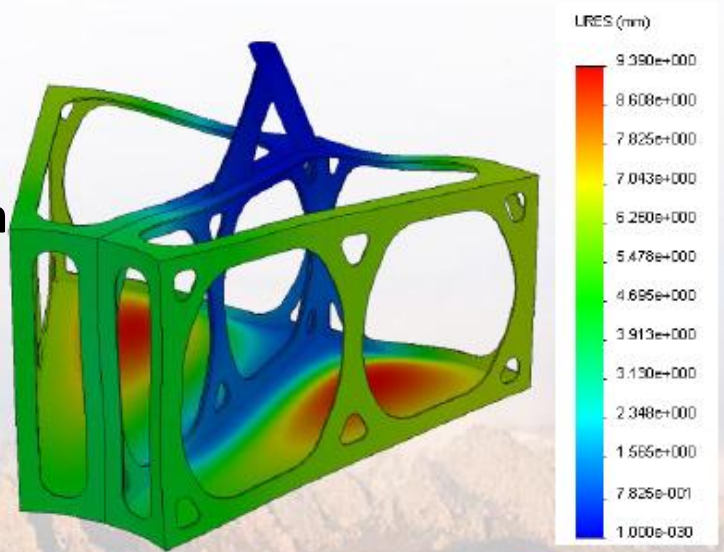
B. Boren

Structural Design





Stress Results

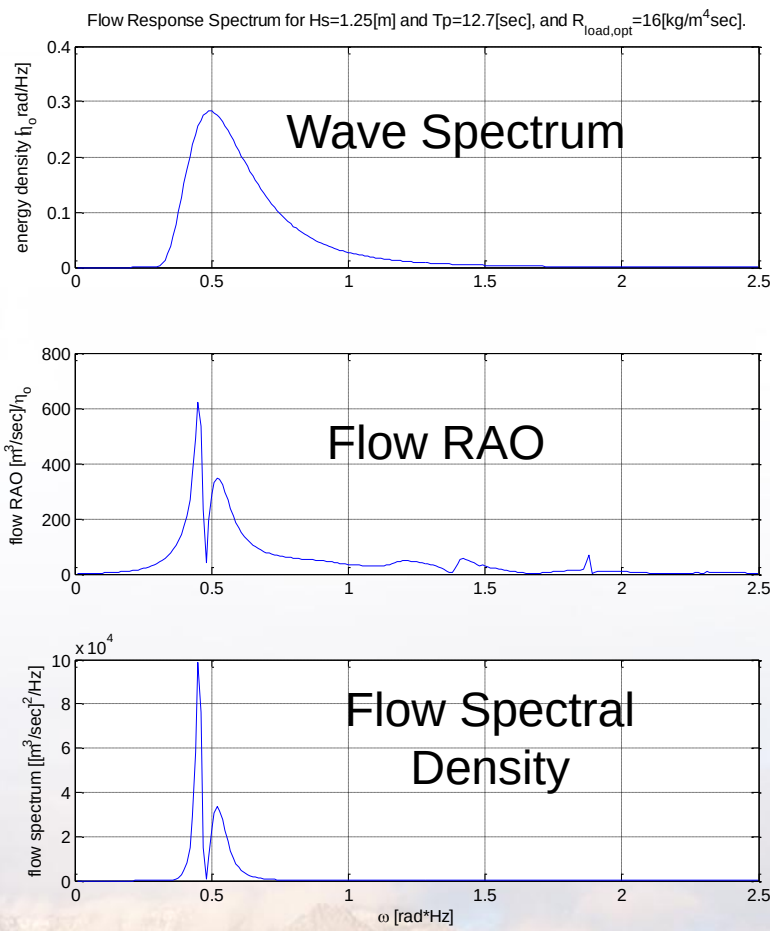


Displacement Results
(Deformation Scale: 95.81)

- **Initial Design: use standards to obtain conservative baseline structure**
  - Center of Gravity
  - Moments of Inertia
- **Structural Integrity: perform FEA to ensure FOS standards**

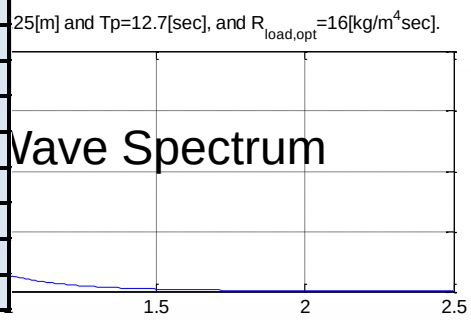
Performance Modeling

- **Equations of motion for a device are derived from governing equation(s) which are composed of the following terms**
  - Hydrodynamic
  - Hydrostatic
  - Viscous Damping
  - Mooring
  - Control
- **Device archetype dictates the form of the governing equation(s) through the hydrodynamic contribution**
- **Device type dictates the required/constrained degrees of freedom that must be solved**
- **Governing equation(s) can be solved in the frequency or time domain to obtain device power and motion estimates**
  - Frequency Domain: linear, fast-solving, estimation only
  - Time Domain: nonlinear, higher accuracy
- **Estimates of average annual power are found by populating each bin of the JPD in the climate**

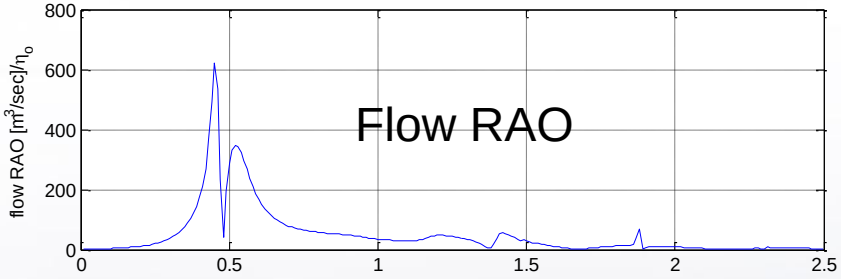


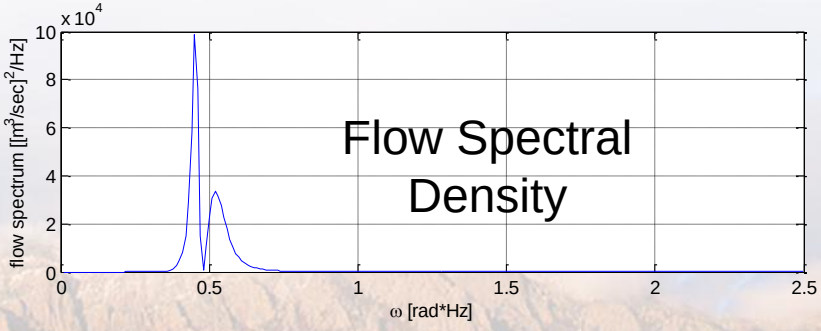
e Modeling

Peak Period, Tp [sec]													
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
0.1	0.1	0.3	0.8	1.5	2.4	3.1	3.7	3.2	4.0	3.7	3.2	2.6	2.3
0.6	1.1	2.8	7.2	13.9	21.2	28.1	33.0	28.6	35.8	33.7	28.8	23.8	20.8
1.8	3.2	7.7	**20.1**	38.6	58.8	77.9	91.7	79.6	99.4	93.5	79.9	66.2	57.7
3.5	6.2	15.1	39.3	75.7	115.3	152.7	179.7	155.9	194.8	183.3	156.6	129.7	113.0
5.8	10.2	24.9	65.0	125.2	190.6	252.5	297.1	257.7	322.0	302.9	258.9	214.4	186.9
8.7	15.3	37.2	97.1	187.0	284.7	377.2	443.8	385.0	481.0	452.5	386.7	320.2	279.2
12.2	21.4	51.9	135.7	261.2	397.6	526.8	619.9	537.8	671.8	632.1	540.1	447.2	389.9
16.2	28.4	69.1	180.6	347.8	529.4	701.4	825.3	716.0	894.5	841.5	719.1	595.4	519.1
20.9	36.5	88.8	232.0	446.7	680.0	900.9	1060.0	919.6	1148.9	1080.9	923.7	764.8	666.7
26.1	45.6	110.9	289.8	558.0	849.4	1125.3	1324.1	1148.7	1435.1	1350.1	1153.8	955.3	832.8
31.8	55.8	135.5	354.0	681.7	1037.6	1374.7	1617.5	1403.3	1753.1	1649.3	1409.5	1167.1	1017.4
38.2	66.9	162.5	424.6	817.7	1244.6	1649.0	1940.3	1683.3	2103.0	1978.5	1690.7	1399.9	1220.4



- $F_{ViscousDamping}$ **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.



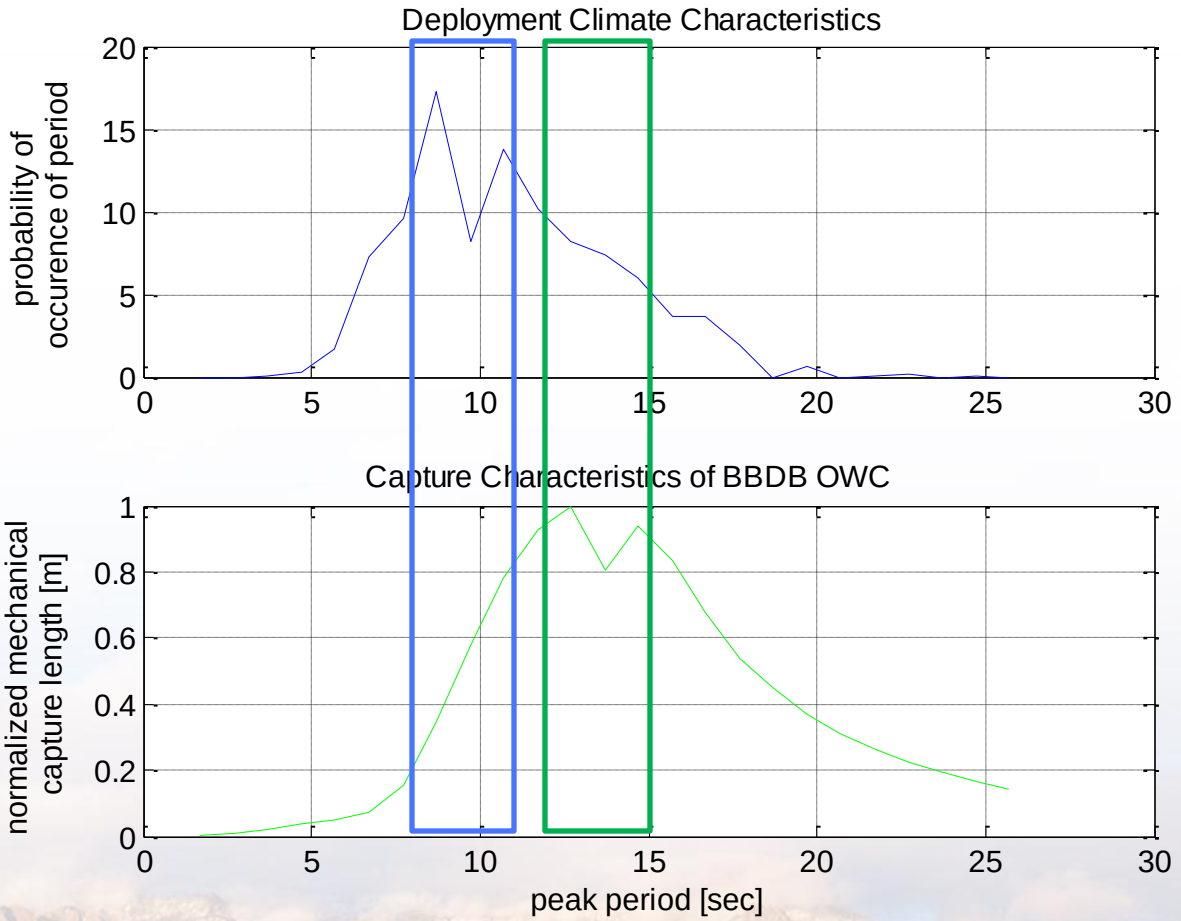


Performance Model Outcome

- The average power for each sea state is found through

$$\langle P \rangle = R_{control} \int_0^{\infty} |u|^2 S(\omega) d\omega$$

- 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.



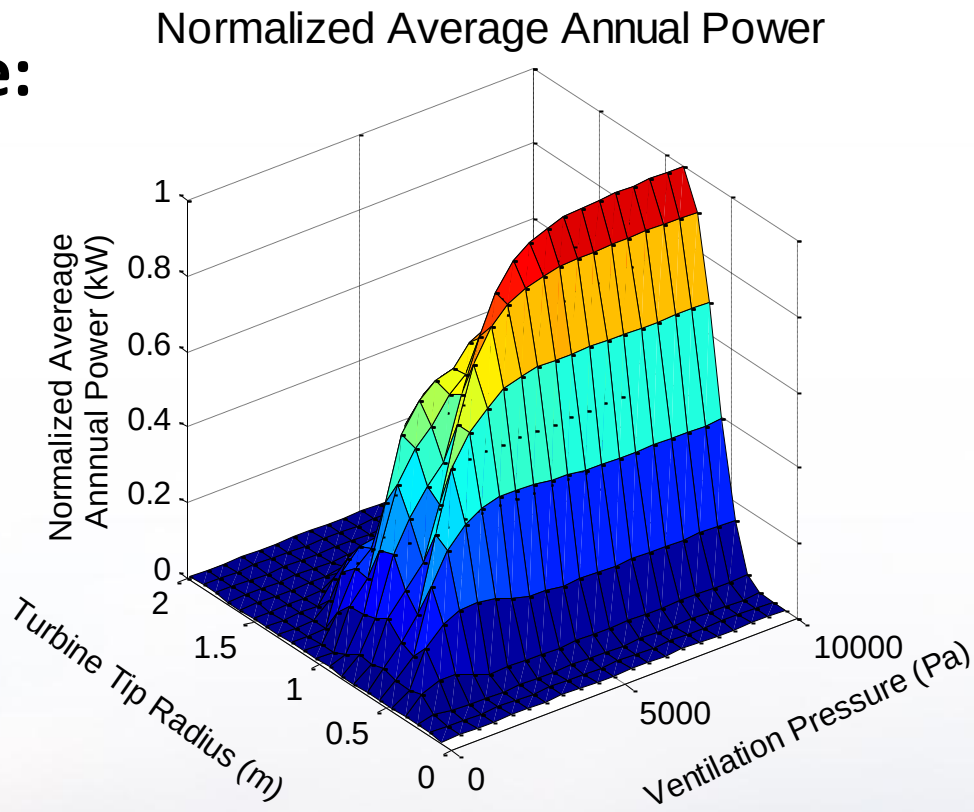
Most Probable Periods in Climate

Largest Capture Length by Device

PTO 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 PTO's**
  - Added redundancy can increase WEC availability but may adversely effect cost or efficiencies
- **PTO size**
  - Must be optimized for the climate variability
- **PTO efficiency**
- **PTO serviceability and reliability**
  - The PTO and its subcomponents are the most likely to break, need to really consider O&M for this component



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 Farm Modeling

Monterrey Bay Sensitivity Analysis

Model Parameters:

- WECs modeled with baseline SWAN capabilities (T/R)
- 10 WEC Farm with 2X, 5X and 10X spacing
- Varied WEC coefficients and incident wave conditions (117 combinations)
- Monitored wave height, period, and direction at 15 output locations around and landward of array

Results

- Transmission coefficient is most sensitive parameter largely effecting Hs
- Largest effects landward of array (but not always in-line)
- Lower Directional Spreading Coefficient (DSC) enables wave direction changes to penetrate further
- Tp most affected by DSC
- Wave direction most affected by DSC
- More densely packed arrays have larger effects near the array
- Less densely packed arrays have larger effects further away from array

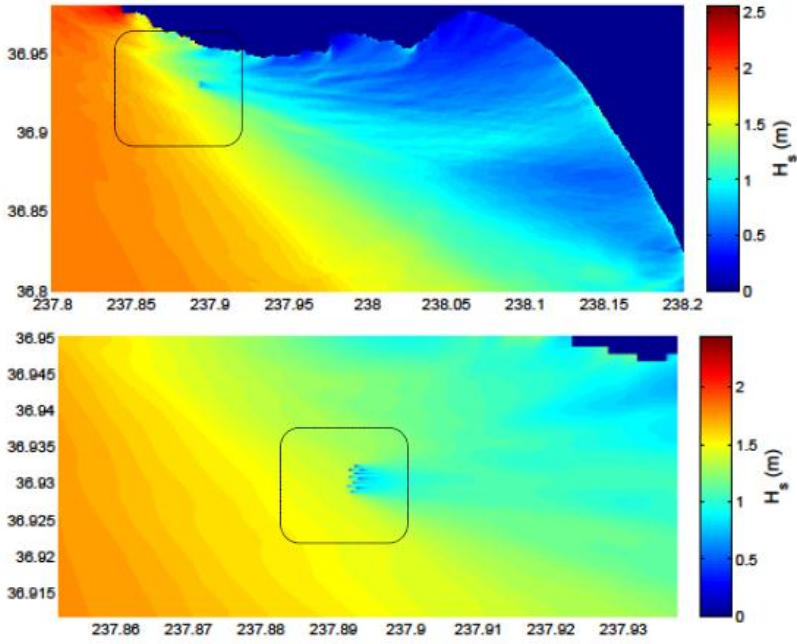


Table 2: Sensitivity analysis parameter values

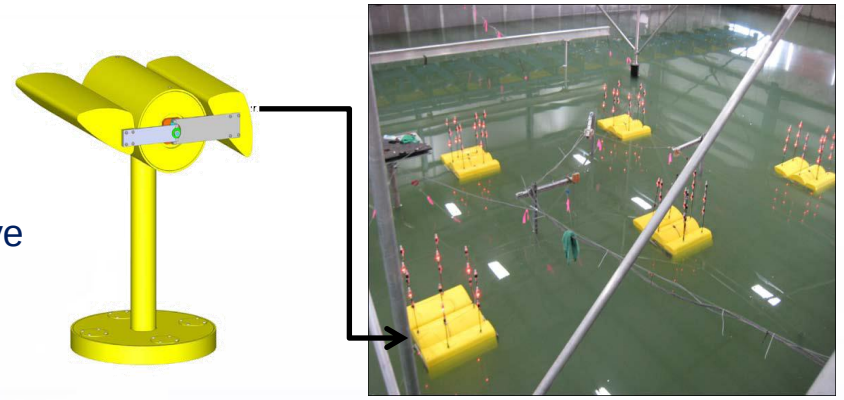
SWAN Coefficient	Value(s)
Transmission (C)	[0, 0.2, 0.4, 0.6, 0.8, 1.0]
Reflection	[0. 0.25]
Frequency Spreading (gamma)	[3.3, 10]
Directional Spreading (m)	[2, 10]

WEC Farm Modeling

SNL-SWAN Development

Tsunami Basin Sensitivity Analysis:

- WECs modeled with baseline SWAN capabilities (T/R)
- 5 WEC Farm based on Columbia Power's WEC array test in the Oregon State University (OSU) Tsunami Wave Basin Varied WEC coefficients and incident wave conditions based on wave test cases (693 combinations)
- Monitored wave height, period, and direction at wave gage locations for direct comparison to test data



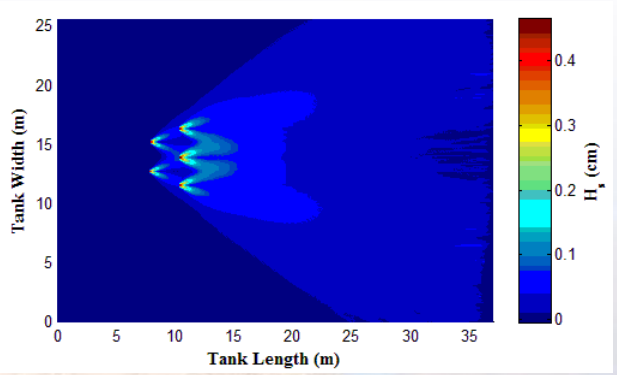
Columbia Power's WEC Array Test in the Oregon State University Tsunami Wave Basin

WEC Module Development:

- SWAN's baseline capabilities inaccurately model WECs
- WEC Module will be a frequency- and directional-dependent energy sink defined in SWAN
- OSU Tsunami Wave Basin test data will be used to validate the WEC Module

Table 3: OSU Tsunami Basin Sensitivty Analysis Parameters

Test #3 Real Seas (Irregular Waves)								
Sea State	Shape	Hm0 (cm)	Tp (s)	Mean Wave Direction (°)	# of WECs	Transmission Coeff	Reflection Coeff	Spreading Index
7	1			1	3	11	1	3
Oregon - 1	PM	4.54	1.62	0	1, 3, 5	0 : 0.1 : 1.0	0	4, 10, UD
Oregon - 2	PM	7.58	1.42	0	1, 3, 5	0 : 0.1 : 1.0	0	4, 10, UD
Oregon - 3	PM	7.58	1.82	0	1, 3, 5	0 : 0.1 : 1.0	0	4, 10, UD
Oregon - 4	PM	7.58	2.22	0	1, 3, 5	0 : 0.1 : 1.0	0	4, 10, UD
Oregon - 5	PM	13.6	2.22	0	1, 3, 5	0 : 0.1 : 1.0	0	4, 10, UD
HI - Kaneohe	PM	4.54	1.22	0	1, 3, 5	0 : 0.1 : 1.0	0	4, 10, UD
IR - M4 buoy	PM	10.6	1.62	0	1, 3, 5	0 : 0.1 : 1.0	0	4, 10, UD



SWAN Tsunami Basin Model Results for 5 WEC Array with Hs = 7.58 [m], Tp = 2.22 [s] and DSPR = 4.

Marine Hydro-Kinetic

Turbines

WECs

Reference Model

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

R. Jepsen &
D. Bull

Reference Model Project

- **Project goal is 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 models.
  - Environmental considerations.
- **Designs are intended to be conservative and robust.**
- **Each design will be verified with scaled testing**
- **Cooperative effort sponsored by DOE and lead by SNL:**

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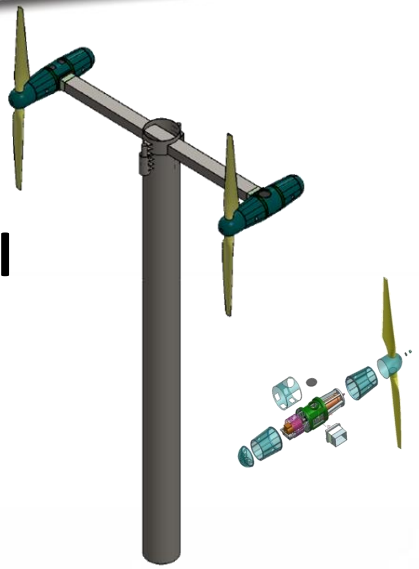
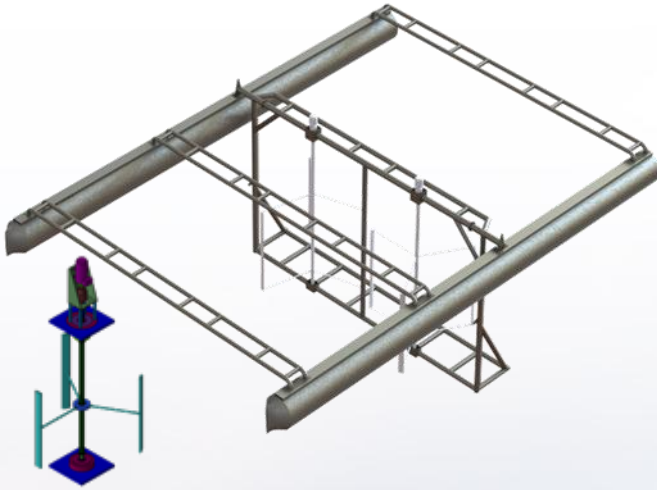
Reference Models

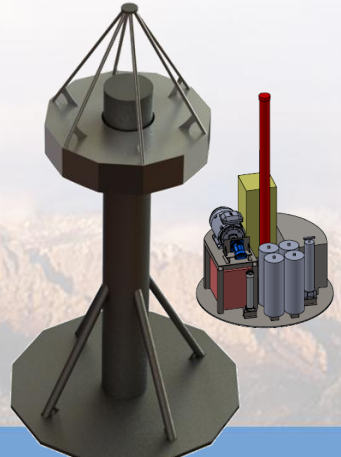


- Reference Model 1: Dual rotor, 2-blade turbine in tidal resource

- Reference Model 2: Cross flow turbine in river resource



- Reference Model 3: Point Absorber WEC in No. Cal. wave resource



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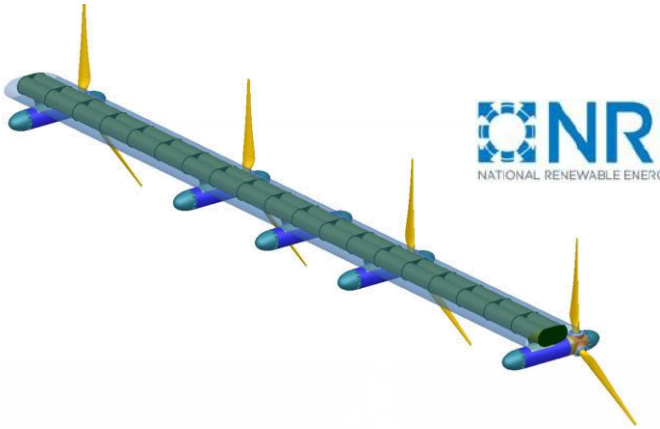
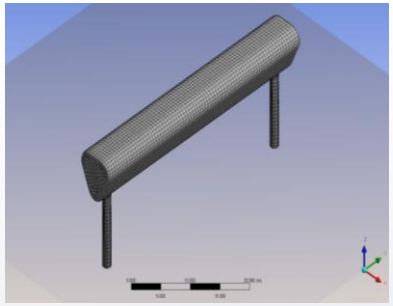
revision Supporting visionary renewable energy projects

Reference Models

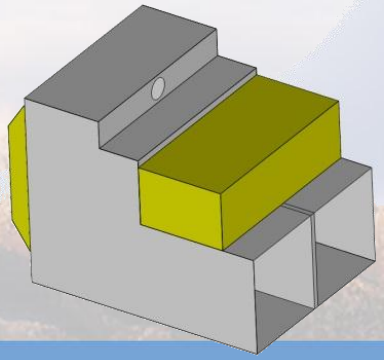
- **Reference Model 4: Quadruple rotor, 3-blade turbine in Gulf Stream resource**



- **Reference Model 5: Surge Device in No. Cal. wave resource**
  - Device architecture still under development



- **Reference Model 6: BBDB in No. Cal. wave resource**



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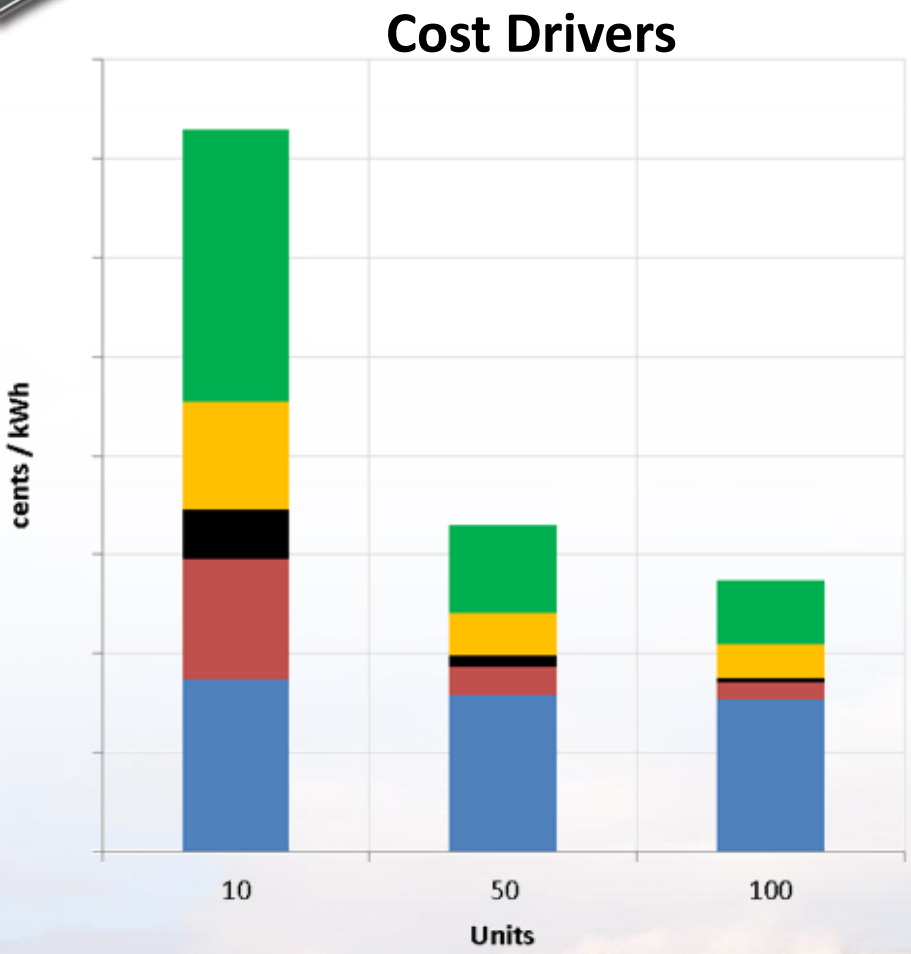
Economic Analysis



- Insurance
- Environmental regulatory compliance
- Marine operations
- Shore side operations
- Replacement parts & labor
  - failure risk analysis
- Other

- Pre-installation Studies
- Installation

- Recreational Study
- NEPA Process
- Monitoring Setup
- Siting & Scoping

- Subsea cable design
- Dockside infrastructure
- O&M Vessel

- Structure
- Powertrain
- Power electronics
- Mooring system

R. Jepsen &
D. Bull

Value of Reference Model Project

- **A recent study by Babarit[1] compared eight distinct resonant WEC designs through multiple cost measures.**
  - Absorbed Energy/mass
  - Absorbed Energy/surface area
  - Absorbed Energy/PTO force.
- **All resonant designs controlled simply with resistive tuning in the time domain**
  - Resistive value is maintained for the duration of a sea state.
- **Papers' Conclusion: cost performance is on the same order for all 8 devices**
  - Surprising when such a variety of devices types and sizes are evaluated with a wide range of operating principles.
- **Reference Model project will produce actual COE.**
  - Mimicking a true company by evaluating: component designs considering both operational and survival conditions, environmental concerns, and O&M
  - This methodology is the only way to identify viable designs

Numerical benchmarking study of a selection of wave energy converters. A. Babarit, J. Hals, M. J. Muliawan, A. Kurniawan, T. Moan, J. Krokstad. Renewable Energy 41, 44-63.

Offshore Wind

Design and Tool Development

Structural

Regulatory

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

NNSA National Nuclear Security Administration

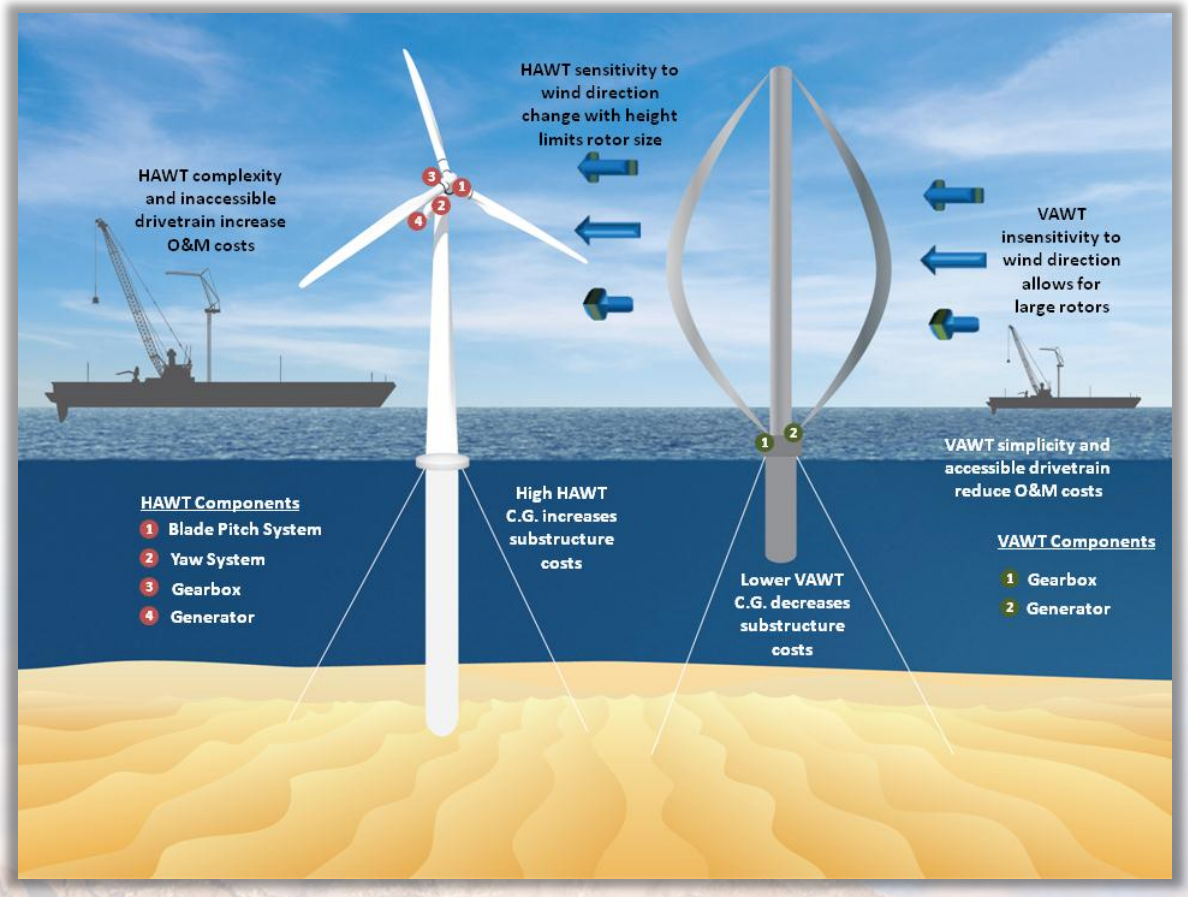
Sandia National Laboratories

M. Barone &
J. Paquette

Innovative Offshore Vertical-Axis Wind Turbine Rotors

Overview:

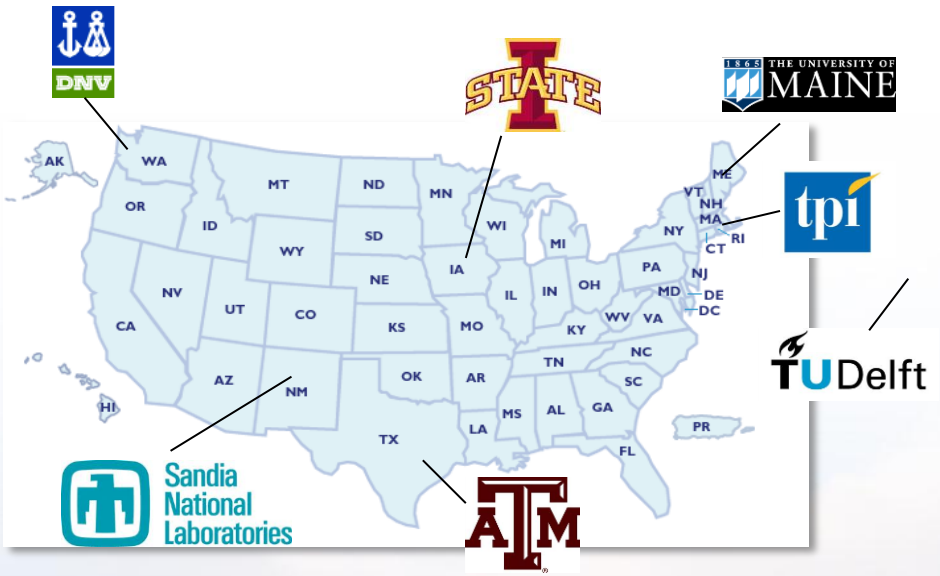
- This project focuses on improving the VAWT rotor sub-system through improvements in aerodynamics, materials, blade manufacturing, and test methods.
- Innovative rotor designs will be developed that reduce system COE.
- Designs will then be tested at sub-scale to prove their feasibility and increase the TRL of VAWT technology for offshore deployment.



M. Barone &
J. Paquette

Offshore VAWT Project Structure

Partners



Work Packages

Preliminary Design of Novel Offshore VAWT Rotor (All Partners)
(What does it look like?)

Floating VAWT System and COE Analysis (SNL, U. of Maine)
(What does it cost?)

Materials and Manufacturing (SNL, ISU, TPI)
(How do you build it?)

Proof-of-Concept Testing (SNL, ISU, U. of Maine)
(Can it work?)

K. Ruehl

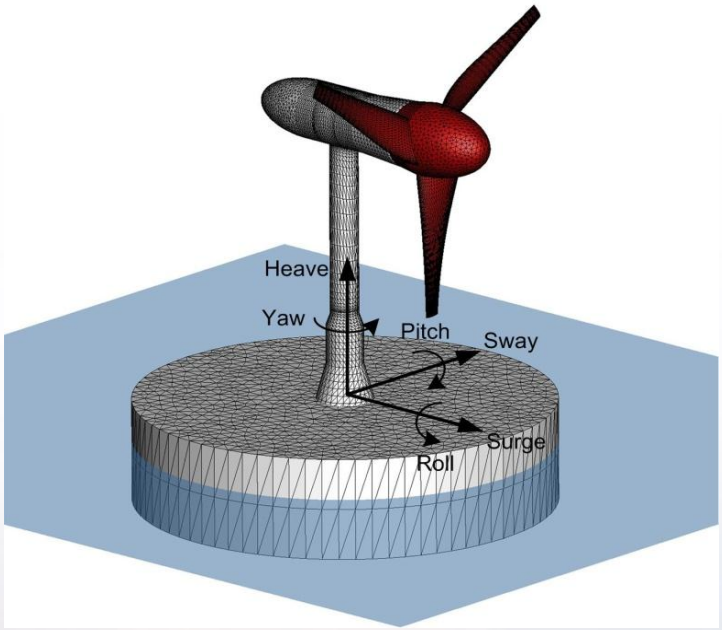
High-resolution modeling of floating offshore wind turbines and farms

Overview:

- The primary contributions of the SNL effort in this project will be the coupling of near field and large scale models to evaluate offshore wind farms and individual platform reaction to waves and modeling fluid-structure interaction effects.

Numerical Modeling:

- 1.1 Turbine scale model
  - Accounts for specific turbine and platform design
  - Simulates dynamics of complete offshore wind turbine
  - 6DOF coupled wind/wave model
- 1.2 Wind-farm scale model
  - Informed from turbine scale model
  - Models wind turbines using actuator disk and actuator line parameterizations
  - Accounts for wave effects on wind-farm
- 1.3 Multi scale model
  - Informed from wind-farm scale model to large scale Weather Research and Forecasting (WRF) model and Regional Ocean Model System (ROMS)



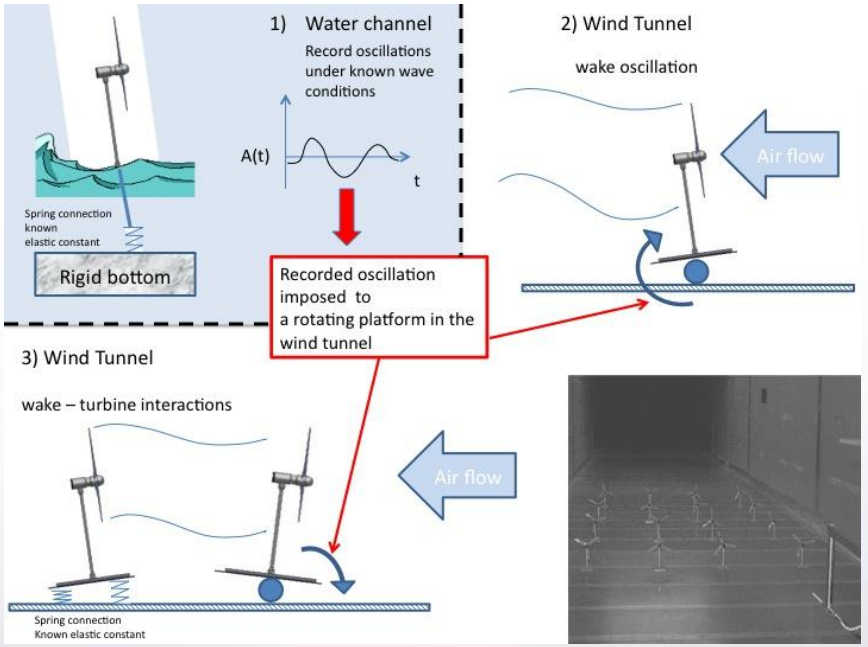
High-resolution modeling of floating offshore wind turbines and farms

Experimentation:

- 3.1 Floating Platform Model
  - Tested in SAFL wave flume without airflow
  - Used to validate floating platform numerical model
- 3.2 Wind Turbine Model
  - Tested in SAFL wind tunnel with turbine on a moving platform
  - Used to validate turbine-scale numerical model
- 3.3 Wind Farm Model
  - Tested in SAFL wind tunnel with elastically mounted turbines
  - Used to validate wind-farm scale numerical model

Turbine and Platform Configuration:

- Floating Platform
  - Scaled OC4 semi-submersible platform
  - In collaboration with Principle Power Inc.
- Offshore Turbine
  - 13.2 MW Sandia Reference Turbine
  - Pure research turbine designed for large scale offshore wind applications



UMN Planned Experiments

Offshore Wind

Design and Tool Development

Structural

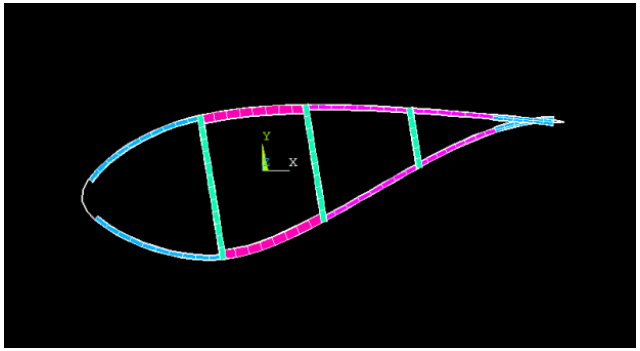
Regulatory

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Large Off-Shore Rotor Development

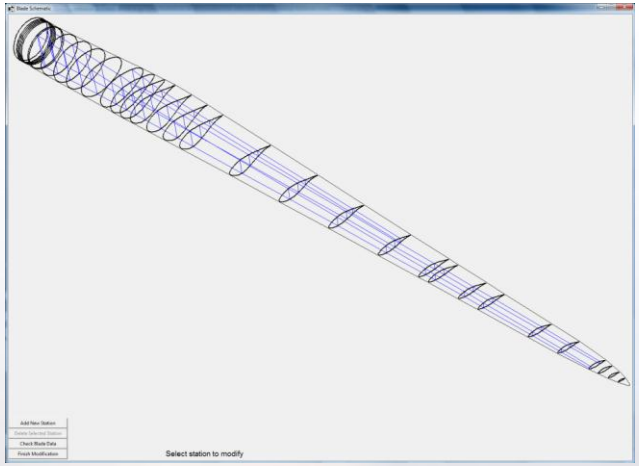
Objectives:

- Research and document challenges and opportunities for large offshore HAWT blades including barriers to continued rotor swept area growth
- Evaluate new design concepts for weight reduction to reduce gravitational loading and mitigate of aeroelastic instability for large blades
- Make models and design studies available to researchers



Approach:

- Follow GL and IEC guidelines for stress/strain, buckling, tip deflection, and fatigue life to determine a detailed composite layup satisfying design loads.
- Make large blade (100-meter) and turbine (13.2 MW) design models available to other researchers in academia and industry including SNL100-00, SNL100-01, etc.



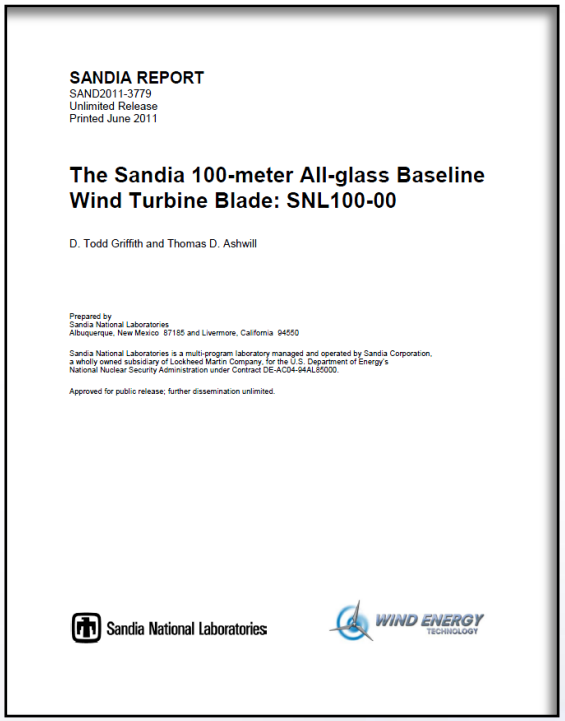
Cont'd; Large Off-Shore Rotor Development

Highlights:

- Public release of model data for design studies (SNL100-00 blade and SNL13.2MW-Land turbine); ***Largest publicly available blade and turbine design models.***
- Sandia Design Scorecard introduced to track effect of blade innovations

Outlook:

- Continue to support partners using SNL100-00 model including structural optimization and CFD studies.
- Continue investigation of large blade design concepts (e.g. carbon study, geometry, and core materials) to reduce blade weight/cost; mitigate buckling, gravitational fatigue and flutter instability
- Near completion of carbon fiber study to produce an updated SNL100-01 blade design and make publicly available
- Completion of a blade manufacturing cost model to evaluate scale-up of manufacturing operations from 40- to 100-meter blade production as well as blade cost comparisons for Sandia 100-meter blade design variants.



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

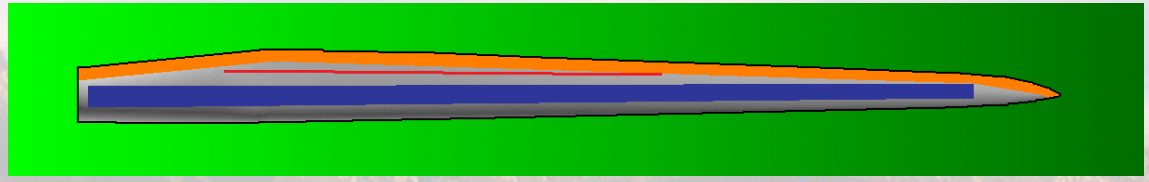
Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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

Approved for public release; further dissemination unlimited.

Sandia National Laboratories WIND ENERGY TECHNOLOGY

Public domain large blade and turbine models.



Structural Health and Prognostics Management (D. Todd Griffith)

Objectives:

- Develop a roadmap for the application of advanced structural health monitoring (SHM) and prognostic control for offshore wind turbines.
- Quantify potential for offshore O&M cost reduction and increased energy capture

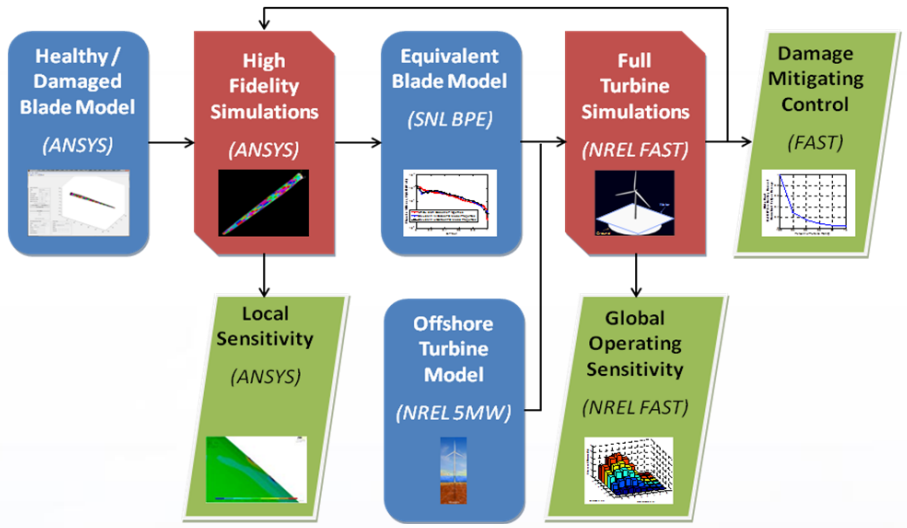
Approach:

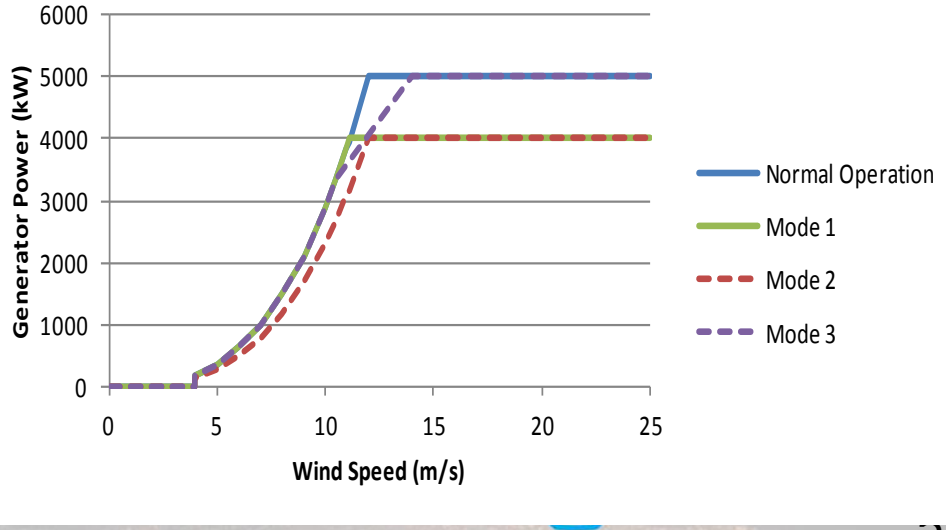
- Simulate damage and faults in the rotor (and other components); then quantify sensitivity and impact of damage at global and local scales of the model
- Couple SHM with a newly developed O&M cost model
- Utilize the coupled model to perform cost/benefit analysis for various scenarios (advanced controls, preventive maintenance, sensing options, etc).

Impact:

- The cost for offshore O&M has been estimated to be 2 to 5 times that of onshore wind farms.
- This work seeks to mitigate these rising costs.

Reduce O&M costs AND maximize energy capture





Cont'd; Structural Health and Prognostics Management (D. Todd Griffith)

Highlights:

- **Paper presented as podium presentation in the Scientific Track at EWEC (Copenhagen, April 2012); titled "Prognostic Control to Enhance Offshore Wind Turbine Operations and Maintenance Strategies".**

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Unlimited Release
Printed Month and Year

Offshore Structural Health and Prognostics Management: 2011 Q4 Report

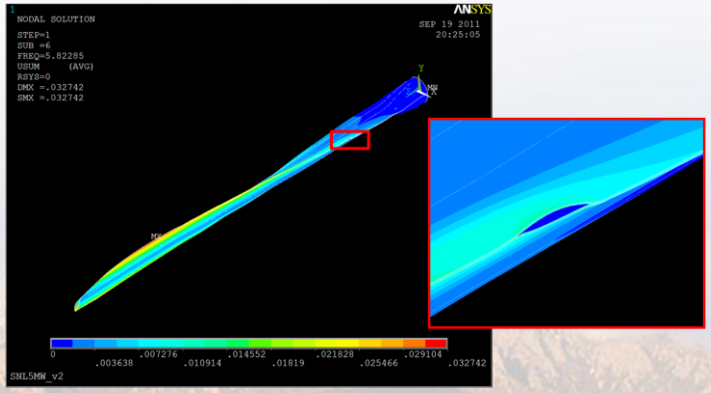
D. Todd Griffith, Joshua A. Paquette, Brian R. Resor, Jonathan R. White and Nathanael C. Yoder

Sandia National Laboratories

Prognostic Control to Enhance Offshore Wind Turbine Operations and Maintenance Strategies

Outlook:

- **Comprehensive FY12 final report coming soon:**
  - **SHM studies for common failure modes/faults in rotor**
    - **shear web disbond, trailing edge disbond**
    - **rotor imbalance (aerodynamic, pitch error, mass)**
  - **Cost model documented and exercised on initial scenarios**



Offshore Wind

Design and Tool Development

Structural

Regulatory

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Offshore Radar Mitigation and Outreach (D. Todd Griffith)

Objectives:

- **Identify key players in offshore turbine/radar interaction and identify key offshore radar issues.**
- **Developing an initial plan to mitigate the identified offshore radar issues with a goal to increase wind development with reduced radar permitting issues.**
- **Document offshore-specific radar issues and initial mitigation plan**

Report outlining offshore specific issues and stakeholders is forthcoming.

Core Topics

Mooring

Sediments

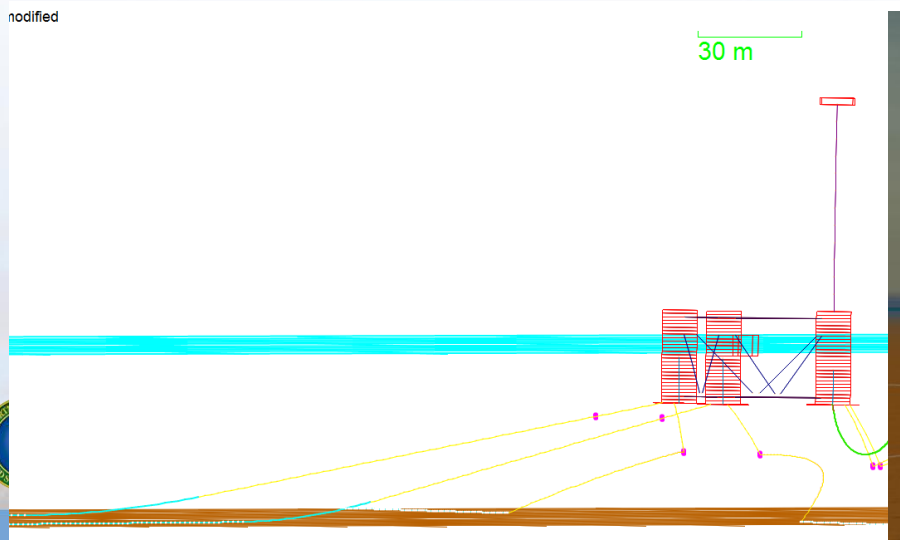
Materials (still need)

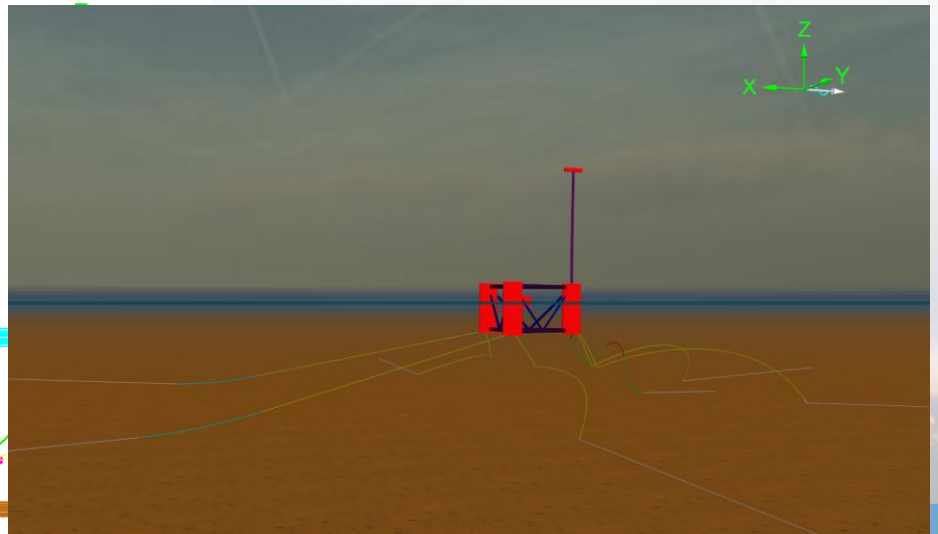
Controls

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Anchor & Mooring Modeling

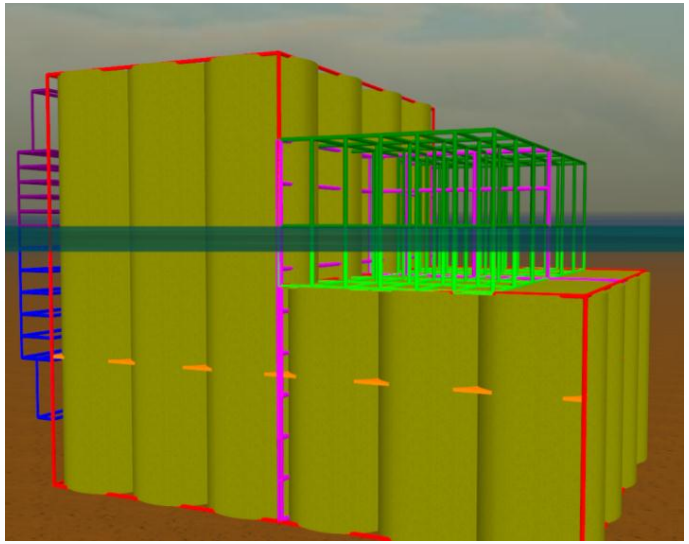
- Anchor and Mooring must be designed to survive the extreme environment at the deployment location
  - These environments drive the sizing of the mooring system components.
- Use DNV Standards to assess mooring: 100-yr return for waves & wind, 10-yr return for current
- Large amplitude responses of the WEC must be predicted in these extreme environments
  - Motions are typically beyond the limits of classic (radiation/diffraction) frequency domain potential flow solvers
- Tools: OrcaFlex and AQWA with coupled cable dynamics.

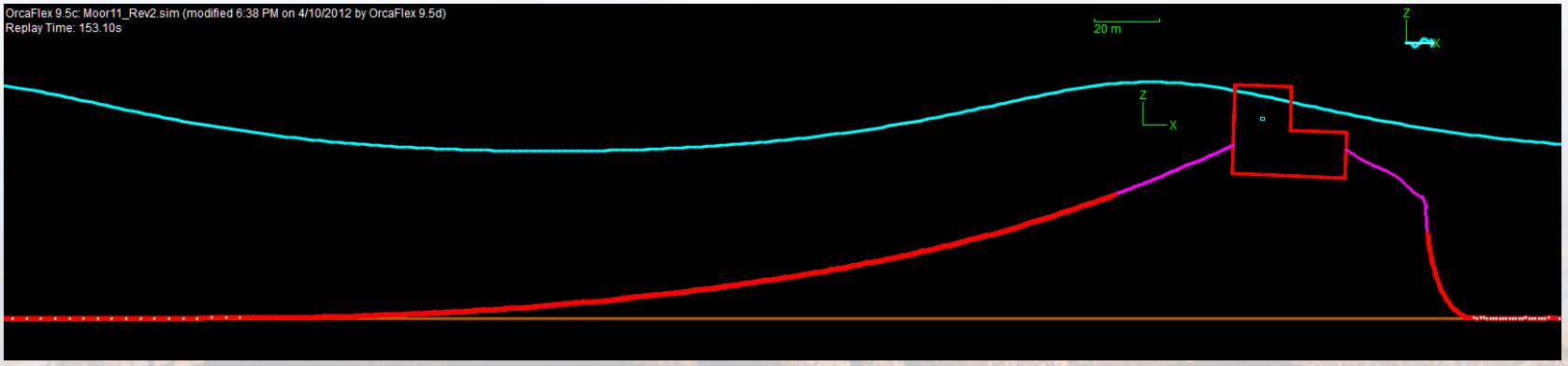




Anchor & Mooring Modeling: WEC Motions

- Use OrcaFlex to build a device with motions determined purely through Morison Eq. (no potential flow input)
  - Model developed using an array of 6-DOF discrete bodies.
  - Rotational response is controlled by distribution and density of discrete bodies
- Paper presented at Oceans '12 (Virginia, October 2012); titled "Methodology for creating nonaxisymmetric WECs to screen mooring designs using a Morison Equation approach".





Core Topics

Mooring

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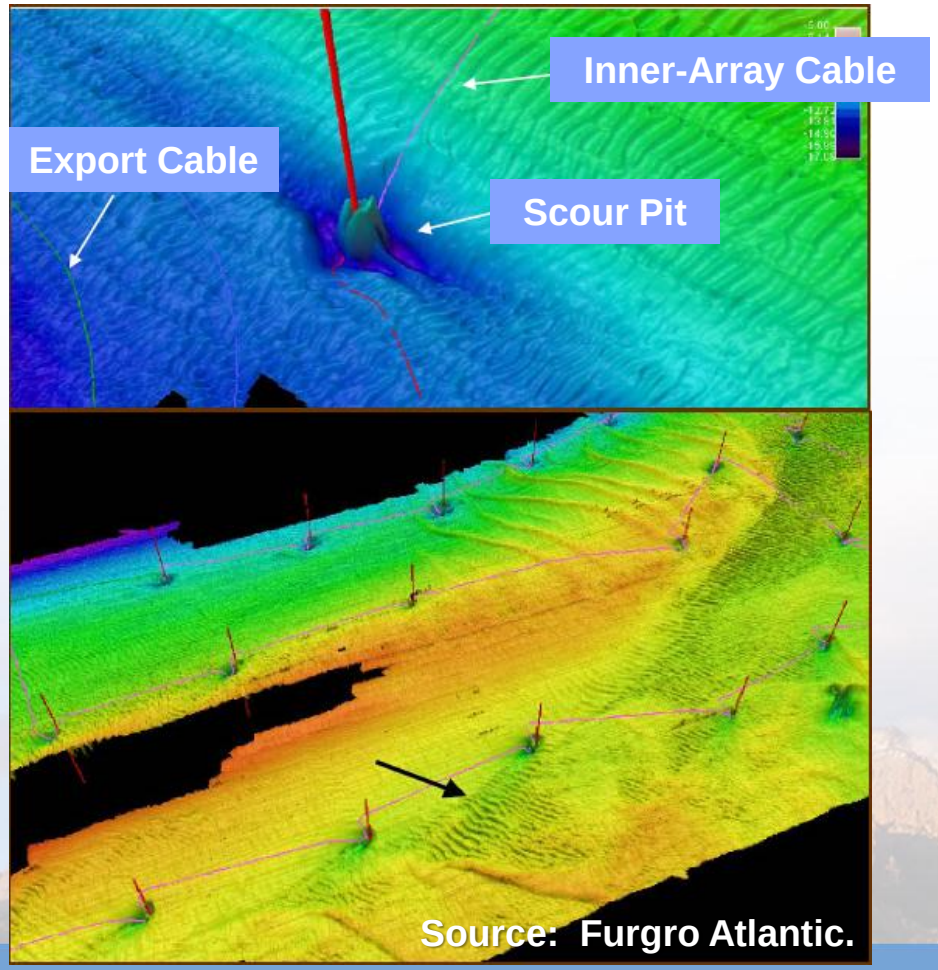
Offshore Sediment Issues

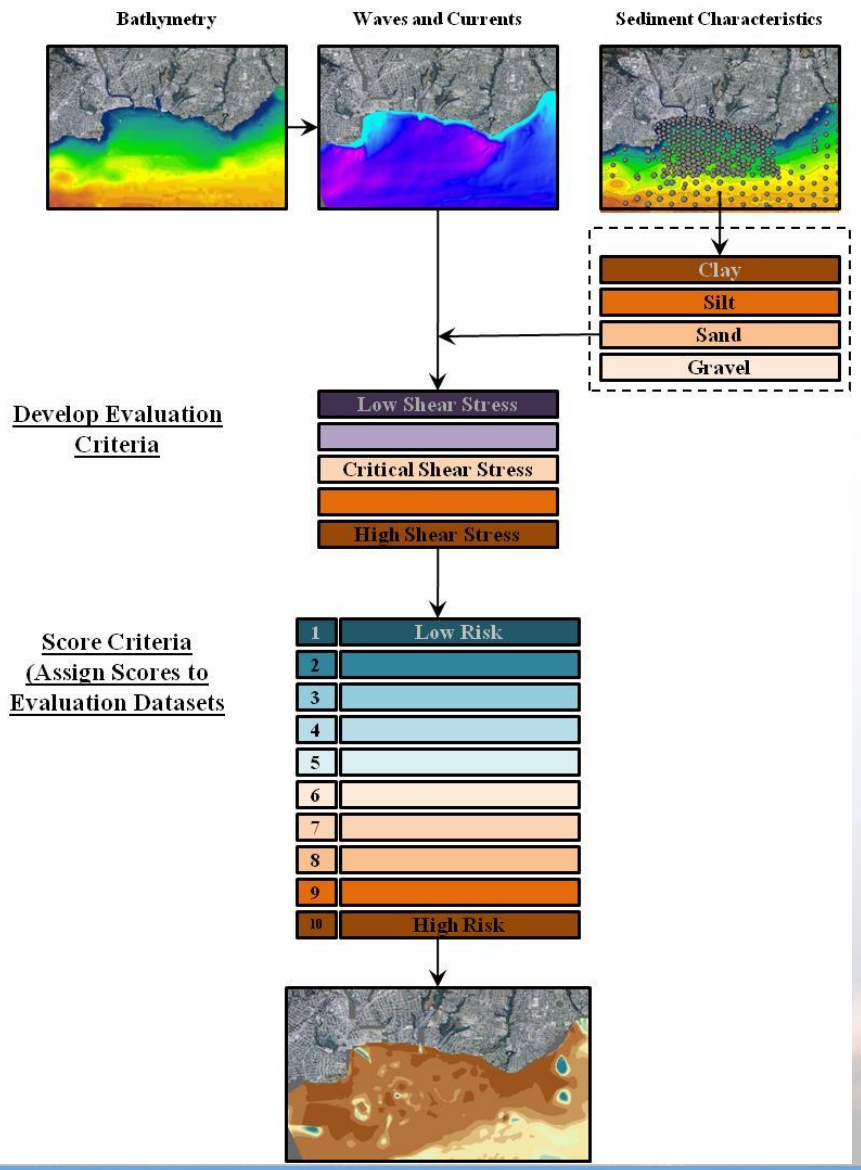
Design Risks:

- Infrastructure failure
  - Over-design
- Expensive maintenance

Ecological Risks:

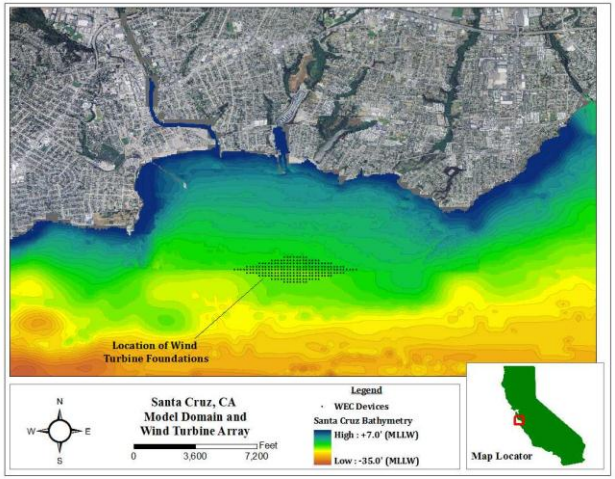
- Damage Aquatic Habitat



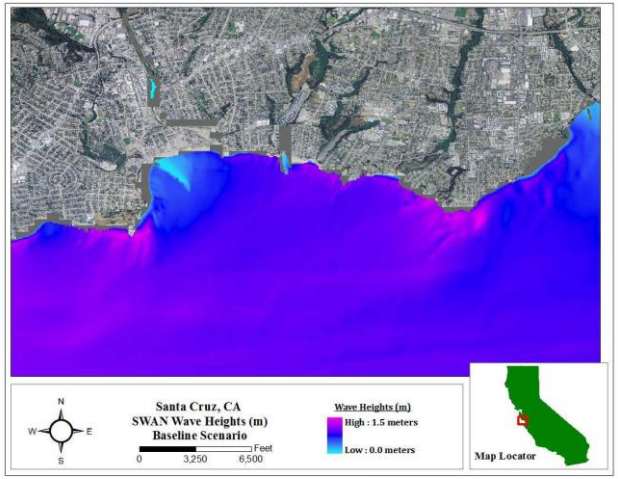


Sediment Mobility Risk

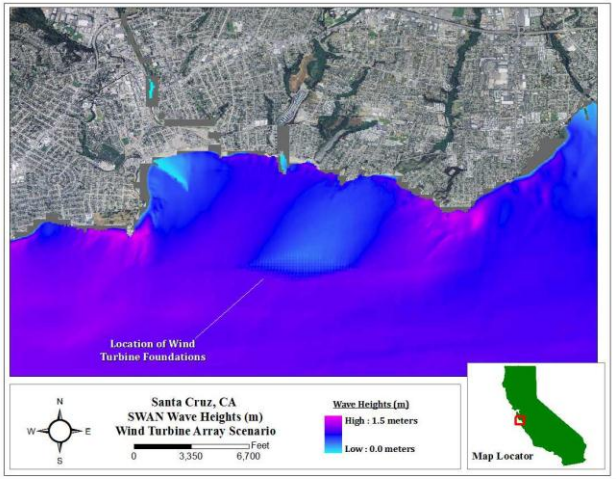
Offshore Wind (OW) Farm Location



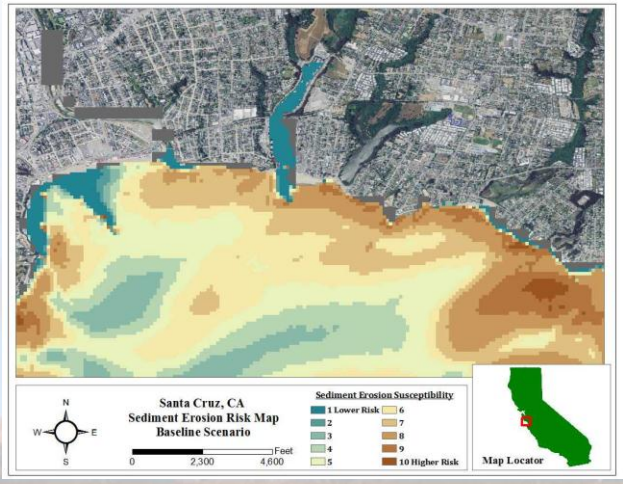
Incident Wave Field



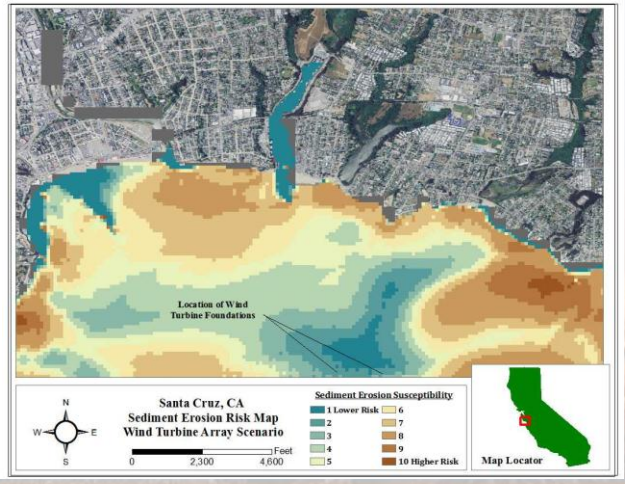
OW Foundation Altered Wave Field



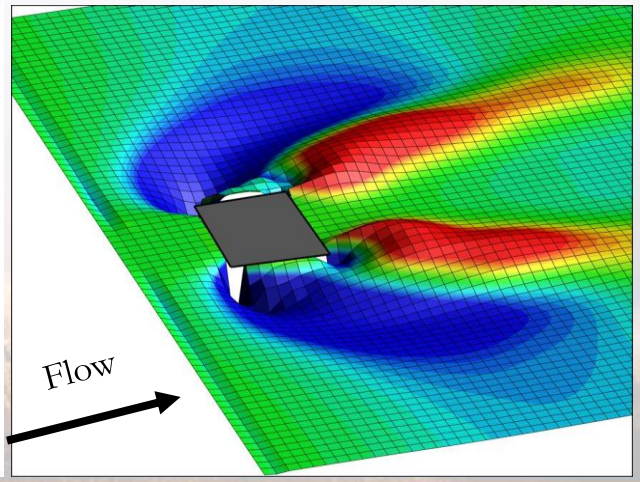
Baseline (No Turbine) Sediment Stability Risk for Site Design/Layout



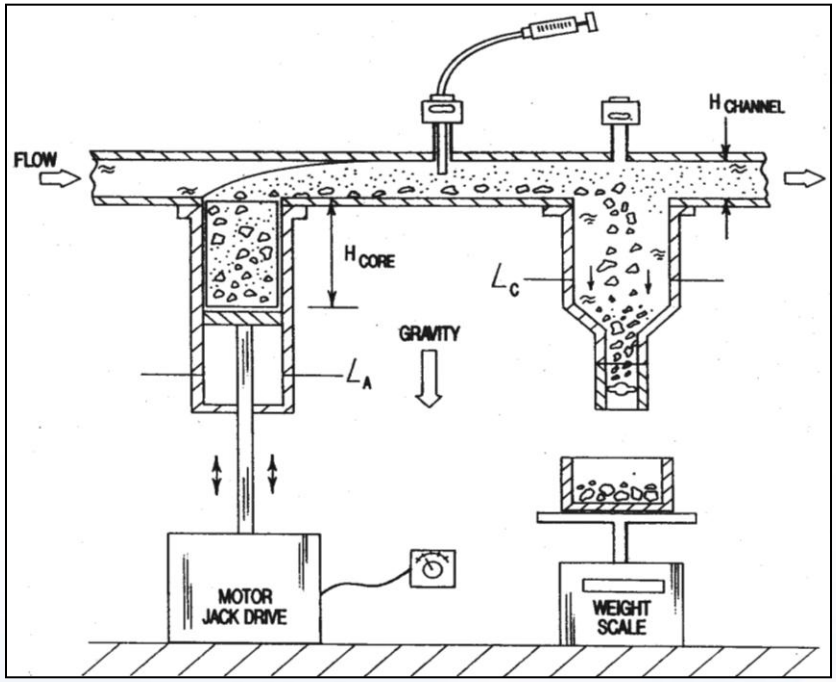
OW Farm Altered Sediment Stability for Ecological Consideration

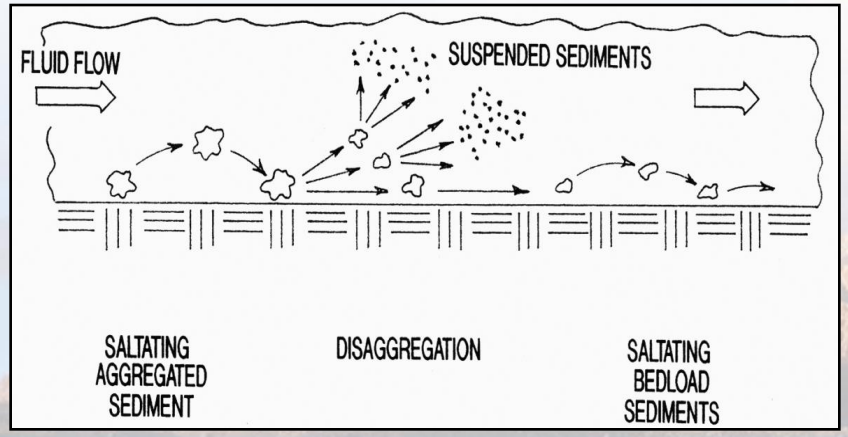


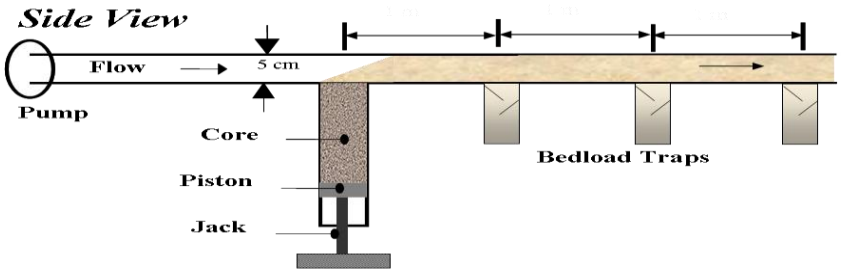
Near-Field Scour Risk for Infrastructure Surety

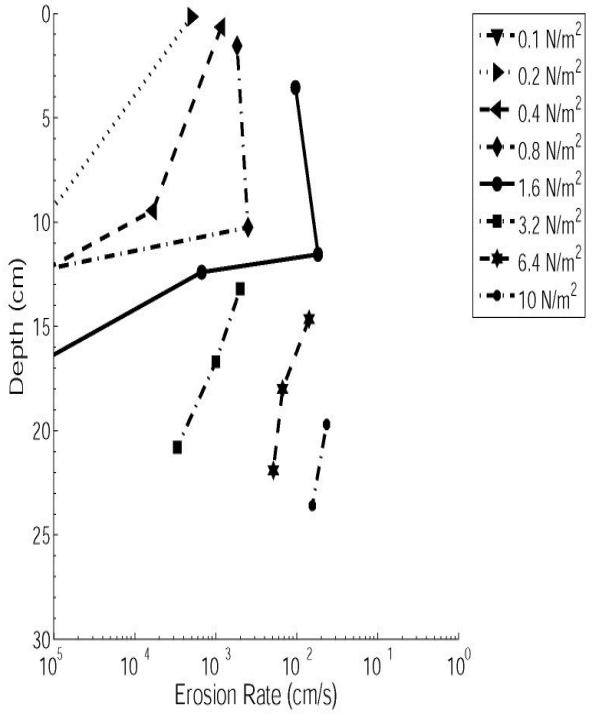


Sediment Field Measurements: River & Tidal (ASSET)



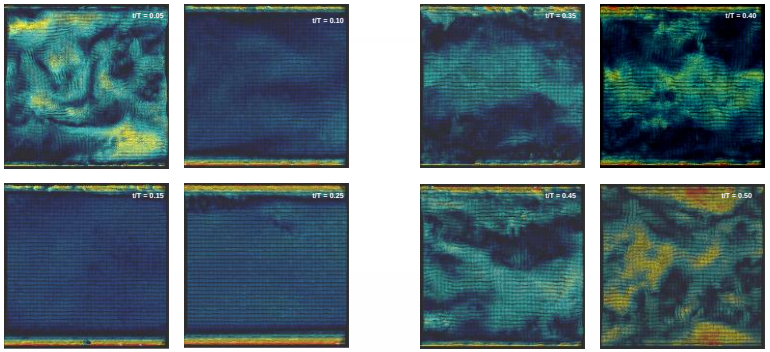




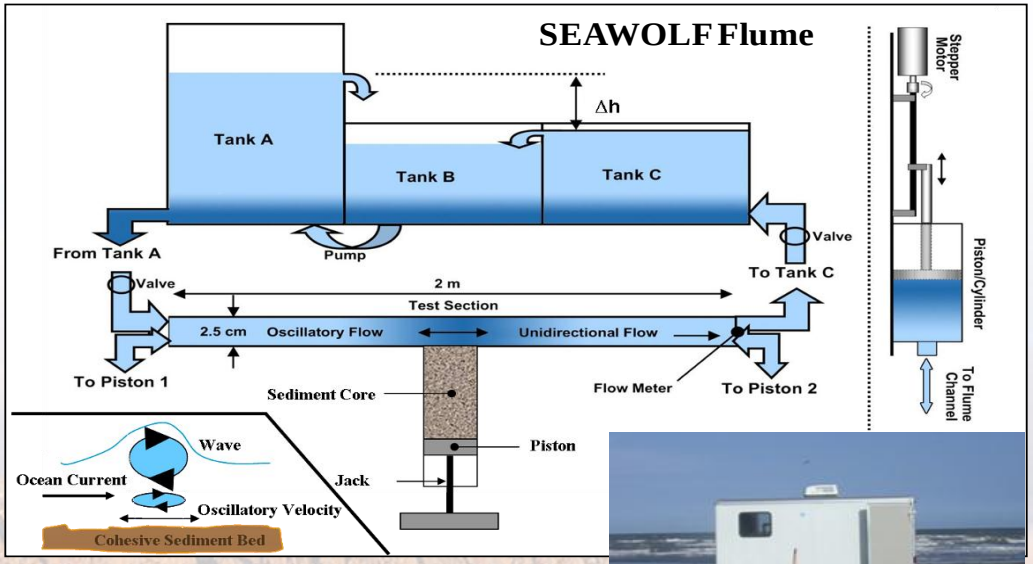


Sediment Field Measurements: Ocean & Estuary (SEAWOLF)

- **ASSET and SEAWOLF Flumes**
  - Patented Sandia Tools
  - Mobile for onsite measurements
  - Simulate extreme events
  - Measure
    - Erosion rate
    - Critical shear stress
    - Transport mode
    - Stratification
    - Cohesive properties



Acceleration Deceleration



Core-Topics

Mooring

Sediments

Materials (still need)

Controls

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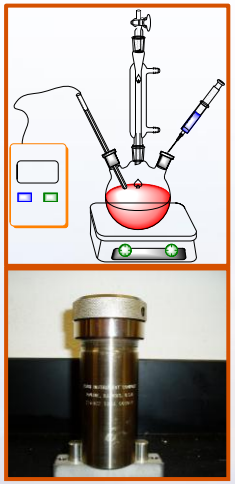
MHK Advanced Materials Program

Challenges: (1) environmental degradation (e.g., corrosion, biofouling, mineral fouling, sediment fouling/erosion, cavitation, etc.); (2) component materials reliability; (3) environmental impact (toxicity).

Impact: development cycle, component selection, performance, reliability, O&M, cost.

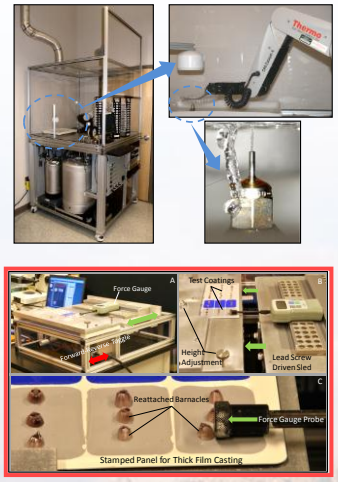
Program Approach: **Industrial Guidance** **Technology Transfer** **Novel Materials & Coatings**

Novel Coatings Synthesis



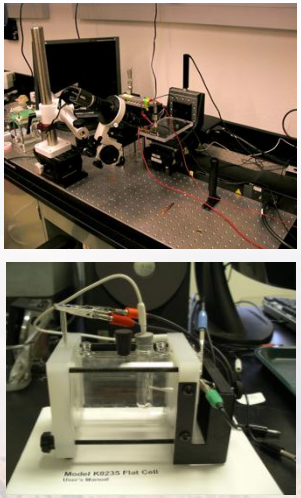
SNL, BYU

Biofouling Testing



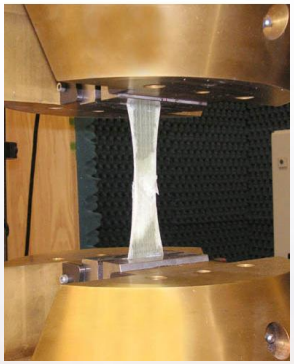
SNL, NDSU

Corrosion/Reliability Testing



SNL

Composite Fabrication & Performance Testing



SNL, MSU

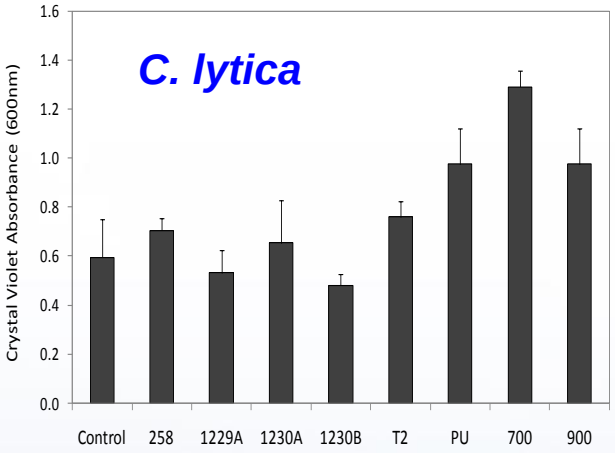
Environmental Monitoring

ORNL

Sandia National Laboratories

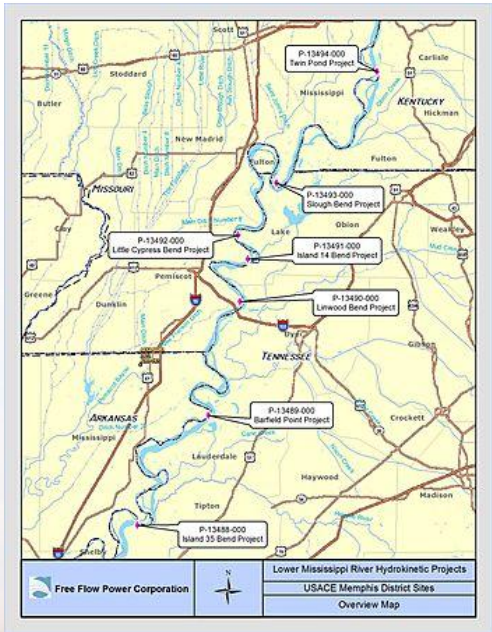
Coatings & Materials: Industrial Support

Biofilm Testing of
Owens-Corning Composites

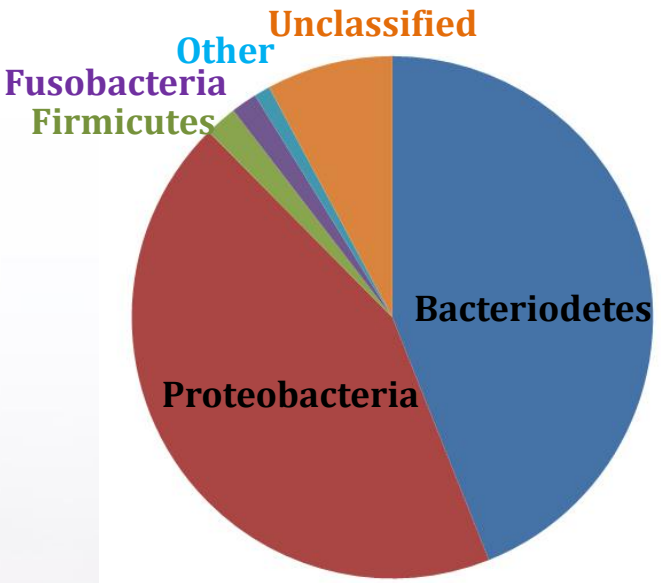


Biofouling & Corrosion Testing of
E-Paint

Biofilm Characterization & Composite Testing on
Free Flow Power
Devices Deployed in Mississippi



Biofilm Characterization on
Verdant Power Systems
Deployed in East River



Sandia National Laboratories

Advanced Materials at a Glance

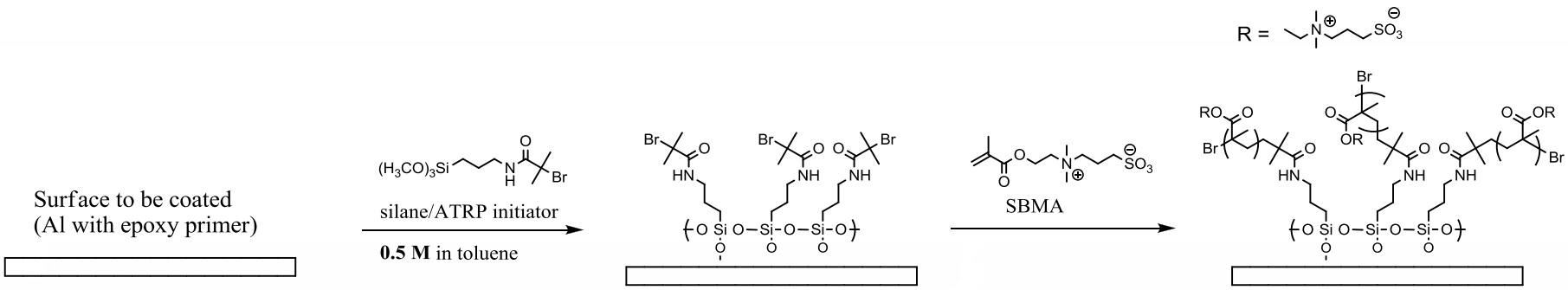
Industrial Support & Commercial Materials

- Collaborating with 4 Companies
  - Biofouling/corrosion guidance and testing
- Identified MHK materials & protection Selections
- Performance/reliability testing of commercial coatings & materials
- Mechanical testing of composites/adhesives developed for wind for MHK
- High-throughput antifouling testing correlated to ocean tests.

Novel Materials Development

- Synthesis/Testing of novel anticorrosion & antifouling compounds
  - Driven by environmental issues
  - Candidates for foul release, anticorrosion, antifouling (marine bacteria & algae)
- Collaborating with Oakridge National Labs to determine Toxicity
- Understanding mechanisms of fouling & corrosion at the nanoscale

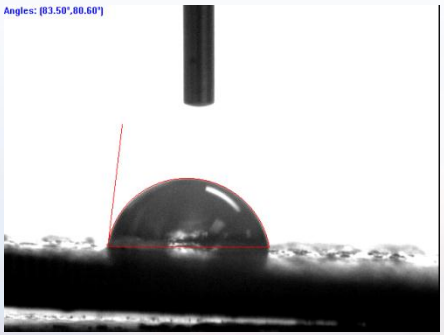
Zwitterionic Polymer Brush Coatings



XPS: 0.5% Si
0% Br
0.3% S

XPS: 4.0% Si
1.6% Br
0% S

XPS: 0.8% Si
0% Br
3.8% S



Contact angle: 82°

Contact angle: 79°

Contact angle: 22°

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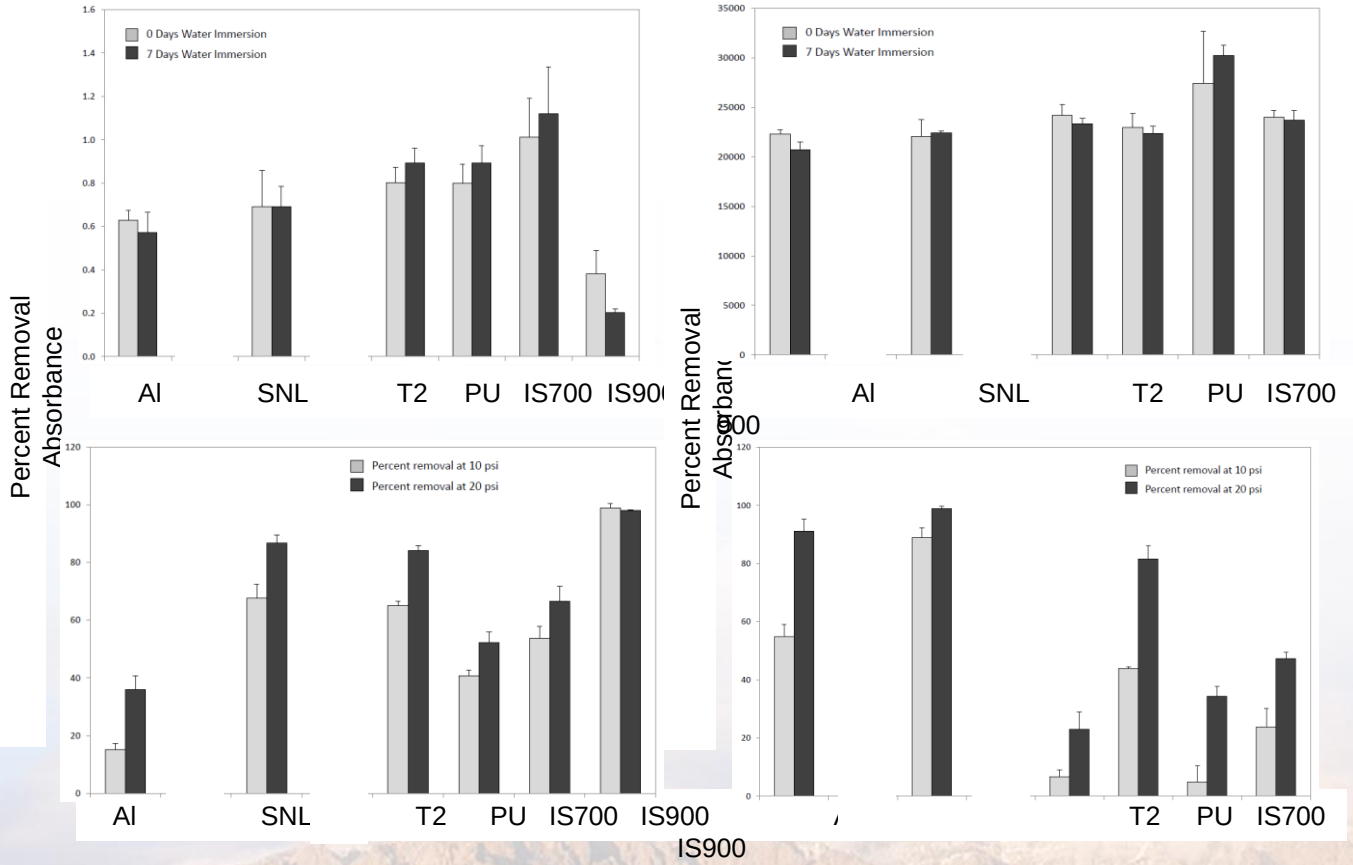
Growth & Adhesion Test Results from NDSU

C. lytica (marine bacterium) N. incerta (marine microalgae)

Biofilm Growth

Biofilm Adhesion



Al = aluminum
SNL = Sandia polymer
T2 = Dow Silastic
PU = polyurethane
IS700 = Intersleek 700
IS900 = Intersleek 900

- Zwitterionic coating is the only one to show good removal properties against both bacterial and microalgae biofilms.
- These results are promising enough to progress to macrofoulant testing.

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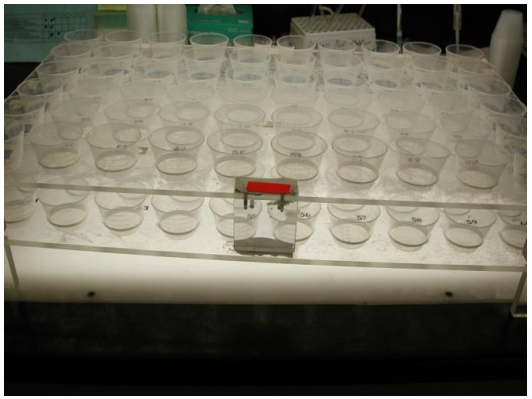
*Environmental Testing at ORNL**

Leachate toxicity testing with freshwater invertebrates (*Ceriodaphnia dubia*) and fish larvae (*Pimephales promelas*).



- Two-week freshwater leachates of coated substrates tested for 48 hour acute survival.
  - Little or no acute toxicity (LC_{50}>100%) has been observed in testing of leachates from Sandia zwitterionic coatings

Cross-Cutting

Mooring

Sediments

Materials (still need)

Controls

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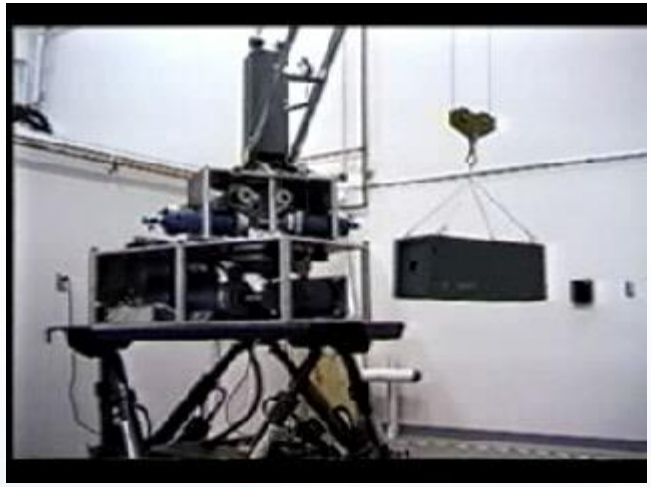
D. Wilson

Payload Pendulation Control From Scaled Testing to ATD Proof of ...t

Theory: Payload Pendulation Control Methodology:

- Swing-free input command filters
- Ship motion compensation feedback control
- Pendulation feedback damping control

Payload Pendulation Control From Scaled Testing to ATD Proof of Concept

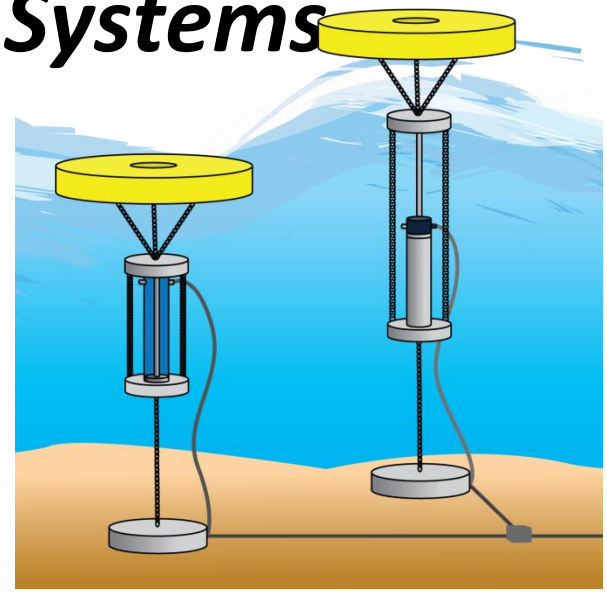


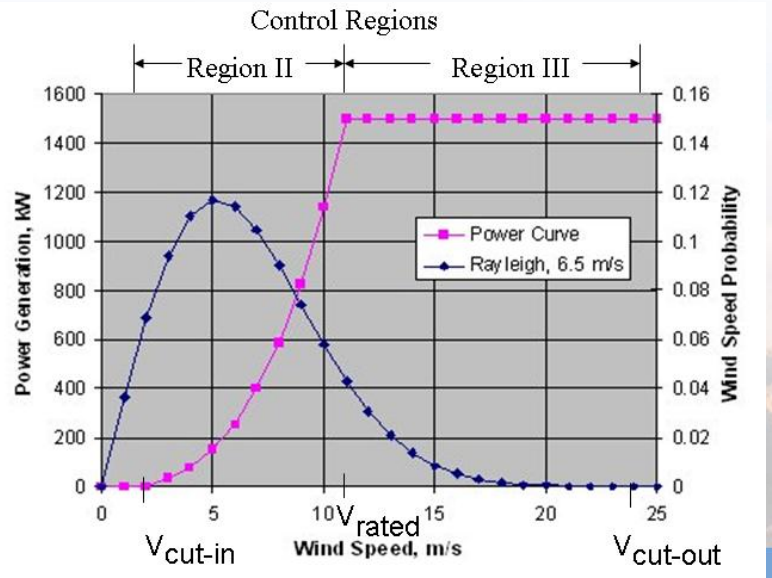
Proof-of-Concept: Demonstrated Shipboard Control Algorithms on Sandia 1/16th Scale Crane

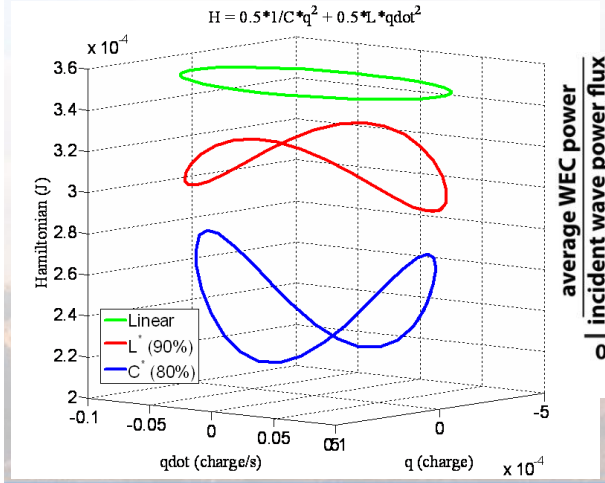
Application: Pier Side Test

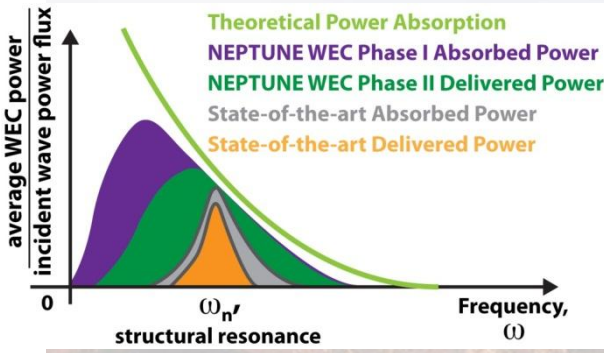
D. Wilson

Renewable Applications: Wind Turbines and Wave Energy Conversion Systems









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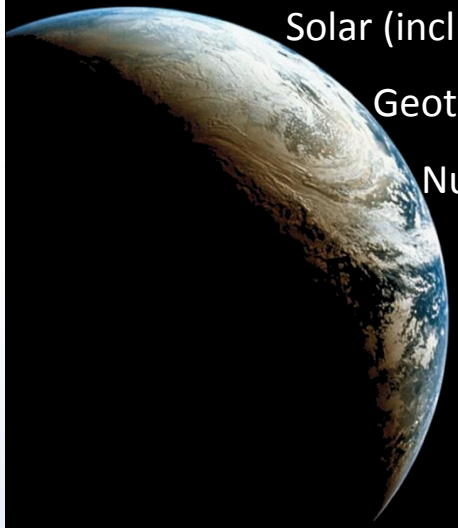
Energy Challenge - Harvest, Transform, and Control Delivery of Available Energy

Energy & Material Resources



- Fossil (coal, oil, gas)
- Solar (including wind and hydro)
- Geothermal
- Nuclear
- Plant, animal and human waste
- CO_2 & other energy conversion byproducts

Energy Processing

Harvest, transform, and deliver exergy* at the necessary amount and rate.

Energy Needs or Services

- Electricity
- Fuel
- Heat
- Cooling
- Chemicals (such as lubricants)
- Clean Water

Metric usually cost or entropy, not exergy!

***EXERGY = AVAILABLE ENERGY = useful portion of energy that allows one to do work and perform energy services**

Supply Generation → **Infrastructure Processing** → **Load Services**

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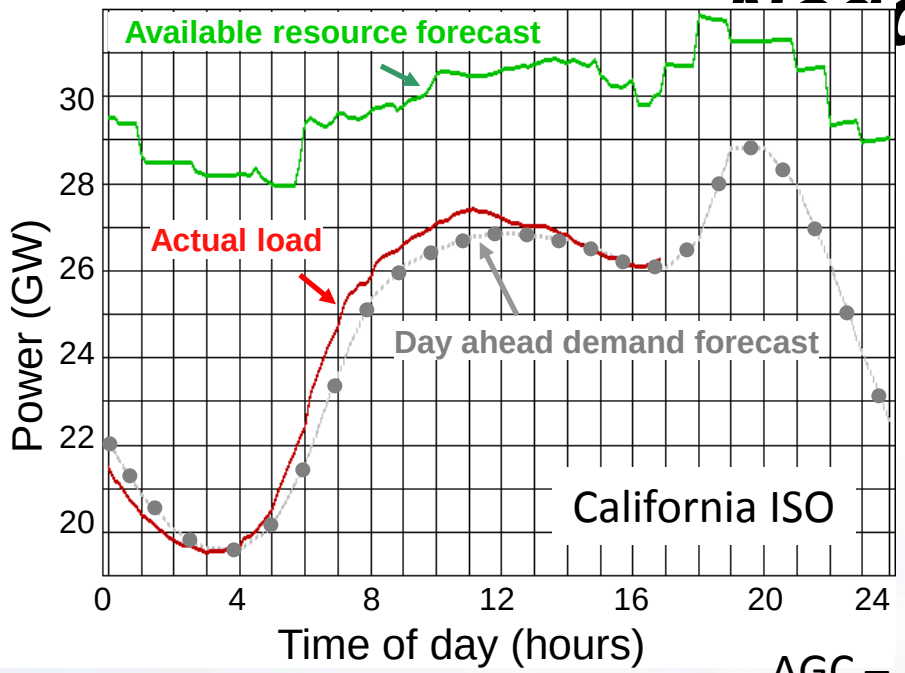
Where We are Today: Open-Loop Grid Control: Loads are Predictable: Renewables Treated as Negative Loads

Forecasting is used to set generation



Existing Electric Power Grid:

- Large spinning carbon-based generators provide stability
- Spinning reserve carbon-based
- No large fluctuations (<10% RE)
  - Decoupled (open-loop)
  - Operator is the closed-loop

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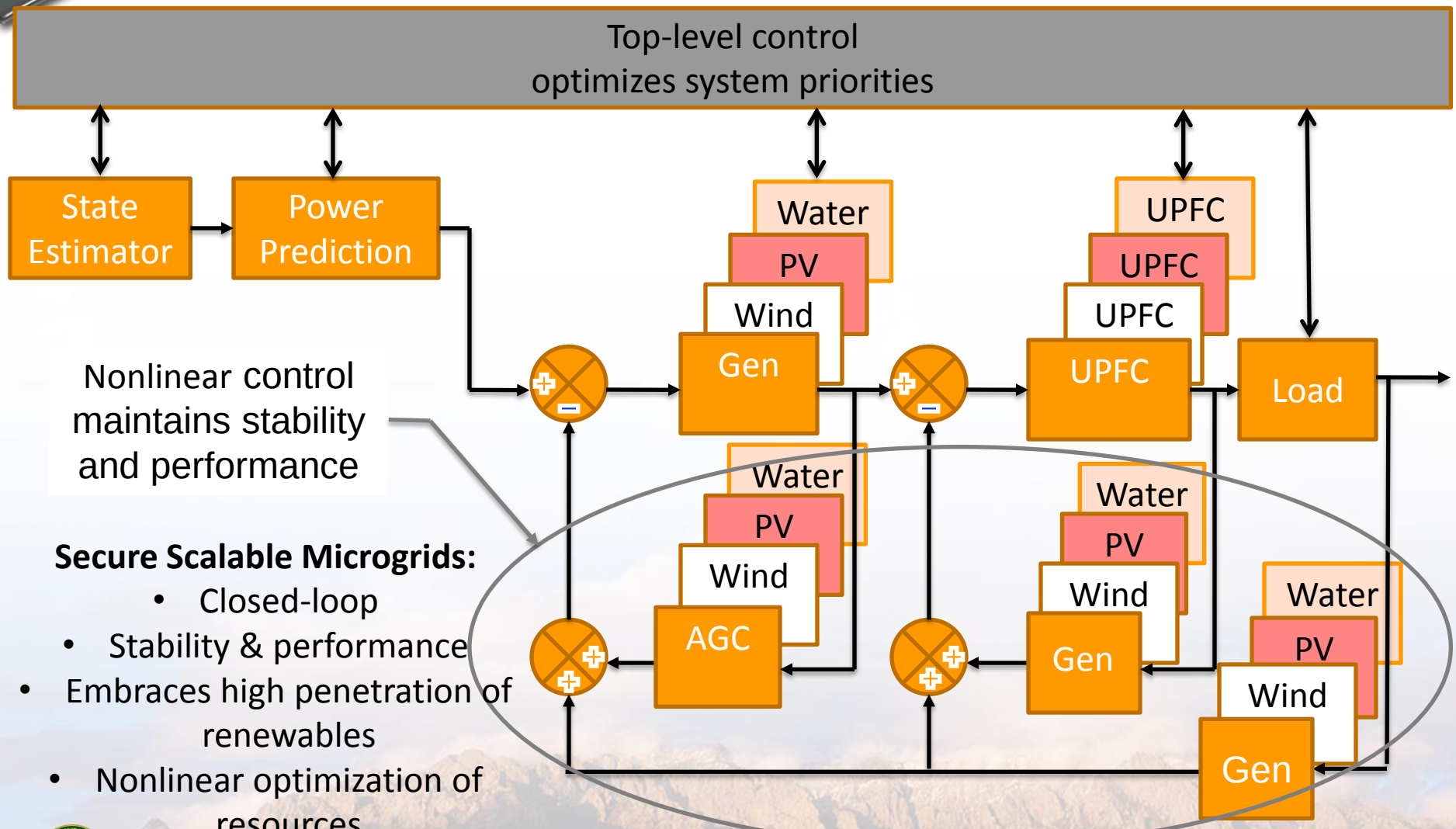
Future Grid: Automated Closed-Loop Control Enables Prioritization and System



Nonlinear control maintains stability and performance

Secure Scalable Microgrids:

- Closed-loop
- Stability & performance
- Embraces high penetration of renewables
- Nonlinear optimization of resources

UPFC - Unified Power Flow Controllers

SNL Water Power Team Members

- Daniel Laird dllaird@sandia.gov
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- Matt Barone mbarone@sandia.gov
- Josh Paquette japaque@sandia.gov
- D. Todd Griffith dgriffi@sandia.gov
- B. Boren, SNL intern OSU PhD student

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Marine & Hydrokinetic Technology Database

http://www1.eere.energy.gov/water/hydrokinetic/default.aspx

- **Goal**: Provide snap shot of the MHK Industry. The database includes companies, projects, project coordinates, capacity, materials, coatings, TRL stages, images, publications, monitoring, etc.
- Updates not only serve to showcase new technology, but supports the assessment of R&D and commercialization for MHK & OTEC

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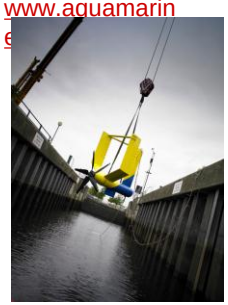
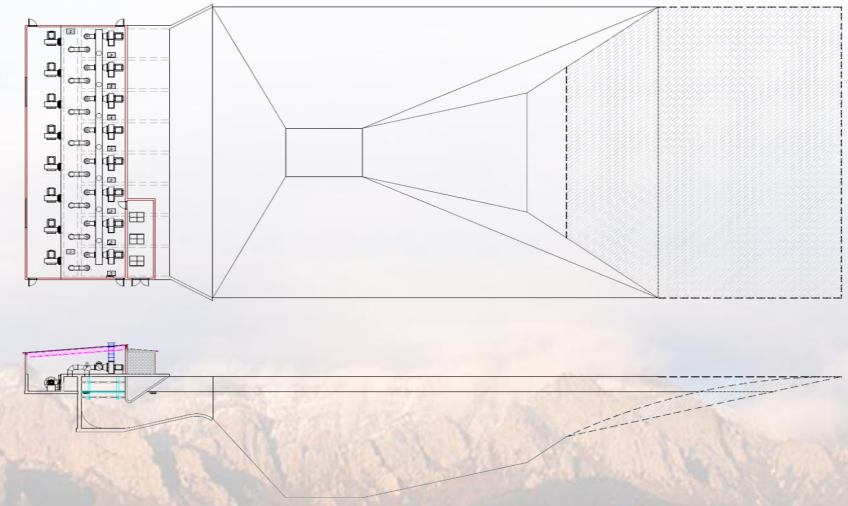
Example of Industrial Review for Materials Considerations

Company	Technology	Description	Components	Materials	Coatings
Pelamis Wave Power (formerly Ocean Power Delivery) http://www.pelamiswave.com/ 	Attenuator	**The Pelamis Wave Energy Converter** is a semi-submerged, articulated structure composed of cylindrical sections linked by hinged joints. The wave-induced motion of these joints is resisted by hydraulic rams, which pump high-pressure fluid through hydraulic motors via smoothing accumulators. The hydraulic motors drive electrical generators to produce electricity. Power from all the joints is fed down a single umbilical cable to a junction on the sea bed. Several devices can be connected together and linked to shore through a single seabed cable.	*Power Conversion Module (consists of a fabricated and painted steel structure that is populated with systems that include motor generator sets, hydraulic cylinders, accumulators, reservoirs and electrical control cabinets) *Tube * Yoke * Nose* latching and unlatching systems* Mooring spread.	main structure is made of mild steel, and ballast, currently in the form of washed sand. There are smaller quantities of various other metals and materials which make-up the machine and its components including: copper, stainless steel, rubber, bearings and plastics.*Power Conversion Module consists of a fabricated and painted steel structure *PWP uses hydraulic fluid which is biodegradable in the marine environment.	A marine paint coating is applied to structural steel surfaces in the atmospheric and splash zone and cathodic protection is applied to areas of the structural steel components in the submerged zone using sacrificial anodes.
Aquamarine Power Evopod® www.aquamarin 	Horizontal	(**Collaborating with Ocean Flow Energy) Evopod** is a semi-submerged, floating, tethered tidal energy capture device. It a simple but effective mooring system that allows the free floating device to maintain optimum heading into the tidal stream. Evopod uses a simple but effective mooring system that allows the free floating device to maintain optimum heading into the tidal stream. It can be accessed by boat for first line maintenance and has been developed specifically to address the need for a tidal current device that can operate in exposed deep water sites where severe wind and waves also make up the environment.	*Power train solution (gearbox, generator, controls) that makes maximum use of standard wind turbine components *Marine aspects (shaft, seals, stern bearing, power export swivel) all employ standard marine components* Floating, semi-submerged body; mooring	standard wind turbine and standard marine components. Maximizes use of off-the-shelf components from commercial shipping and wind power industries.	None listed

Large Scale Field Testing: Sandia Lake

- **Existing and *proposed* capabilities**
  - *1.5 m waves*
  - *1 to 5 s period*
  - **15 m deep basin**
  - *>70 m long basin*
  - 36 m wide basin
  - Overhead lifting
  - **4 trained/certified divers**
  - Technician support
  - Several anchor locations
  - **Instrumentation**
    - 100+ channels
    - Underwater cameras
  - **DOE owned facility**



Questions.

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Expected slides

MHK

- **CACTUS**
- **Ref Model**
- **SNL-EFDC**
- **SNL-SWAN**
- **Acoustics**
- **Blade Design**
- **Multi-DOF power performance**
- **WEC Design**
- **Anchor and Mooring**

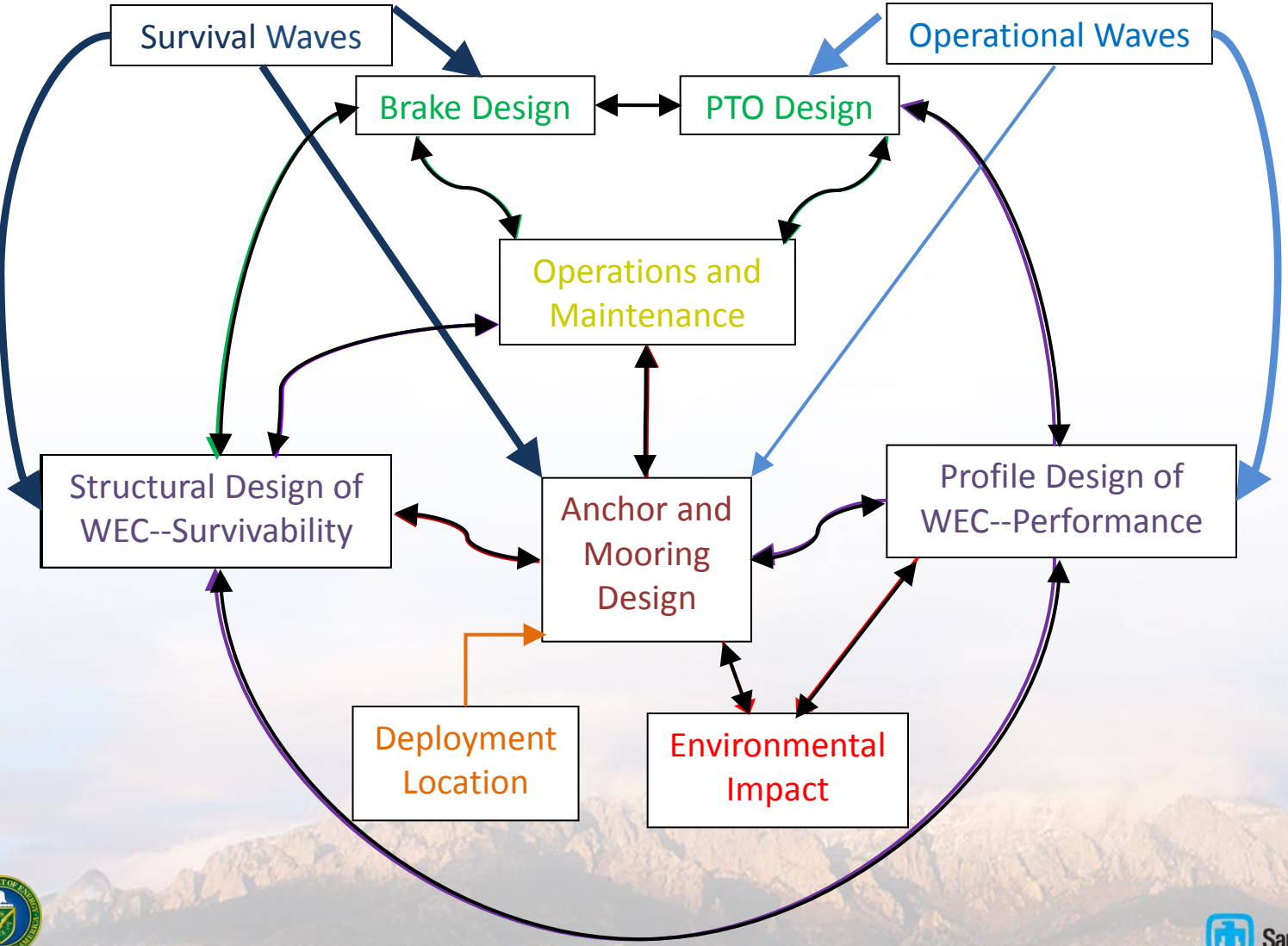
offshore

- **VAWT**
- **Minnesota**
- **SEAWOLF**
- **Large Blade**

Water general

- **Controls**
- **Materials**

WEC Design


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

Sandia Capabilities

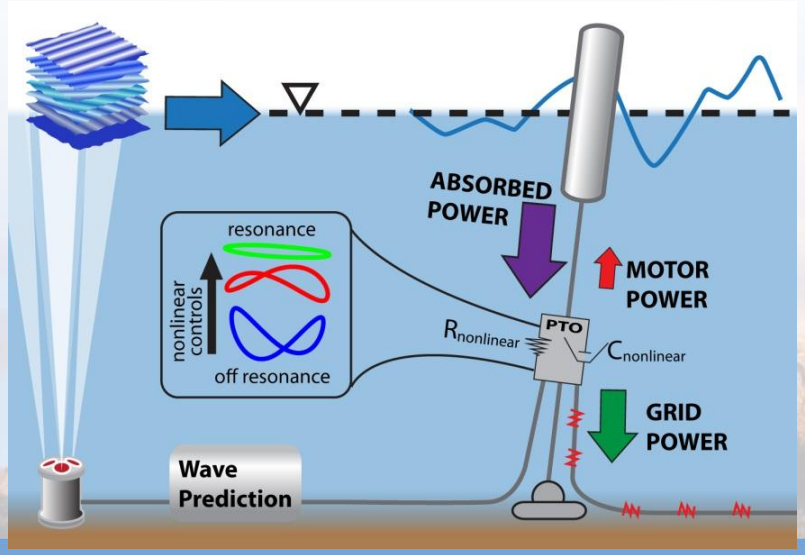
- **Our work allows us to identify COE for a cross section of devices.**
  - This is an internationally unique capability
- **Our work allows us to identify COE drivers for a particular device.**
  - Identify cost drivers: structure, mooring, PTO, etc..
  - Identify major O&M and environmental cost drivers.
- **Our component models allow us to evaluate the maturity of Industry designs.**
  - Our experiences in designing deployable WECs allows us to develop targeted assessments of particular Industry designs
  - The roadmap is partially generated from these experiences and points us towards a devices maturity.
- **The experience of moving through the design process has allowed us to identify industry gaps.**
  - The roadmap is partially generated from these experiences and has highlighted some of these gaps: large experimental test facility, continued experimentation throughout the development process, dynamic structural loading calculations, detailed fatigue and O&M calculations, etc.

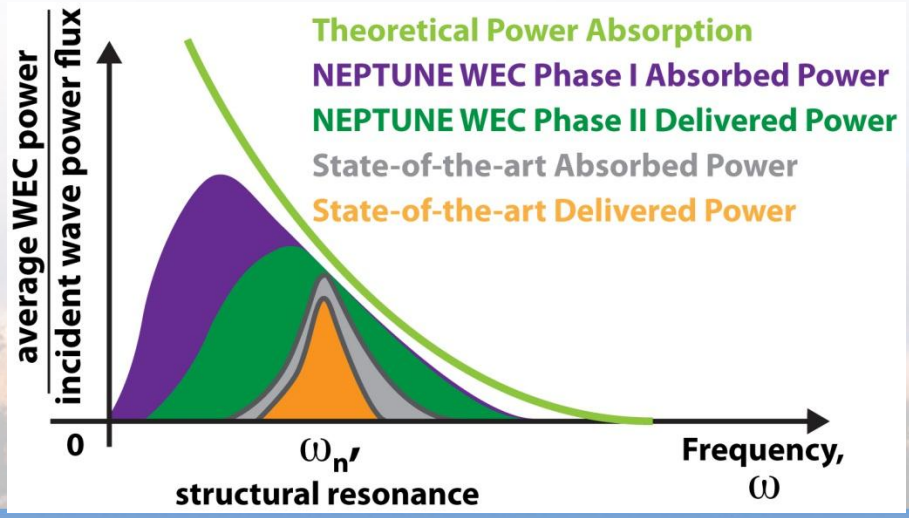
Future Research: NEPTUNE WEC

Nonlinear-controls Extracting Power with TUNEd Wave Energy Converters

- **Major driver of COE is device performance.**
  - Resonant WECs respond to narrow spectrum
  - Resonance is dependent upon device geometry

- **NEPTUNE WEC project.**
  - Extend structurally defined phase-matched absorption to a *controls-based* phase-matched absorption
  - Requires foreknowledge of the incident wave field and device velocity as well as the input of power to allow the PTO to act as a motor
  - Wave foreknowledge will facilitate reactive controls and increase device availability





WE 5.1 Offshore Wind RD&T (SNL)
Daniel Laird

Offshore Task Updates
March 5, 2012

In March 2011 (FY11), SNL initiated an Offshore Wind research portfolio consisting of multiple projects in support of the DOE Offshore Wind program.

These projects provide technology development and assessment in research areas important for technology risk reduction, offshore siting, and reduction in offshore cost of energy.

Outline

5.1 Offshore Wind RD&T (SNL)	Daniel Laird
5.1.1 Structural Health and Prognostics Management	D. Todd Griffith
5.1.2 Innovative Concepts and Approaches	Matt Barone
5.1.3 Large Offshore Rotor Development	D. Todd Griffith
5.1.4 Wind Installations: Sediment Transport, Scour and Foundation Impact Analysis	Jesse Roberts
5.1.5 Strategic Planning & Standards	Daniel Laird
5.1.6 Radar Mitigation and Outreach	D. Todd Griffith
5.1.7 O/S Engineering Support - Cardinal	Daniel Laird
5.1.8 Wind and Wave Loads Analysis and Validation	Josh Paquette
5.1.9 DE-FOA-0000415, Innovative Offshore Vertical-Axis Wind Turbine Rotors	Matt Barone
5.1.10 DE-FOA-0000415, High-resolution modeling of offshore wind turbines and farms	Kelley Ruehl

WE 5.1.1 Structural Health and Prognostics Management (D. Todd Griffith)

Objective:

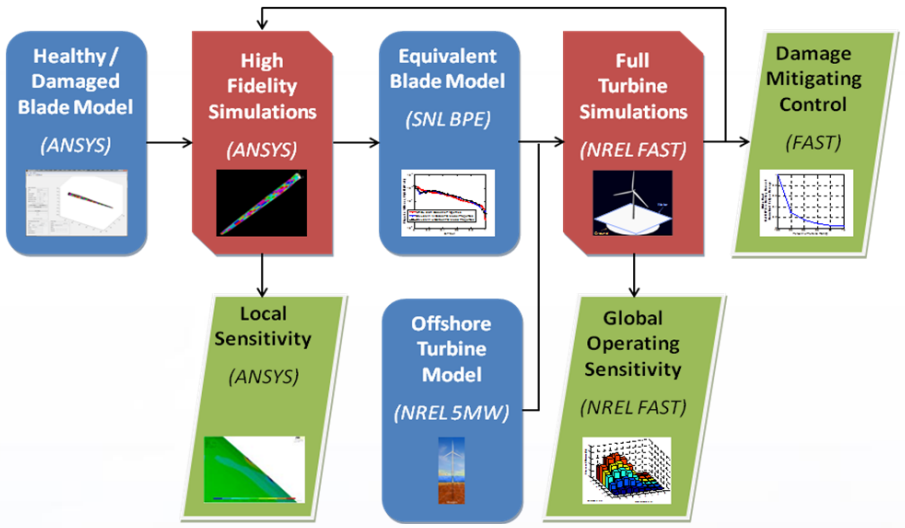
- Develop a roadmap for the application of advanced structural health monitoring (SHM) and prognostic control to O&M of offshore wind turbines.
- Perform cost/benefit analysis of prognostic control for viable sensing options.

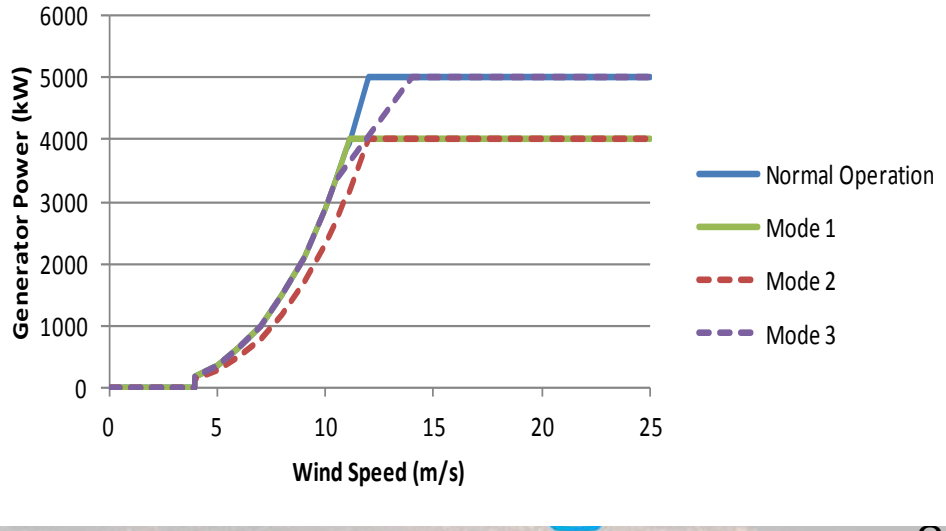
Approach:

- Identify relevant defect, damage, or fault conditions using Sandia BRC, Sandia CREW, and other knowledge bases
- Simulate and quantify sensitivity of damage at global and local scales
- Develop and evaluate robust, cost-effective prognostic control options (i.e. smart loads management) along with viable sensing

Impact:

- The cost for offshore O&M has been estimated to be 2 to 5 times that of onshore wind farms.
- This work seeks to mitigate these rising costs.





Reduce O&M costs AND maximize energy capture

WE 5.1.1 Structural Health and Prognostics Management (D. Todd Griffith)

Highlights:

- Abstract accepted for podium presentation in the Scientific Track at EWEC; titled "Prognostic Control to Enhance Offshore Wind Turbine Operations and Maintenance Strategies".

Outlook:

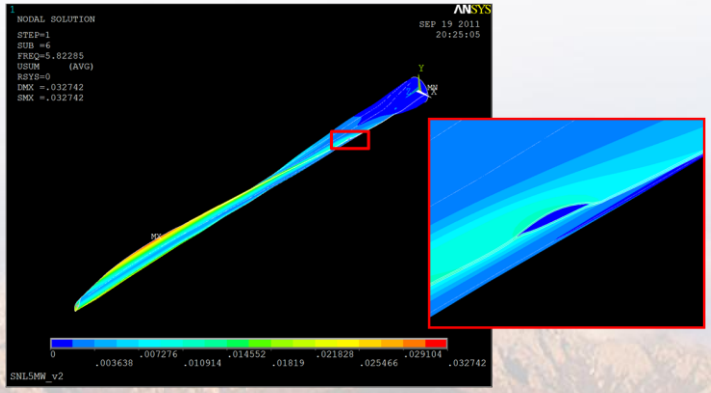
- Simulations of new damage and fault conditions with sensitivity analysis will be completed:
  - shear web disbond
  - rotor imbalance
  - offshore tower/monopile damage
- FY11 SAND report will be finalized; also will be summarized for a journal article to be submitted to Wind Energy


SANDIA REPORT
SAND200X-XXXX
Unlimited Release
Printed Month and Year

Offshore Structural Health and Prognostics Management: 2011 Q4 Report

D. Todd Griffith, Joshua A. Paquette, Brian R. Resor, Jonathan R. White and Nathanael C. Yoder

Sandia National Laboratories



WE 5.1.2 Innovative Concepts and Approaches (M. Barone)

Objective:

- Support the wind program's COE reduction goals through investigation of innovative offshore wind turbine concepts, beginning with the vertical-axis wind turbine.

Approach:

- Provide accessibility to the extensive repository of Sandia VAWT technical data and reports, design codes, and staff experience to further advance this promising avenue of research.
- Investigate updates to SNL VAWT codes

Impact:

- Due to its potential for scaling to large machine sizes, its relative simplicity, and its low center of gravity, the VAWT has potentially large cost advantages for offshore deployment.
- SNL VAWT research history includes the nearly twenty-year DOE-sponsored research program from the mid-1970s to the mid-1990s; in particular design, construction, and testing of a 34 meter diameter, 500 kW, research turbine.

The DOE/Sandia 34 meter VAWT.

Public domain information dissemination and legacy code evaluation

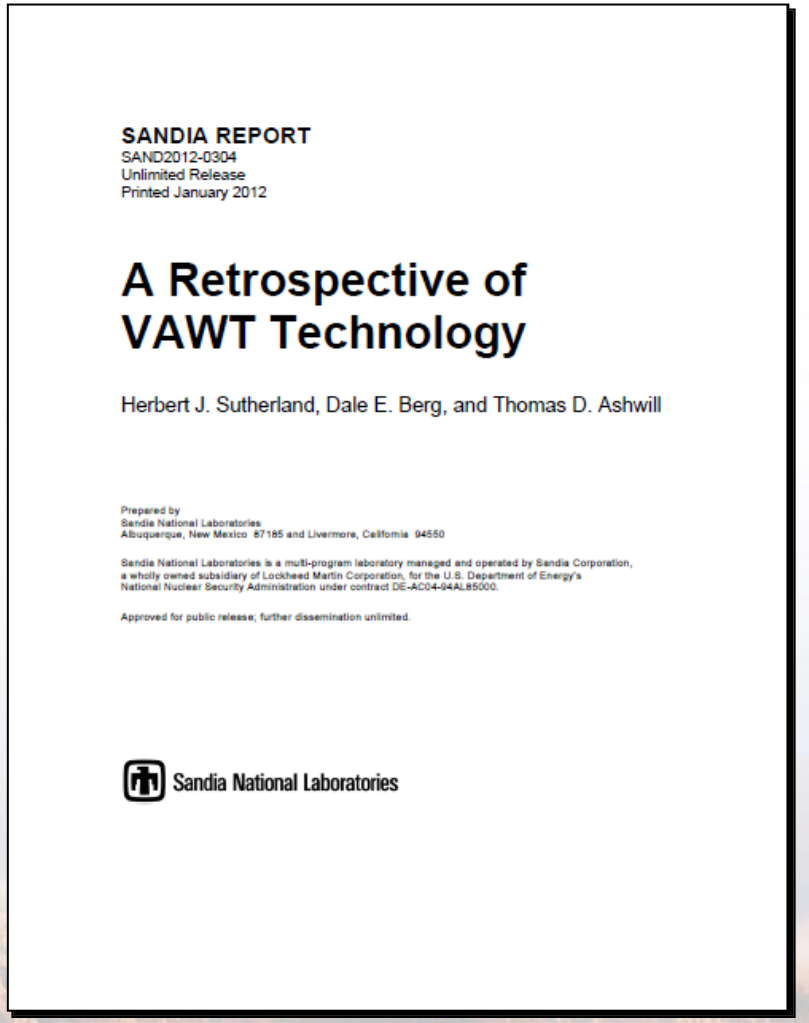
WE 5.1.2 Innovative Concepts and Approaches (M. Barone)

Accomplishments:

- (FY12, Q1) several staff members at Sandia who worked on the 34 meter VAWT project completed a draft report that documents the Sandia VAWT research experience, and defines the state of VAWT research at the close of the previous research program fifteen years ago.

Outlook:

- Building upon the retrospective report, we are investigating the suite of design codes that will be required to fully resurrect a VAWT R&D program.
- Focused on updates to rotor and system cost models for large, offshore VAWTs.



SANDIA REPORT
SAND2012-0304
Unlimited Release
Printed January 2012

A Retrospective of VAWT Technology

Herbert J. Sutherland, Dale E. Berg, and Thomas D. Ashwill

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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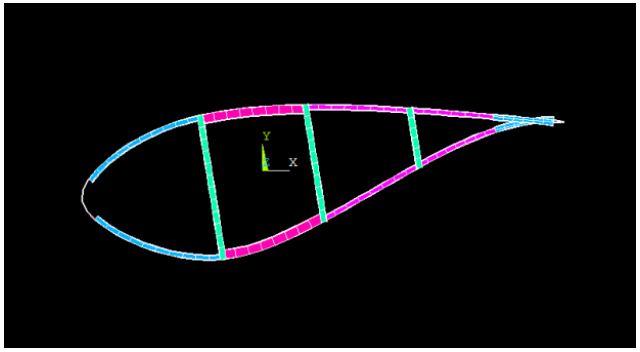
WE 5.1.3 Large Off-Shore Rotor Development (D. Todd Griffith)

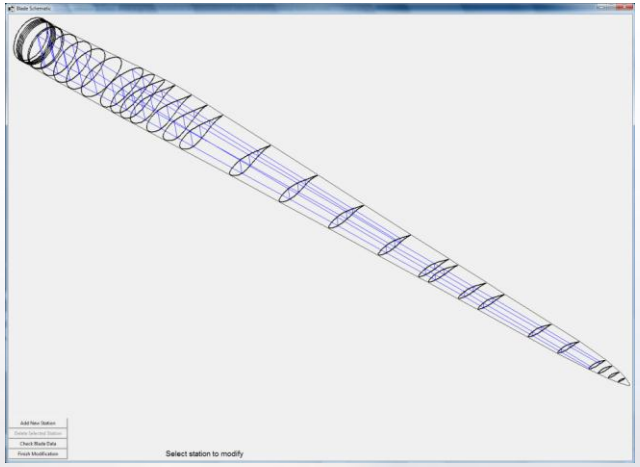
Objective:

- Research and document challenges and opportunities for large offshore HAWT blades including barriers to continued rotor swept area growth
- Evaluate new design concepts for weight reduction to reduce gravitational loading and mitigate of aeroelastic instability for large blades



Approach:

- Follow GL and IEC guidelines for stress/strain, buckling, tip deflection, and fatigue life to determine a detailed composite layup satisfying design loads.
- Make large blade (100-meter) and turbine (13.2 MW) design models available to other researchers in academia and industry including SNL100-00, SNL100-01, etc.



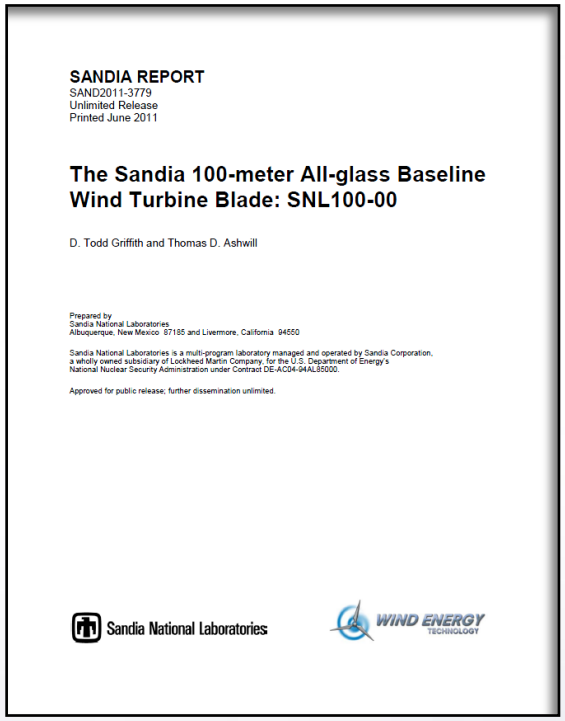
WE 5.1.3 Large Off-Shore Rotor Development (D. Todd Griffith)

Highlights:

- Public release of model data for design studies (SNL100-00 blade and SNL13.2MW-Land turbine); Largest publicly available blade and turbine design models.
- Sandia Design Scorecard introduced
- Podium presentation in Scientific Track at AWEA WindPower Scientific Track (June 2012, Atlanta, GA)
- Invited presentation at Blade Manufacture (Germany November 2012).

Outlook:

- Continue investigation of large blade design concepts (e.g. carbon study, geometry, and core materials) to reduce blade weight/cost; mitigate buckling, gravitational fatigue and flutter instability
- Support partners using SNL100-00 model including structural optimization and CFD studies



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

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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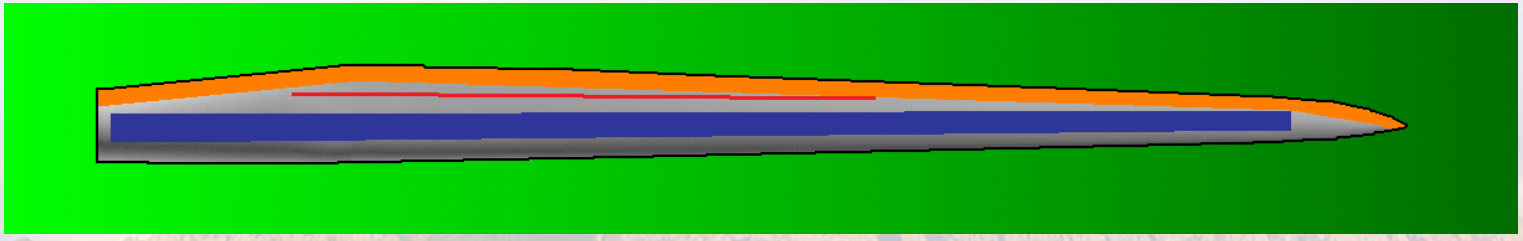
WIND ENERGY TECHNOLOGY



WE 5.1.4 Sediment Transport, Scour and Foundation impact Analysis (Jesse Roberts)

Objectives:

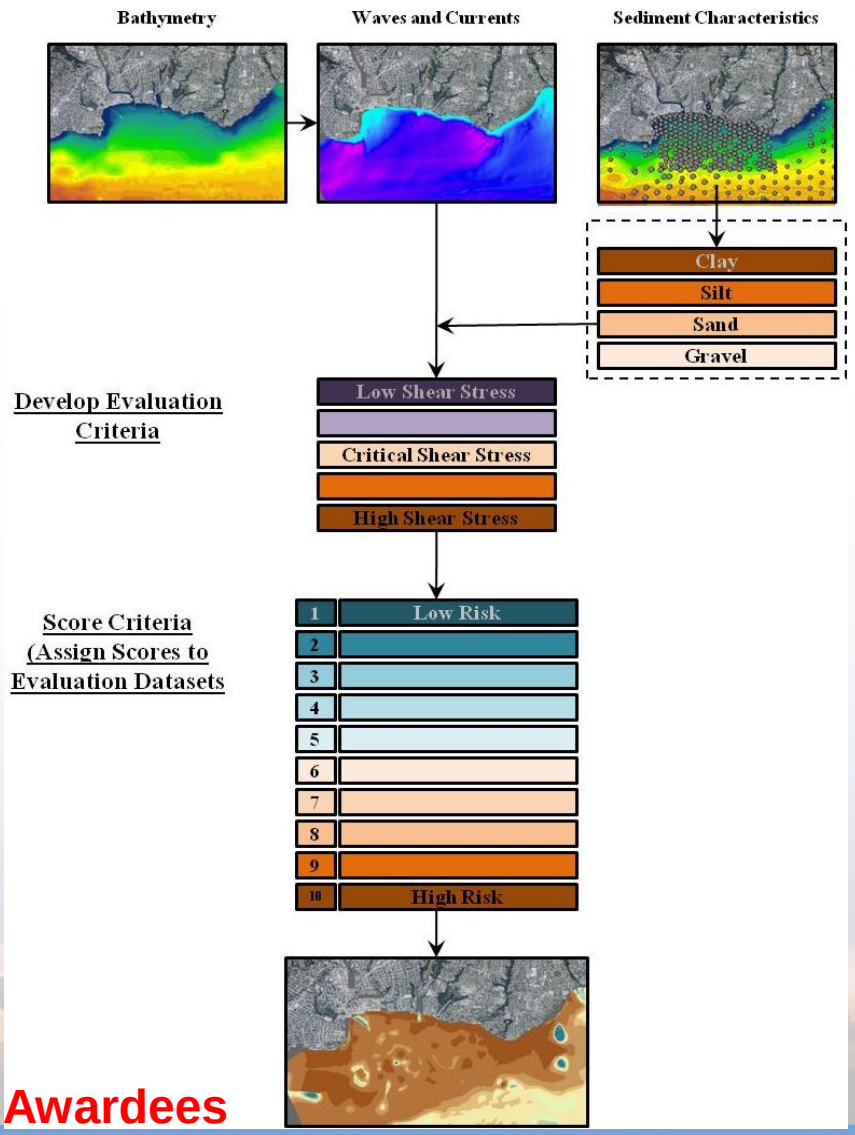
- Develop public domain methods/tools for assessing wind farm and ecosystem risk from sediment mobilization due to seafloor-structure interactions.
- Transfer the tools and techniques to industry for site-specific evaluations required for permitting and design.
- Develop industry guidance on coastal processes and assessment techniques for seabed dynamics to streamline OWF design and permitting

Approach:

- Integrate site specific information into models to assess spatial patterns of likely sediment erosion, deposition, and transport during typical and extreme conditions.
- Site characterization measurements are combined with model simulation to supplement the understanding of the site's sediment dynamics and commensurate effects on the seabed upon installation of offshore wind turbine arrays.

Impact:

- Reduce lifecycle costs through intelligent OWF array design that consider seabed dynamics (reduced maintenance)
- Reduce time and costs associated with permitting by enabling prediction of site-specific environmental responses to OWF designs (accelerate the permitting process)
- Define and reduce OWF risk from seafloor-structure interactions through better planning, design and mitigation.



Critical to Offshore Siting, Could Support All Demonstration FOA Awardees

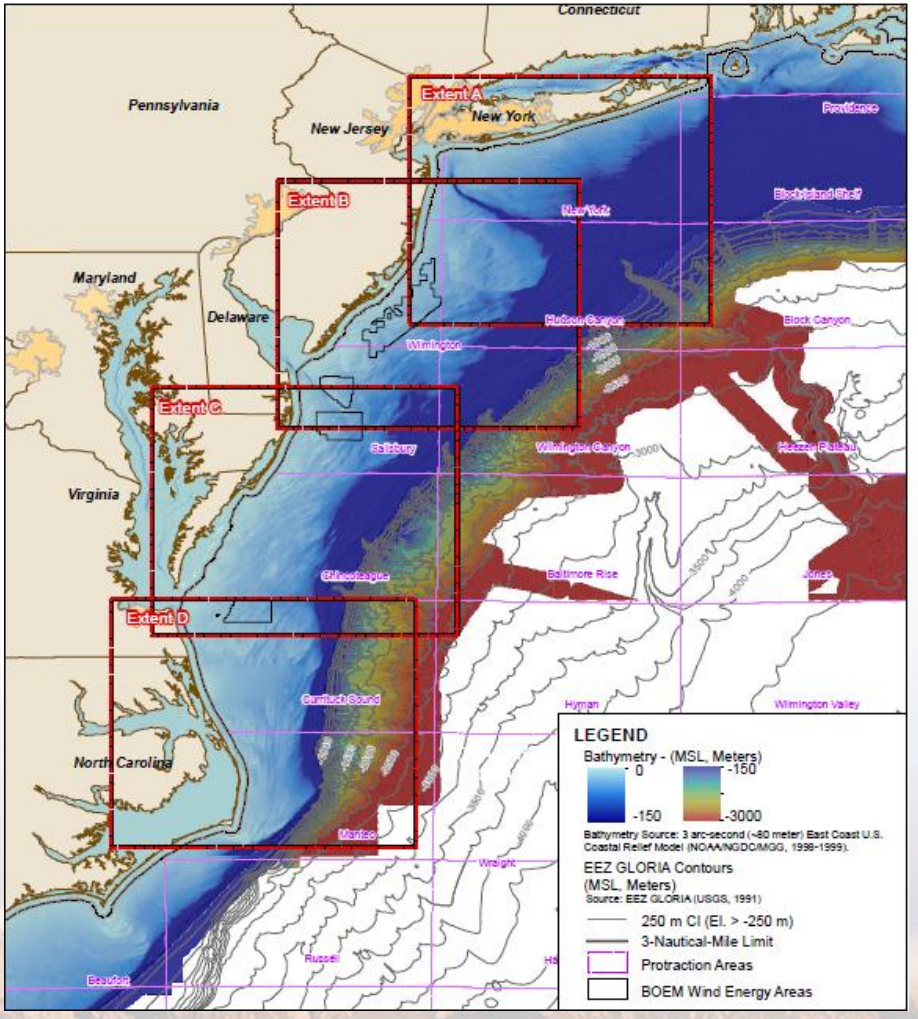
WE 5.1.4 Sediment Transport, Scour and Foundation Impact Analysis (Jesse Roberts)

Accomplishment:

- Completed draft report describing a methodology to estimate the probability of sediment mobilization and scour due to the presence of offshore wind structures using Monterey Bay, CA as a test bed.
- Completed validation of Monterey Bay wave and circulation models
- Completed NDA with Fugro Atlantic.
- Completed contract with Fugro Atlantic and received first report outlining available data on the Atlantic coast between Long Island and Cape Hatteras (Mid-Atlantic).

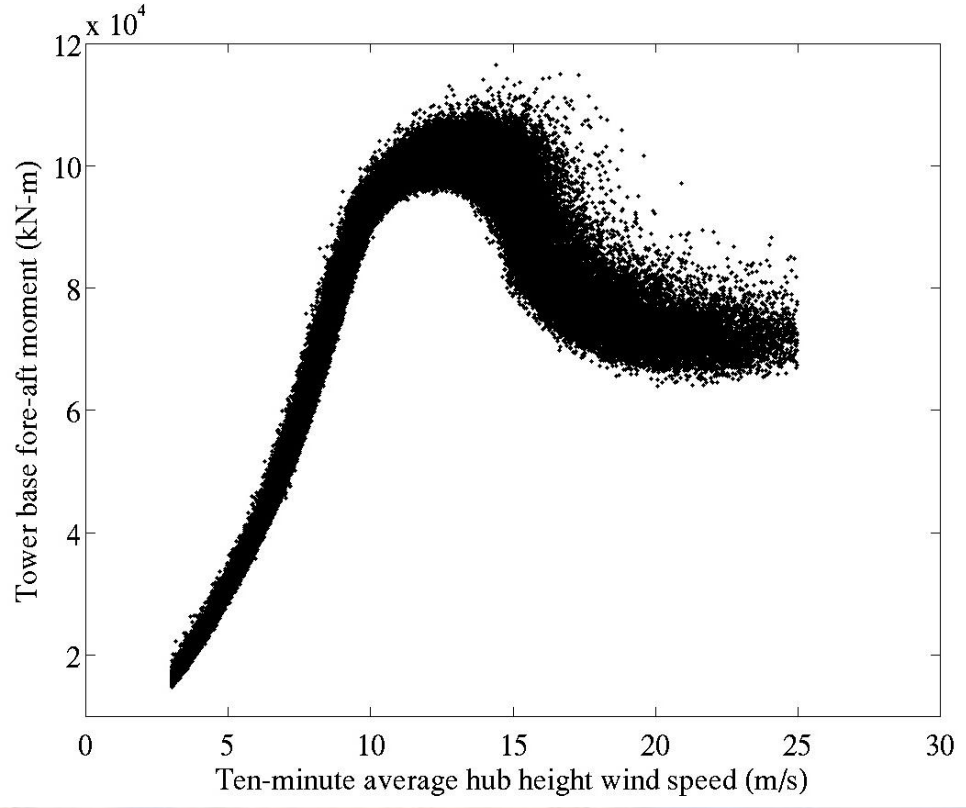
Outlook:

- Complete draft guidance document that will help streamline OWF design and permitting.
- Develop a large circulation model of the Mid-Atlantic to serve as boundary conditions for site-specific models of seabed dynamics.



WE 5.1.8 Wind and Wave Loads Analysis & Validation (Josh Paquette)

- Abstract accepted to EWEC 2012 Conference "Simulating the Entire Life of an Offshore Wind Turbine"
- Currently, 16 years of combined wind/wave loading on NREL 5MW shallow water have been completed
- Represents largest offshore wind turbine simulation (~1M 10-minute simulations) to date worldwide
- Will be used to inform load extrapolation models in wind turbine standards



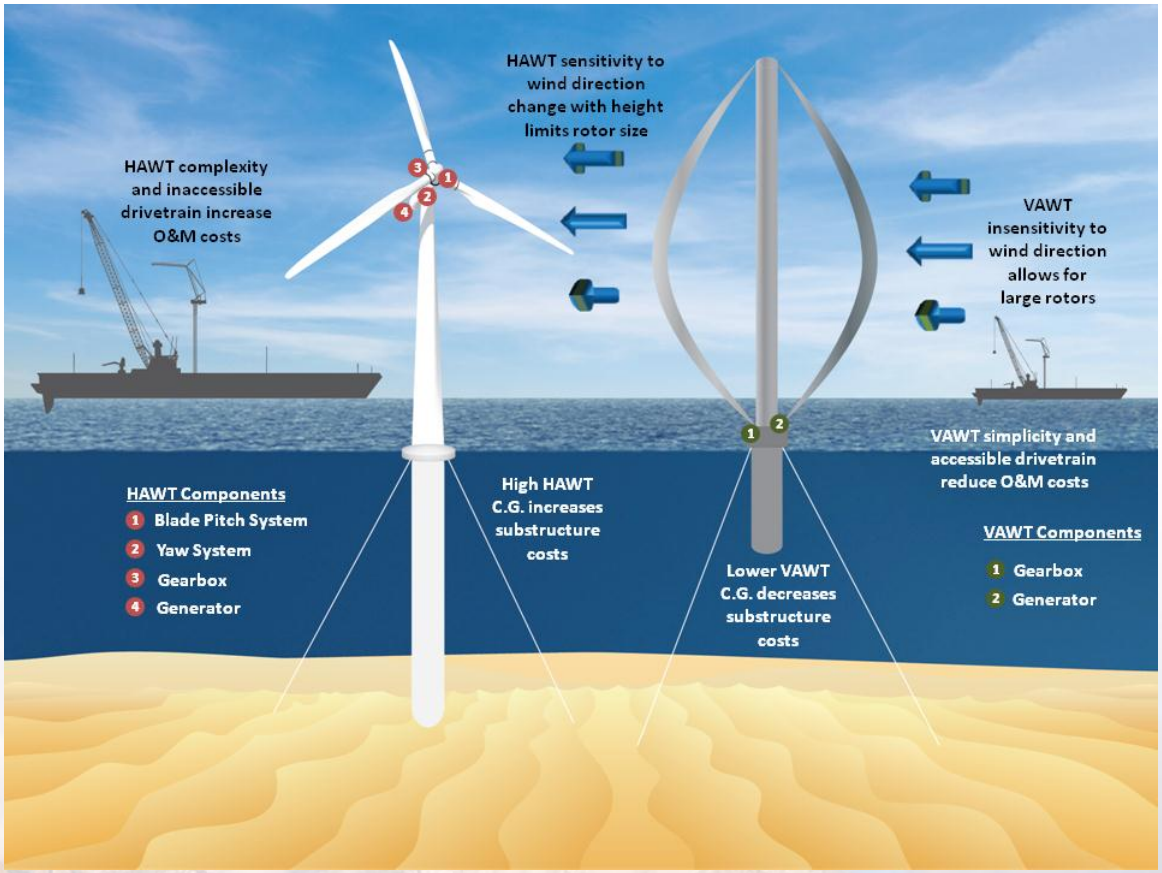
Simulated Offshore Wind Turbine Tower Fore-Aft Loads

Leverage Sandia HPC to improve standards

WE 5.1.9 (DE-FOA-0000415) Innovative Offshore Vertical-Axis Wind Turbine Rotors (Matt Barone)

Overview:

- **This project focuses on improving the VAWT rotor sub-system through improvements in aerodynamics, materials, blade manufacturing, and test methods.**
- **Innovative rotor designs will be developed that reduce system COE.**
- **Designs will then be tested at sub-scale to prove their feasibility and increase the TRL of VAWT technology for offshore deployment.**



WE 5.1.9 (DE-FOA-0000415) Innovative Offshore Vertical-Axis Wind Turbine Rotors (Matt Barone)

Q1 Accomplishments

- Aero-structural reference model built for the 500 kW SNL 34-meter test-bed VAWT;
- Design codes were written to generate Darrieus VAWT blade shapes and build aerodynamic and structural rotor models;
- Aerodynamic model has been coupled to the DAKOTA optimization toolkit to enable design calculations;
- Contracts placed with 3 of 4 project partners (4^{th} nearly complete)

Outlook

- Project kickoff meeting with partners and collaborators being held 6-7 March in Albuquerque, NM
- EU DeepWind project, UK Aerogenerator project, and Principle Power floating platform OEM have all expressed interest in collaborations

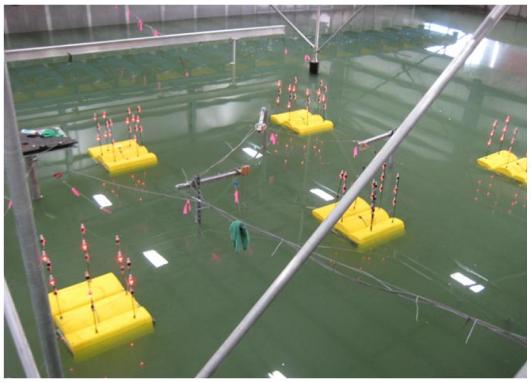
WE 5.1.10 (DE-FOA-0000415) High-resolution modeling of offshore wind turbines and farms (Kelley Ruehl)

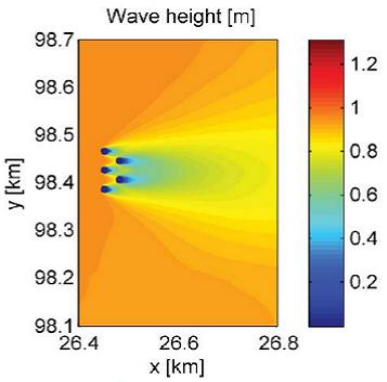
Overview:

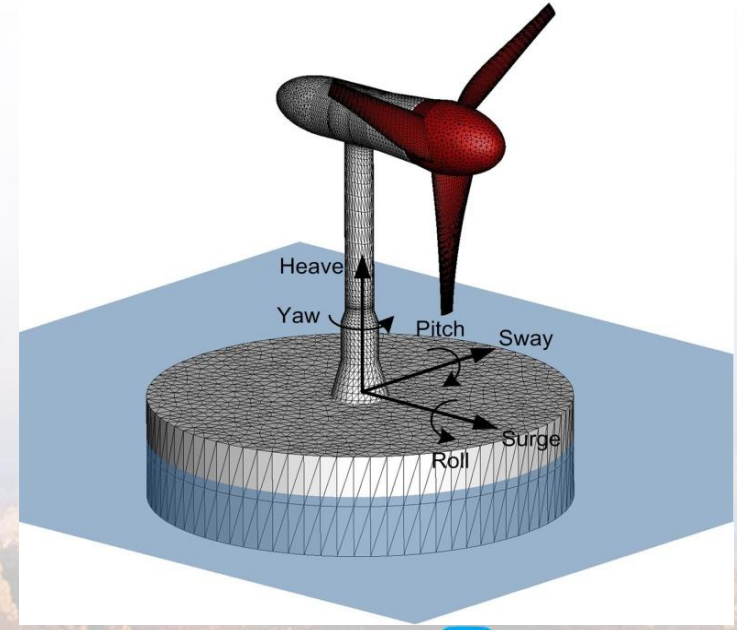
- SNL and the University of Minnesota were awarded a collaborative project to investigate high-resolution modeling of floating offshore wind turbines and farms.
- The University of Minnesota is the project lead
- The primary contributions of the SNL effort in this project will be the coupling of near field and large scale models to evaluate offshore wind farms and individual platform reaction to waves and modeling fluid-structure interaction effects.

Approach:

- The research consists of three distinct components:
  - 1) Development of an advanced, multi-scale and multi-resolution computational framework for simulating offshore wind turbines and farms
  - 2) Formulation of the computational tools to take full advantage of massively parallel computational resources
  - 3) Validation of the models with laboratory and field-scale experiments.







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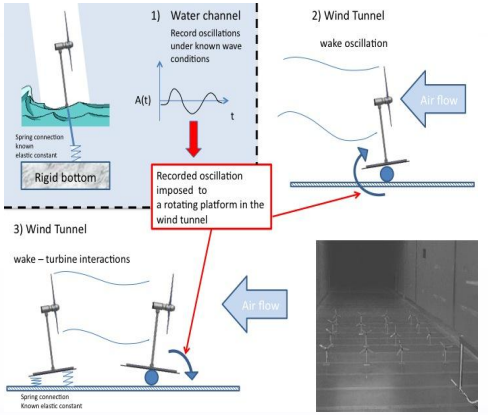
WE 5.1.10 (DE-FOA-0000415) High-resolution modeling of offshore wind turbines and farms (Kelley Ruehl)

Q1 Accomplishments

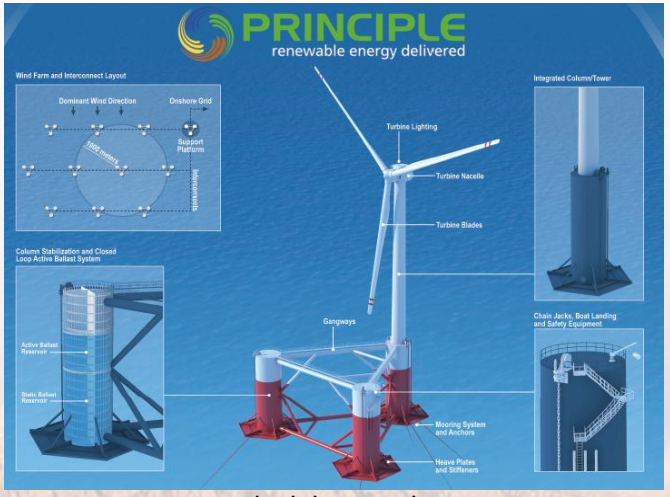
- Organized and held the offshore wind kickoff meeting at SNL on Feb. 8 with participation from University of Minnesota, SNL, Principle Power, and Clipper Windpower
- NDA process started with Principle Power

Outlook

- Decided to model 10MW Clipper offshore turbine design with Principle Power WindFloat platform design
- NDA and contract with Principle Power near completion for 10MW WindFloat platform design (nearly complete)
- Requested 10MW offshore turbine design specs necessary for modeling effort from Clipper Windpower



Planned Wind and Wave Experiments



www.principlepowerinc.com

Sandia National Laboratories

MHK Research Activities at Sandia National Laboratories

Daniel Laird
Program Manager
Water Power Technologies
Sandia National Laboratories

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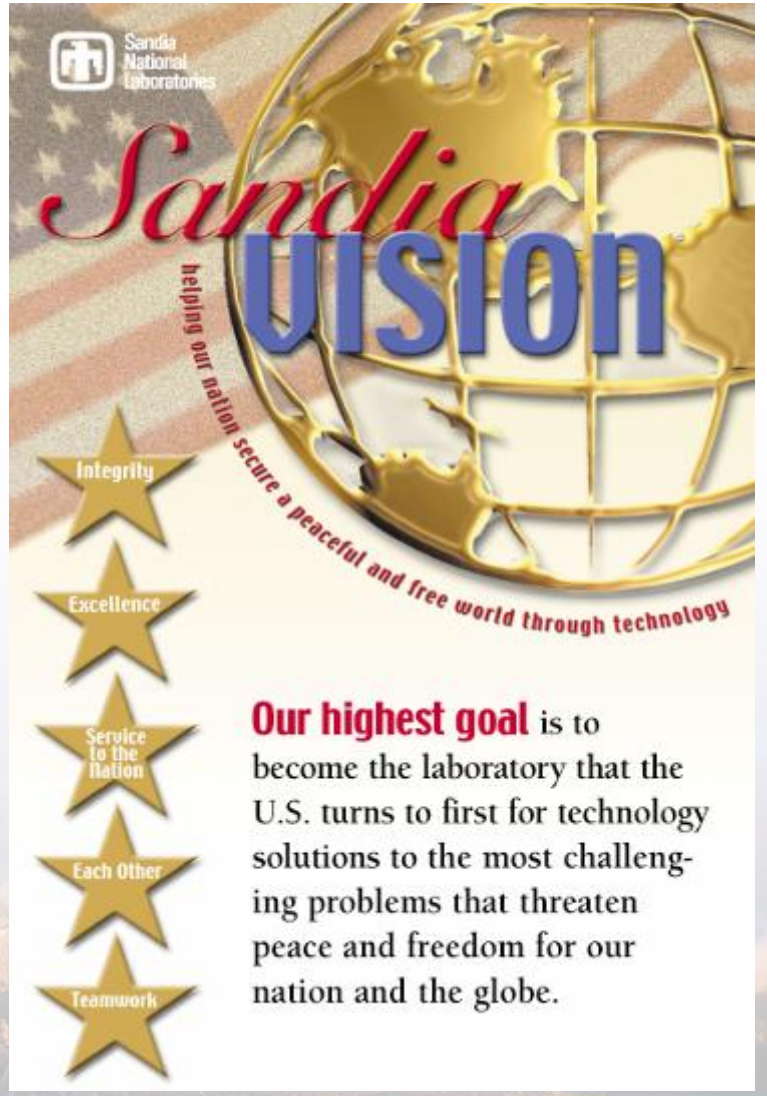
National Nuclear Security Administration

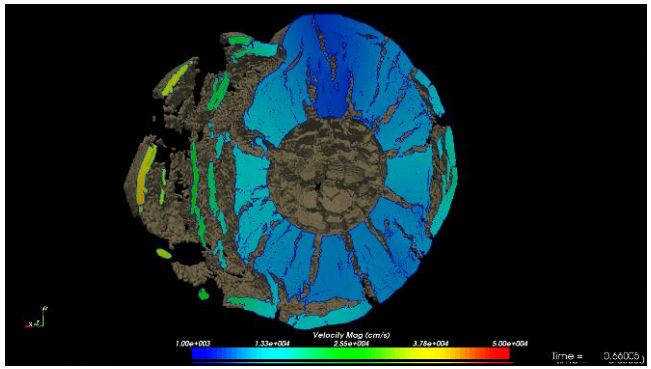
Sandia National Laboratories

Our Business: National Security

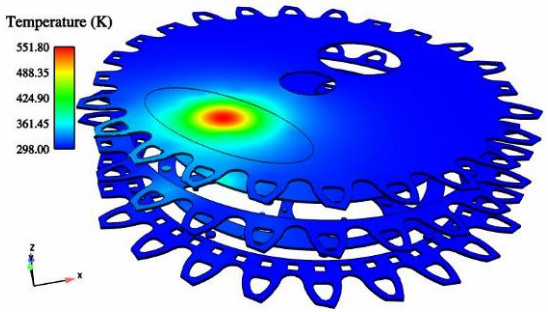
- Broad mission in developing science and technology applications to meet our rapidly changing, complex national security challenges
- Safety, security and reliability of our nation's nuclear weapon stockpile



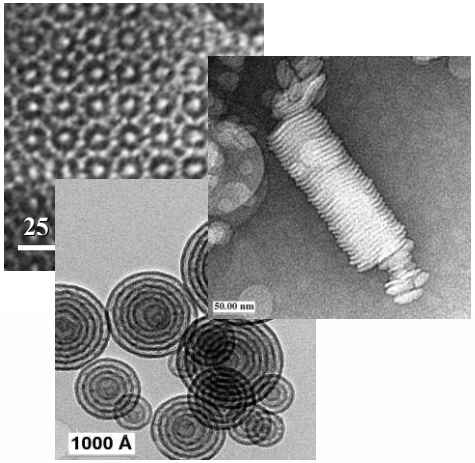
Our Mission Focus Relies on Strong Science and Engineering



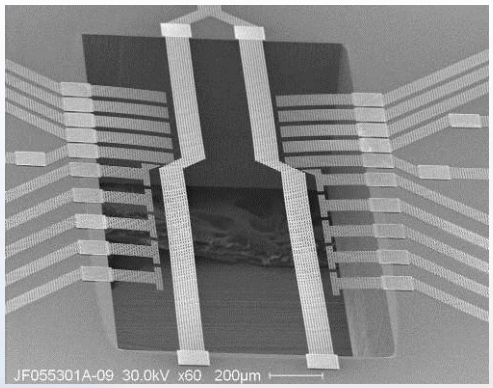
Computational and Information sciences



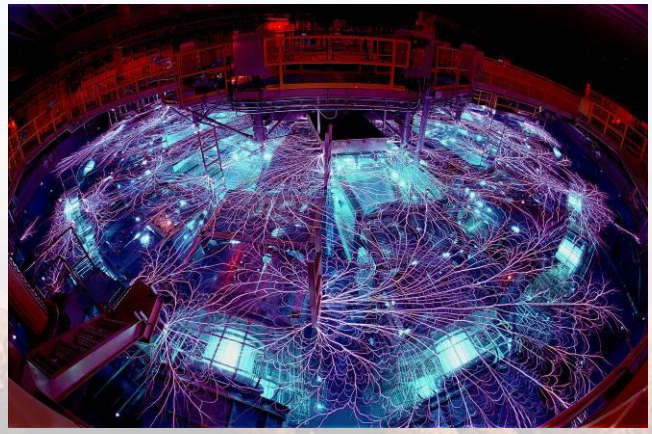
Engineering Sciences



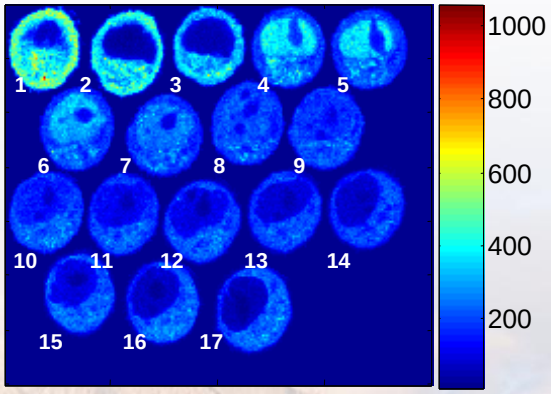
Materials Science and Technology



Microelectronics and Photonics



Pulsed Power



Bioscience

National Nuclear Security Administration

Sandia National Laboratories

Distributed Facilities

Albuquerque,
New Mexico

Kauai Test Facility,
Hawaii

Tonopah Test Range,
Nevada

Yucca Mountain,
Nevada

WIPP, New Mexico

Pantex, Texas

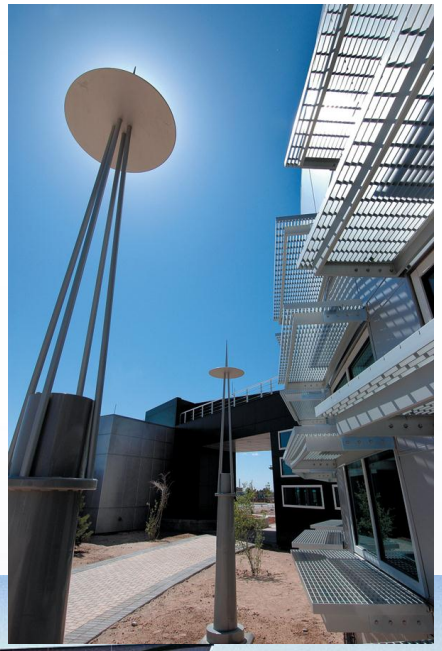
Livermore, California

Sandia

Sandia National Laboratories

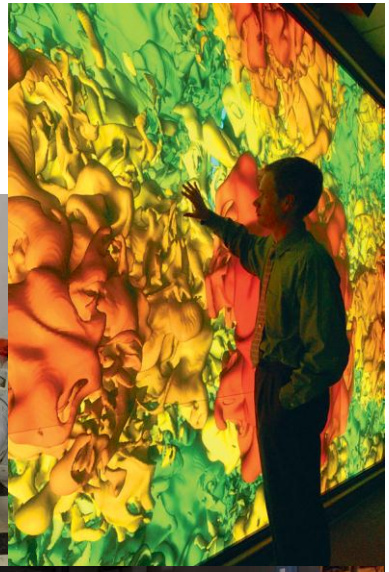
Unparalleled Large-Scale Facilities and Test Capabilities

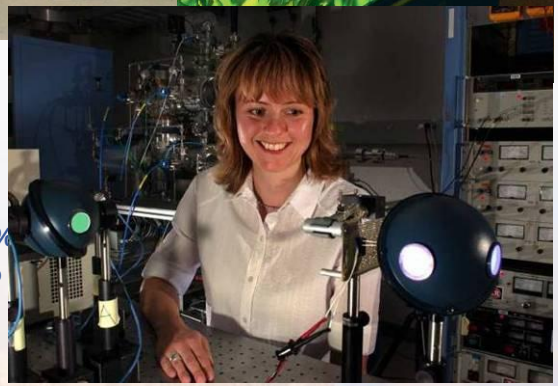
- User facilities
- Designated national capabilities
- Z-Machine and radiation effects
- Real-life physical test ranges

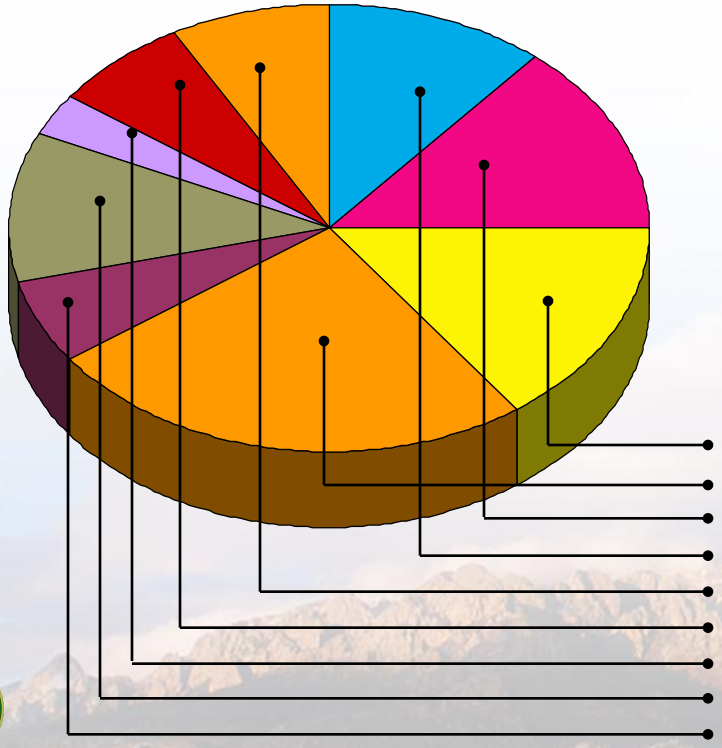


Highly Skilled Workforce

- More than 8,600 full-time employees
- More than 1,500 PhDs and 2,700 MS/MAs
  - 2,200 on-site contractors
  - $2.7 billion FY08 total bud







Mechanical Engineering - 16%
Electrical Engineering - 22%
Other Engineering - 15%
Other Science - 6 %
Physics - 6%
Chemistry - 6%
Math - 2%
Computing - 16%
Other Fields - 6 %

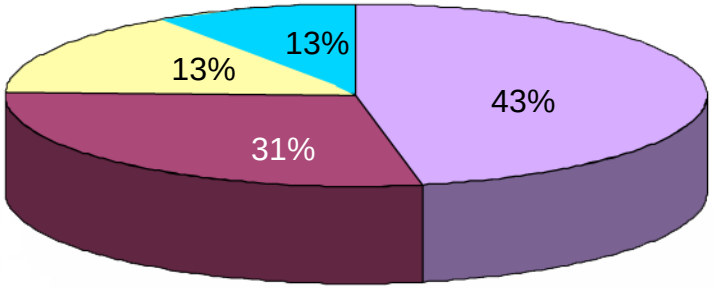
Sandia National Laboratories

People and Budget

(As of October 15, 2010)

- On-site workforce: 11,677
- Regular employees: 8,607
- Gross payroll: ~$898.7 million

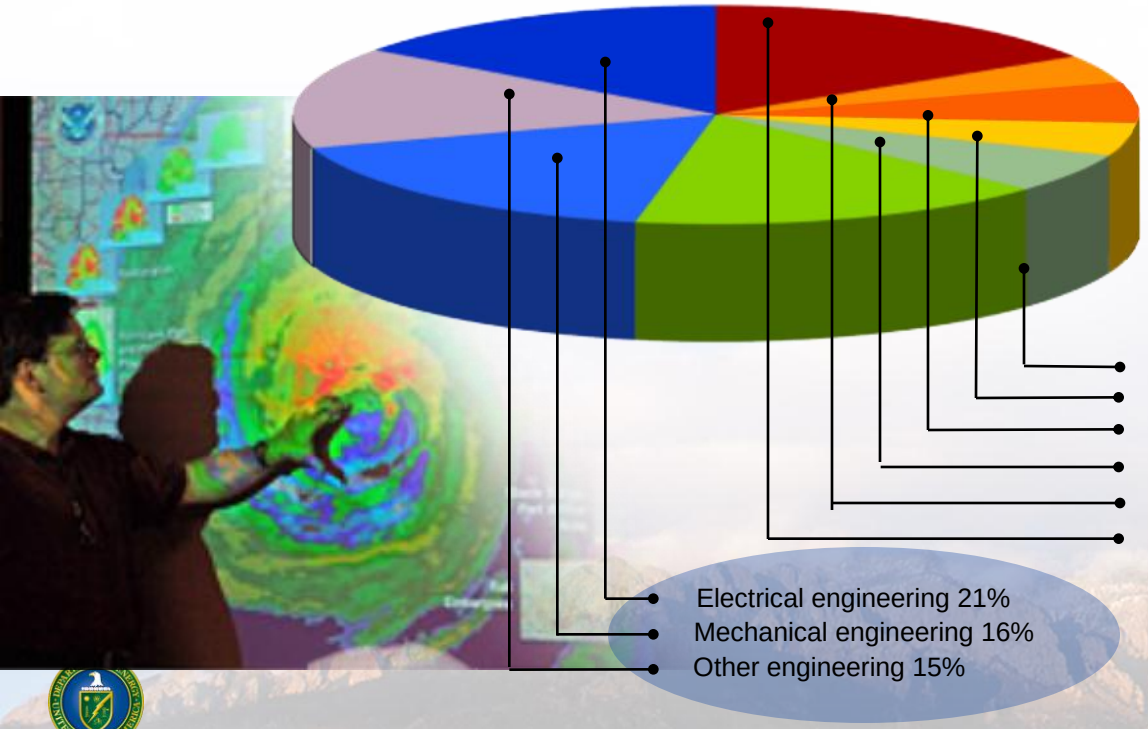
FY10 operating revenue
$2.3 billion



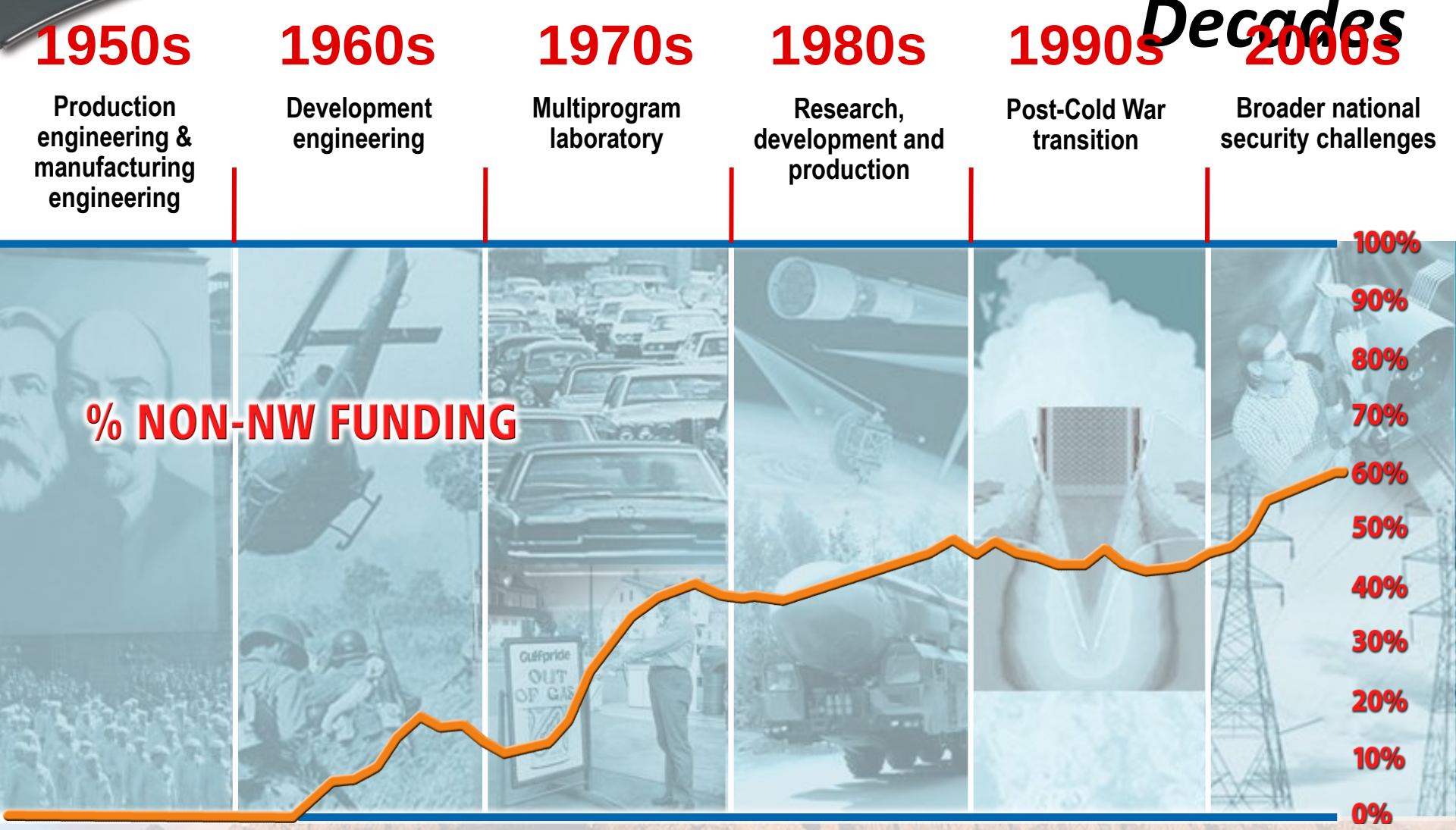
(Operating Budget)

- Nuclear Weapons
- Defense Systems & Assessments
- Energy, Climate, & Infrastructure Security
- International, Homeland, and Nuclear Security

Technical staff (4,277) by discipline:



The Mission Has Evolved for Decades



Sandia National Laboratories

Catastrophic Event Mitigation

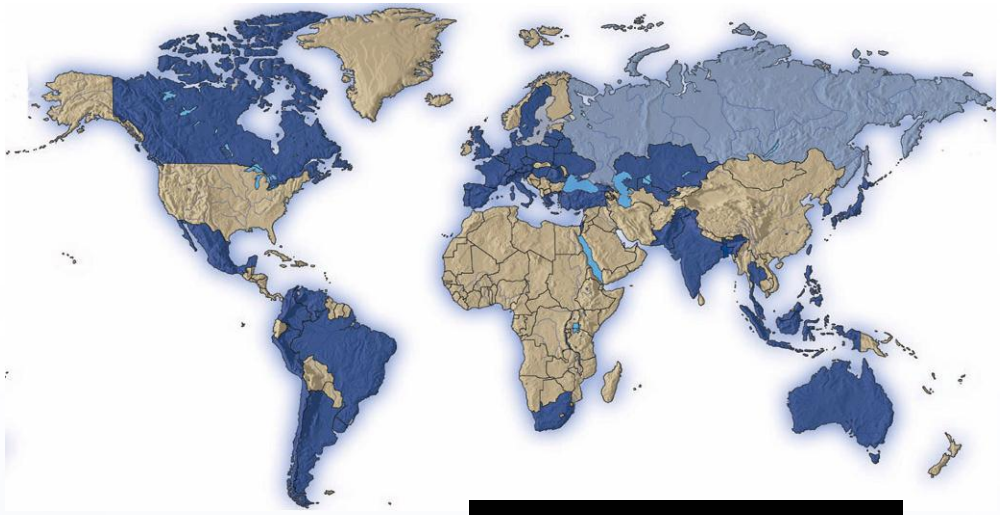
- Chemical and Biological Countermeasures
- Radiological and Nuclear Countermeasures
- Explosives Countermeasures
- Information Analysis
- Red Teaming
- Border and Transportation Security
- Systems Analysis

National Nuclear Security Administration

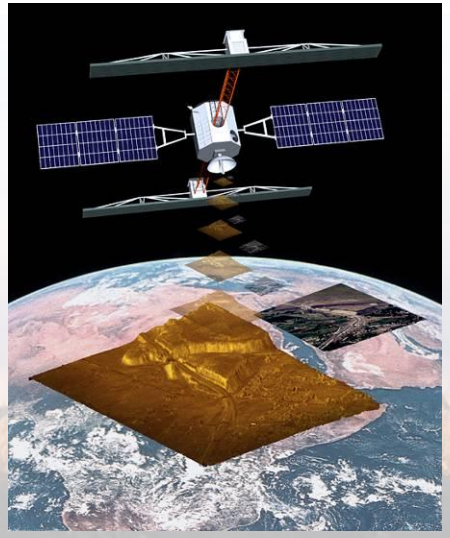
Sandia National Laboratories

Energy, Resources, and Nonproliferation

Making the World a Safer Place



- Technologies for detecting proliferation activities
- Performance and vulnerability assessments
- Monitoring and verification
- Cooperative international security programs
- Physical security



National Nuclear Security Administration

Sandia National Laboratories

Energy, Resources, and Nonproliferation

Energy, Water, and Security Enabled by Science & Technology

- Secure energy supplies for national security
- Clean, abundant and affordable energy
- Water research
- Infrastructure protection

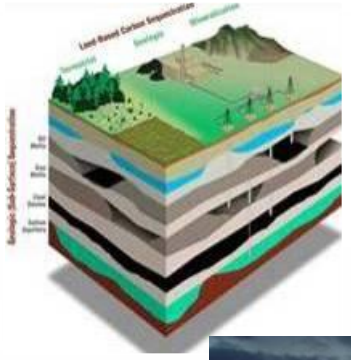
National Nuclear Security Administration

Sandia National Laboratories

Energy Policy Act of 2005

- Encourages Expanded Energy Supplies (Fossil, Renewables, Nuclear and Hydrogen)
- Supports Siting New Nuclear Power Plants
- Enhances Liquefied Natural Gas (LNG) Facility Siting
- Vehicle Efficiency
- Improved Electric Grid Reliability
- Lighting

Energy Futures Program



Develop and Demonstrate Persistent Energy Sources – Electricity and Transportation
Create a Flexible and Enabling Energy Infrastructure
Enhance Energy Storage Capabilities

Sandia National Laboratories

Renewable Energy and Storage Activities

- Concentrating Solar Power

- Wind

- Energy Storage

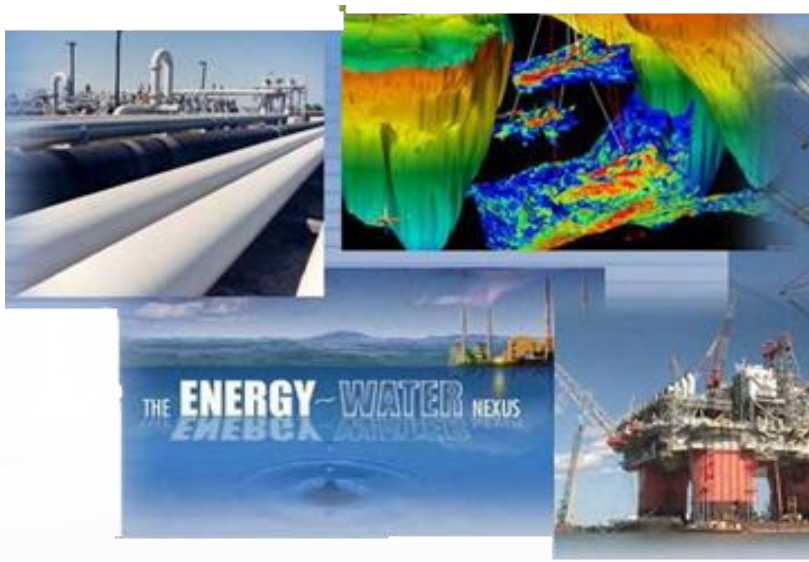
- Geothermal

- Photovoltaics

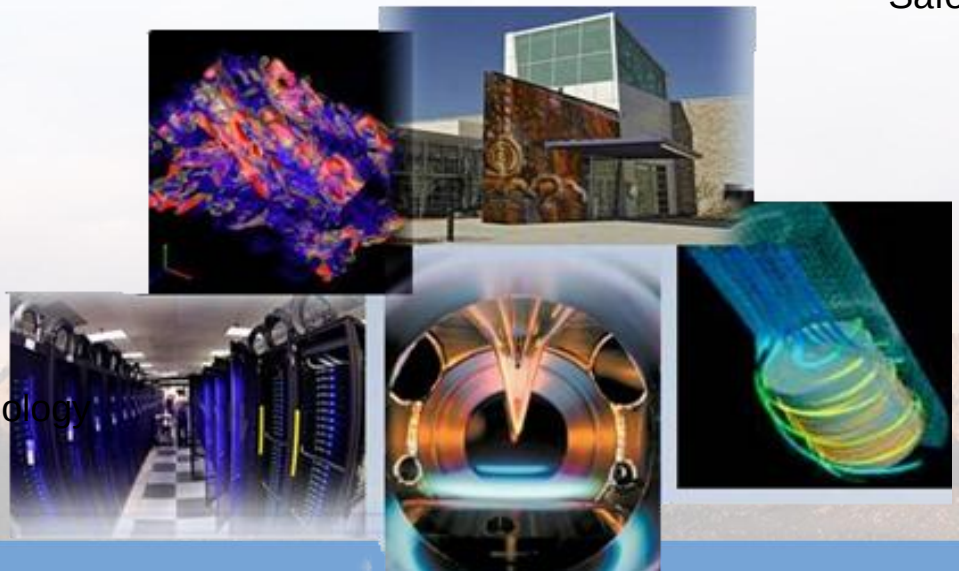
Sandia National Laboratories

Sandia National Laboratories are Contributing to Our Nation's Energy Future

Energy Supply, Energy Efficiency, and Environmental Stewardship



Safe, Secure, Reliable Energy Supply and Infrastructure



Science and Technology

Sandia National Laboratories

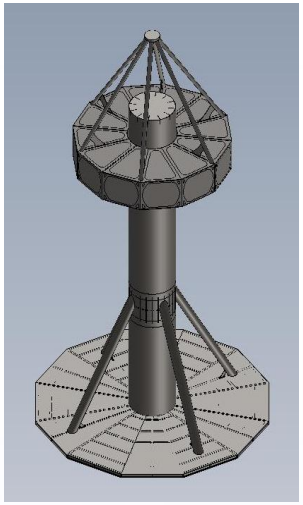
MHK Technology: Development of Performance Tools and Models

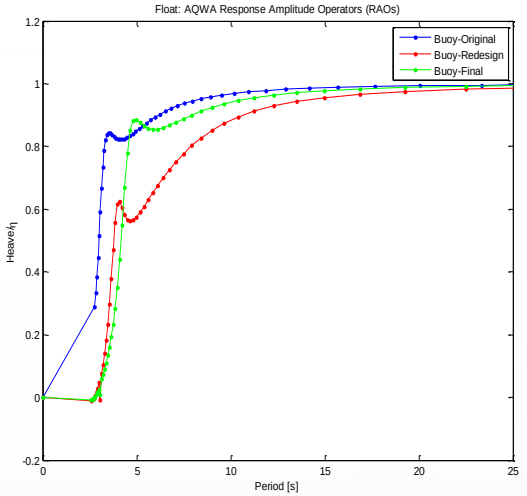
- **Program Objectives**
  - Create design and analysis tools specific to marine power devices
  - Create and apply a modeling framework to support device research and testing
  - Prediction of power, loads, and properties of both single devices and device arrays
    - Steady and turbulent inflow conditions
    - Surface wave effects
    - Interactions with the environment
  - Provide materials and coatings solutions for MHK designs

Wave Energy Conversion

Single Device

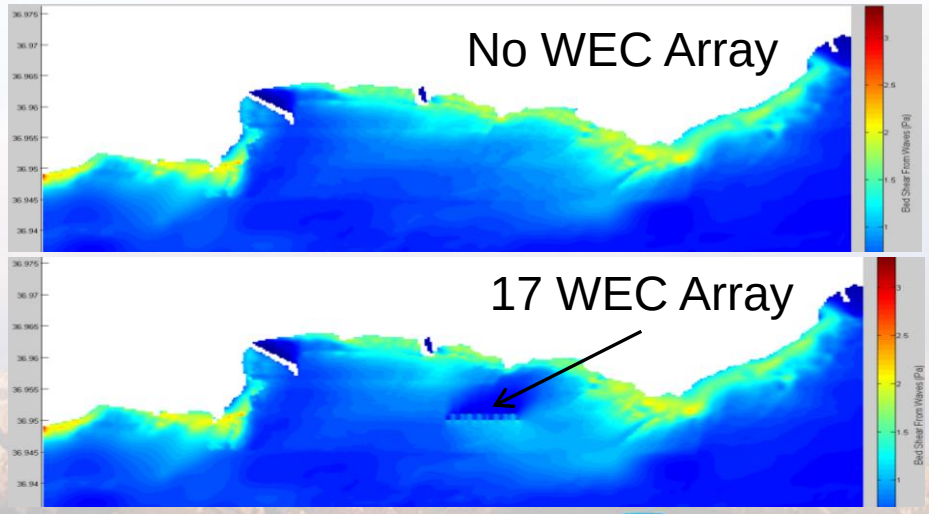
- Integrate Fluid-Structure interactions with performance modeling including PTO





Device Arrays

- Represent devices as reflection and/or transmission sink
- Integrated into SWAN/SNL-EFDC

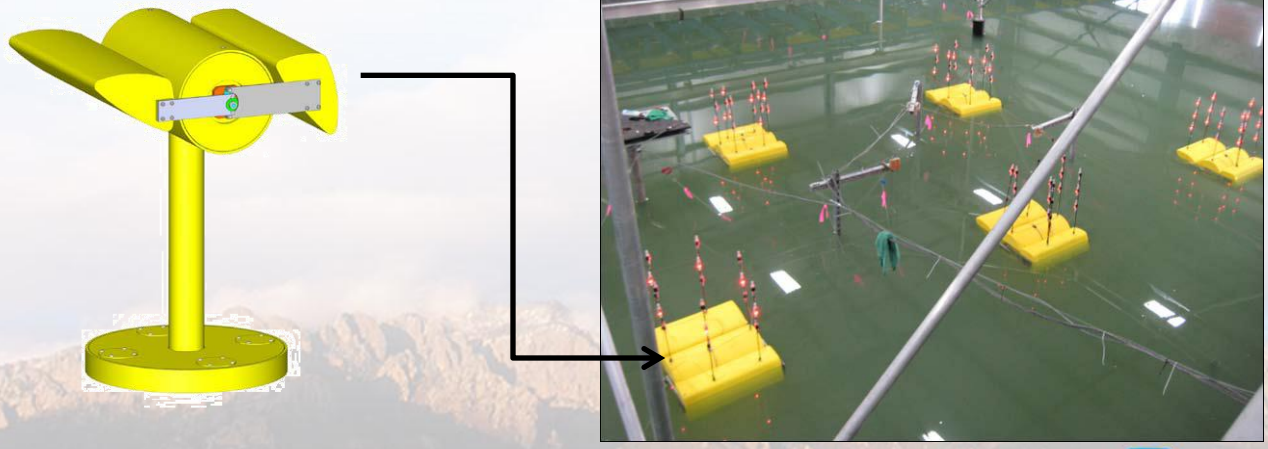


Sandia National Laboratories

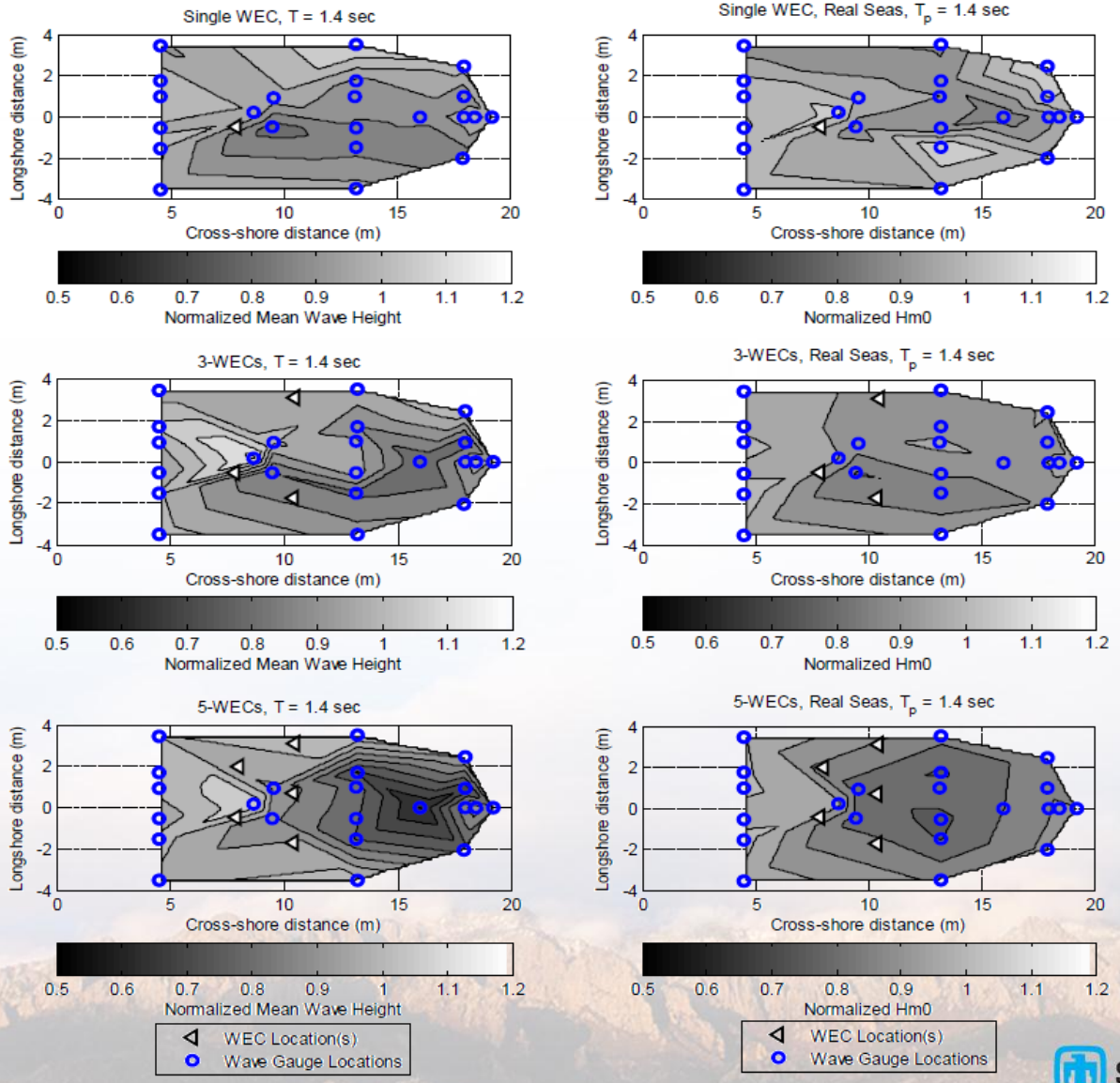
WEC Testing

- **Goal:** In collaboration with OSU and Columbia Power, generate test data for WEC arrays to support code development and validation.

- **Motivation:** Once completed, this experimental test matrix will provide a basis for model validation and allow for a performance modeling tools for optimization WEC arrays



Test Results*



1 WEC

3 WEC

5 WEC

Wave direction

*Haller et al., 2011 EWTEC

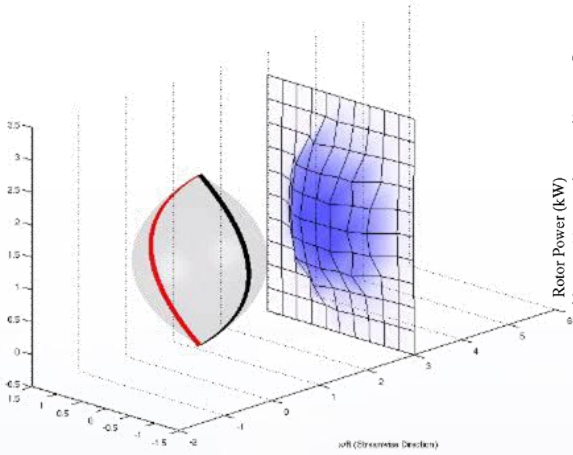
Sandia National Laboratories

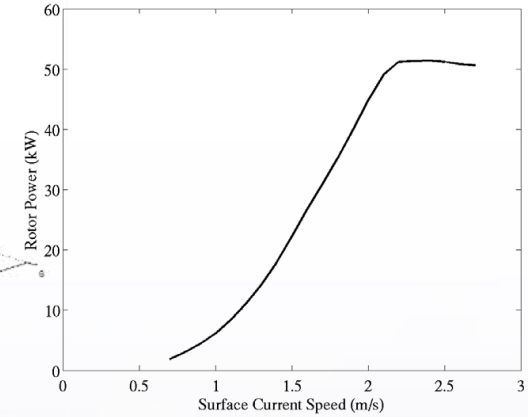
Wave Device Modeling

- **Accomplishments**
  - Preliminary implementation of WEC arrays in SWAN/SNL-EFDC model
  - Validation testing for WEC array at OSU (with CPT)
  - Application of AQWA/Simulink model for WEC on Reference Model (with OSU)
- **Upcoming Milestones and Products**
  - Wave design tools development roadmap
  - Further model development and validation for WEC arrays. Release 1st version of SNL-EFDC model for WEC arrays end of FY12.

Turbine Device Modeling

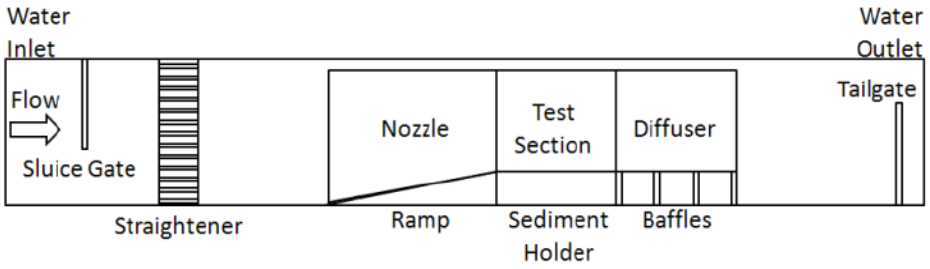
- **Single Device**
  - Development of CACTUS Code for both cross flow and axial flow turbine analysis
  - Design and test of high performance turbine blade (with UC Davis)

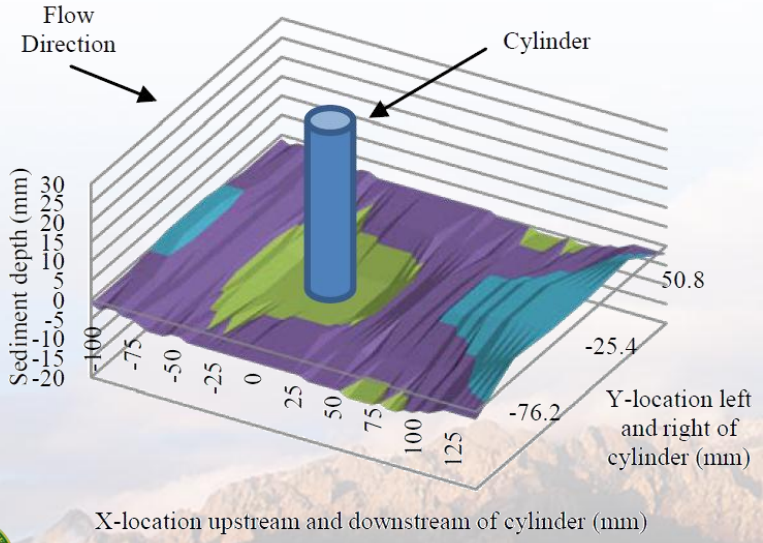




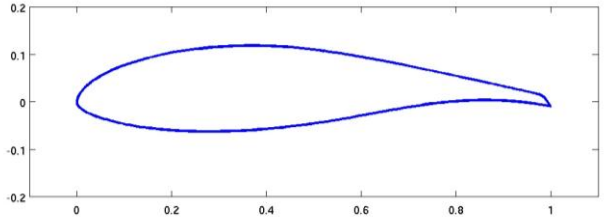
Turbine Testing

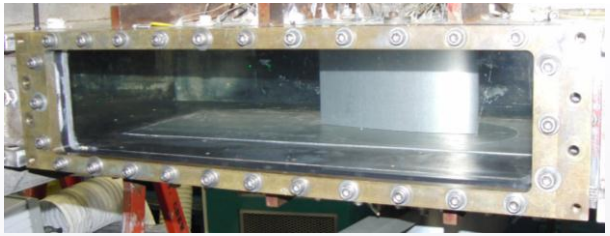
Bucknell University: Model testing for foundation performance and scour

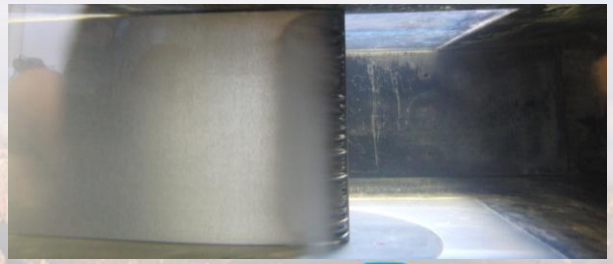




Penn State ARL: Model testing for blade and turbine performance





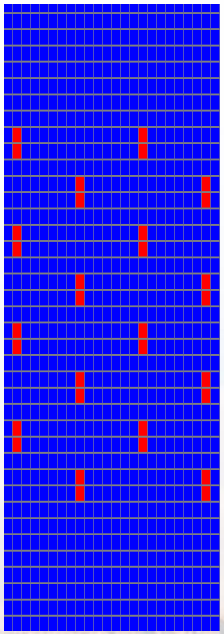


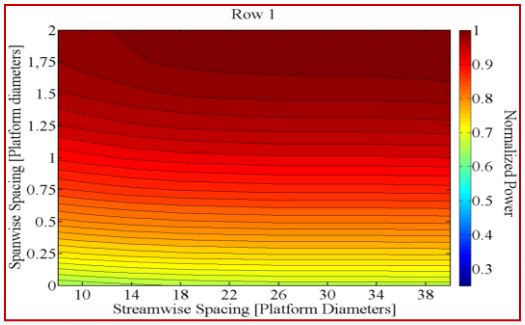
Turbine Array Modeling

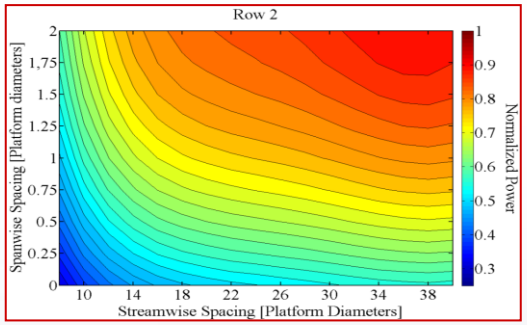
Array Modeling

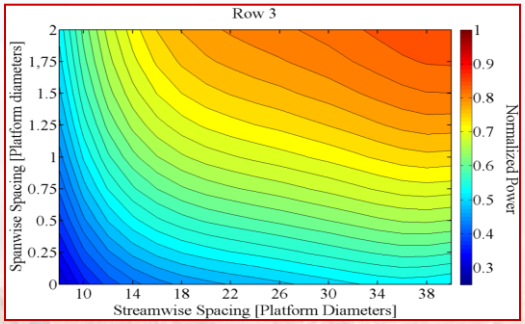
- SNL-EFDC has been developed to include MHK devices as momentum/energy sinks
- The model is partially validated with more tests planned in the laboratory and field (ORNL, UW, **UM/SAFL**)

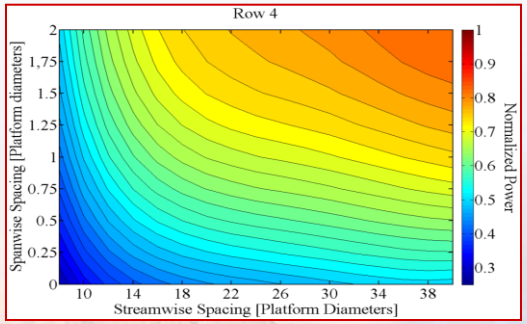
Flow direction











Turbine Device Modeling

Accomplishments

- Release of SNL-EFDC MHK Version 1 for turbine array performance Modeling
  - Training already done for one developer and group of regulators
- CACTUS code validated for wind test cases and applied for Reference Model performance analysis
- High performance blade design completed

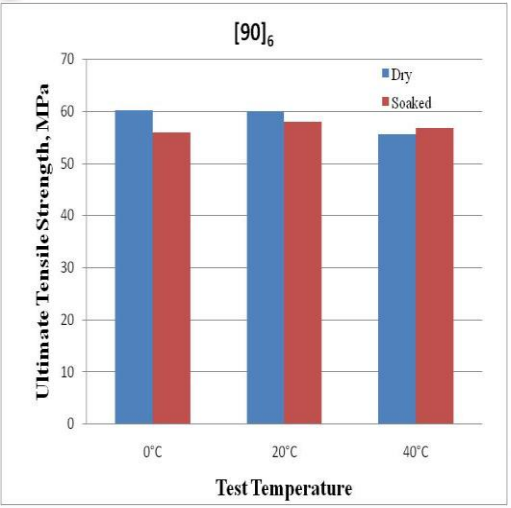
Upcoming Milestones and Products

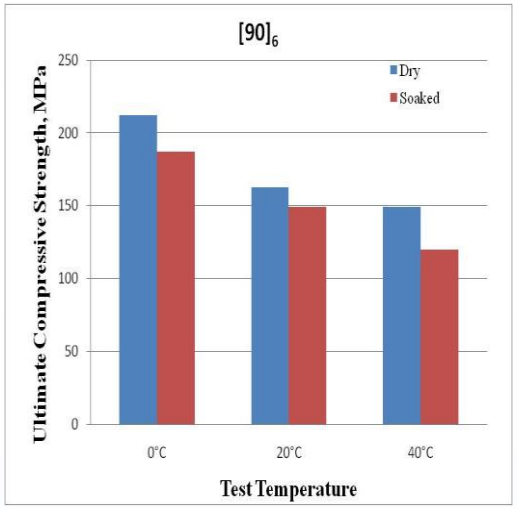
- Additional training planned for developers on a first come first serve basis
- Validation testing in the field (with developer support) and lab for SNL-EFDC model
- Water tunnel testing for blade and turbine performance validation (blade design and CACTUS performance)

Model Testing for Code Development and Validation

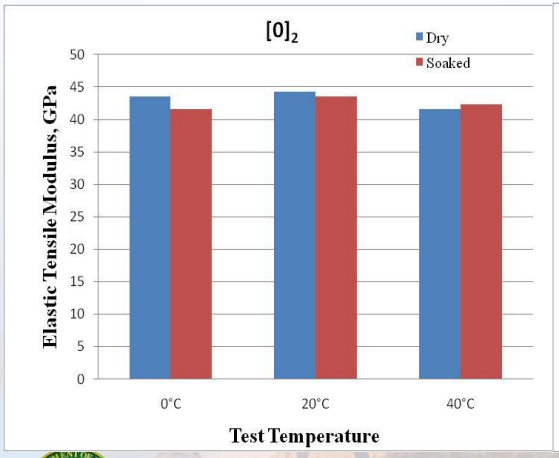
- **Accomplishments**
  - Expanded test scope with CPT allowed a relevant set of data for developing and validating the WEC array performance code SNL-EFDC for a variety of cases
  - Blade performance and cavitation testing in Penn State ARL 12 inch tunnel
  - Preliminary testing in Bucknell flume for foundation performance and scour
- **Upcoming Milestones and Products**
  - Implement into SNL-EFDC for WEC arrays
  - Turbine testing at ARL for 3 blade design in large tunnel
  - Continue testing at Bucknell to validate scour model

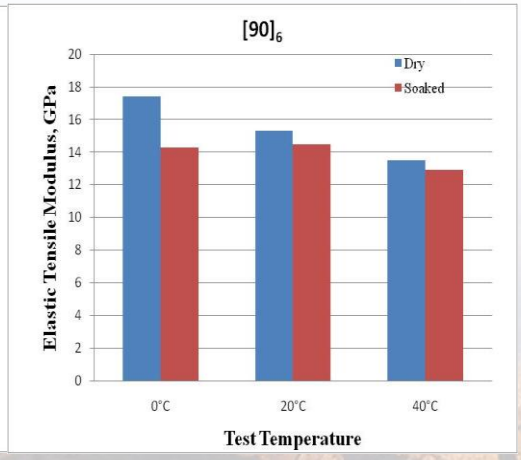
Materials and Coatings

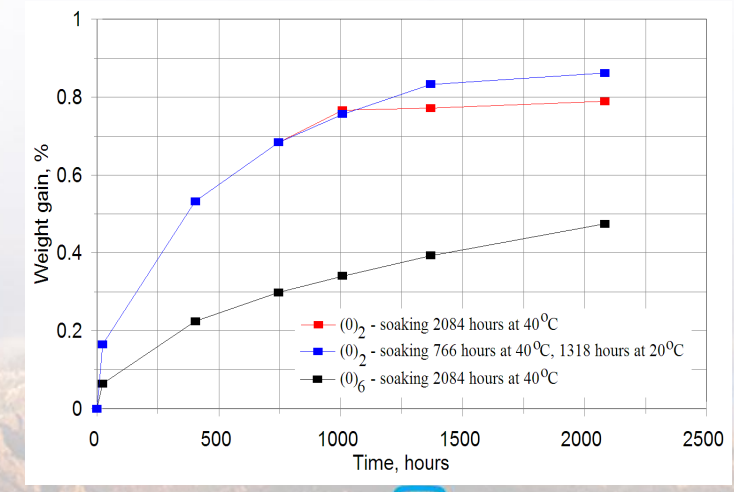




- Montana State University
- Moisture Absorption
- Mechanical Testing on salt water immersed composites
- Fabrication







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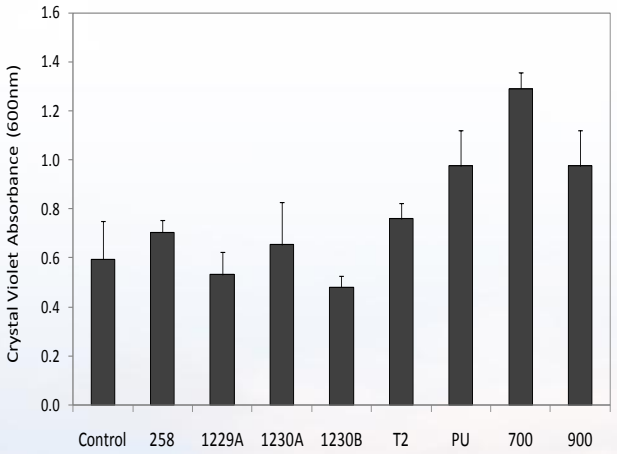
Materials & Coatings

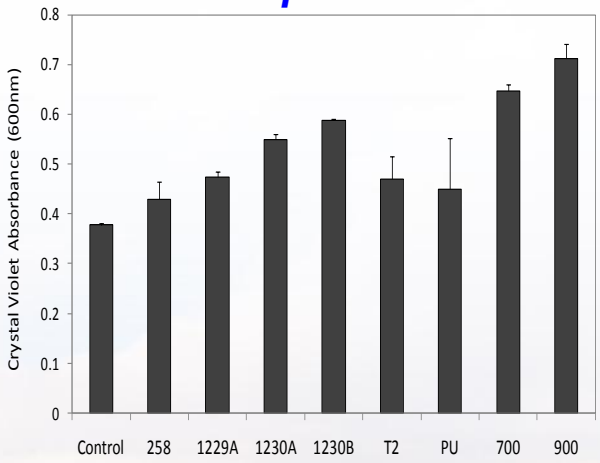
Evaluated the first set of antimicrobial treated materials from Owens-Corning for their ability to mitigate biofilm growth and adhesion towards the marine bacteria, *Cellulophaga lytica* and *Halomonas pacifica,* and the microalgae diatom, *Navicula incerta*.

- No substantial reduction in bacterial or microalgae biofilm growth was observed for the experimental coatings.

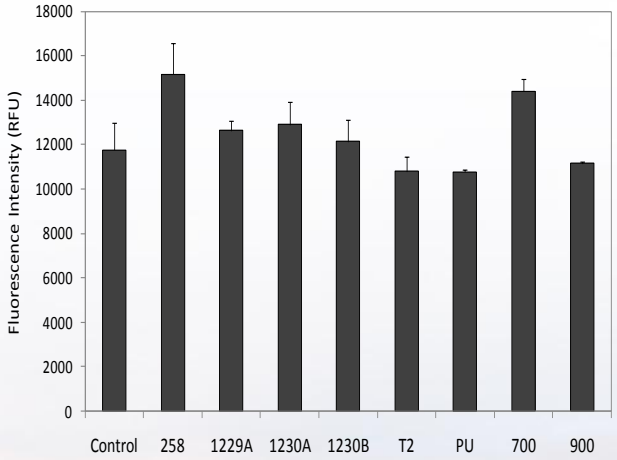
C. lytica



H. pacifica



N. incerta



- **NDSU**
- **Biofilm Characterization of Owens-Corning**
- **Also characterized all of SNL materials**

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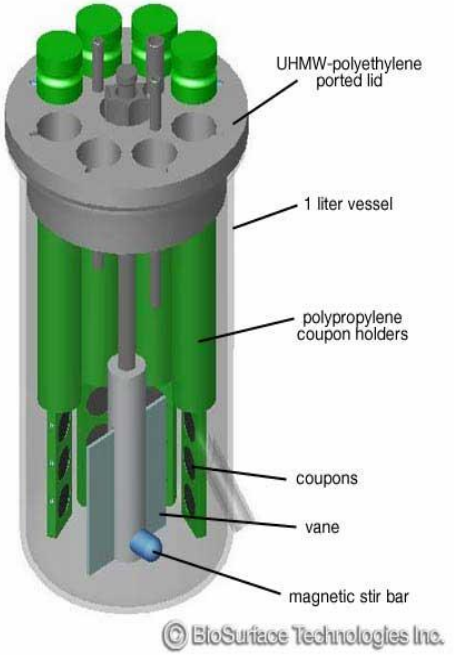
Materials & Coatings

- **Testing at SNL**
- **Biofilm baseline measurements on commercial materials & coatings**



Test ID	Coating Source	Material	Significantly less fouling than control?	Fouling reduction (log CFU/cm^2)	Fouling Reduction (%)
EP2000	ePaint	SS	No	---	---
EP2000	ePaint	Al	No[1]	---	---
EP2000	ePaint	PVC	No	---	---
SN-1	ePaint	HDPE	No[2]	---[3]	---
SN-1	ePaint	SS	No[2]	---[3]	---
SN-1	ePaint	HR	No[2]	---[3]	---
SN-1	ePaint	PVC	No[2]	---[3]	---
SN-1	ePaint	Al	No[2]	---[3]	---
INT-757	Intersleek	PC	Yes	0.67	79
INT-757	Intersleek	SS	Yes	0.81	85
INT-757	Intersleek	HDPE	No	---	---
INT-757	Intersleek	HR[4]	No	---	---
INT-757	Intersleek	PVC	No	---	---
INT-757	Intersleek	Al	No	---	---
INT-970	Intersleek	PC	Yes	0.79	84
INT-970	Intersleek	SS	Yes	0.39	60
INT-970	Intersleek	HDPE	Yes	0.55	72
INT-970	Intersleek	HR[4]	No	---	---
INT-970	Intersleek	PVC	Yes	0.55	72
INT-970	Intersleek	Al	Yes	0.75	82
KNC 821B	S. Dirk	SS	No	---	---
KNC 821E	S. Dirk	SS	No	---	---
KNC 821F	S. Dirk	Al	No	---	---
KNC 821D	S. Dirk	Al	No	---	---
N/A	M. Hibbs	SS	No	---	---
N/A	M. Hibbs	HDPE	No	---	---
7-67-C	M. Hibbs	PVC	No	---	---
7-73-C	M. Hibbs	PVC	No	---	---
7-73-B	M. Hibbs	PVC	Yes	0.37	57
7-74-N	M. Hibbs	SS	No	---	---
7-73-K	M. Hibbs	SS	No	---	---
7-67-D	M. Hibbs	Al	No	---	---
1228B	Corning	Composite	No	---	---
1229A	Corning	Composite	No	---	---
1230A	Corning	Composite	No	---	---
1230B	Corning	Composite	No	---	---

1 More growth on coated coupon, assumed to be because the coating shielded the cells from the antimicrobial properties of Al.
2 Active ingredient thought to have leached into the reactor solution, thus impacting biofilm growth on controls as well.

3 Approximately 2.8 log CFU cm^{-2} more than EP2000 samples.

Materials and Coatings

Accomplishments

- Biofouling & Corrosion Baseline measurements on commercial materials/coatings
- Static tensile and compressive strength testing on salt water immersion effects on wind composite materials
- Leveraging Salt Fog Spray –testing on composites
- Development of new antimicrobial & anticorrosion materials
- Biofilm characterization initiated on Owens-Corning & Verdant products
- 12 students & postdoctoral research experiences
- REU student granted DOE Center for Integrated Nano Technology user proposal access to characterize anticorrosion nanocomposite materials.
- Coatings for the Prevention of Biofouling in Marine Environments, Technical Advance filed on 8/9/11, SD#12087.

Upcoming Milestones and Products

- Continued work on Owens-Corning, Verdant, Free Flow Power Biofilm Characterization
- Sending samples to ORNL for Toxicity, ARL for cavitation
- Continue to optimize synthesis of new anticorrosion/biofouling coatings

MHK Environmental Studies

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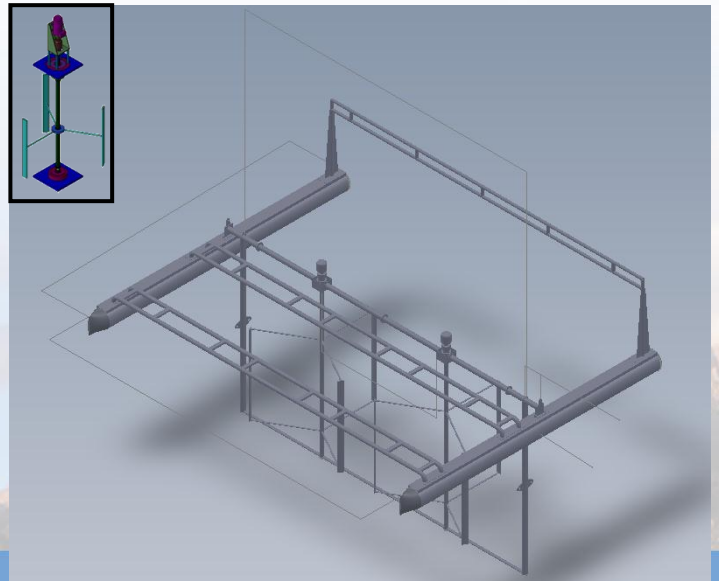
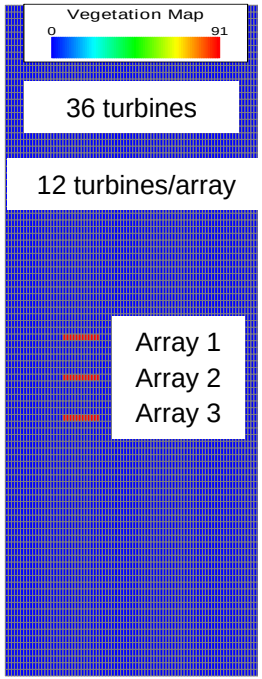
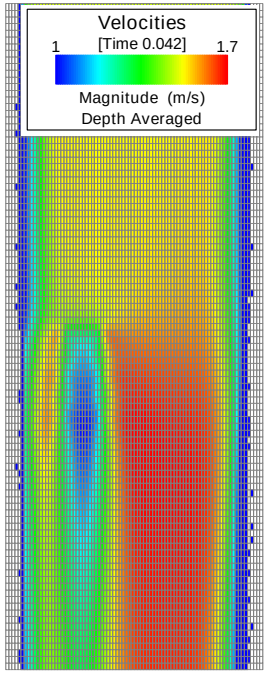
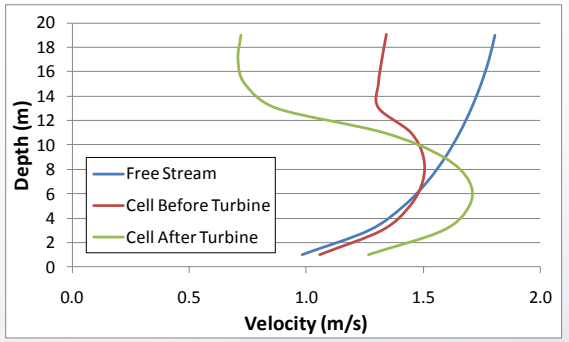
MHK Friendly Tool Development

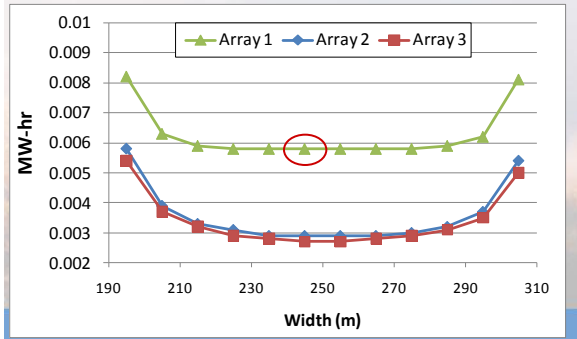
- **Major Accomplishments/Challenges**
  - Verification/validation of SNL-EFDC code against available lab data (Q2) and ongoing with the availability of new flume data collected at SAFL and field test data in Mississippi River
    - Challenge- small scale flume data presents scale issues for use with large scale code such as EFDC.
  - Completed two SNL-EFDC training courses
    - Free Flow Power (8/9-10/2011) in Albuquerque
    - FERC, BOEMRE, SPAWAR, DOE (8/25-26/2011) in Washington, DC
- **FY11/FY12 and beyond**
  - Support developers/regulators use of SNL-EFDC and develop our own site and reference models to evaluate array optimization











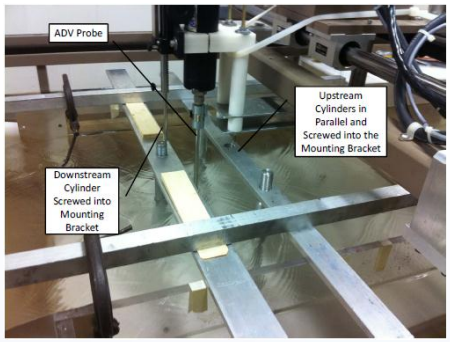
Field and Lab Testing

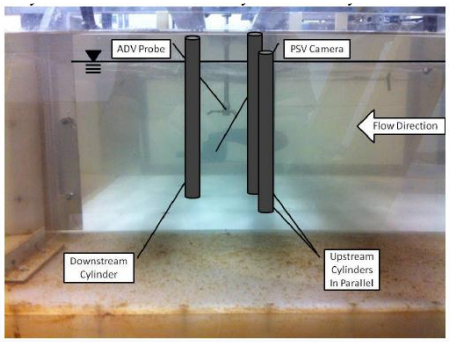
Purpose/Benefit to Industry

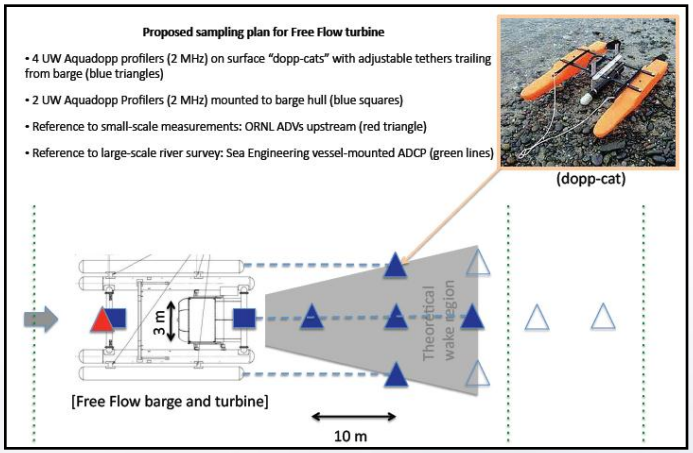
- Characterize the physical environment and influence of MHK devices to support model validation

Final Products

- Critical data sets to support model validation







Work Efforts

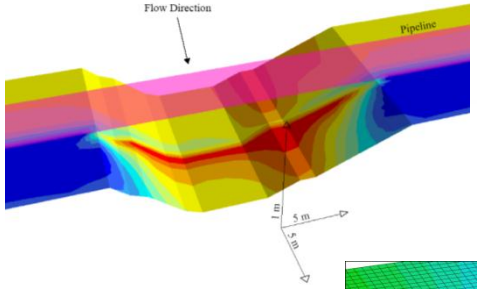
- **Inflow, Fluid-Structure, and Wake Characteristics**
  - Mississippi River (FFP demonstration site)
- **Suspended Sediment Characteristics**
  - Puget Sound (Admiralty Inlet)
- **Scour and Sedimentation :**
  - SNL SEAWOLF and ASSET Flumes
  - Bucknell Sediment Flume

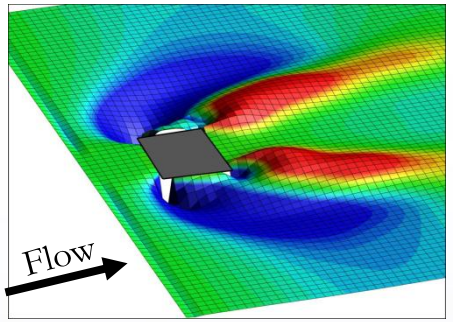
Field and Lab Testing

- **Major Accomplishments/Challenges**
  - Completed data collection of suspended sediment in Admiralty Inlet, Puget Sound
    - Helped to close noise budget in Admiralty Inlet and develop relationship between SSC and tides
  - Verified flow characteristics and made initial measurements of sediment erosion around cylinders within the Bucknell Flume. Designed turbine array experiments.
    - Challenge- obtaining realistic and consistent flow within a scaled flume and creating sediment test section
  - Created test plan for field measurements around FFP demonstration turbine.
    - Challenge- decreased flows may delay measurements until December (Original date was September)
- **FY11/FY12 and beyond**
  - Continue oceanographic and sediment characterization in ocean, tidal, and river systems in support of
    - Conceptual and site model development
    - model validation
    - advancing our knowledge of MHK influence on the environment with MHK specific data sets.
  - Make scaled measurements of erosion and scour around scaled turbines of various array designs

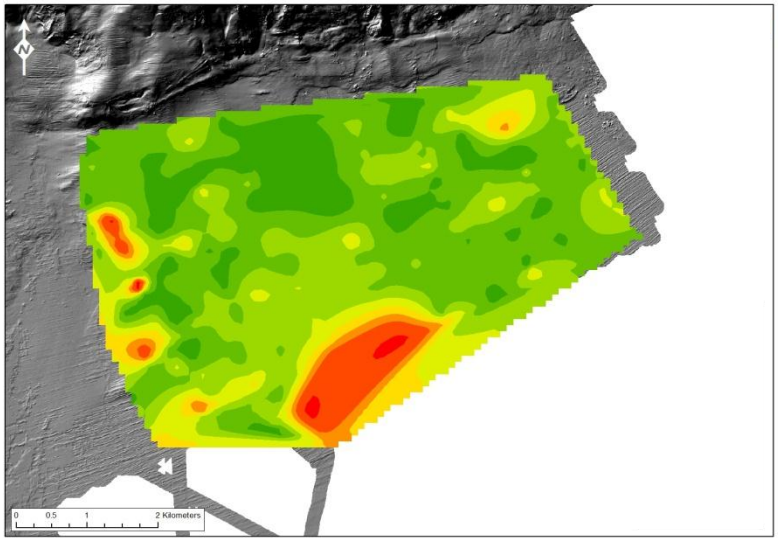
Spatial Maps of Sediment Stability

- **Purpose/Benefit to Industry**
  - Reduce WEC and MHK turbine farm risk from sea- and/or river-floor instabilities
- **Final Products**
  - Open-source methodology for the creation and use of spatial maps of sediment stability to support siting, planning, and permitting of WEC and MHK turbine array configuration

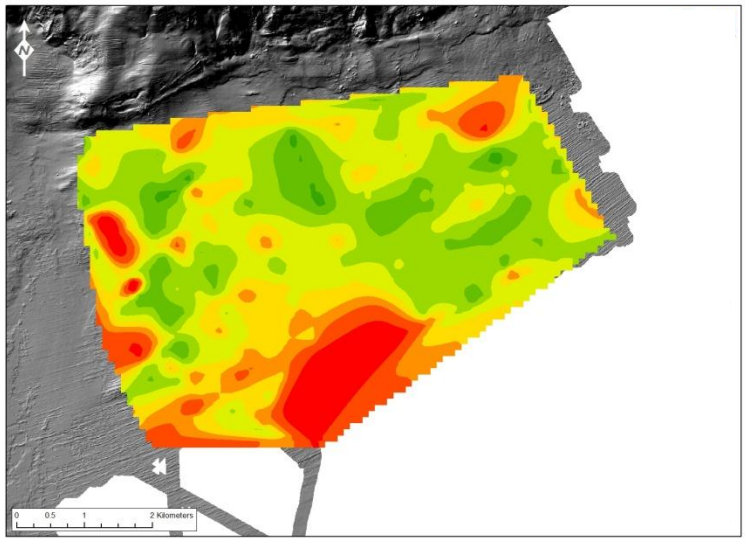




Erosion potential after 2 years



Erosion potential after 10 years



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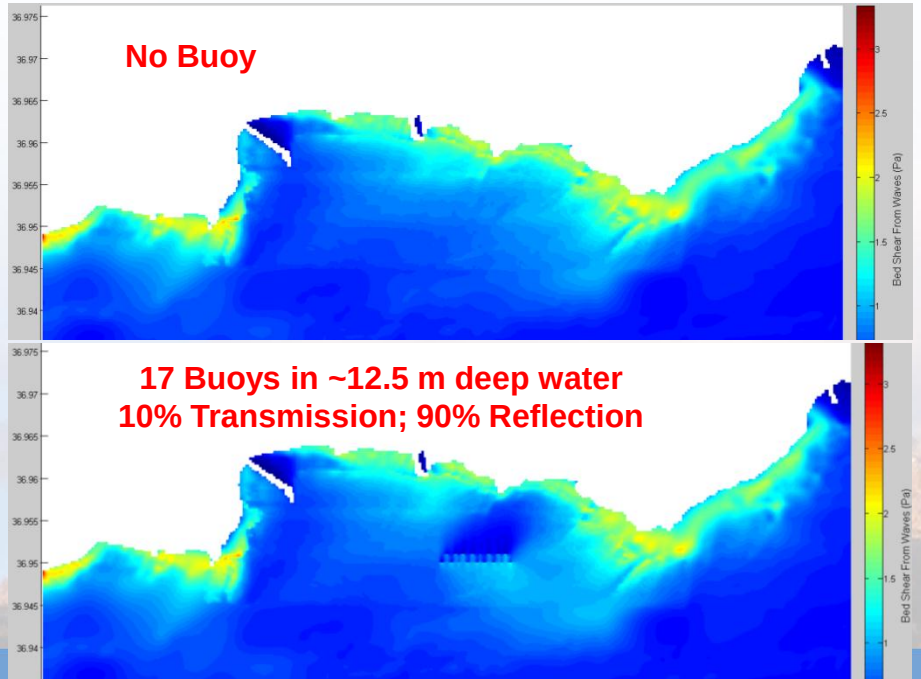
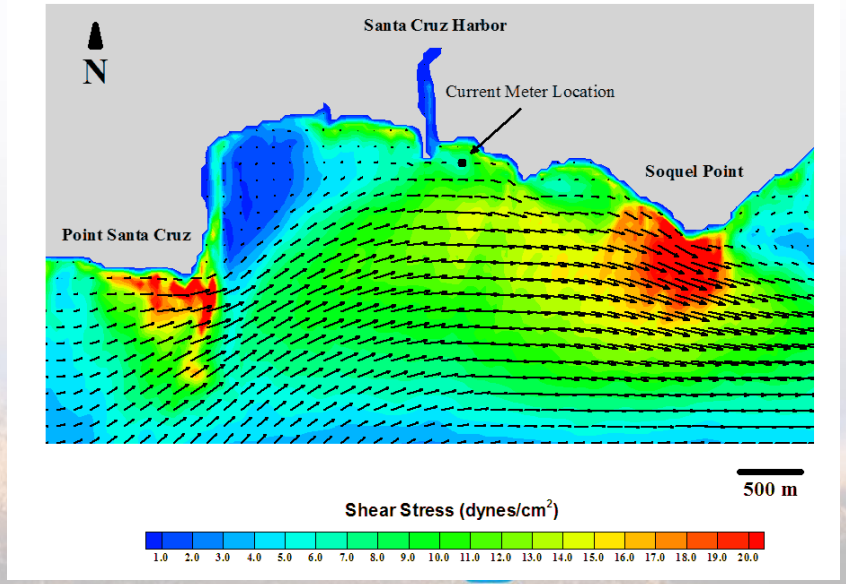
Spatial Maps of Sediment Stability

- **Major Accomplishments/Challenges**
  - Initiated development of a methodology to simulate WEC devices within SWAN to characterize the changes to wave spectra and radiation shear stresses due to the presence of a WEC array
- **FY11/FY12 and beyond**
  - Finalize open-source methodology for sediment stability risk maps and train others on its use. Support developers/regulators use of code(s) and develop our own site and generic models to evaluate influence of arrays on local- and far-field sediment stability.

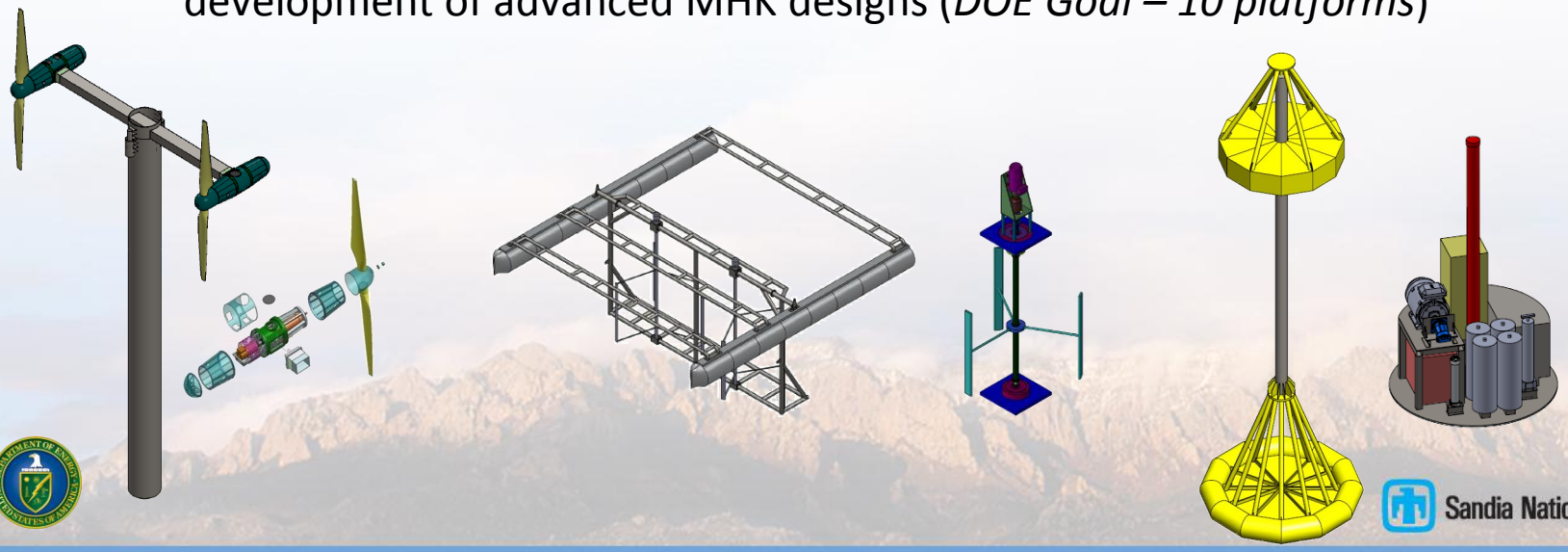




Reference Model Development

- **Goal:** Develop a representative set of Reference Models (RM) for the MHK industry to develop baseline cost of energy (COE) and evaluate key cost component/system reduction pathways.

- **Motivation:** Industry needs for COE targets with regard to technology type, and identify future innovation opportunities to prioritize research and cost reduction pathways
  - Promote and assist a vibrant and cost effective MHK industry
  - Develop and disseminate system design tools and/or MHK models for the development of advanced MHK designs (*DOE Goal – 10 platforms*)



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Vertical-Axis Wind Turbines

Back to the Future?

Daniel Laird
Program Manager
Water Power Technologies
Sandia National Laboratories
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NNSA National Nuclear Security Administration

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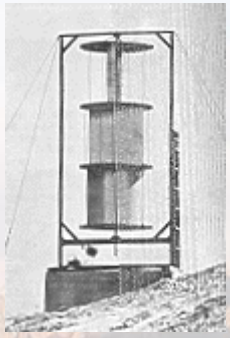
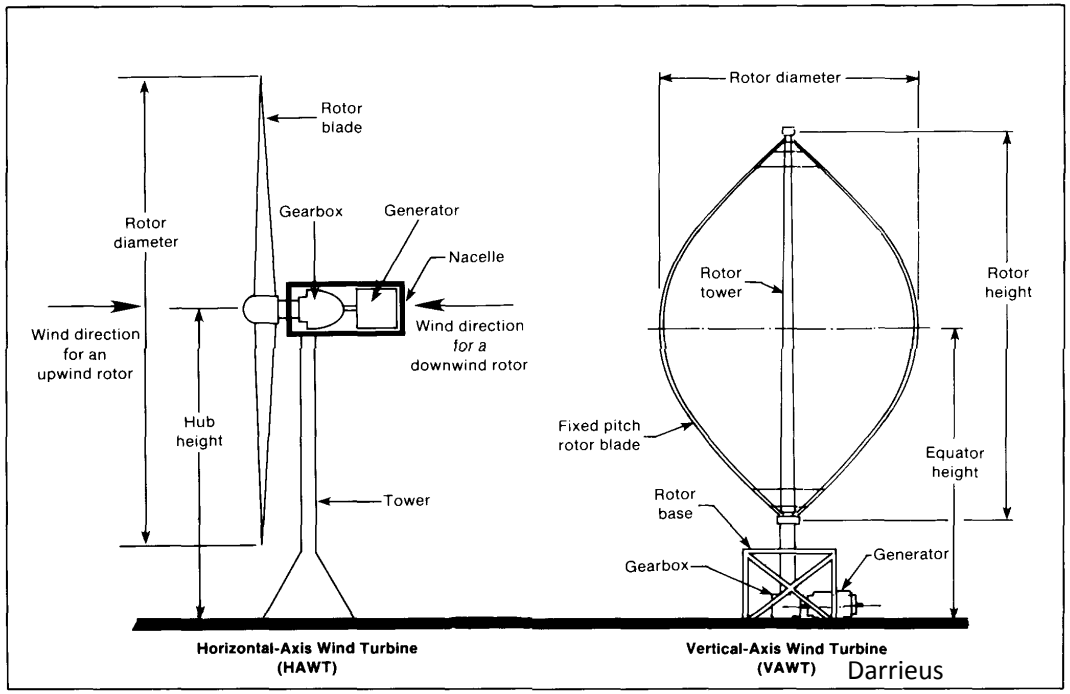
What is a VAWT?

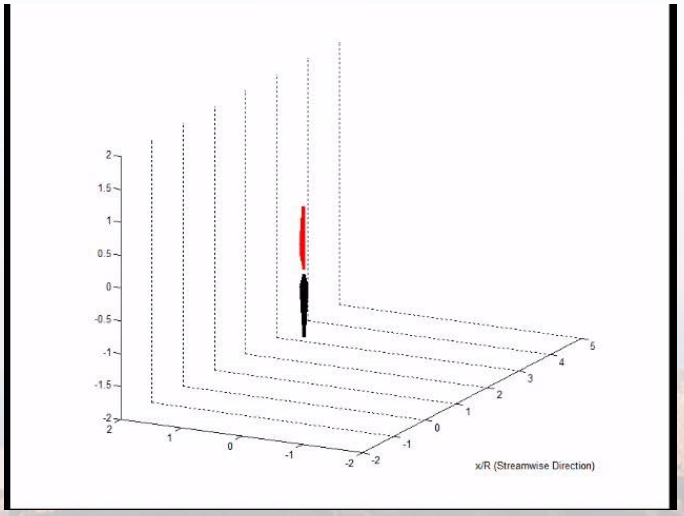
- Any wind turbine architecture utilizing a vertical axis of rotation

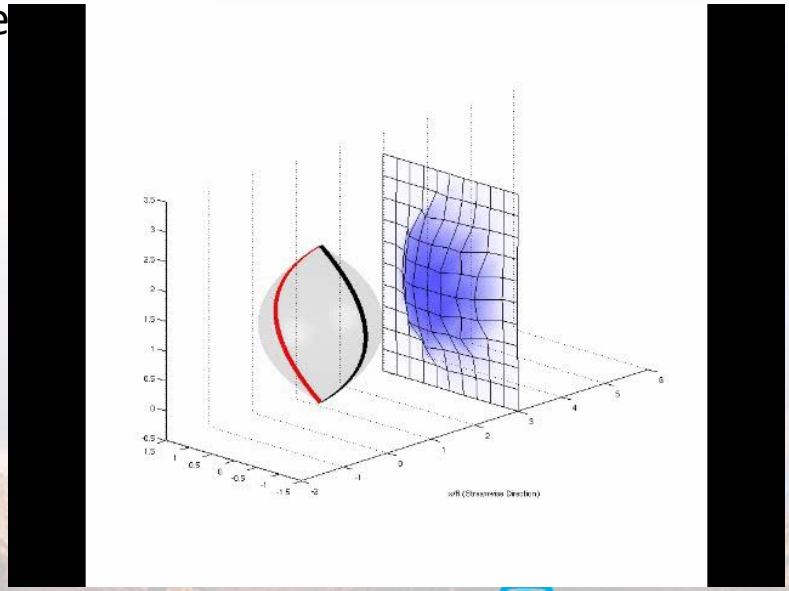




Vertical Axis Wind Turbine (VAWT) Basics

- **VAWTs generate torque (and power) using lift forces on the blades (like HAWTs)**
- **Aerodynamic design problem is very different between HAWTs and VAWTs**
  - HAWTs extract momentum and energy using a steady circulation (lift) that is attached to the blades.
  - VAWTs extract momentum and energy using unsteady, cyclical circulation (lift) that is shed into the wake





Sandia VAWT History

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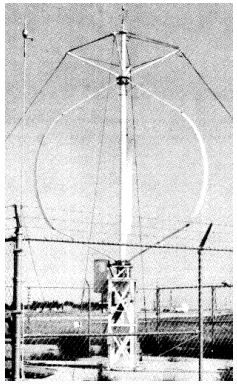
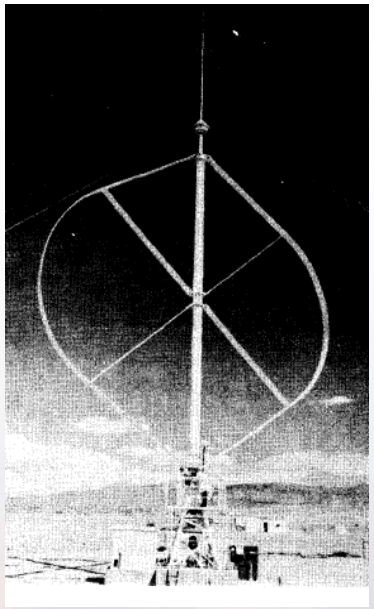
Sandia VAWT Research

1974-1995



5m VAWT



65kW 17m VAWT

Early test machines located at Sandia
Used to validate codes and test designs

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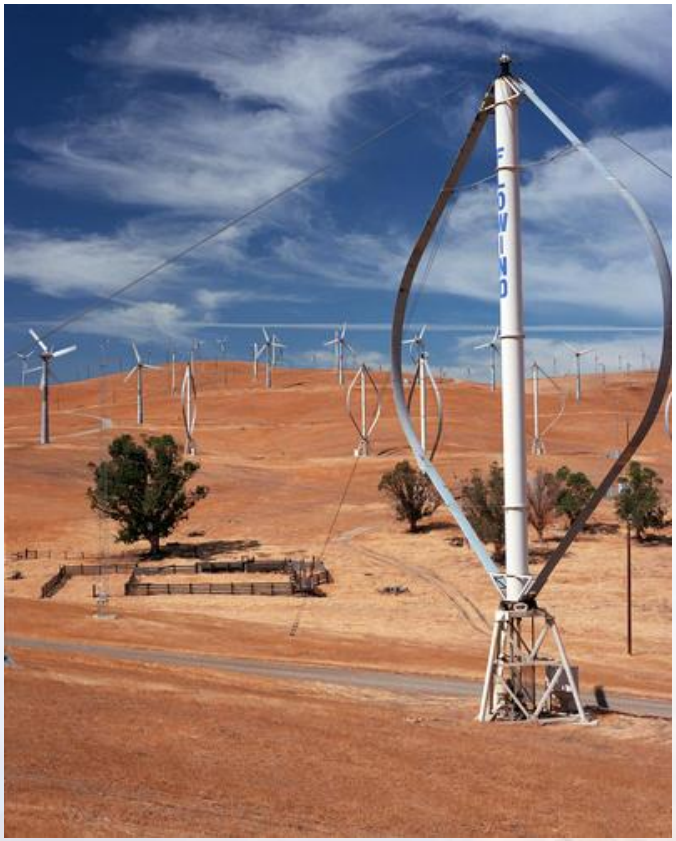
Sandia VAWT Research

1974-1995 cont

Technology Transfer → FloWind and others



17-m, 100 kW Full-Darrieus VAWT

Over 500 VAWTs Deployed -
Primarily in Altamont Pass

EHD Turbine

3.5MW Eole

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Sandia VAWT Research

1974-1995 cont

34m VAWT Test Bed

- **Located in Bushland, TX**
  - Dedicated: May, 1988
  - Decommissioned: Spring, 1998
- **Rotor: 34-m Dia, 50-m Height**
- **Performance:**
  - Variable Speed: 25 to 38 rpm
  - Rated Power: 500 kW
- **Heavily Instrumented**

  72 Strain, 25 Environmental,

  22 Performance, 29 Electrical
- **Large Database, Many Publications**

- **Demonstrated a Full-System Approach to Design of Wind Turbine**
- **Innovative Instrumentation and Data Analysis Techniques Developed and Demonstrated**
- **Large Database for Validating VAWT Design Tools**
- **A Large Set of Validated Design Codes**

Haven't we already endured this?

i.e. disco, LPs, Betamax, pet rocks

Add tombstone clipart of "VAWT Technology" - 1996

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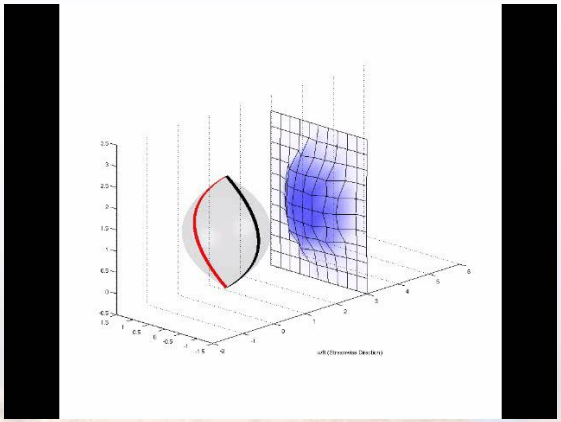
Sandia VAWT Research

2010-present



DOE Water Power Program – CACTUS code
Code for Axial and Cross-flow Turbine Simulation

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Sandia VAWT Accomplishments

1975	SNL Wind Program Established
1977	17m VAWT Fabricated
1979	VDART3 Vortex-based VAWT Aerodynamics Analysis Code Developed
1980	Dynamic Stall Model Incorporated in Aero Codes
1981	First Wind-Turbine Specific Airfoils Designed
1981	Impact of Stochastic Wind on Wind Turbine Fatigue First Investigated
1982	FloWind Technology Transfer Initiated
1984	VAWTPOWER Technology Transfer Initiated
1988	34m VAWT Test Bed Dedicated
1988	SNL/MSU Material Database Established

Sandia VAWT Publications

A representative listing of Sandia reports on VAWT Technology

"Measured Data for the Sandia 34 Meter Vertical Axis Wind Turbine"
T.D. Ashwill, SAND91-2228

"Numerical Simulation of VAWT Stochastic Aerodynamic Loads Produced by Atmospheric Turbulence: VAWT-SAL Code"
G.F. Homicz, SAND91-1124

"Selected Papers on Wind Energy Technology" (a compilation of 16 technical papers on VAWT Technology)
Sandia National Laboratories Staff, SAND90-1615

"Initial Structural Response Measurements and Model Validation for the Sandia 34-Meter VAWT Test Bed"
T.D. Ashwill, SAND88-0633

"Modal Testing the EOLE"
T.G. Carne, J.P. Lauffer, A.J. Gomez, SAND87-1506

"Aeroelastic Effects in the Structural Dynamic Analysis of Vertical Axis Wind Turbines"
D.W. Lobitz, T.D. Ashwill, SAND85-0957

"Structural Design of the Sandia 34-Meter Vertical Axis Wind Turbine"
D.E. Berg, SAND84-1287

Some 30 additional reports dealing with VAWT technology can be found on the Sandia Wind & Water Power Technology web site at http://windpower.sandia.gov/topical.htm#VAWTARCHIVE

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Opportunities

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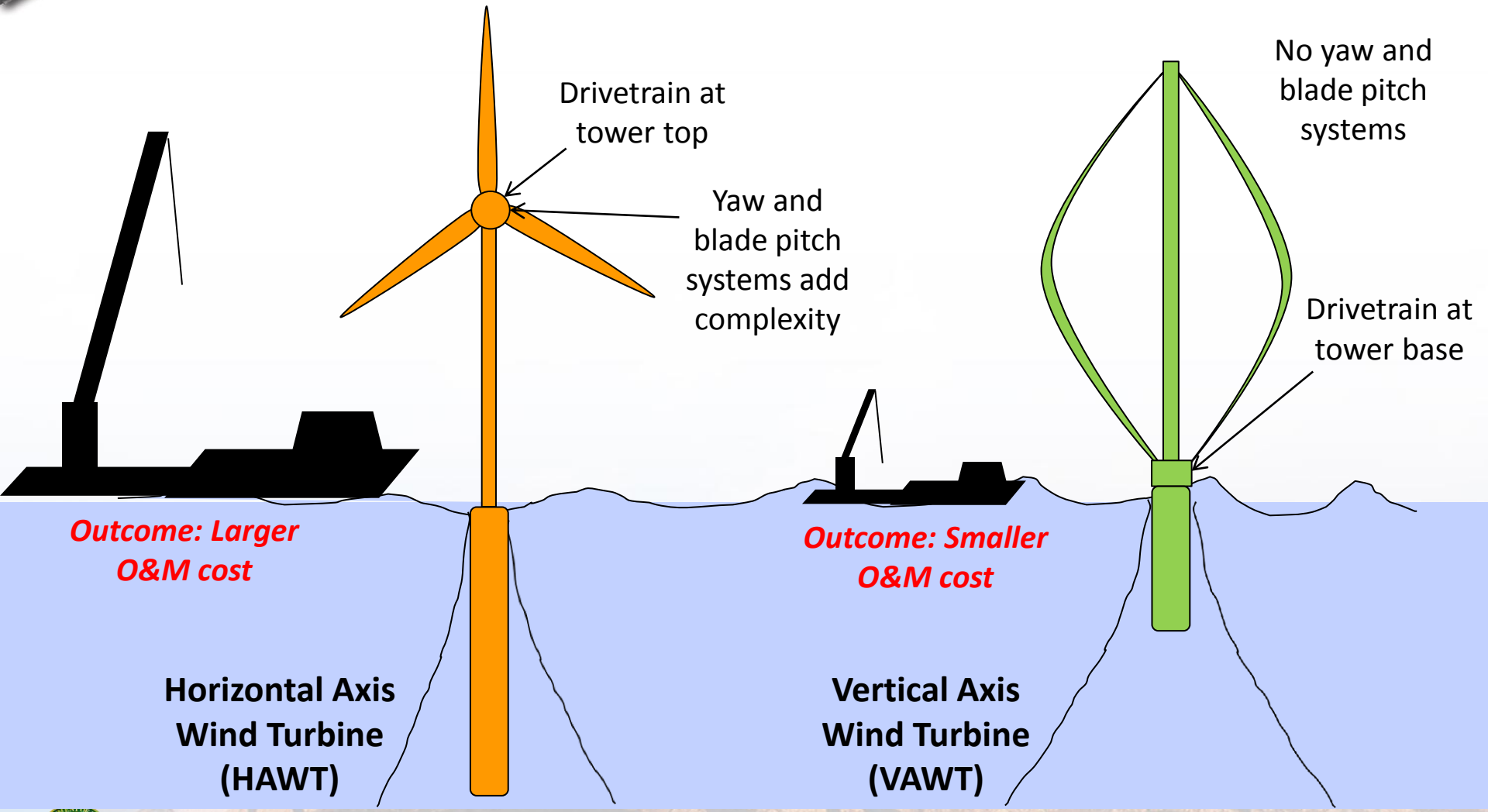
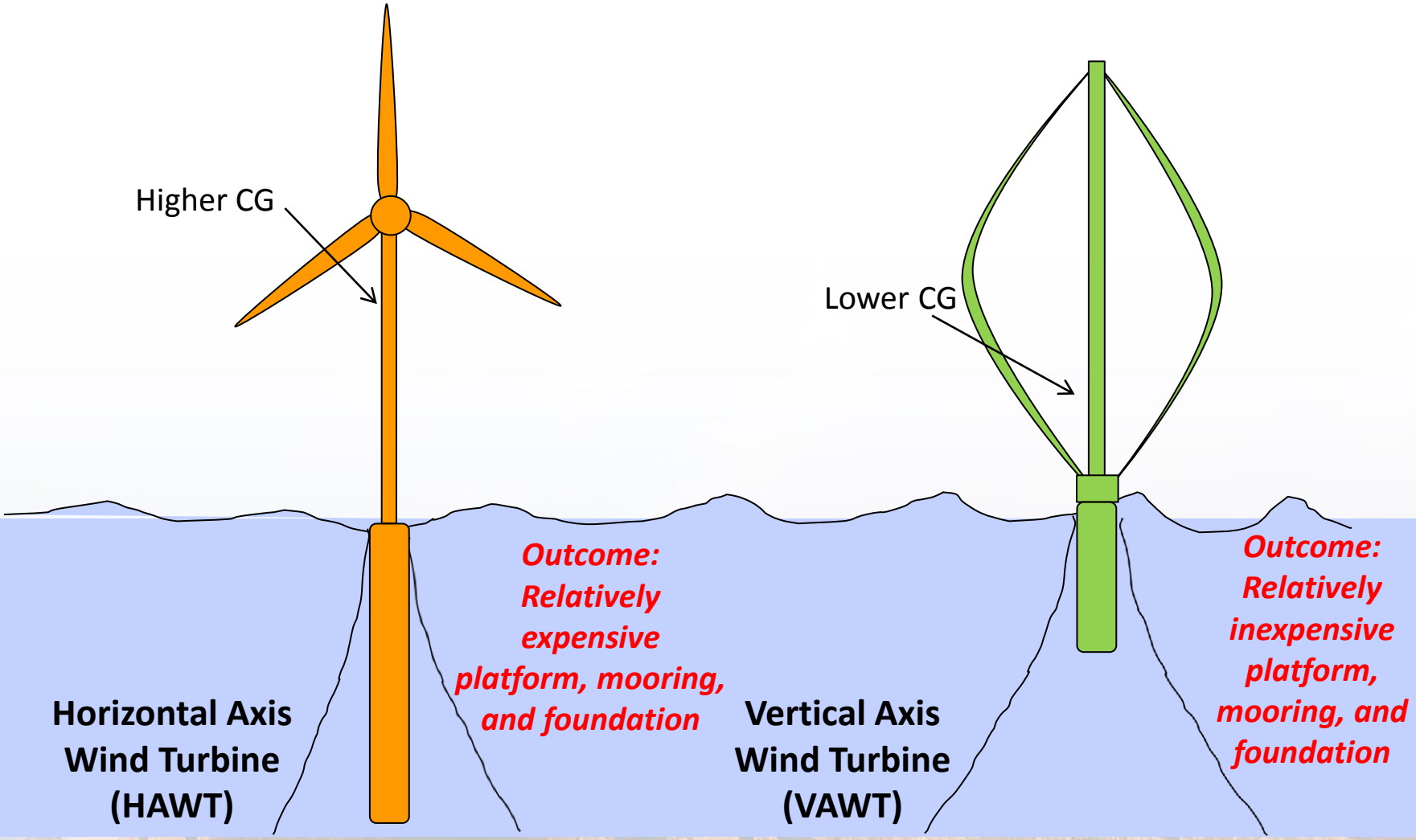
Offshore Design Challenge:
O&M Costs > 25% of the Total Project Cost



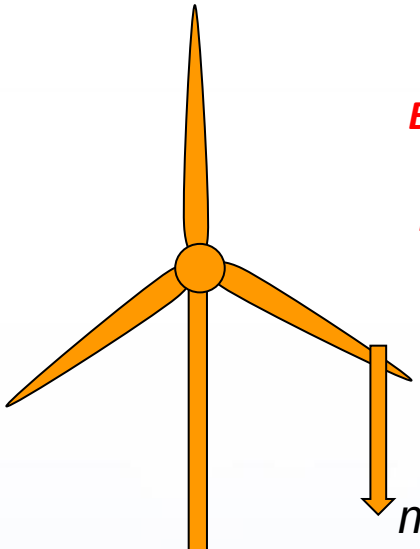
Offshore Design Challenge:
Floating Foundation Costs > 20% of Total Project Cost



Offshore Design Challenge:
Increased Supporting Infrastructure Cost Demand Larger Rotors

Operating cyclical gravity loads and resulting fatigue impact increase with rotor size

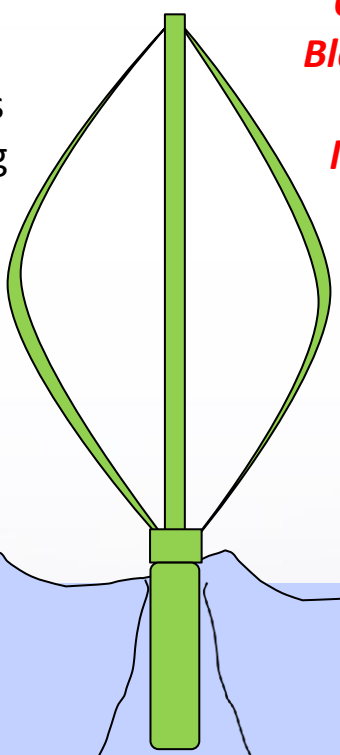
Outcome: Blade weight becomes increasingly difficult design challenge with larger rotors



Horizontal Axis Wind Turbine (HAWT)

Operating cyclical gravity loads and resulting fatigue impact are minimal

Outcome: Blade weight does not limit rotor size

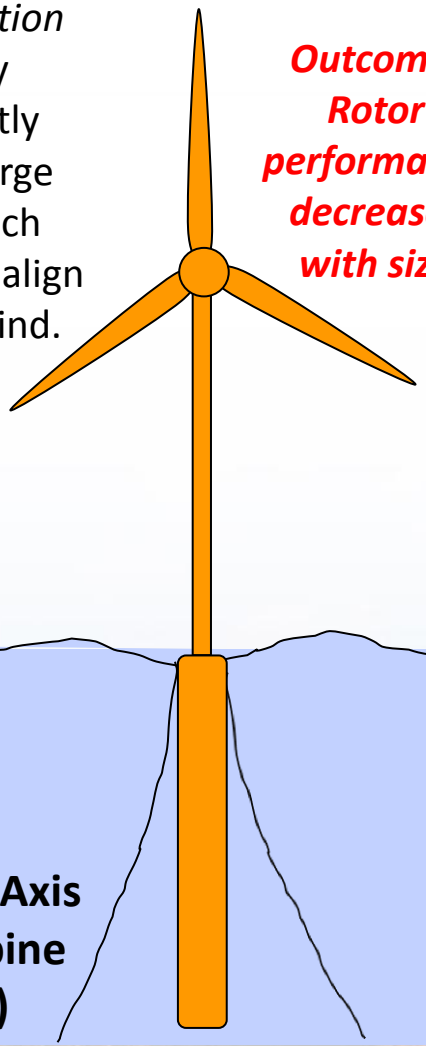


Vertical Axis Wind Turbine (VAWT)

Offshore Design Challenge:
Increased Supporting Infrastructure Cost Demand Larger Rotors

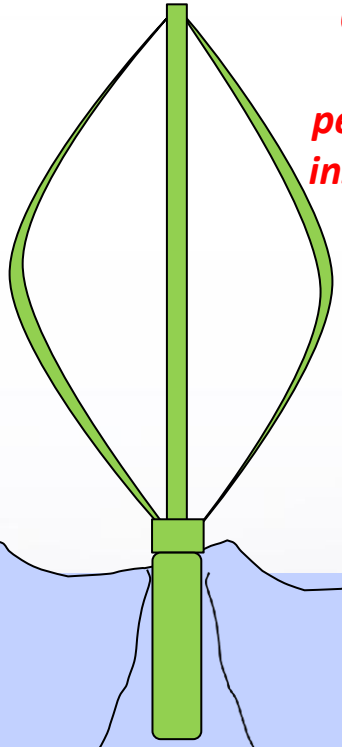
Wind *direction* can vary significantly across a large rotor, which attempts to align with the wind.

Outcome: Rotor performance decreases with size



Horizontal Axis Wind Turbine (HAWT)

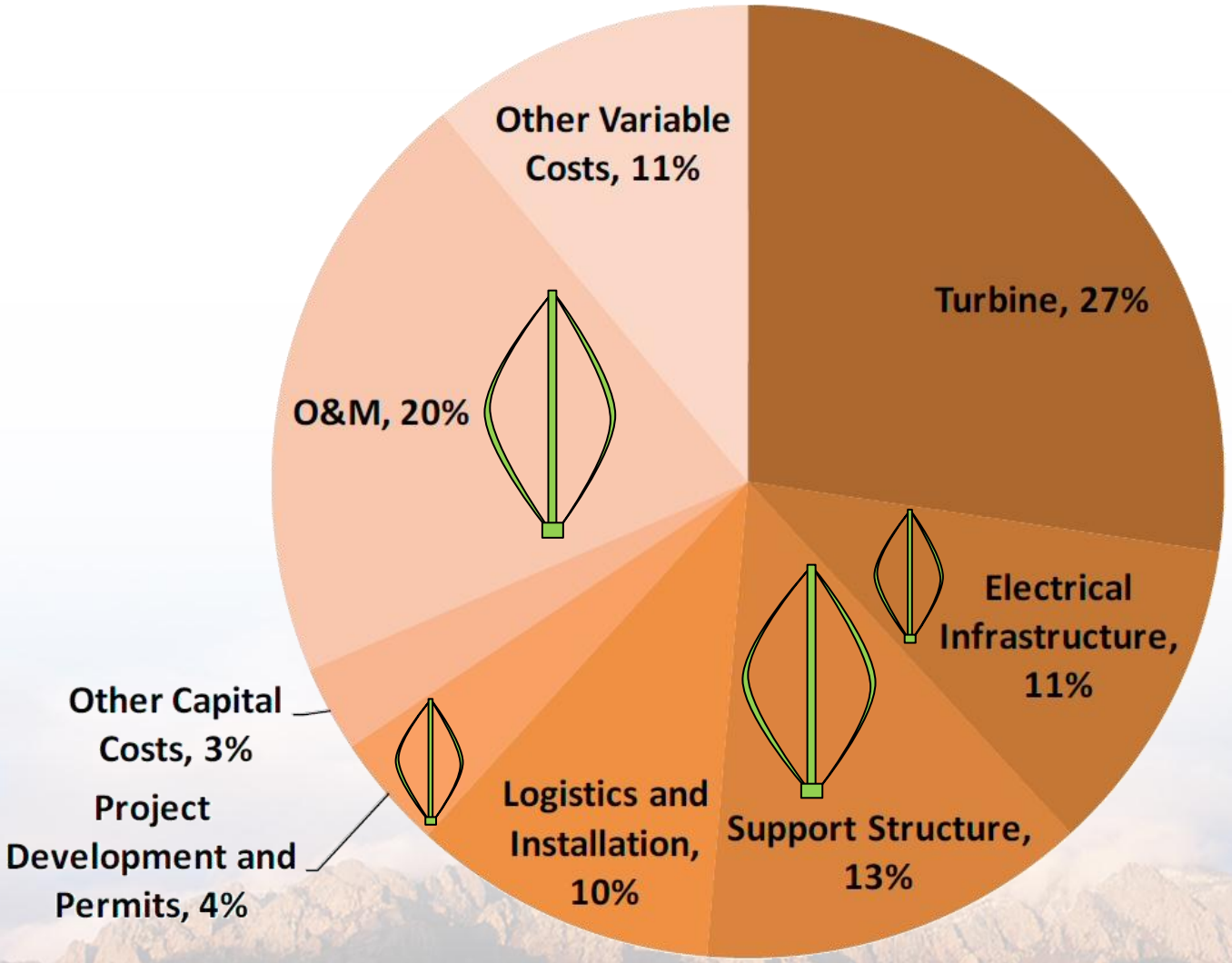
VAWT rotor energy capture is insensitive to wind direction.



Outcome: Rotor performance insensitive to size

Vertical Axis Wind Turbine (VAWT)

Offshore Life-cycle Cost Breakdown



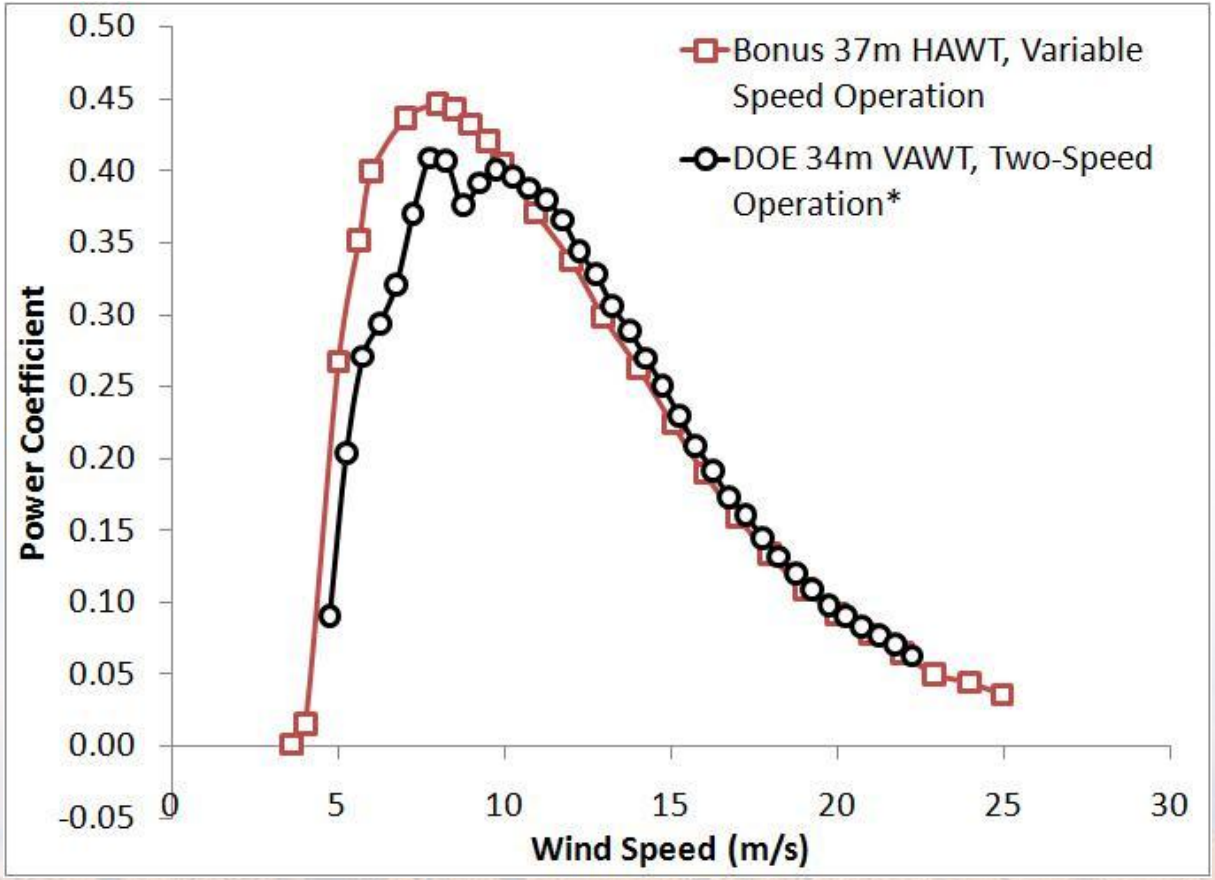
Sandia National Laboratories

Challenges

Sandia National Laboratories

VAWT Efficiency

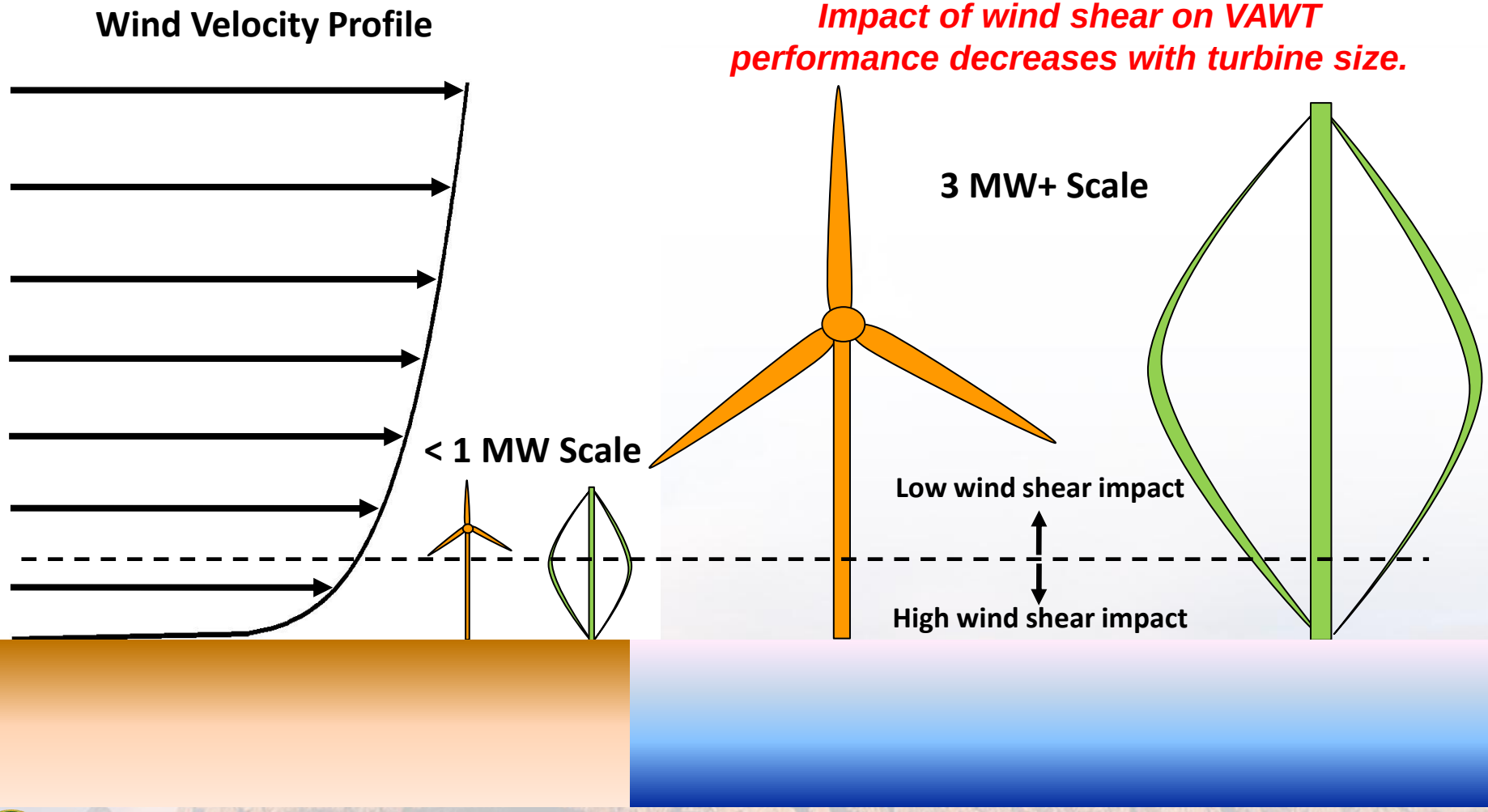
Measured turbine efficiency for circa 1990 variable speed, stall regulated HAWT compared with the DOE 34 m research VAWT (1990).



***True variable speed VAWT operation would improve performance at low wind speeds.**

Sandia National Laboratories

VAWTs and Wind Shear



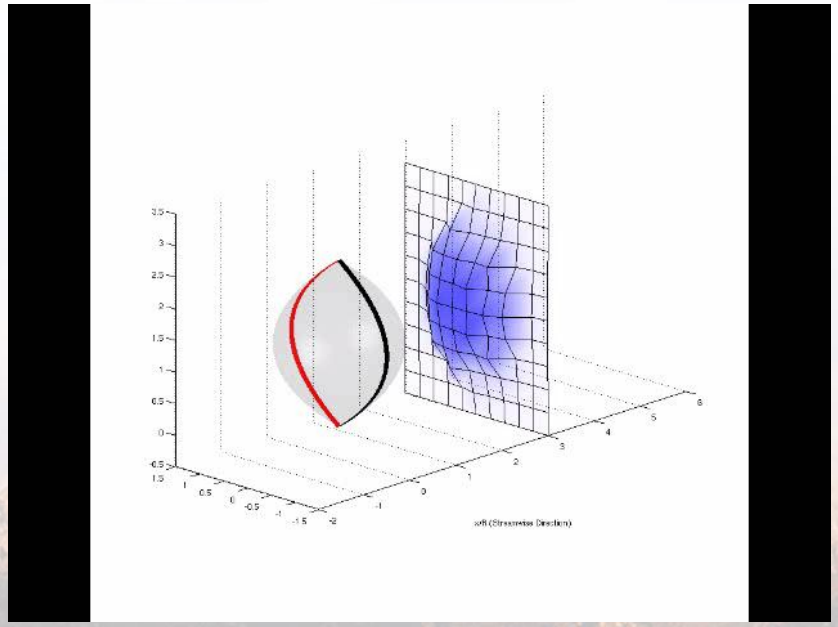
Current Activities

Sandia National Laboratories

VAWT Performance Analysis: CACTUS Code

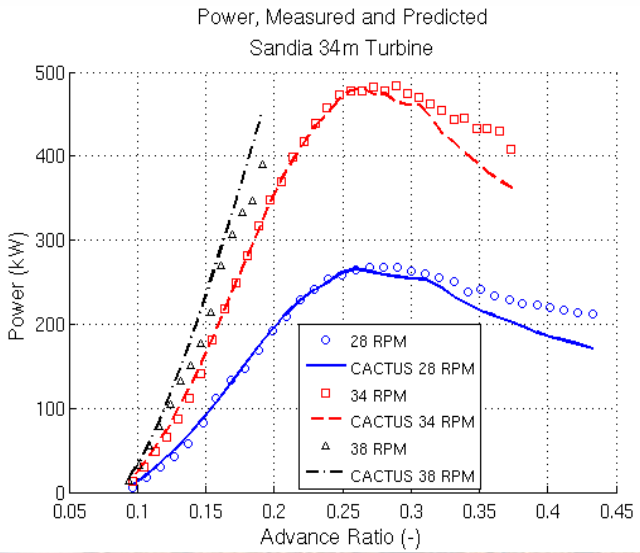
- **Code for Axial and Crossflow TUrbine Simulation**
- **Turbine Performance and Rigid-Body Hydrodynamic Loads Prediction**
  - Blade aerodynamics described by a lifting line
  - Wake dynamics described by an array of vortex filaments
  - Empirical model for parasitic drag losses from strut and blade/strut attachments

Simulation of a Darrieus VAWT

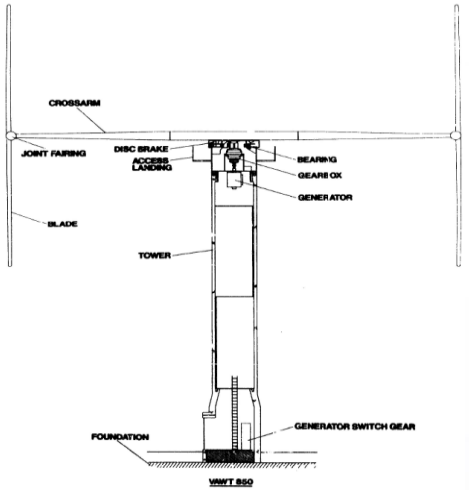


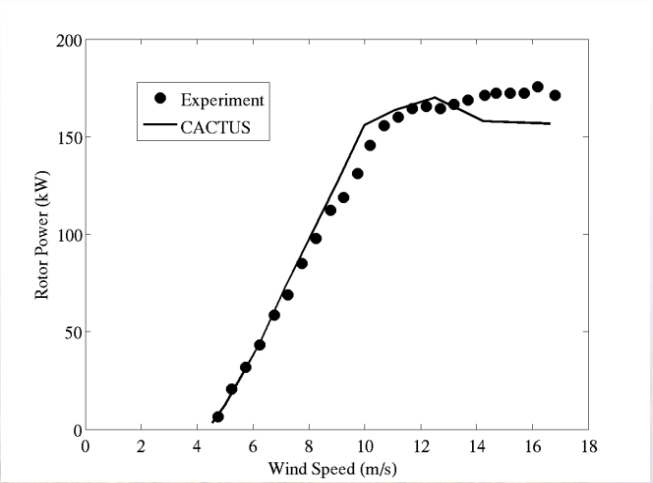
CACTUS Validation

DOE 34 m Darrieus Testbed



UK VAWT 850 H-VAWT



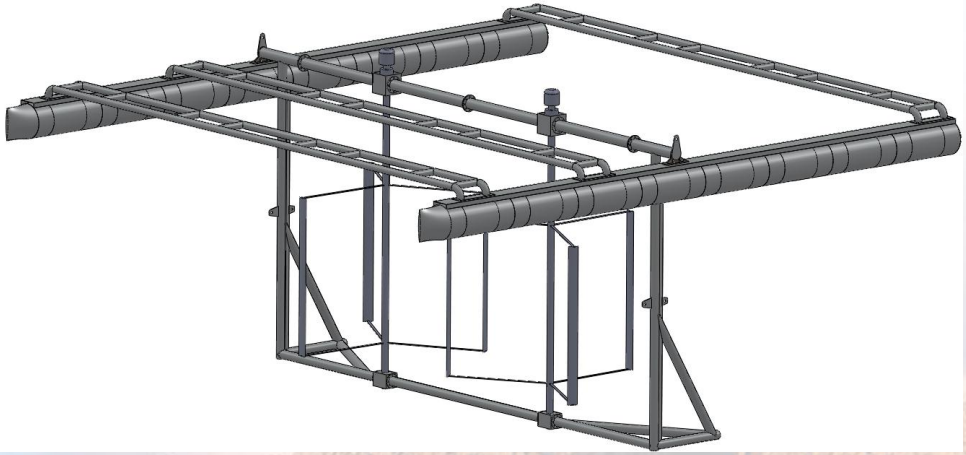


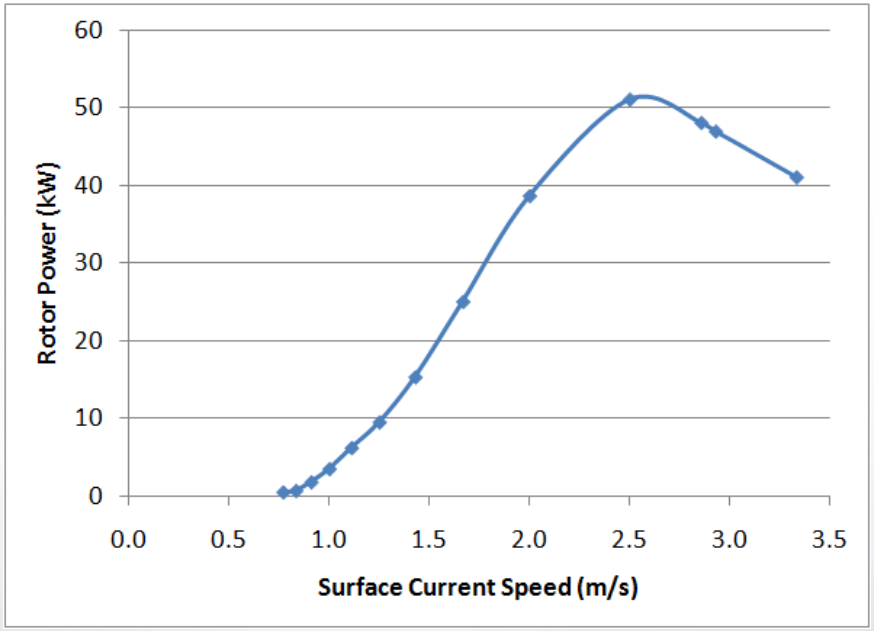
Murray, J. and Barone, M. "The development of CACTUS: a wind and marine turbine performance simulation code, ASME Wind Energy Symposium, Orlando, FL, January 2011.

Sandia National Laboratories

MHK Reference Model for Riverine Device

Rotor Parameter	Value
Rotor Height (Blade Length)	4.84 m
Rotor Diameter	6.45 m
Rotor Swept Area	31.25 m^2
(Constant) Rotational Speed	14.8 RPM





What Others are Doing

Sandia National Laboratories

European Offshore VAWT Research

- **"Future Deep Sea Wind Turbine Technologies", or "DeepWind", Project funded under the EU Seventh Framework Programme**
  - Consortium including Riso-DTU, TU-Delft, Aalborg U., industry partners
  - Investigating deep water offshore VAWTs
  - Funding of €3M
- **Dr. Carlos Simao Ferreira visited Sandia during the month of November**
  - Aerodynamics PI of the DeepWind project from TU-Delft
  - SNL/Delft exchanged information on modeling techniques and design philosophies for VAWTs and MHK cross-flow turbines
- **SNL currently has MOU's with Riso-DTU, TU-Delft, and ECN (Jan. 2011)**

Innovative Offshore Vertical-Axis Wind Turbine Rotors

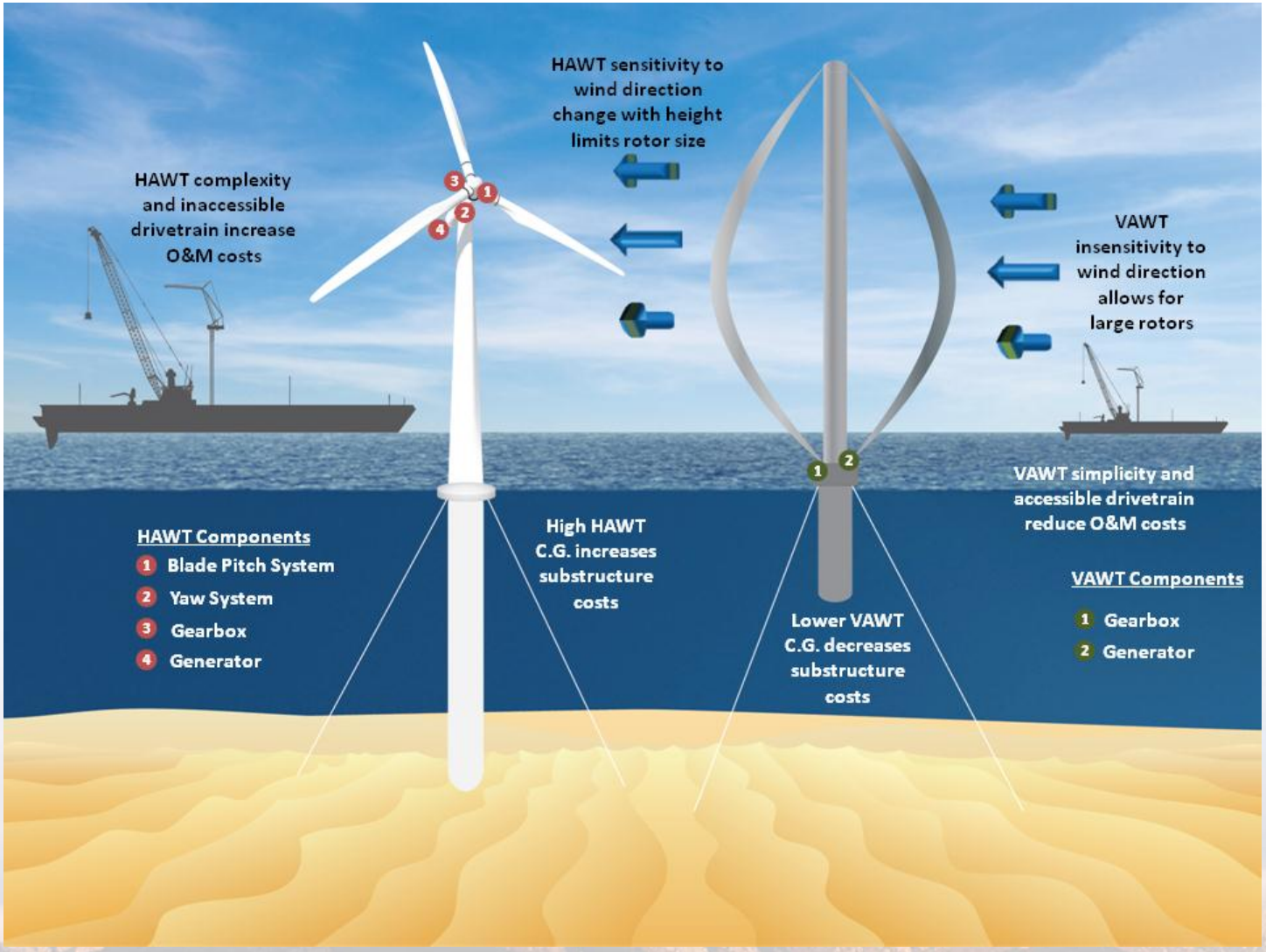
Project Overview
March 6-7, 2012

Matt Barone and Josh Paquette

Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

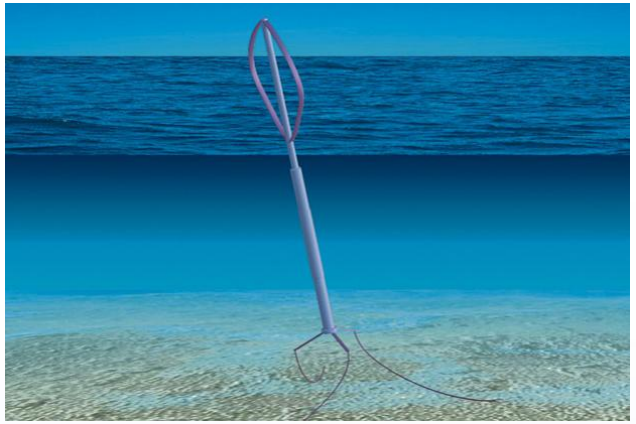
Project Motivation



Collaboration Opportunities

Aerogenerator Project – Wind Power Ltd.

DeepWind Project - EU

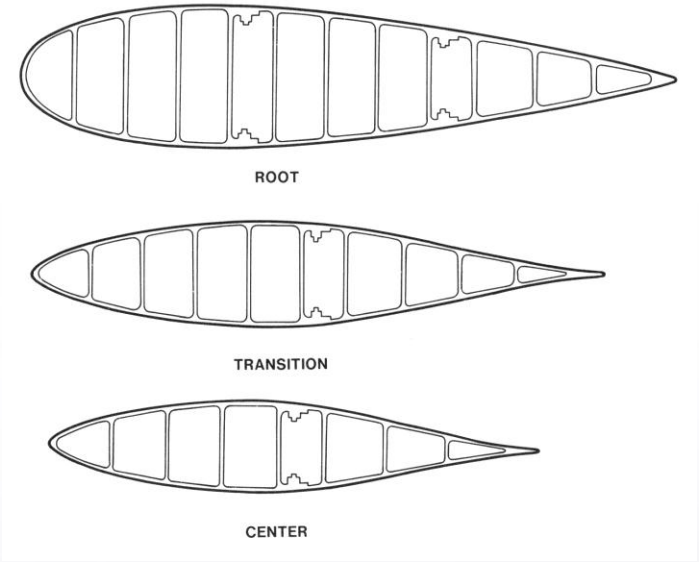


Principle Power

Sandia National Laboratories

Important "Firsts" or "Almost Firsts"

- **Full Variable Speed with Programmable Controller**
  - Avoid Structural Resonances
  - Regenerative Braking
  - Optimal Rotor Speed for Power Production
- **Natural Excitation Technique (NeXT) for Modal Testing of Large Structures**



- **Fatigue Material Database**
- **VAWT Specific Airfoils: Sandia NFL Airfoil Family**

  Largest, Open Multi-Cell Extrusions Ever Made (to date)

VAWTs for Off-Shore Applications

- **Aerodynamics**
  - SNL NLF Airfoils, Summer Airfoils
  - Better Structural Characteristics: "Thick Airfoil" Series
  - Eliminate and/or Fair Struts and Joints
- **Blade Materials**
  - Composite Materials
  - Molded Composite Structure
    - High Bend-in-Place Stresses
    - Tailored Chord Distribution
- **Drive Train and Power Components**
  - Variable Speed with Regenerative Braking
  - Brake System
  - Direct-Drive
  - Vertically Mounted Generators

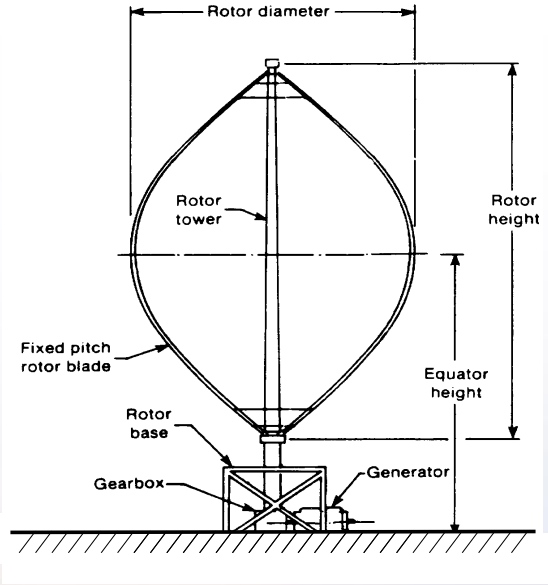
VAWT Technology

- **Savonius Rotor (Bucket Rotor)**
  - Low Efficiency
  - High Torque, Low Speed
  - Easily Fabricated
- **Darrieus Rotor**
  - Efficiency Equivalent to HAWT

    Betz Limit of 59.3% Efficiency
  - Blades Attached at Both Ends
  - Constant-Cord (Step-Tappered) Airfoil Section

    Minimal Loss in Aerodynamic Efficiency
  - Minimal Bending Stresses

    Troposkien Shape (Swinging Rope)
  - Heavy Components at Ground Level

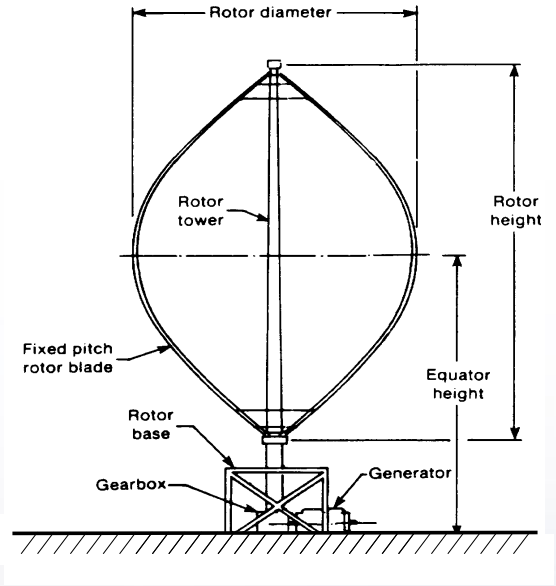


VAWT Technology

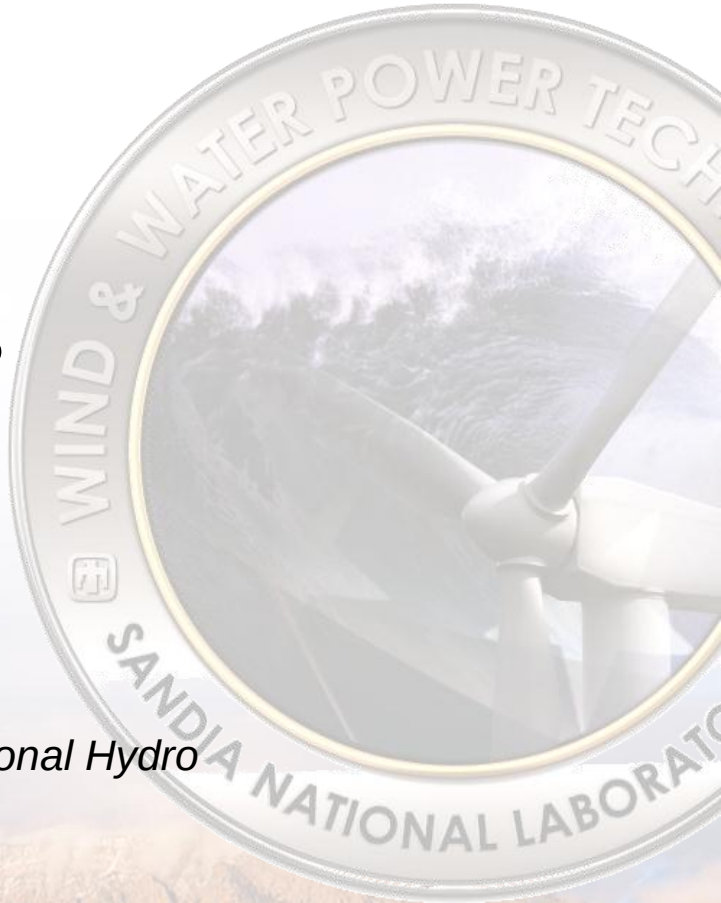
- Long Blades
  - Twice as Long as Equivalent HAWT Blade
  - Innovative Materials & Manufacturing Techniques
- Active Aerodynamic Control
  - Passive Power Control: SNF Airfoils
  - Aerodynamic Brakes
- Large Footprint: Guy System

  Cantilever Designs
- Torque Ripple

  Compliant Drive Train
- Power Train
  - May or May Not Self Start: Starting System Required
  - Right-Angle Transmission



MHK Research Activities at Sandia National Laboratories

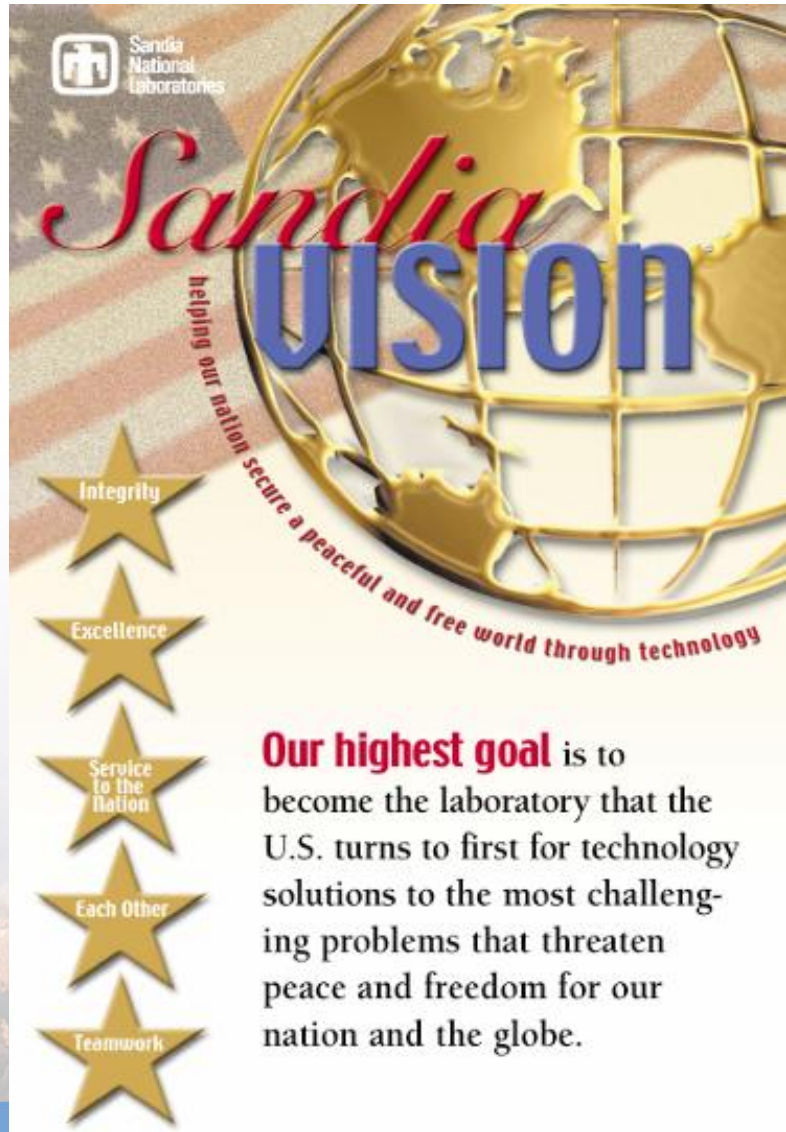


Dr. Daniel Laird
Program Manager
Water Power Technologies
Marine Hydrokinetics, Offshore Wind, Conventional Hydro
Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Our Business: National Security

- Broad mission in developing science and technology applications to meet our rapidly changing, complex national security challenges
- Safety, security and reliability of our nation's nuclear weapon stockpile



Distributed Facilities

Albuquerque,
New Mexico

Kauai Test Facility,
Hawaii

Tonopah Test Range,
Nevada

Yucca Mountain,
Nevada

WIPP, New Mexico

Pantex, Texas

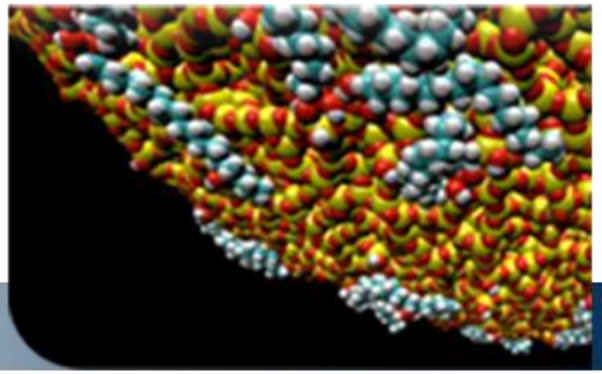
Livermore, California

Sandia National Laboratories

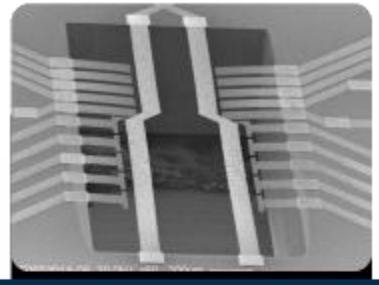
Science and Engineering Foundations

Computing and information science

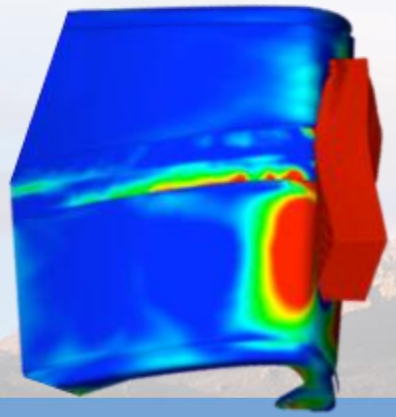
Materials science



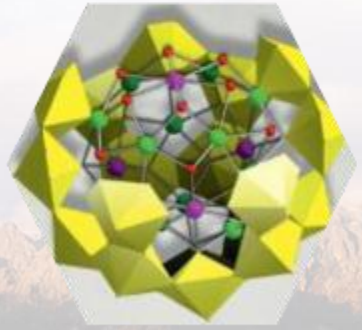
Nanodevices and microsystems



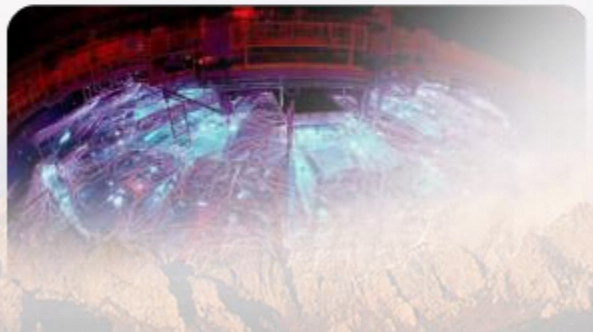
Engineering sciences



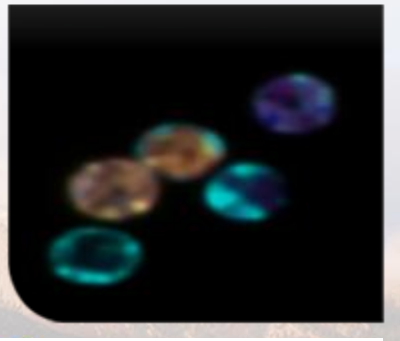
Geoscience



Radiation effects and high-energy density science



Bioscience

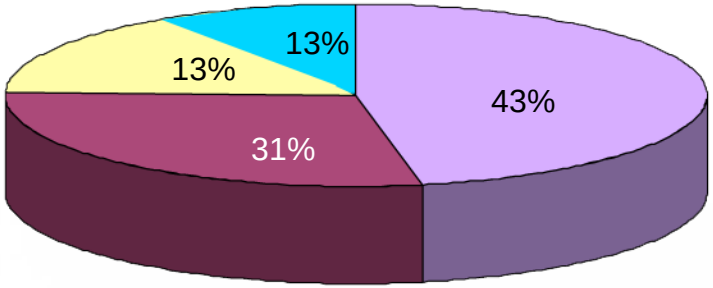


Sandia National Laboratories

People and Budget

- On-site workforce: 11,677
- Regular employees: 8,607

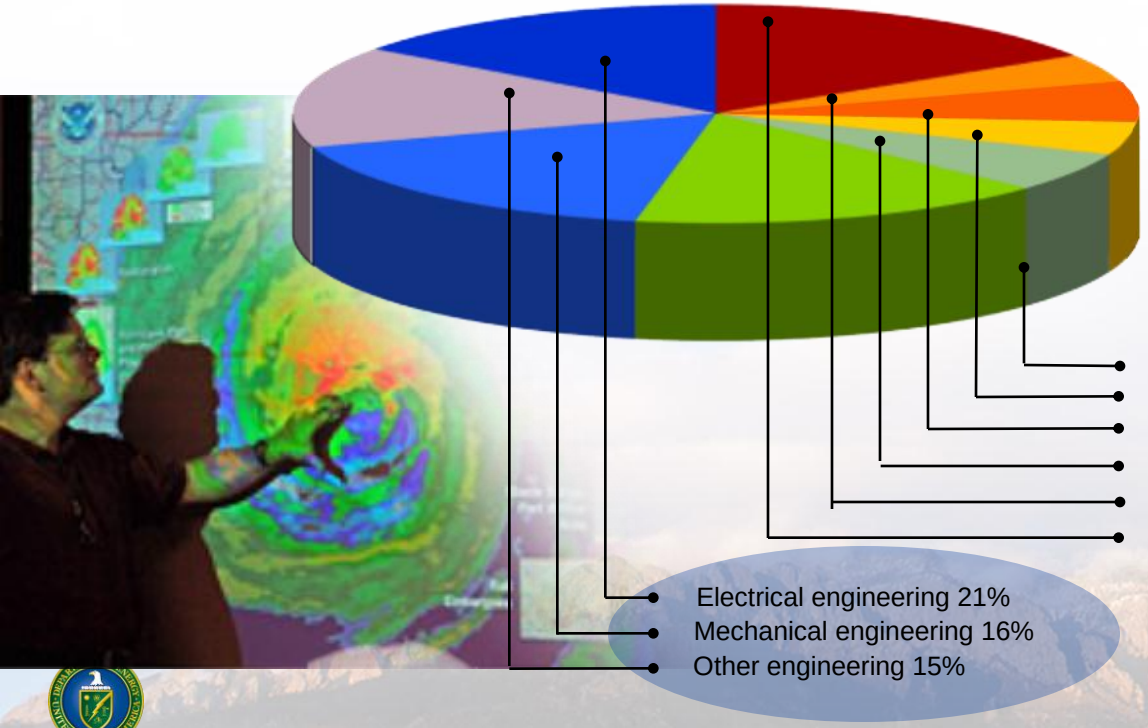
FY10 operating revenue
$2.3 billion



(Operating Budget)

- Nuclear Weapons
- Defense Systems & Assessments
- Energy, Climate, & Infrastructure Security
- International, Homeland, and Nuclear Security

Technical staff (4,277) by discipline:



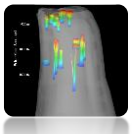
Sandia National Laboratories

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



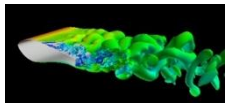
DOE's Tech Transfer Initiative was established by Congress in 1991

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

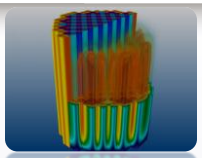
Combustion Research Facility (CRF) opens to researchers

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

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

Sandia National Laboratories

Renewable Energy Research at Sandia

- **Renewable Energy Portfolio**
  - Water Power
    - Marine Hydrokinetics
    - Conventional Hydro
  - Wind Energy
    - Land-based
    - Offshore
  - Photovoltaics
  - Concentrating Solar Power
  - Geothermal
  - Biofuels
  - Sunshine to Petrol

- **Security**

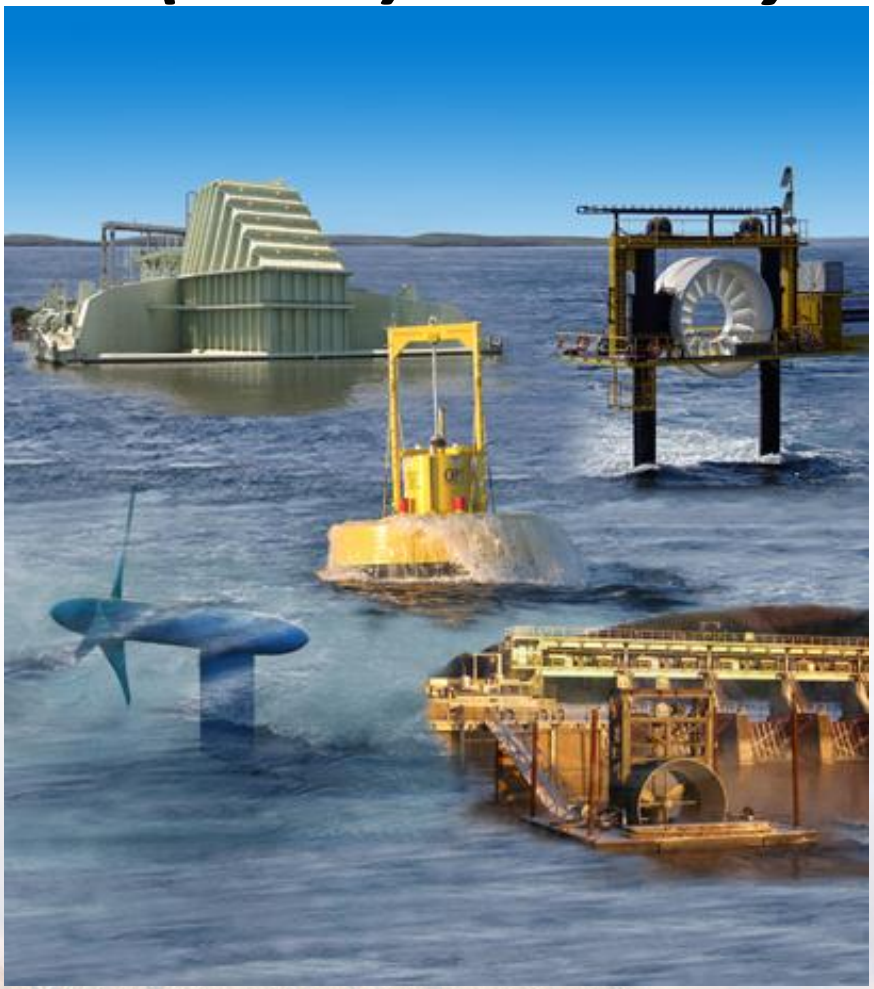
  With it's long history in weapons and national security, Sandia has a proven track record in protecting sensitive information and enforcing export control

Only national laboratory with a comprehensive renewable energy portfolio and a national security focus

Sandia National Laboratories

State of the Marine Hydrokinetic (MHK) "Industry"

- **Wave: >100 Devices***
  - Attenuator
  - Pitching/Surging/Heaving/Sway (PSHS)
  - Oscillation Water Column
  - Overtopping Device
  - Submerged Pressure Differential
- **Current/Tidal: >60 Devices***
  - Horizontal Axis Turbine
  - Vertical Axis Turbine
  - Oscillating Hydrofoil
  - Venturi

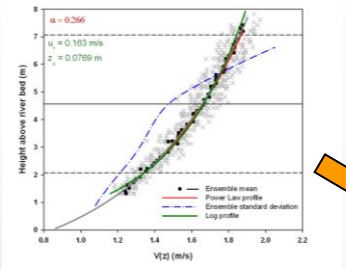


Sandia National Laboratories

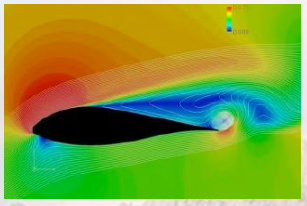
Verdant Power Composite Rotor Project

2008-2012

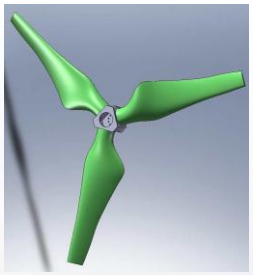
- **Verdant requested assistance with rotor design, analysis, and testing**
  - CRADA – 2008, WFO - 2009
- **Leverage Sandia's extensive expertise in composite wind turbine rotors**
- **Team: VPI, SNL, NREL**
- **Program/Industry Impact**
  - Development of water current inflow characterization and modeling tools
  - Leverage wind technology investment for MHK applications
  - Advancement of U.S.-based renewable energy design and manufacturing base



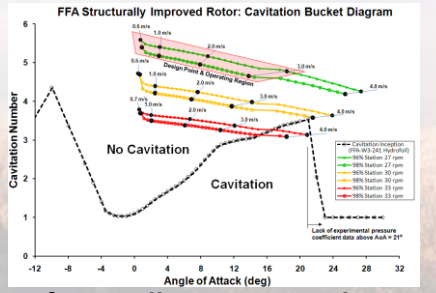
Characterize Inflow and Loads



Utilize High-Performance Computing to Simulate and Select Hydrofoils



Develop Design



Perform Full-System Simulations

Lab and Field Testing

Deployment

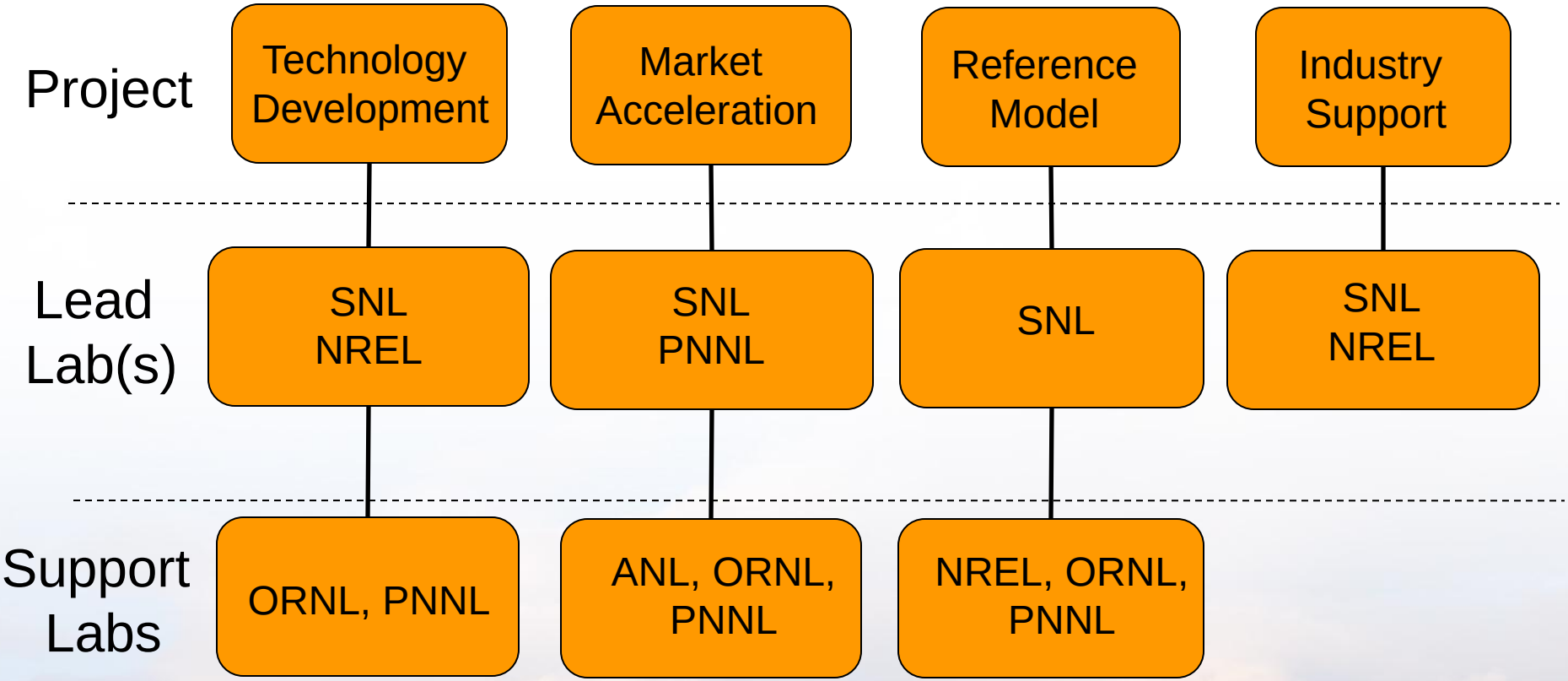
Sandia National Laboratories

Sandia MHK Research Program

- **Started in 2009**
- **Heavily leveraged Sandia resources in**
  - wind energy research
  - science and engineering core competencies
  - hydrodynamics
  - sediment transport
- **Current Program Elements**
  - Technology Development
  - Market Acceleration
  - Reference Model Development

Sandia National Laboratories

Primary DOE/National Lab MHK Projects

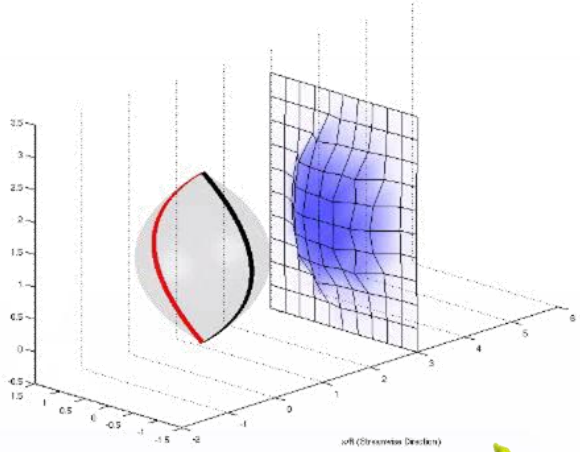


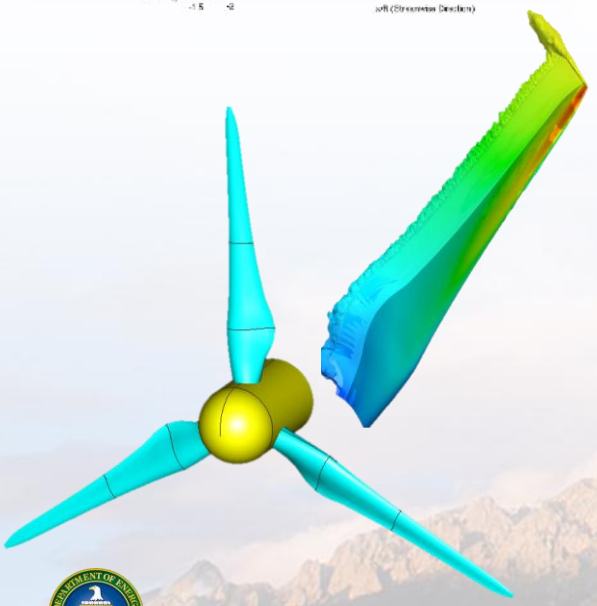
Sandia National Labs (SNL), National Renewable Energy Lab (NREL), Pacific Northwest National Lab (PNNL), Oak Ridge National Lab (ORNL), Argonne National Lab (ANL)

Sandia National Laboratories

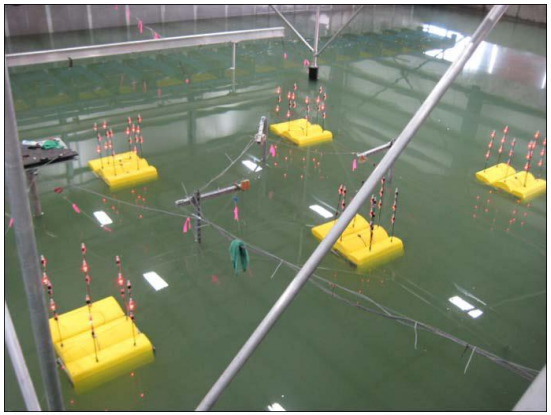
Technology Development

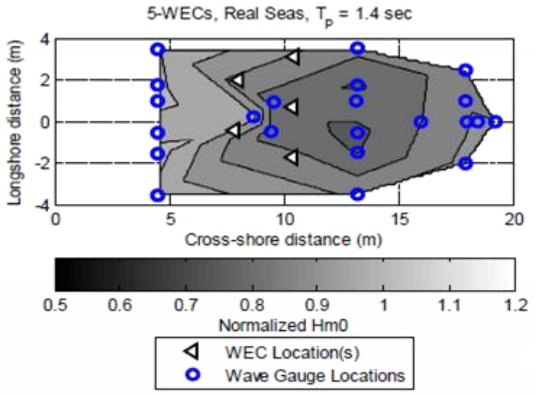
Simulation Tools



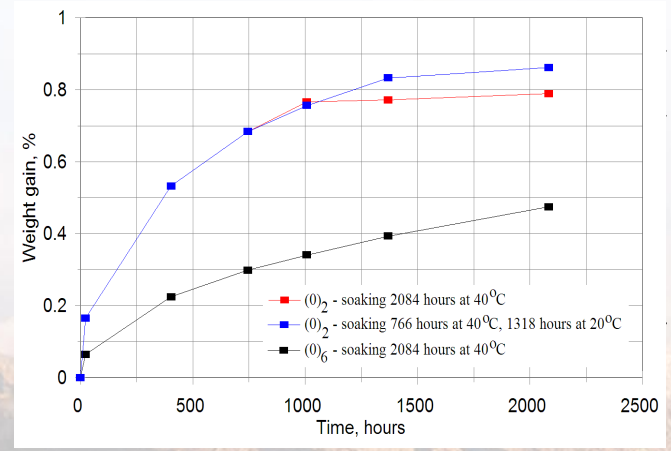


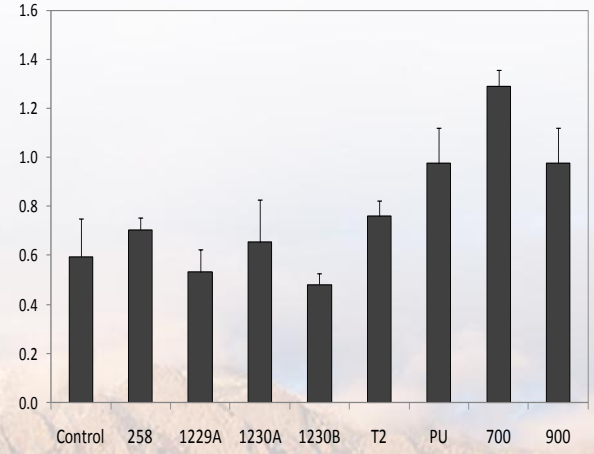
Experimental Validation





Materials





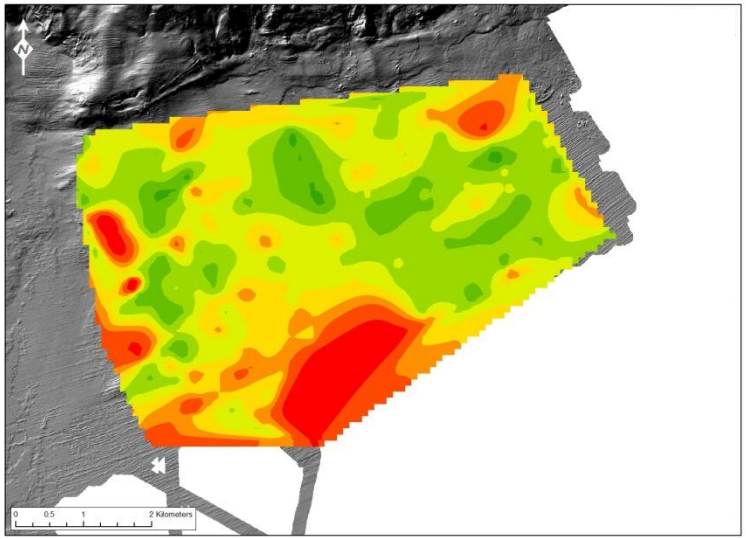
Sandia National Laboratories

Market Acceleration

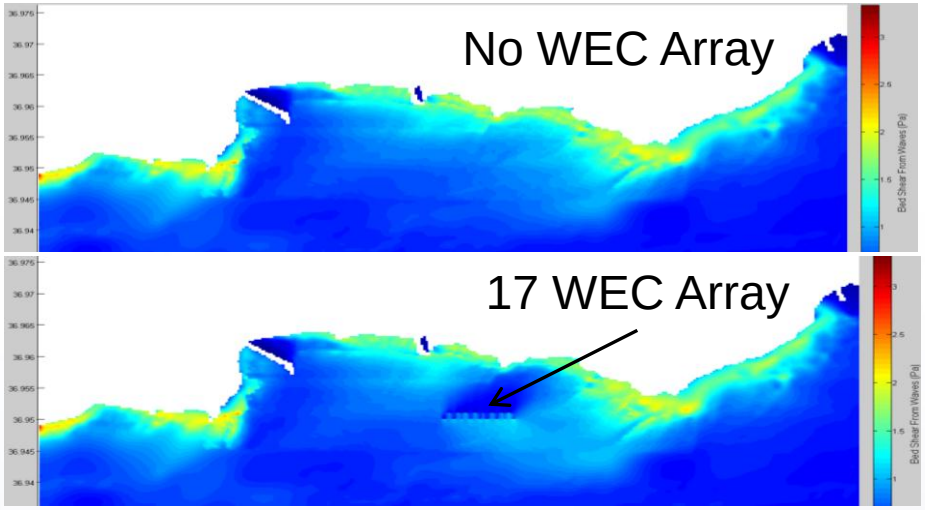
Environmental Effects

Sediment Stability Maps

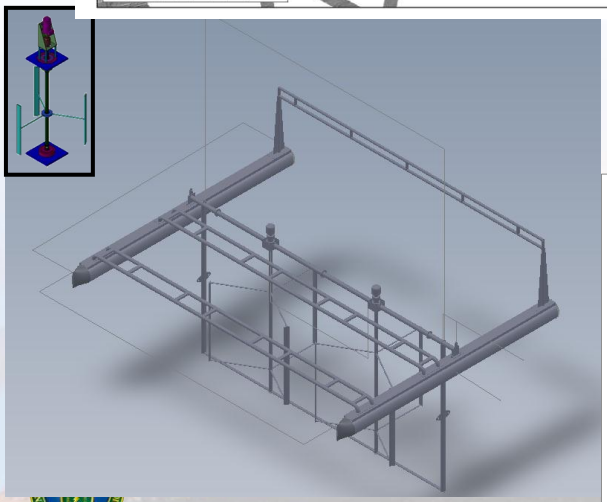
Erosion potential after 10 years

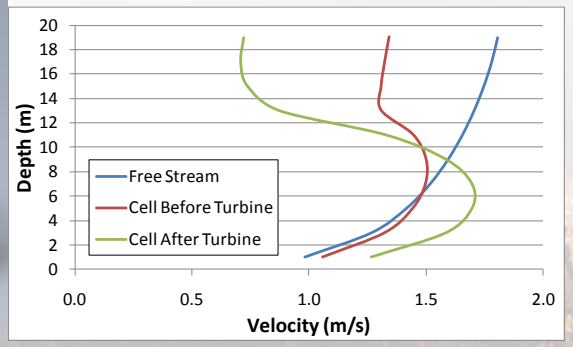


Array Modeling



Device Simulation





Field Testing

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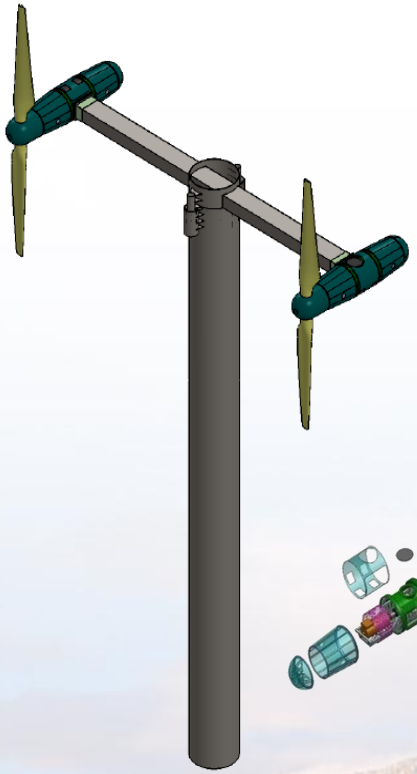
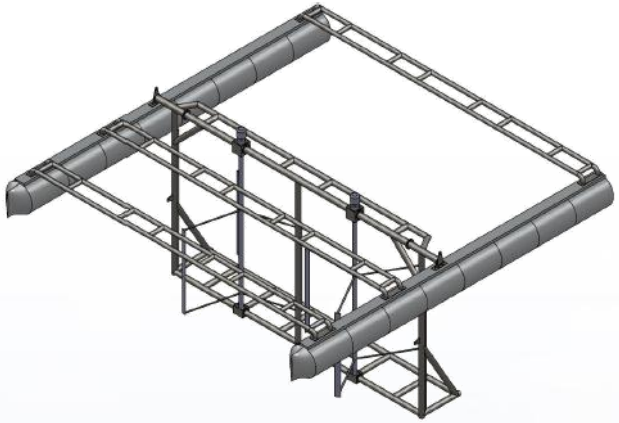
Reference Models

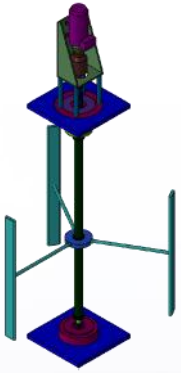
Develop Reference Models for the MHK industry to develop baseline cost of energy (COE) and evaluate key cost component/system reduction pathways.

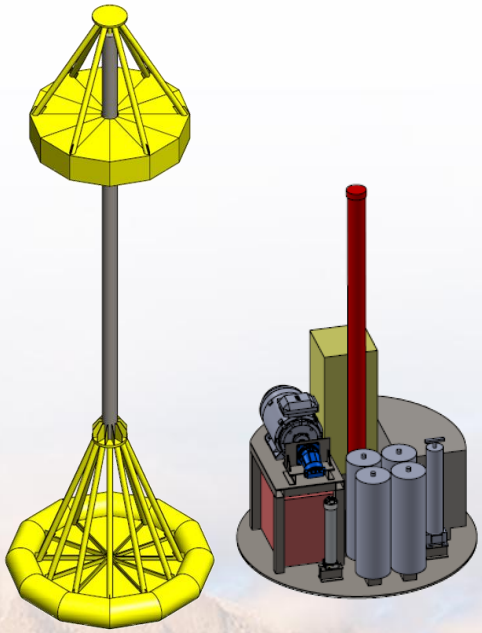


RM#1 Tidal Turbine



RM#2 River Turbine





RM#3 WEC Point Absorber

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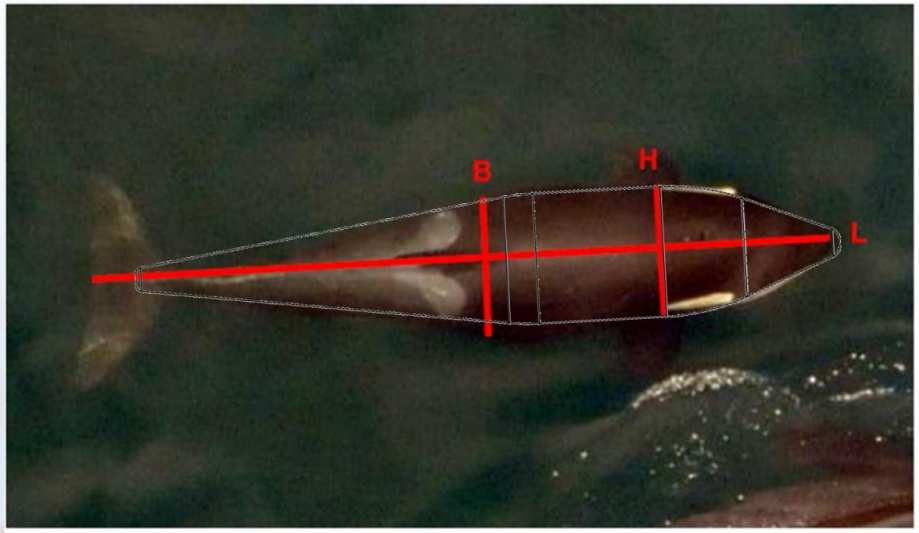
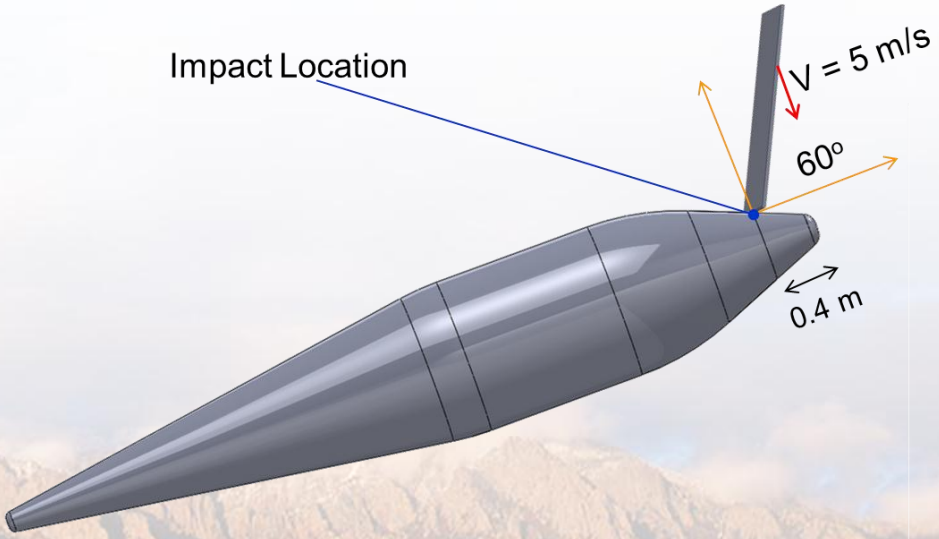
Industry Support

- Public Utility District No.1 of Snohomish County
- Tidal current device - Puget Sound
  - Concern regarding Southern Resident Killer Whales





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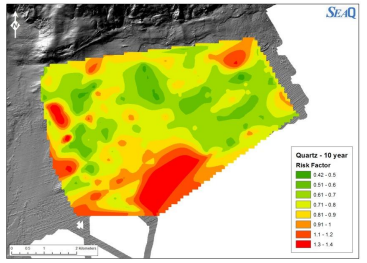
Sandia Offshore Wind Energy Research Program

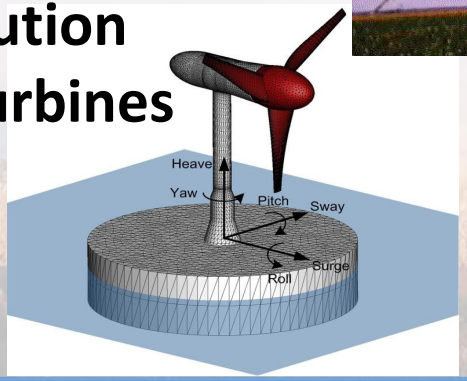
- Structural Health and Prognostics Management

- Large Offshore Rotor Development
- Sediment Transport, Scour and Foundation Impact Analysis



- Radar Mitigation

- DE-FOA-0000415, Innovative Offshore VAWT Rotors
- DE-FOA-0000415, High-resolution modeling of offshore wind turbines and farms



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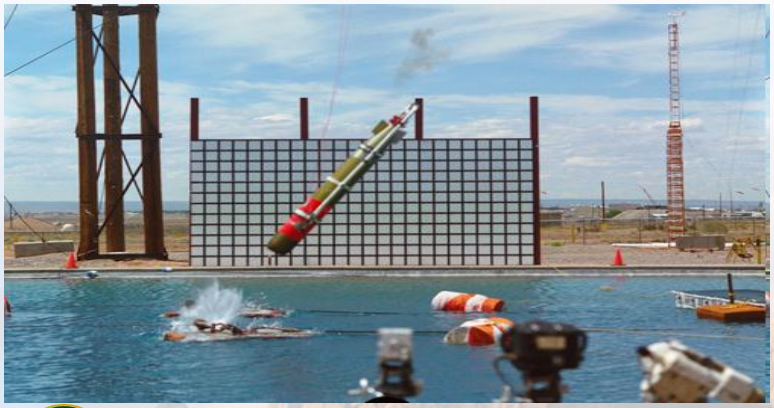
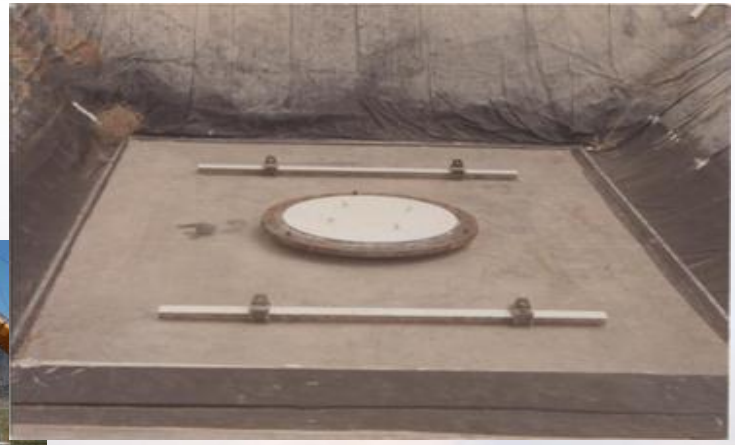
Sandia Lake Facility



Existing Capabilities

- **15 m deep basin (extension to 24 m)**
- 57 m long basin
- 36 m wide basin
- Overhead lifting
- **4 trained/certified divers**
- Technician support
- Several anchor locations
- **Instrumentation**
  - 100+ channels
  - Underwater cameras

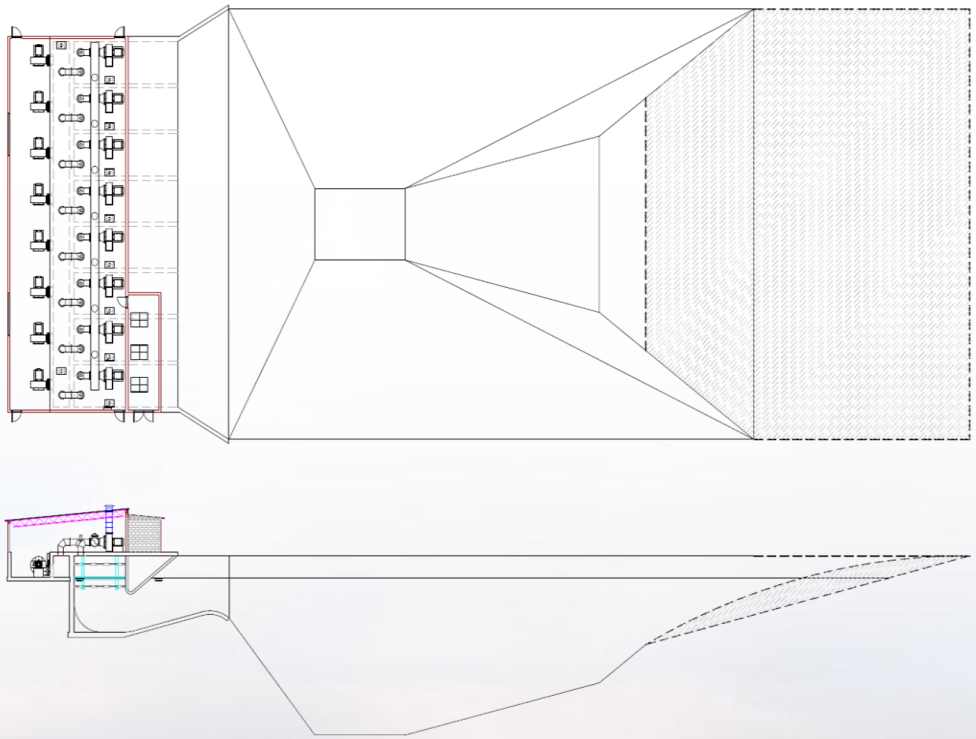
Lake when empty



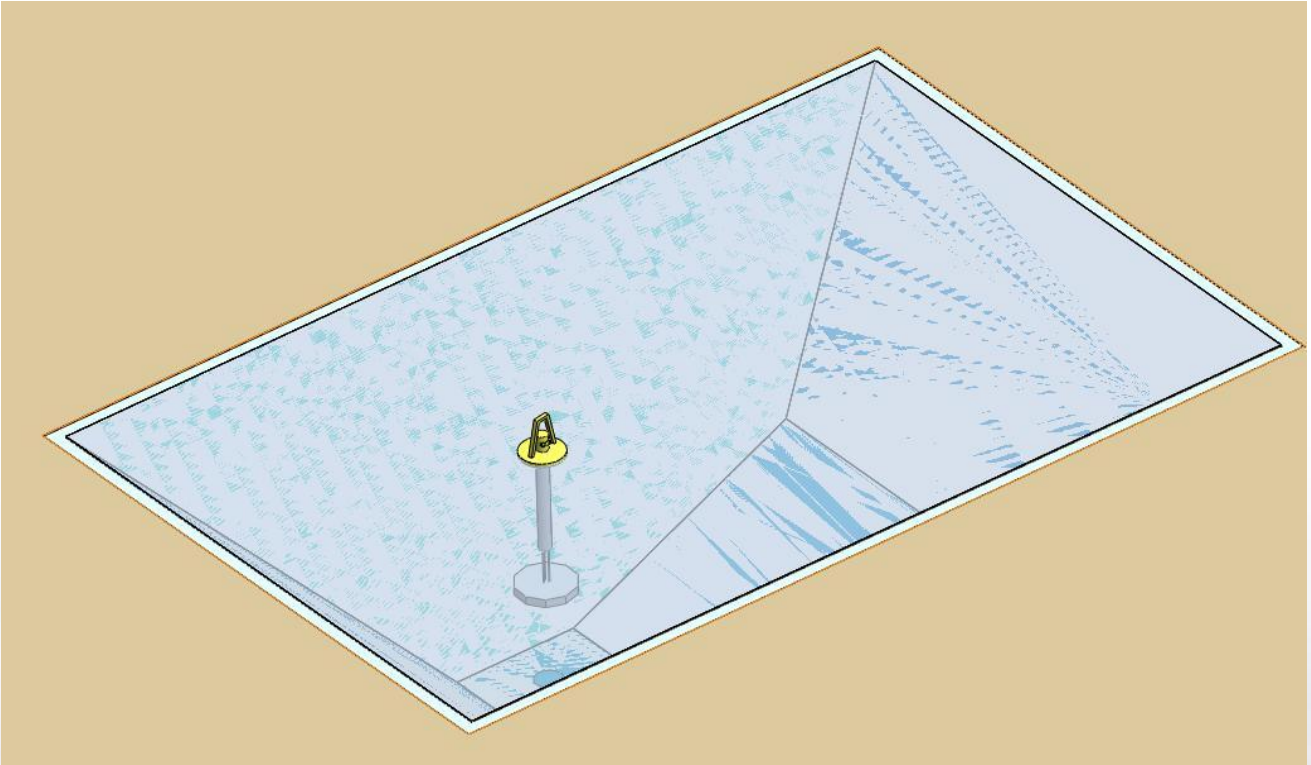
Concrete pad at bottom. Anchor points and extension cover shown

Modification for Sandia Wave Facility

- **Assess cost and need for proposed capabilities**
  - *1.5 m waves*
  - *1 to 5 s period*
  - **15 m deep basin**
  - 57 m long basin
  - 36 m wide basin
  - Overhead lifting
  - **4 trained/certified divers**
  - Technician support
  - Several anchor locations
  - **Instrumentation**
    - 100+ channels
    - Underwater cameras



SNL Lake: Illustration of 10 kW OPT Type Point Absorber



Water Power Program Mission

- **Research, test, and develop innovative technologies capable of generating renewable, environmentally responsible, and cost effective electricity form water resources.**
  - Marine Hydrokinetic Technologies
    - Resource
      - Wave energy has a potential resource of 400 GW
      - Tidal currents have a potential resource of 60 GW
      - Free flowing rivers have a potential resource of 60 GW
    - R&D Focus
      - Determine convertible resource potential
      - Address environmental challenges
      - Demonstrate performance viability and identify technology leaders
      - Identify key cost drivers and opportunities for cost reduction

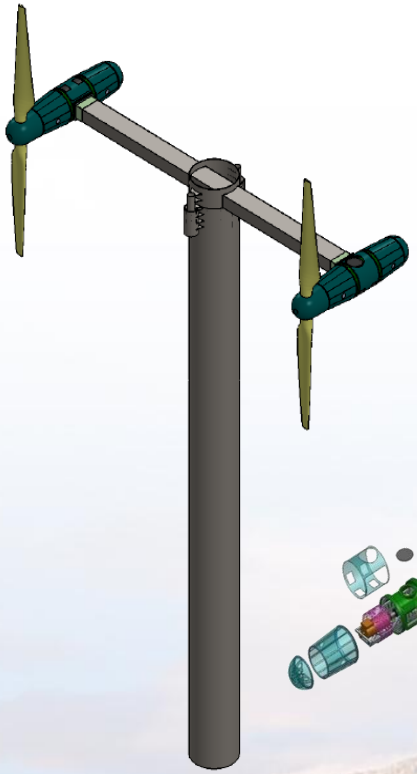
1.0 Technology Development
1.2 MHK Technology Assessment
Reference Model Development

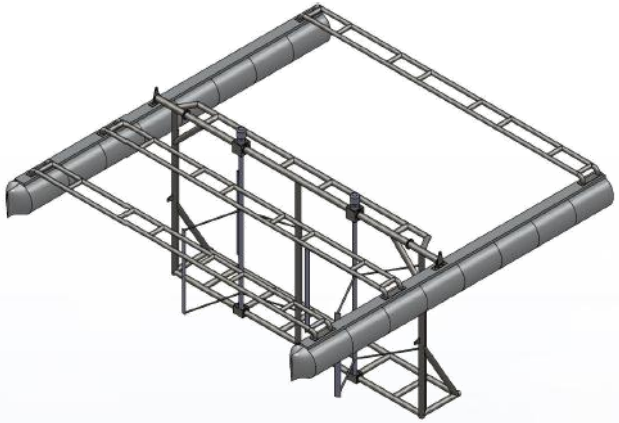
Goals

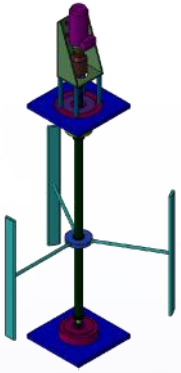
1) Develop baseline cost of energy (COE) for reference WEC and turbine designs in representative resources
2) Identify and evaluate key cost reduction pathways.

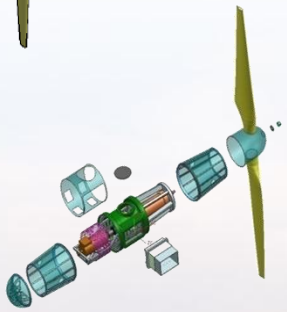
Reference Models

Goal: Develop a representative set of Reference Models (RM) for the MHK industry to develop baseline cost of energy (COE) and evaluate key cost component/system reduction pathways.

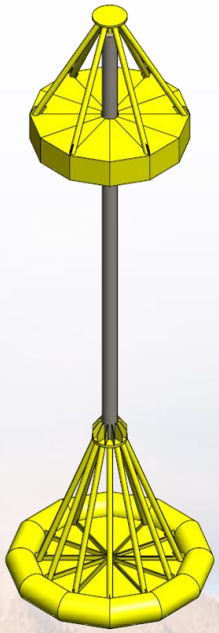


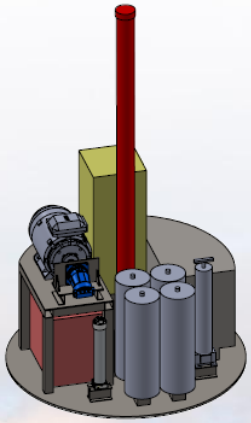






RM#2 River Turbine

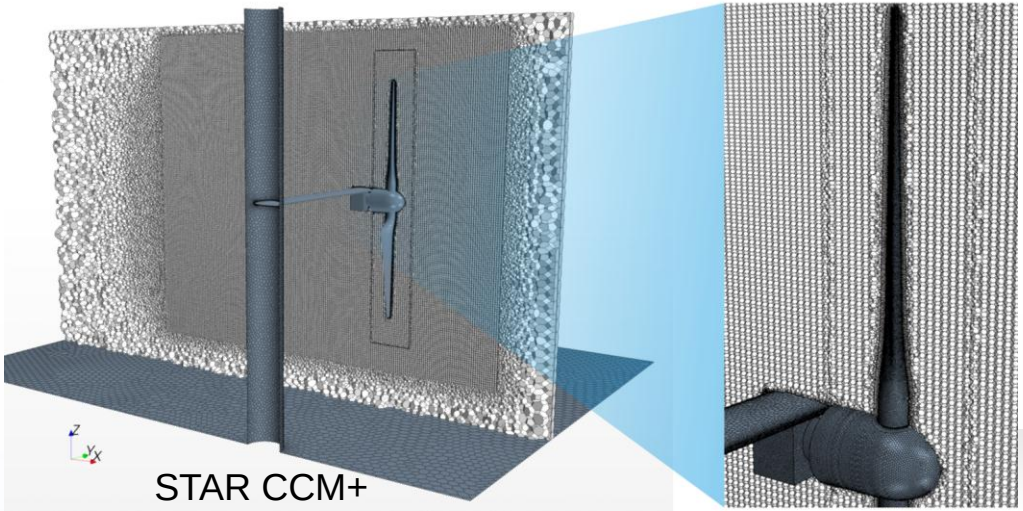


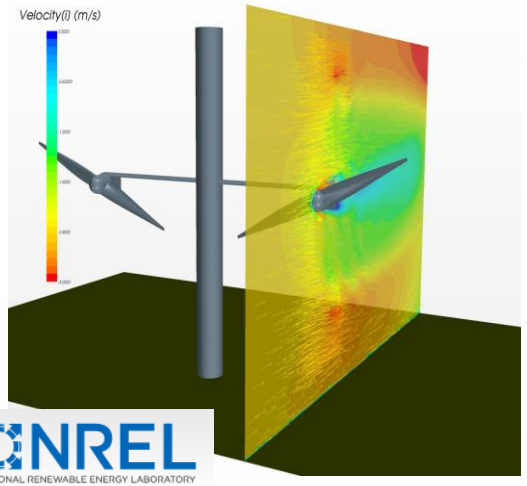


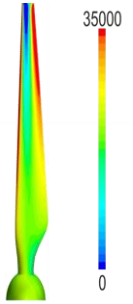
RM#1 Tidal Turbine

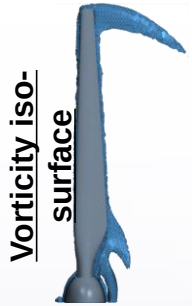
RM#3 WEC Point Absorber

Reference Models: Application of Analysis Tools

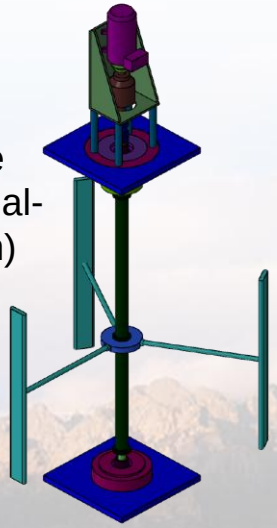








CACTUS (Code for the Analysis of Cross and axial-flow TUrbine Simulation)



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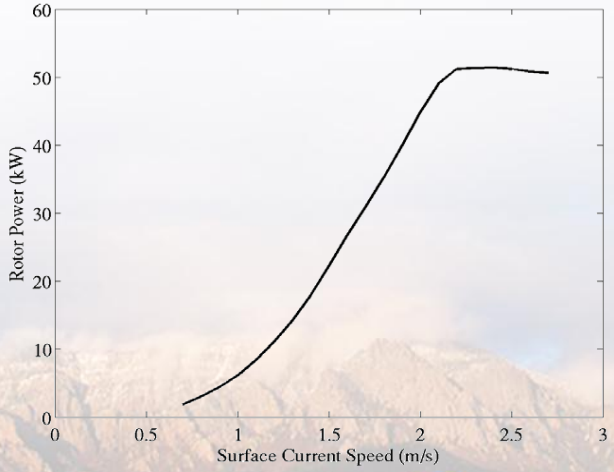

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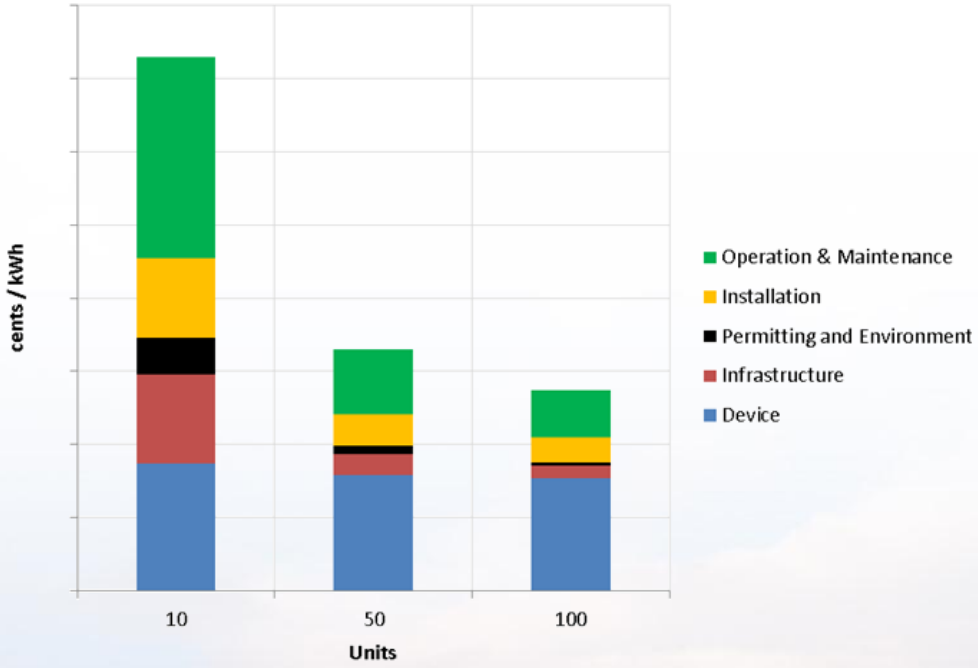
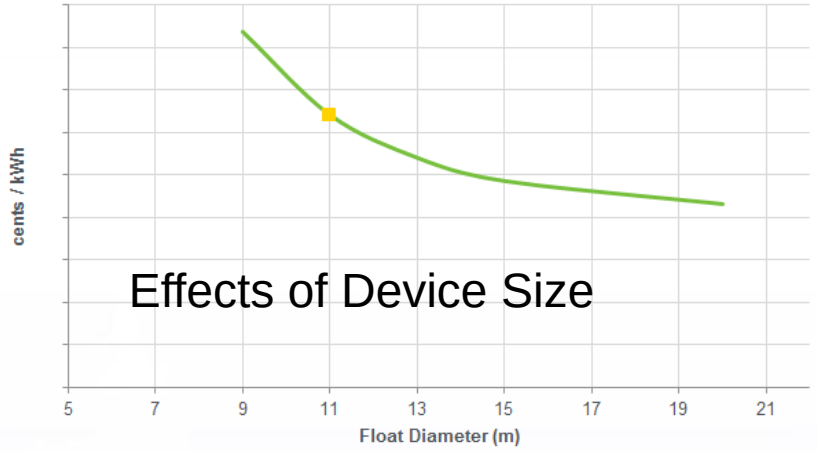
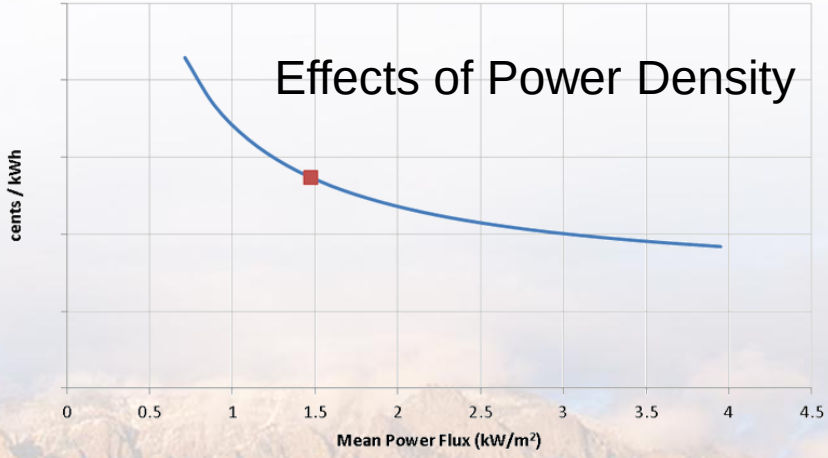
Reference Model: Impact on COE

Cost Drivers







1.0 Technology Development

1.3 MHK Research, Tools, and Testing

Goals

1) Reduce LCOE through development and application of tools to assist with the design, development, and optimization of MHK devices
2) Facilitate the testing of a wide variety of MHK systems and components
3) Generate relevant and reliable data on cost, performance, and reliability

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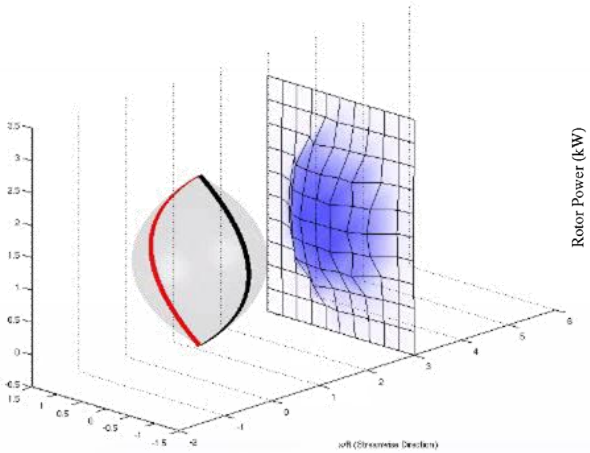
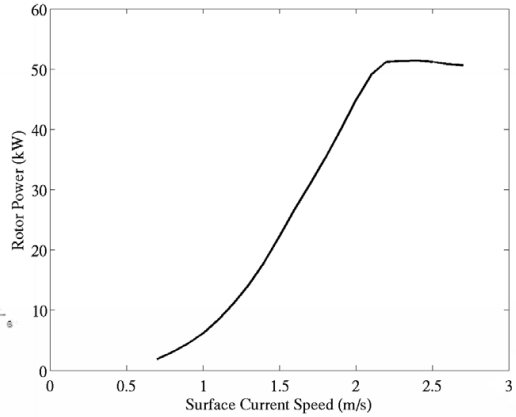
Simulation Tool Development: Single Turbine & Array Performance

Sandia National Laboratories

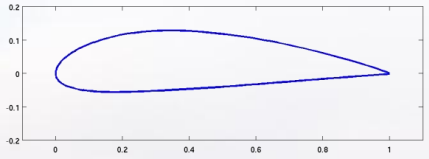
Single Turbine: Modeling Performance

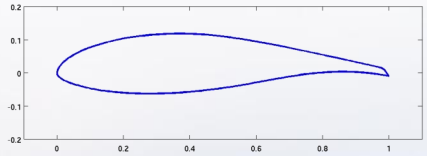
- **Single Device**
  - Development of CACTUS Code for both cross flow and axial flow turbine analysis

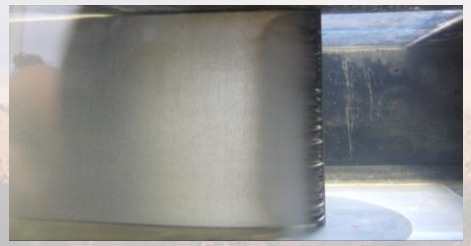




  - Design and test of high performance turbine blade (with Penn State ARL and UC Davis)







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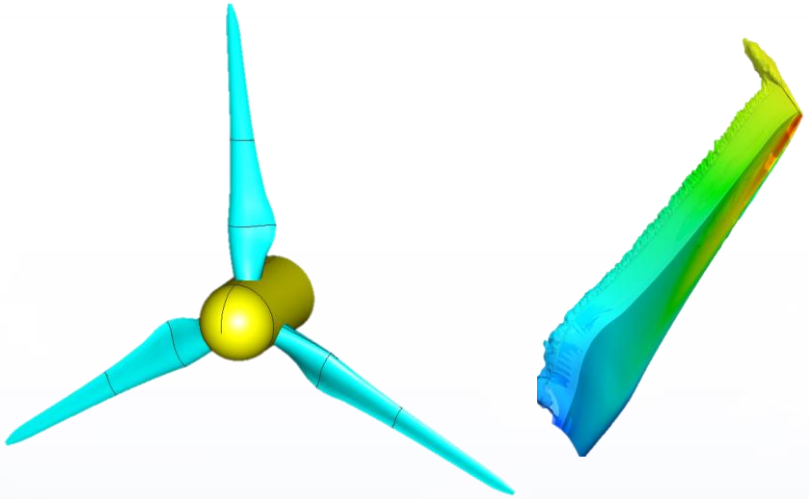
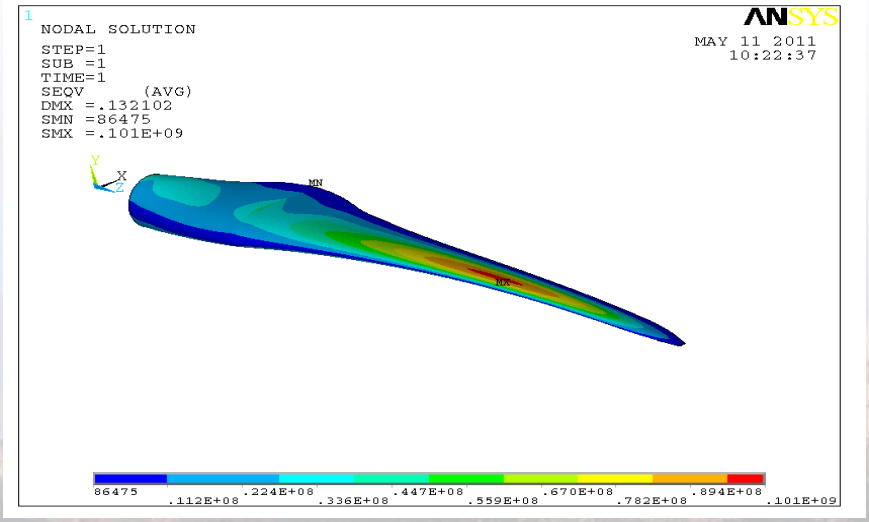
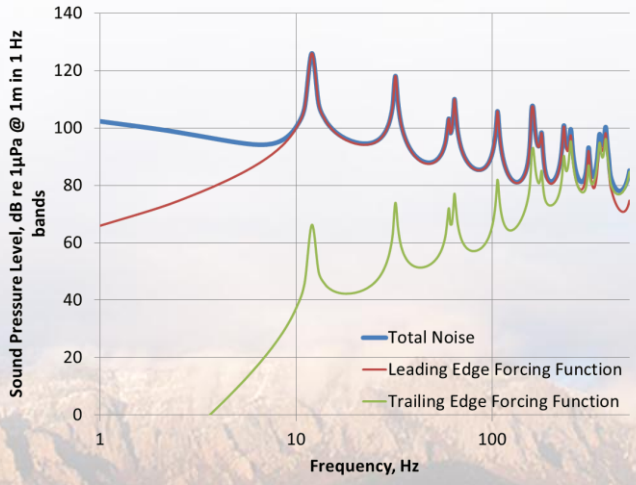
Single Turbine: Modeling Acoustics



- **Objectives**
  - Develop methodology to predict acoustic signature of MHK turbines
  - Predict acoustics from a representative turbine
- **Uses**
  - Inform acoustic dose/response studies
  - Design quieter blades





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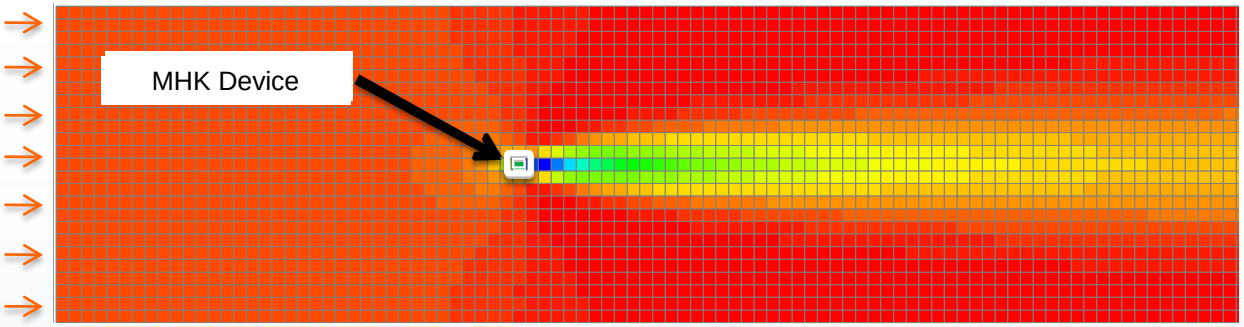
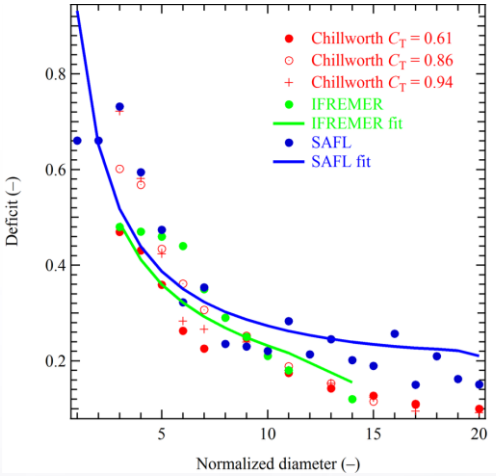
SNL-EFDC Development and Validation

- **EFDC = Environmental Fluid Dynamics code, originally developed by EPA as an open-source environmental modeling tool applicable to rivers, lakes, estuaries, and ocean.**
- **SNL-EFDC enhanced to account for the presence of MHK-turbines (MHK Friendly)**
- **Validated against flume data. Field data collection in March.**



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



K-ε modifications

Empirical constants

$$S_K = \frac{1}{2} C_T A_{MHK} \left(\beta_p U^3 - \beta_d U K \right)$$

$$S_\varepsilon = C_{\varepsilon 4} \frac{\varepsilon}{K} S_K$$

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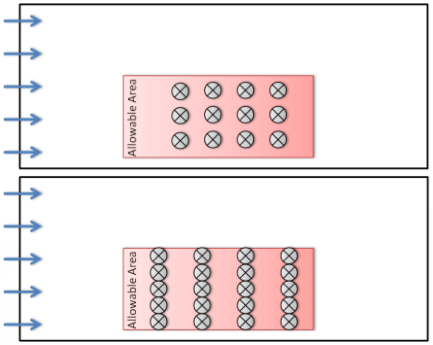
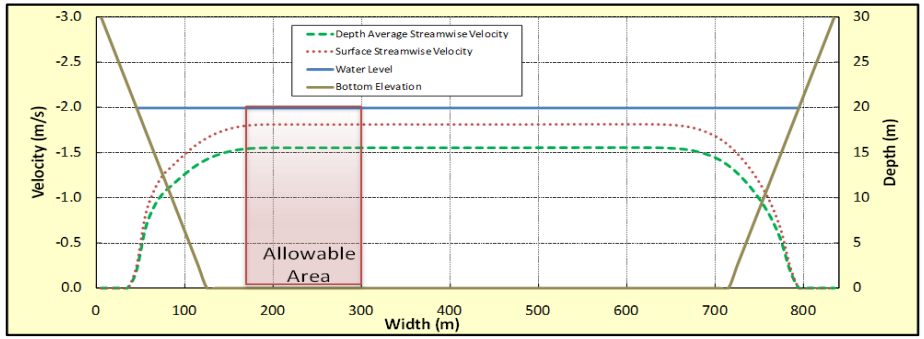
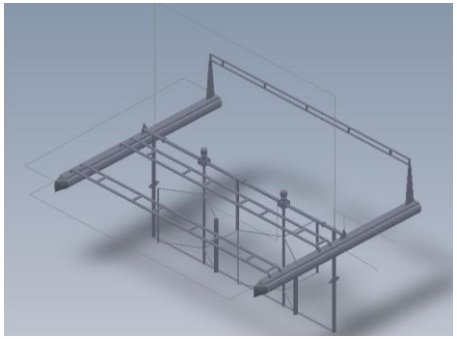
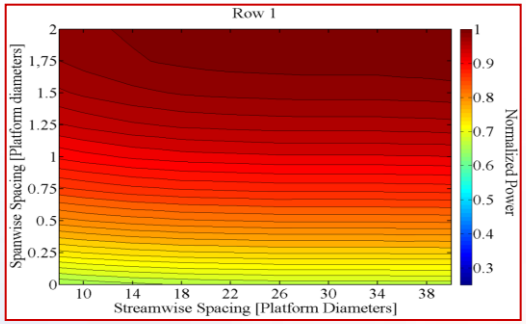
SNL-EFDC for Array Performance

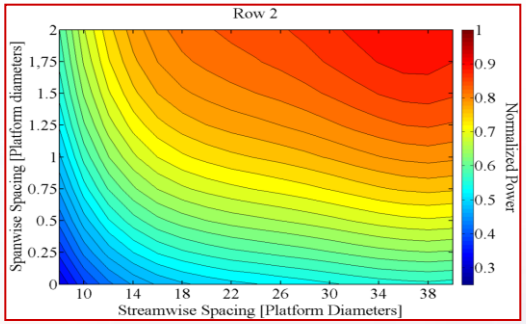
- SNL-EFDC array performance in a large river: maximizing energy per turbine & array
- Energy conversion efficiency strongly dependent on device spacing

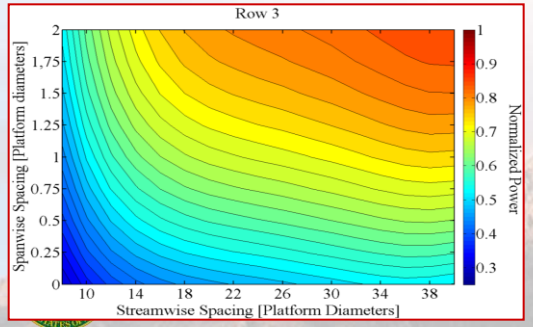


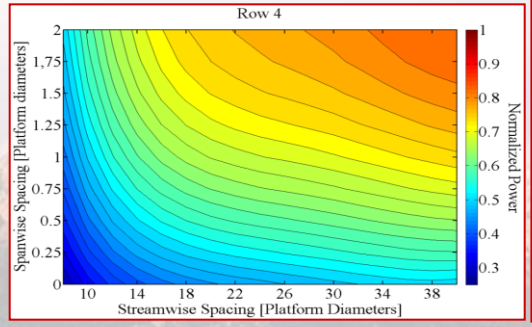












0 Spanwise Spacing = 12 Platforms/row

- 27% more power/row than 1D spanwise spacing (**BUT** deployed **2X** more turbines)
- 44% more power/row than 2D spanwise spacing (**BUT** deployed **3X** more turbines)

1D Spanwise Spacing = 6 Platforms/row

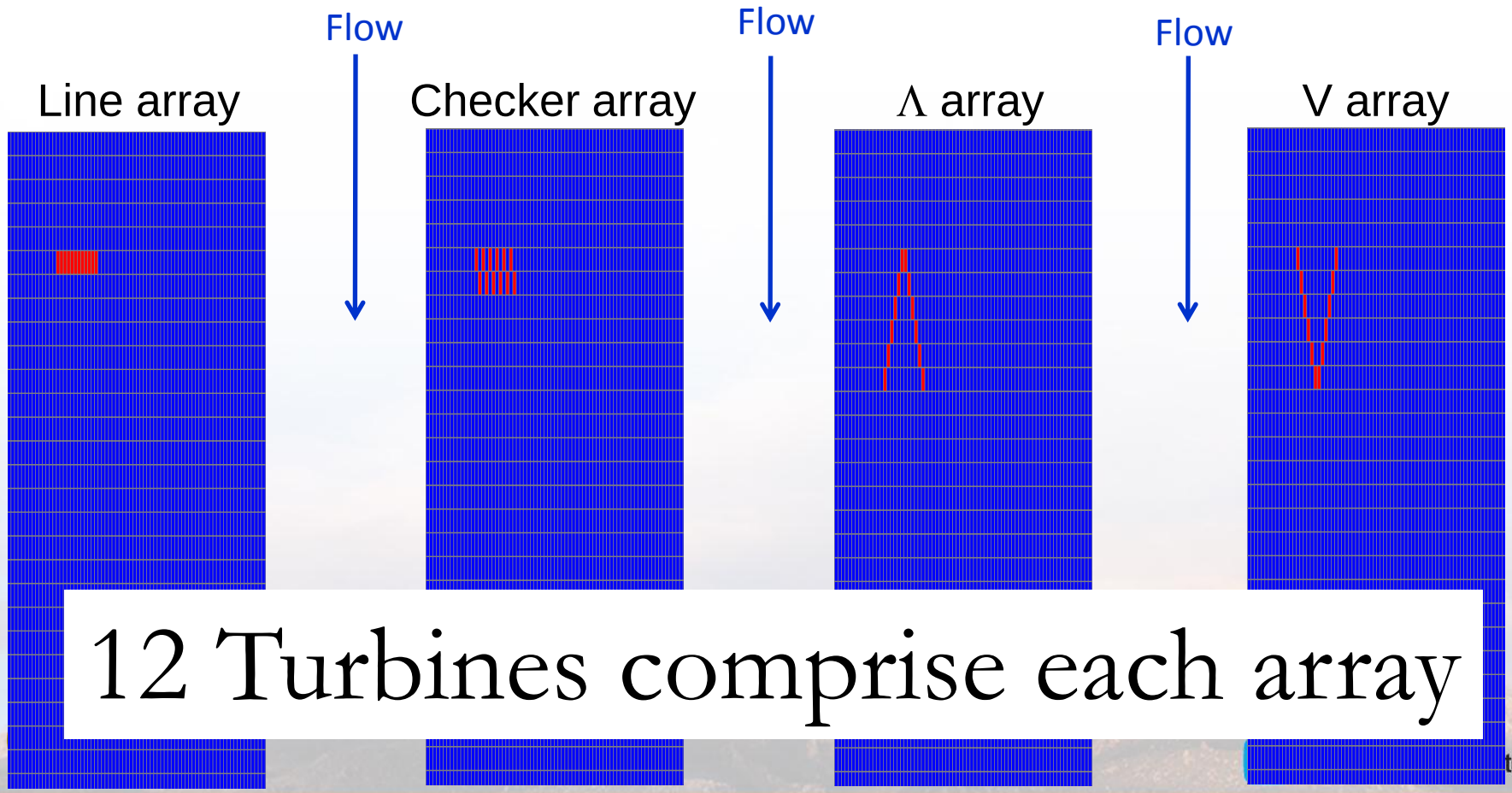
- 23% more power/row than 2D spanwise spacing (BUT deployed **1.5X** more turbines)
- 31% more 'platform average power' per row than 0D spanwise spacing

2D Spanwise Spacing = 4 Platforms/row

- 40% more 'platform average power' per row than 0D spanwise spacing
- 13% more 'platform average power' per row than 1D spanwise spacing

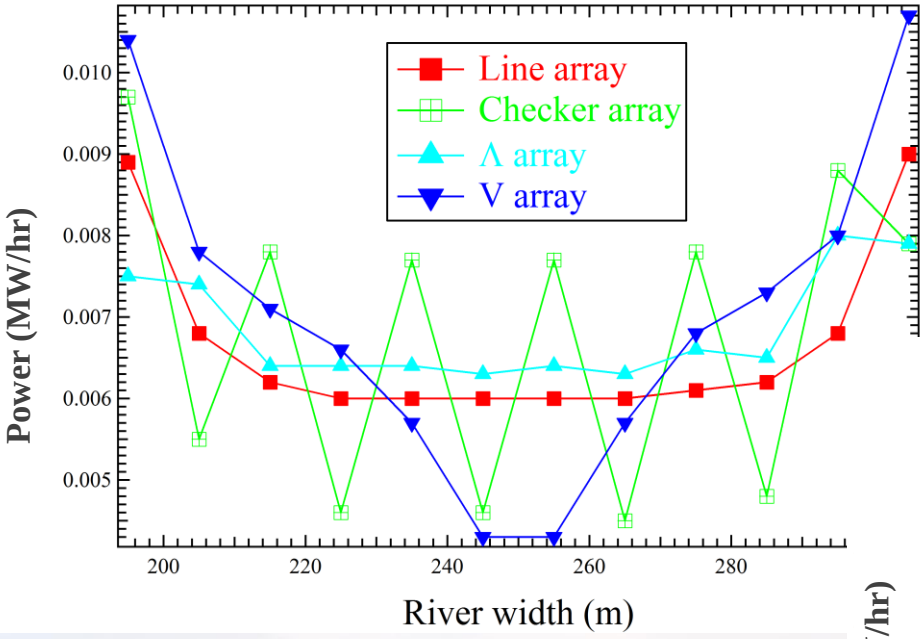
Alternate Turbine Array Configurations

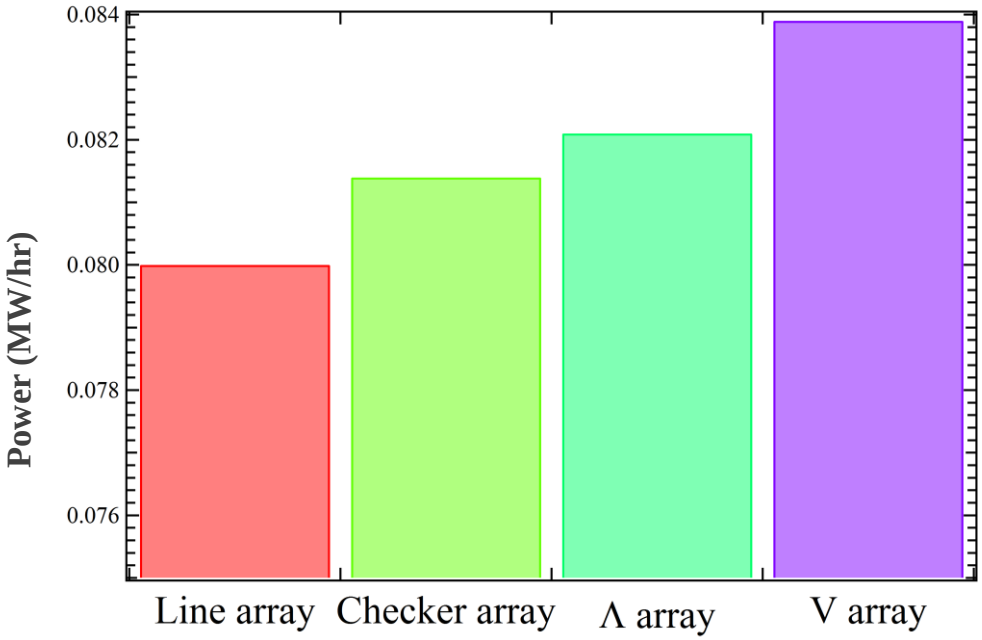
- **Optimizing for maximum energy conversion: Comparing different array configurations**



Turbine Array Comparisons

- **Optimizing for maximum energy conversion: Comparing different array configurations**





Simulation Tool Development: WECs & WEC Arrays

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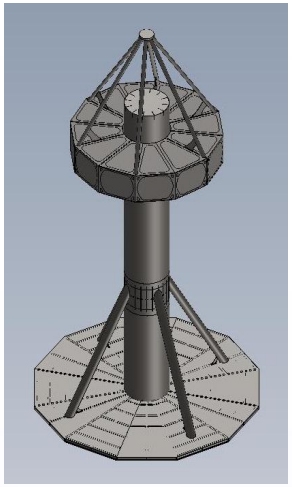
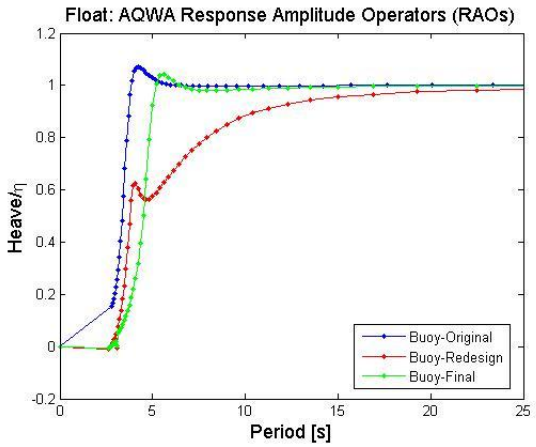
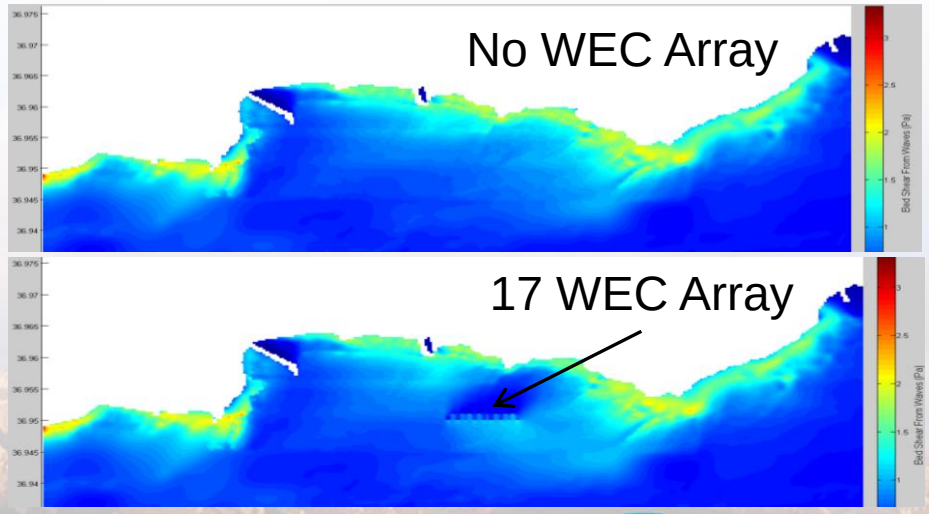
Wave Device Modeling

- **Single Device**
  - Integrate Fluid-Structure interactions with performance modeling including PTO





- **Device Arrays**
  - Represent devices as reflection and/or transmission sink
  - Integrated into SWAN/SNL-EFDC



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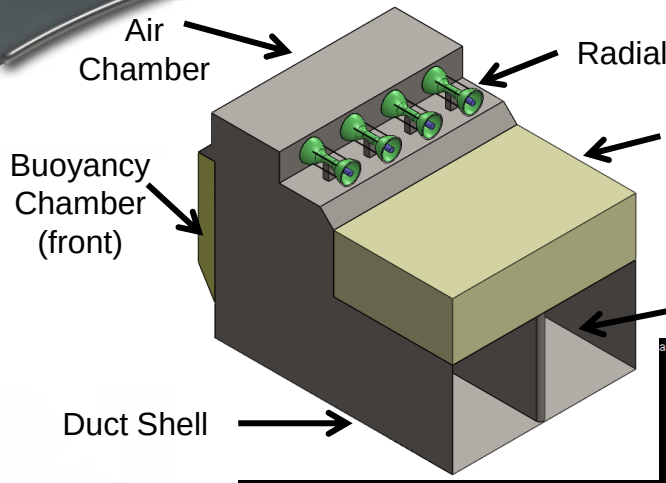
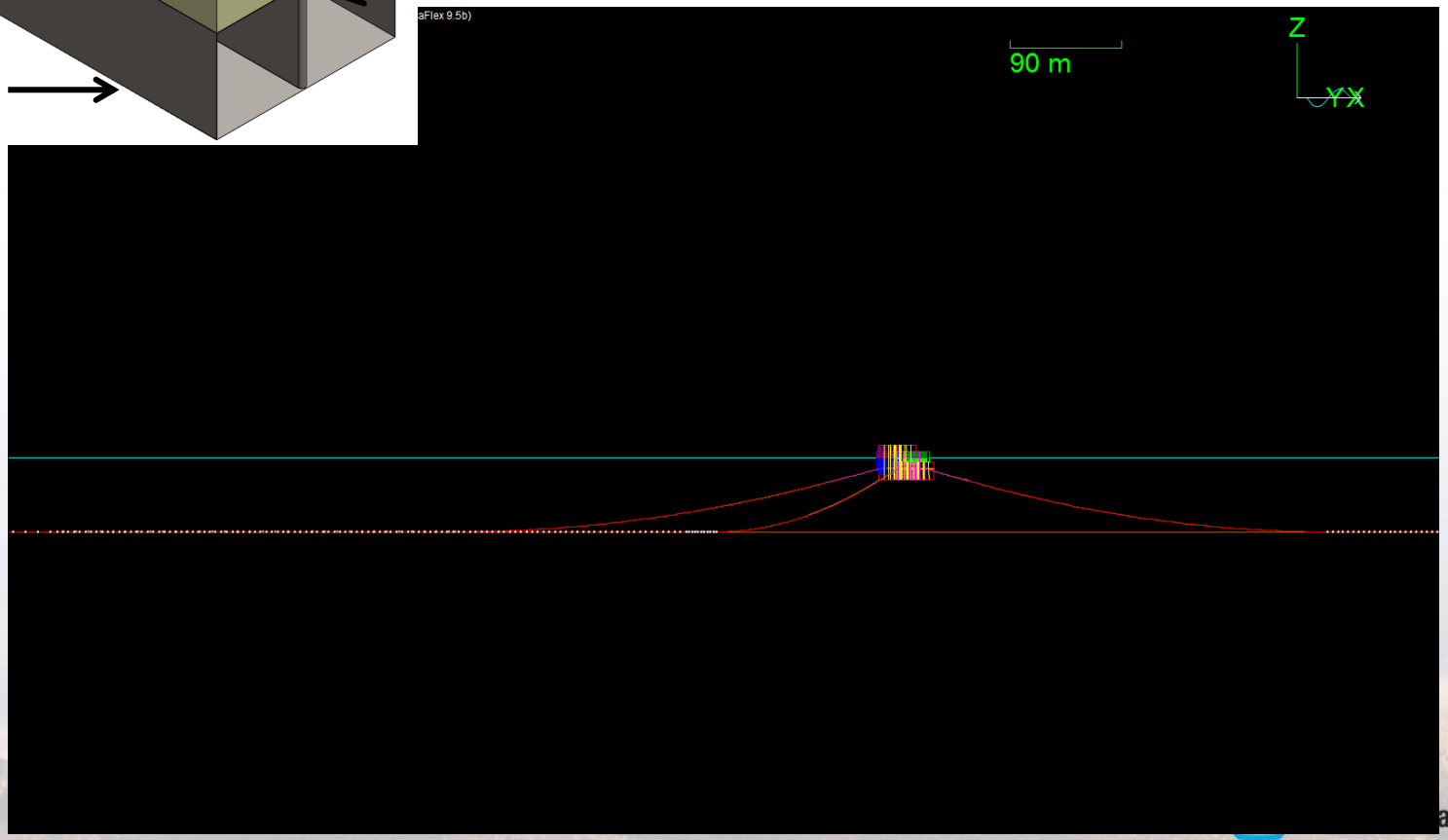
Mooring and Device Modeling





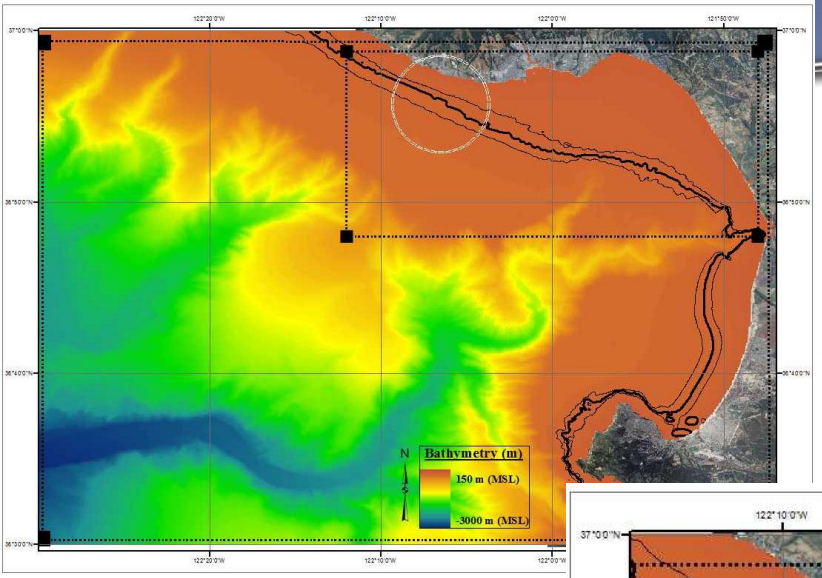
WEC Modeling for Large Scale Hydrodynamics

- **Implementation of WECs within wave model (SWAN), WECs represented as:**
  - discrete obstacles with constant transmission/reflection coefficients (simplest and currently employed technique)
  - 'Dam' obstacles where T/R are a function of incident waves and 'dam' height
  - Frequency filtering obstruction where energy absorption varies across the wave frequency spectrum (i.e. maximum absorption at 7-10s wave periods)

- **Wave Modeling Sensitivity Study in Montery Bay, CA**
  - Expanded on previously validated wave model of Monterey Bay
  - Varied WEC coefficients and incident wave conditions (117 combinations)
  - Varied spacing of 10 WEC array (2.5X, 5X, 10X)
  - Monitored wave height, period, and direction at 15 output locations around and landward of array

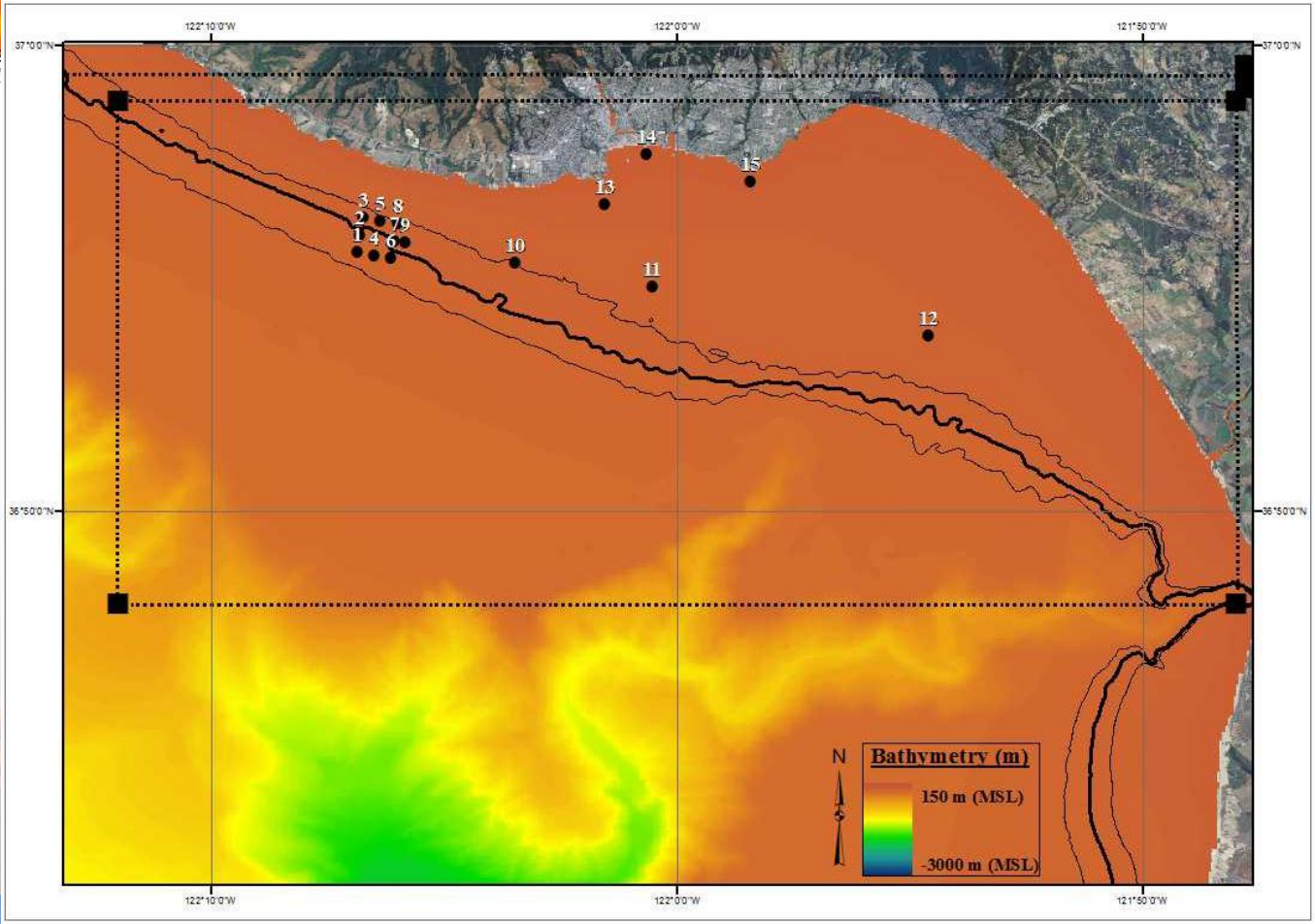
Coefficient	Value(s)
Transmission	[0.00, 0.25, 0.50, 0.75, 1.00]
Reflection	[0.00, 0.25, 0.50]
Frequency Spreading (gamma)	[1.0, 3.3, 10.0]
Directional Spreading (m)	[2.0, 10.0, 25.0]

Monterey Bay Wave Model with WECs and Output Locations

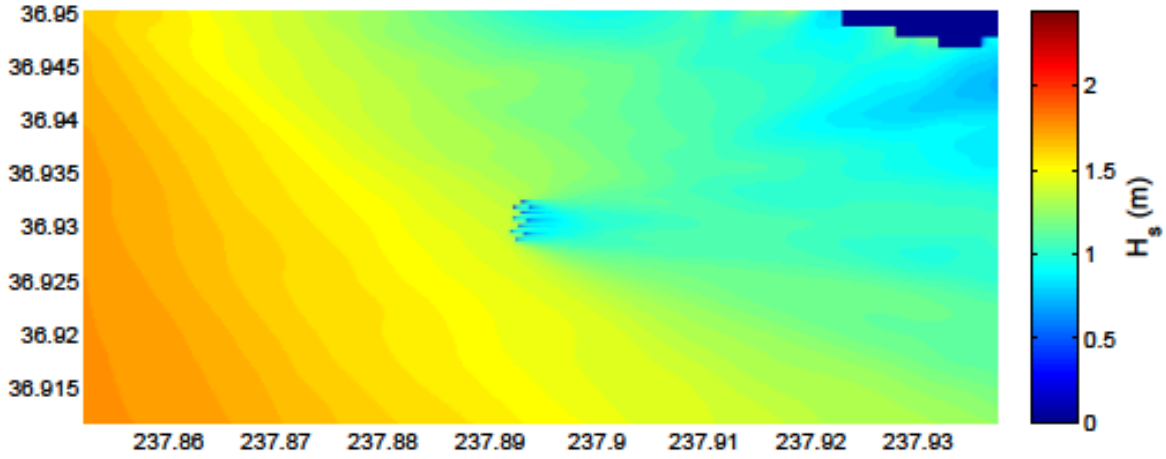


Results

- Trans. coef. Is most sensitive parameter largely effecting Hs
- Largest effects landward of array (but not always in-line)
- Lower FSC enables wave direction changes to penetrate further
- Tp most affected by DSC
- Wave direction most affected by DSC

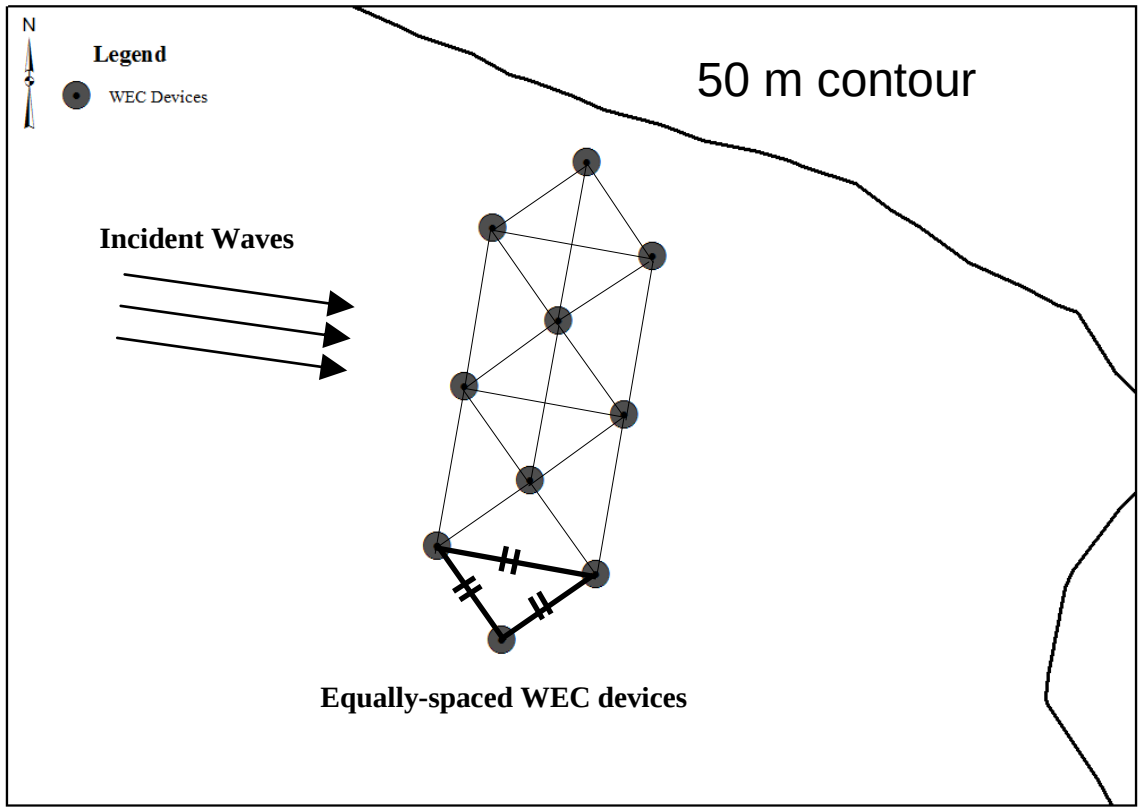


WEC Spacing



2.5X, 5X, 10X

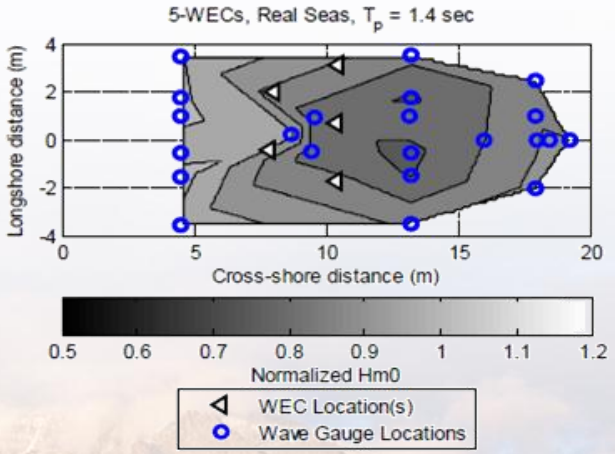
- **Effects of Array spacing**
  - More densely packed arrays have larger effects near the array
  - Less densely packed arrays have larger effects further away from array



WEC Array Data for Model Development and Validation

- In collaboration with OSU and Columbia Power, the first and only test data for WEC arrays has been generated

- In collaboration with OSU, SNL will perform WEC modeling sensitivity study within OSU Tsunami Wave Basin to gain insight into effectiveness of WEC representation techniques and ultimately for model validation



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Materials and Coatings

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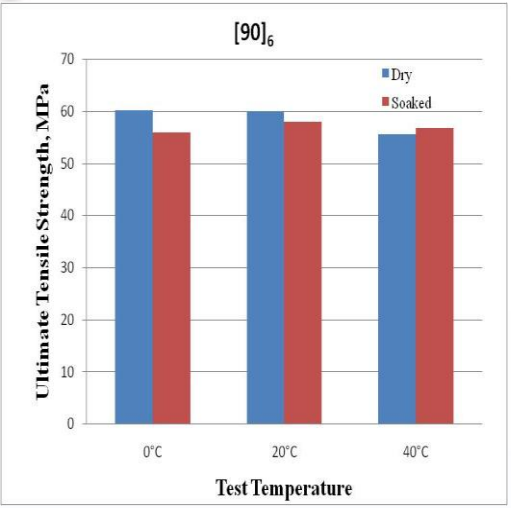
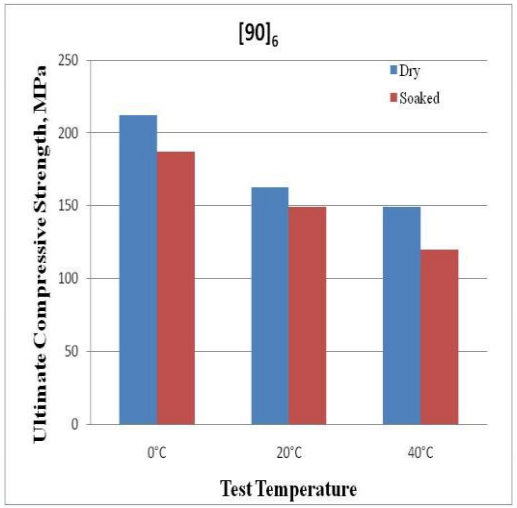
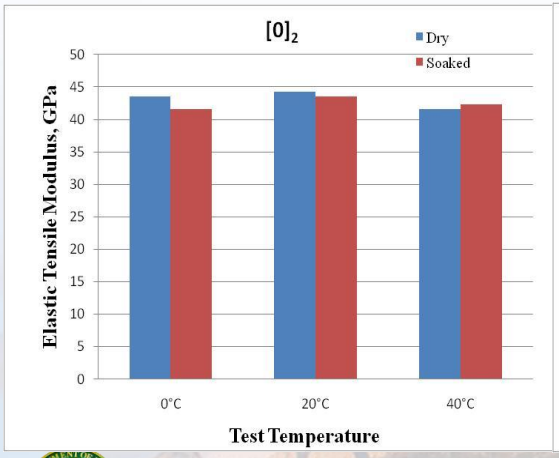
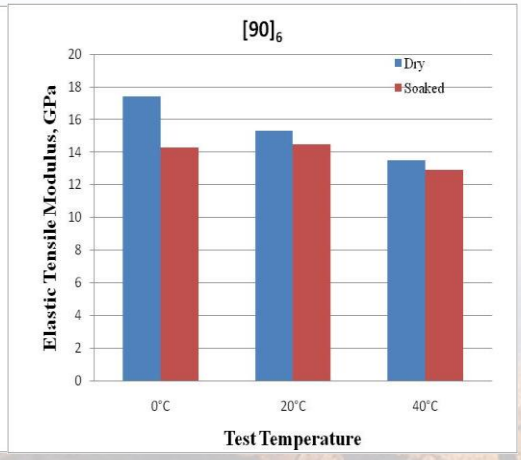
Materials: Marine Composites Database

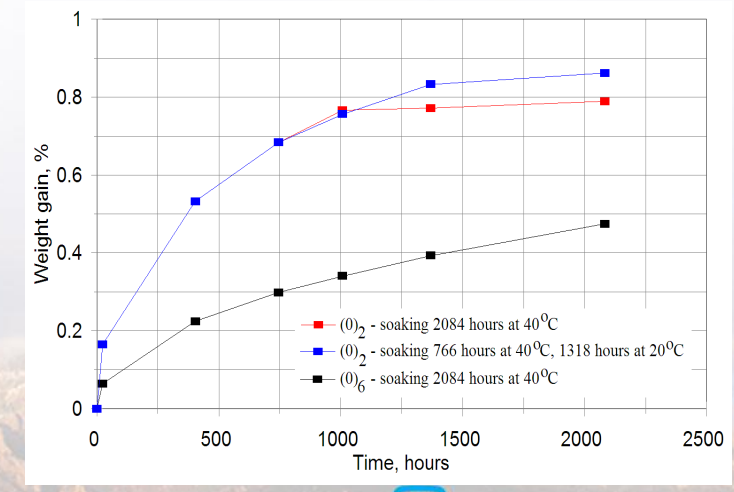




- Montana State University
- Moisture Absorption
- Mechanical Testing on salt water immersed composites
- Fabrication







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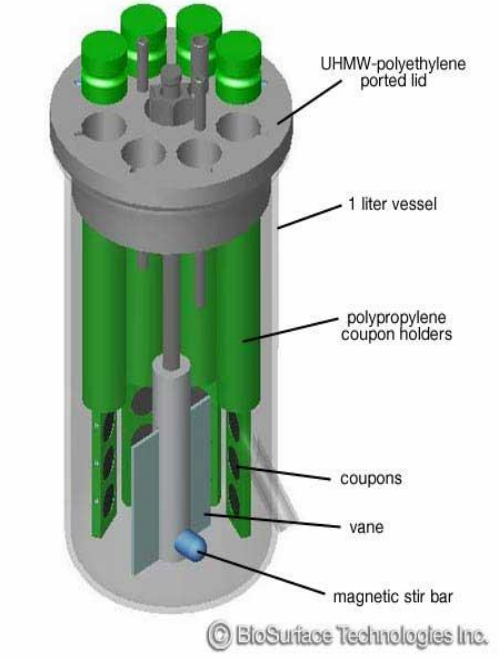
Marine Coatings: Development and Evaluation

- SNL coatings development
- Biofilm baseline measurements on commercial materials & coatings

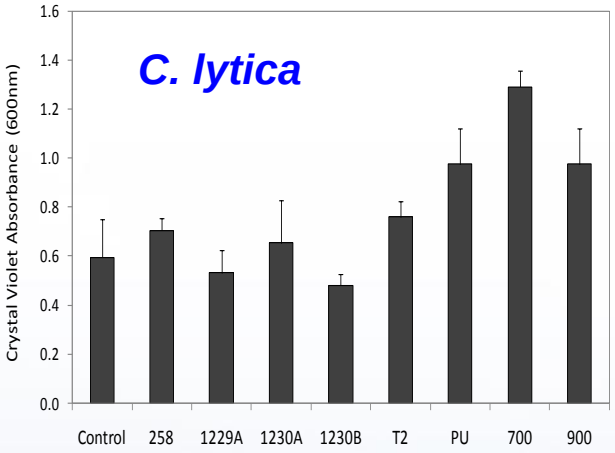


Test ID	Coating Source	Material	Significantly less fouling than control?	Fouling reduction (log CFU/cm^2)	Fouling Reduction (%)
EP2000	ePaint	SS	No	---	---
EP2000	ePaint	Al	No[1]	---	---
EP2000	ePaint	PVC	No	---	---
SN-1	ePaint	HDPE	No[2]	---[3]	---
SN-1	ePaint	SS	No[2]	---[3]	---
SN-1	ePaint	HR	No[2]	---[3]	---
SN-1	ePaint	PVC	No[2]	---[3]	---
SN-1	ePaint	Al	No[2]	---[3]	---
INT-757	Intersleek	PC	Yes	0.67	79
INT-757	Intersleek	SS	Yes	0.81	85
INT-757	Intersleek	HDPE	No	---	---
INT-757	Intersleek	HR	No	---	---
INT-757	Intersleek	PVC	No	---	---
INT-757	Intersleek	Al	No	---	---
INT-970	Intersleek	PC	Yes	0.79	84
INT-970	Intersleek	SS	Yes	0.39	60
INT-970	Intersleek	HDPE	Yes	0.55	72
INT-970	Intersleek	HR	No	---	---
INT-970	Intersleek	PVC	Yes	0.55	72
INT-970	Intersleek	Al	Yes	0.75	82
KNC 821B	S. Dirk	SS	No	---	---
KNC 821E	S. Dirk	SS	No	---	---
KNC 821F	S. Dirk	Al	No	---	---
KNC 821D	S. Dirk	Al	No	---	---
N/A	M. Hibbs	SS	No	---	---
N/A	M. Hibbs	HDPE	No	---	---
7-67-C	M. Hibbs	PVC	No	---	---
7-73-C	M. Hibbs	PVC	No	---	---
7-73-B	M. Hibbs	PVC	Yes	0.37	57
7-74-N	M. Hibbs	SS	No	---	---
7-73-K	M. Hibbs	SS	No	---	---
7-67-D	M. Hibbs	Al	No	---	---
1228B	Corning	Composite	No	---	---
1229A	Corning	Composite	No	---	---
1230A	Corning	Composite	No	---	---
1230B	Corning	Composite	No	---	---

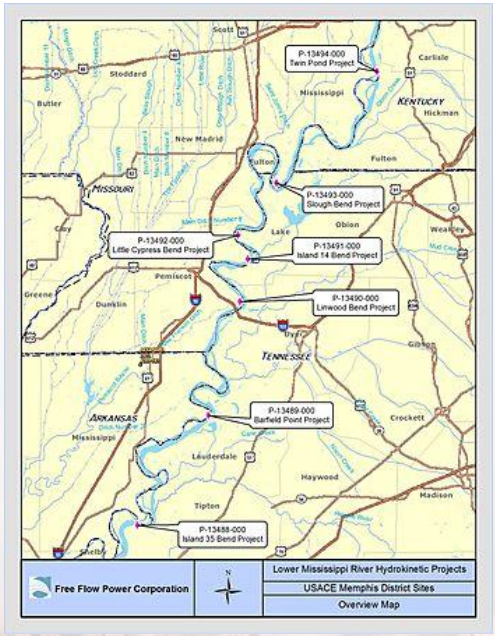
1 More growth on coated coupon, assumed to be because the coating shielded the cells from the antimicrobial properties of Al.
2 Active ingredient thought to have leached into the reactor solution, thus impacting biofilm growth on controls as well.
3 Approximately 2.8 log CFU cm^{-2} more than EP2000 samples.

Coatings & Materials: Industrial Support

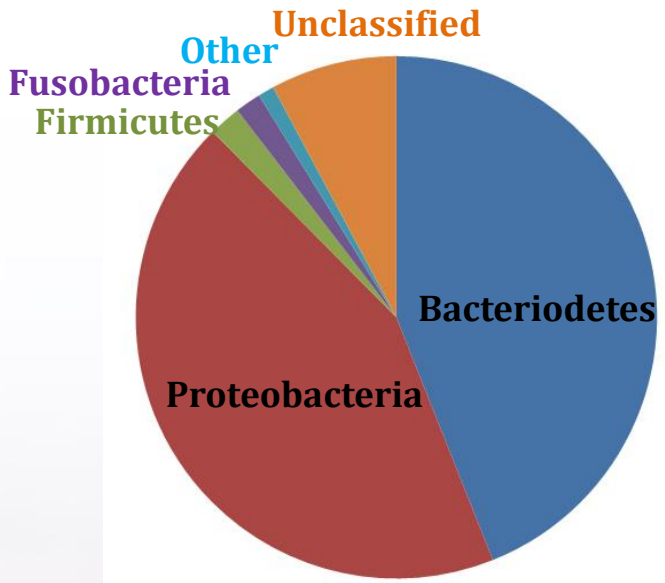
Biofilm Testing of
Owens-Corning Composites



Biofilm Characterization & Composite Testing on
Free Flow Power
Devices Deployed in Mississippi



Biofilm Characterization on
Verdant Power Systems
Deployed in East River



Sandia National Laboratories

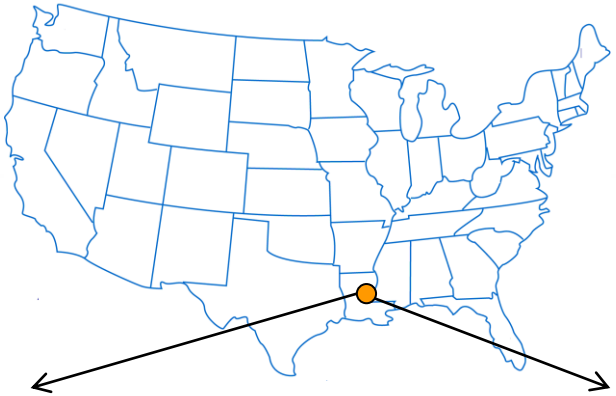
2.1 Market Acceleration Environmental Assessment

Goal

Remove market barriers (for more efficient permitting) by enabling prediction of site-specific environmental responses to user-defined array designs in a technically defensible way

Full-Scale Field Campaign

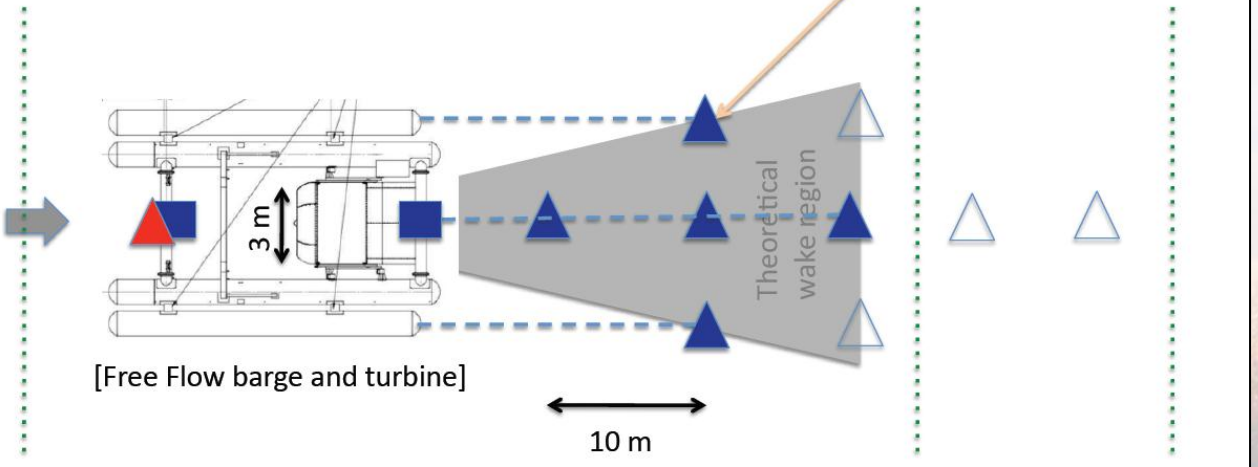
- **Field measurements around FFP full-scale turbine scheduled for last week in March.**
  - Collaboration between SNL, UW, ORNL, and NREL
  - Measurements to include flow, acoustics, suspended sediment, bottom/bank sediment, EMF, power quality, benthos, etc..
  - Data will be public; first of it's kind for MHK-turbine



Proposed sampling plan for Free Flow turbine

- 4 UW Aquadopp profilers (2 MHz) on surface "dopp-cats" with adjustable tethers trailing from barge (blue triangles)
- 2 UW Aquadopp Profilers (2 MHz) mounted to barge hull (blue squares)
- Reference to small-scale measurements: ORNL ADVs upstream (red triangle)
- Reference to large-scale river survey: Sea Engineering vessel-mounted ADCP (green lines)

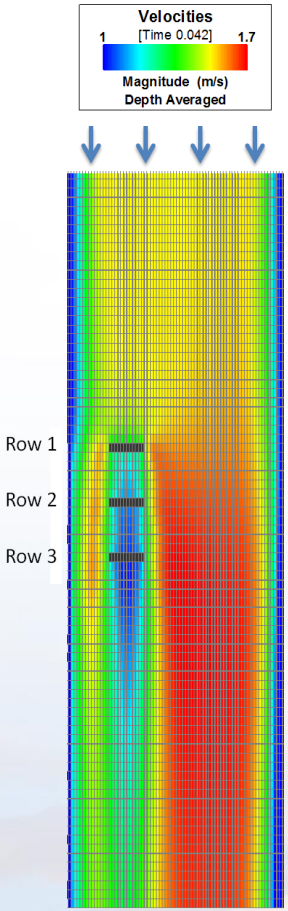
(dopp-cat)

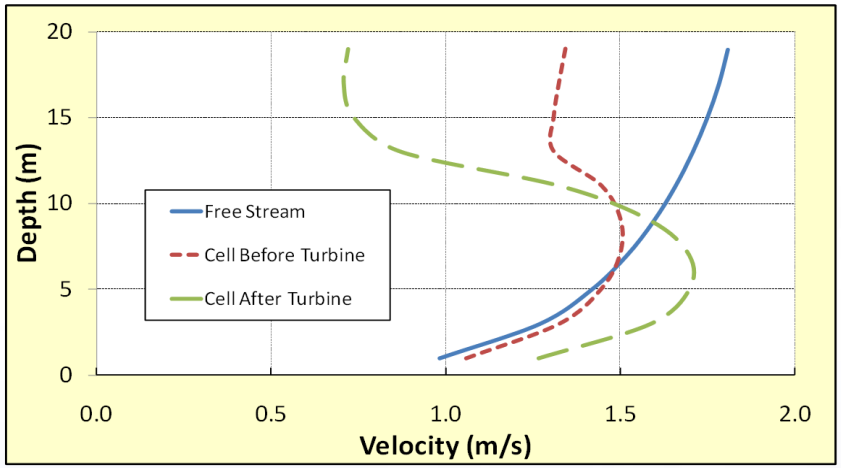


[Free Flow barge and turbine]

Evaluating Environmental Effects

- **SNL-EFDC quantifies effects of altered flow around array**





For this array design, the river velocity increases to either side of and below the array. This altered velocity regime impact both wildlife and shipping traffic. A known effect of the velocity change is its increase on bed and bank shear stress, which could negatively impact sediment transport by increasing risk of bank erosion and inducing modification to the benthic habitat.

$$V_{mhk\ bank} = 1.5 * V_{o\ bank}$$
$$V_{mhk\ bed} = 1.3 * V_{o\ bed}$$

$$\tau \sim V^2$$

$$\tau_{mhk\ bank} \sim \mathbf{2.25} * \tau_{o\ bank}$$
$$\tau_{mhk\ bed} \sim \mathbf{1.7} * \tau_{o\ bed}$$

$$ER \sim \tau^2$$
$$ER \sim V^4$$

$$ER_{mhk\ bank} \sim \mathbf{5} * ER_{o\ bank}$$

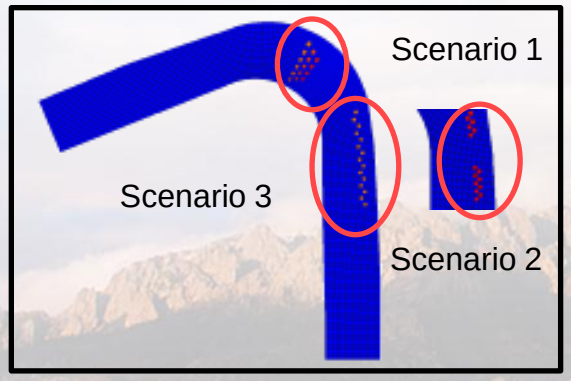
$$ER_{mhk\ bed} \sim \mathbf{3} * ER_{o\ bed}$$

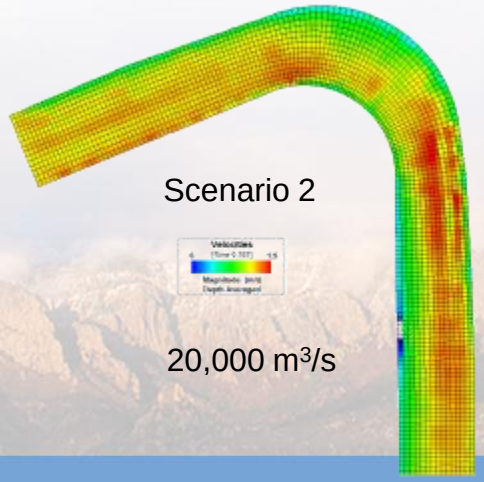
Model can inform Environmental Sampling Plans

Sandia National Laboratories

Environmental Studies: Mississippi River

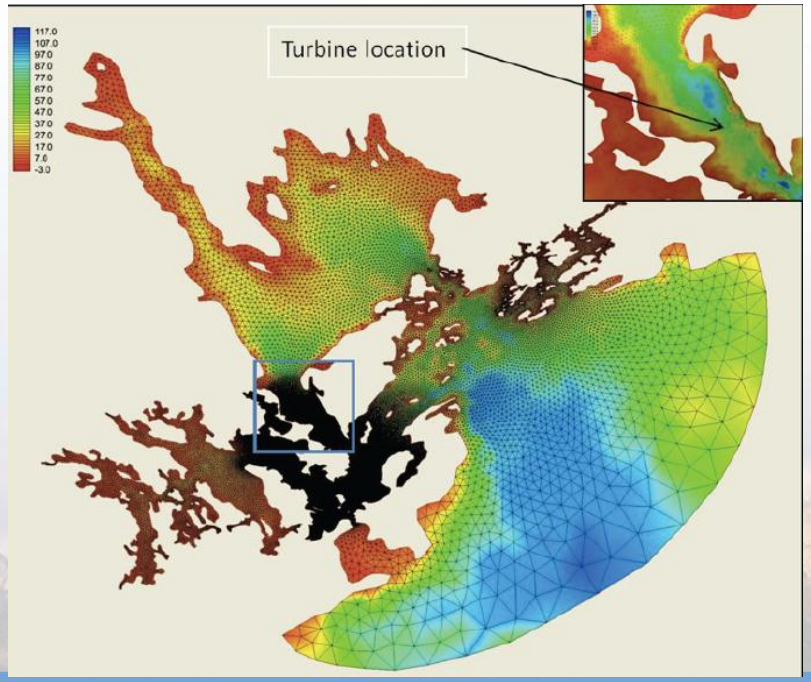
- **Project Objectives**
  - Investigate the potential for alterations to river height due to emplacement of an array of turbines in relation to increased **risk of flooding**
  - Determine changes in **bottom and bank sediment stability** caused by alterations to river flow through and around various arrays of turbines
- **Status**
  - Developed model of Scotlandville Bend (near Baton Rouge, LA) and working with **FFP** on implementing realistic array scenarios
  - Added functionality to SNL-EFDC to allow placement of turbines based on a reference plane in the water (previously turbines were placed relative to the local bed elevation)
  - Planned additional environmental measurements to support modeling objectives, to be coordinated with field campaign around FFP turbine in late March.

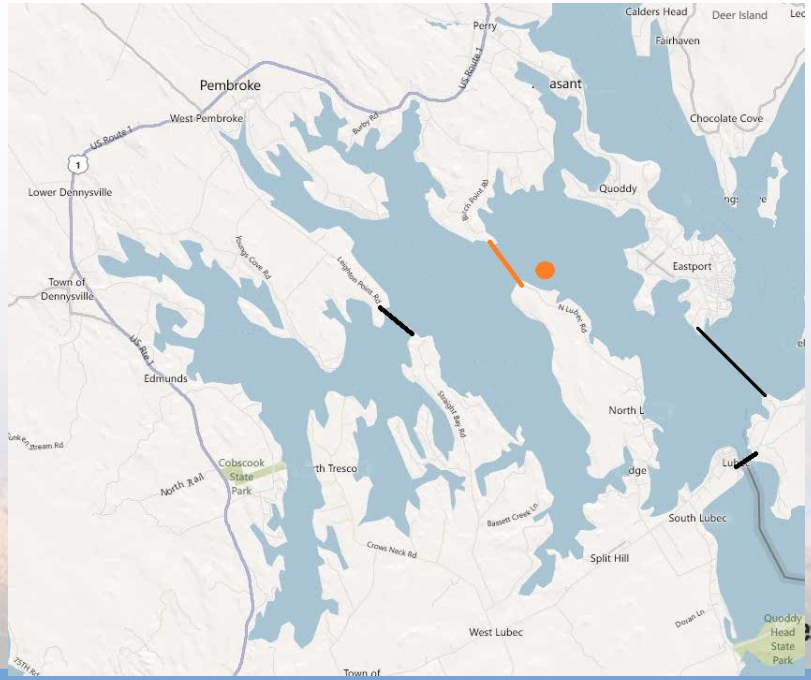




Environmental Studies: Cobscook Bay

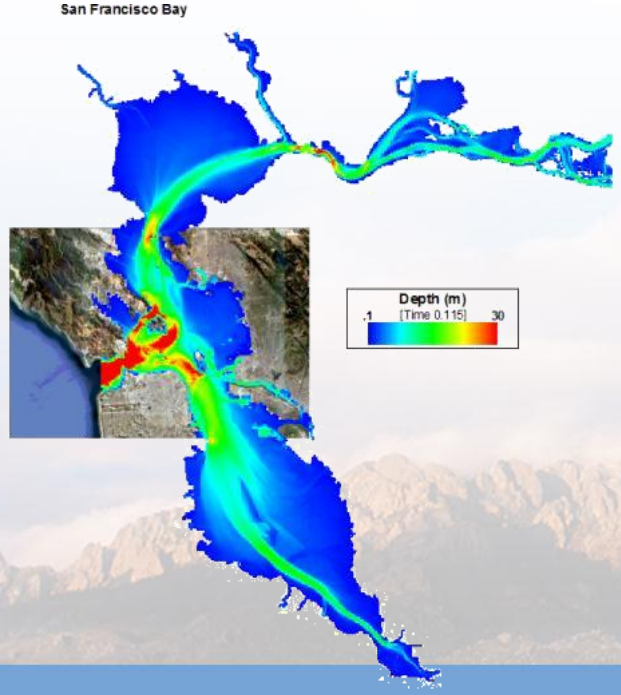
- **Project Objectives**
  - Investigate the potential for altering the natural dispersion/migration of baby scallops
- **Status**
  - Collaborating with **ORPC** and **U. Maine** professor, Dr. Huijie Xue, on model development
    - Dr. Xue has a large domain model that focuses on the Western Passage
  - Developed a **boundary extraction tool** that can extract water/land boundaries (including islands) from an image via a 'flood filled method'.

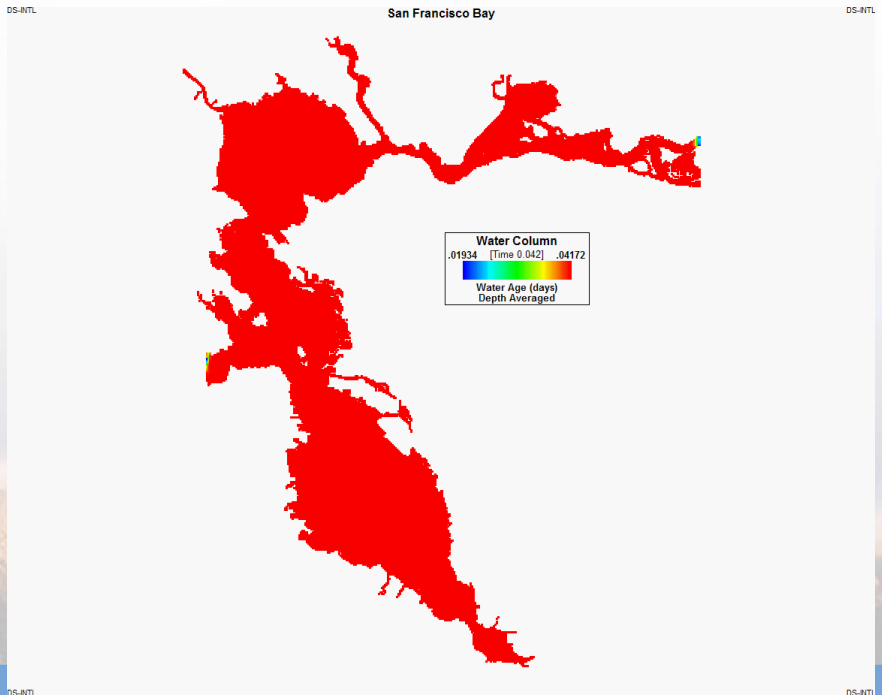




Environmental Studies: San Francisco Bay

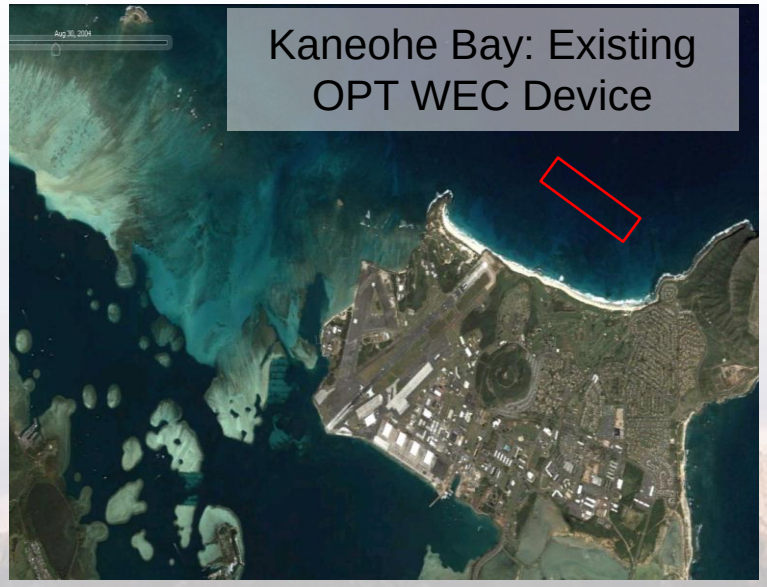
- **Project Objectives**
  - Investigate the relationship between the **amount of energy converted** in the tidal throat (under and behind the Golden Gate Bridge) to the **residence time/water age** within the Bay
- **Status**
  - Base model has been developed and run with and without MHK
    - 28 day simulation of spring/neap tidal cycle, requires 6 days computation time
    - Initial results show that effects of 60, 10-m MHK-turbines (producing ~**3,000 MW·hr** of energy) has **negligible affect on flushing**





Environmental Studies: Kaneohe Bay

- **Project Objectives**
  - Assess potential changes to wave, current, and sediment transport patterns from WEC installations
- **Status**
  - Collaborating with **Navy** and **University of Hawaii**, supporting Navy Environmental Assessment
  - Collecting baseline data for model parameterization
    - Wave spectra, bathymetry, sediments, etc…



SNL-EFDC Technology Transfer and Outreach Plan

- **Status**
  - Provided user training courses to **Free Flow Power** team and members of **FERC**, **BOEM**, **DOE** and **Navy-SPA-WAR** – received very **Positive Feed Back**
  - **Verdant** and **ORPC** received Self-guided training material with follow on training later this year
  - Technology transfer is broken into two categories:
    1. Those intending to run the software for site specific studies (mostly developers and their partners/consultants, but may include regulators)
    2. Those who need a working knowledge of the software's capabilities (mostly regulators)
- **Products/Opportunities**
  - **SNL-EFDC Users Training Course:** A 2-3 day class intended for those who intend to run the software. Limited to 10 or less trainees for focused 1-on-1 and site specific training.
  - **SNL-EFDC Self-guided Users training course:** Provided in advance of full course to maximize class time efficiency, or as stand alone for those who don't qualify for individual training.
  - **SNL-EFDC Capabilities Workshop:** A 1 day course intended to introduce students to software functionality in support of technical and regulatory reviews.
  - **SNL-EFDC Self-guided Capabilities Workshop:** Provided to those unable to attend workshop.
  - **Student Internships:** Students with an interest in MHK can apply for an SNL internship and be trained on the tool to support SNL projects. Then transfer their knowledge to others directly.

CONVENTIONAL HYDROPOWER

Goal

Develop an integrated tool set for optimizing the operational efficiency and environmental performance of hydroelectric power plants

Sandia National Laboratories

CONVENTIONAL HYDROPOWER

Water Use Optimization:
Development and Demonstration of Advanced Forecasting, Power and Environmental Planning and Management Tools and Best Practices

Multi-National Laboratory project team:

DOE Award (August, 2009)

Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

Pacific Northwest NATIONAL LABORATORY

Sandia National Laboratories

Tom Lowry

06926 - Earth Systems Analysis

Janet Barco

06122 - Water Power Technologies

Asmeret Bier

01462 - Cognitive Modeling

Scott Griffin

06925 - Actionable Knowledge Solutions

Sandia National Laboratories

DOE's Conventional Hydropower Program and the Water Use Optimization Project

The importance of the Development and Demonstration of Advanced Hydropower Planning and Operational Decision Tools

DOE's resource assessment identified 5,677 sites in the United States with undeveloped capacity of about 30,000 MW. By comparison, today there is about 80,000 MW of hydroelectric generating plants in the United States.

http://www.water.ca.gov/swp/facilities/Oroville/index.cfm

The DOE's conventional hydropower activities

- **Increasing generating capacity and efficiency at existing hydroelectric facilities**
- Adding hydroelectric generating capacity to non-powered dams
- **Reducing environmental effects**

Link of the Water Use Optimization Project to DOE's Program Objectives

- Increase power production by optimizing operations within the myriad of constraints
- Allow for rapid evaluation of new technologies and management options
- Evaluate new development within the regulatory framework

http://www.ag.unr.edu/saito/research/Blue_Mesa.htm

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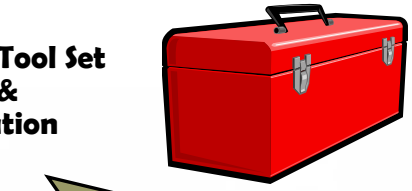
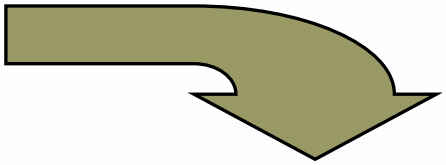
Purpose, Objectives, & Integration

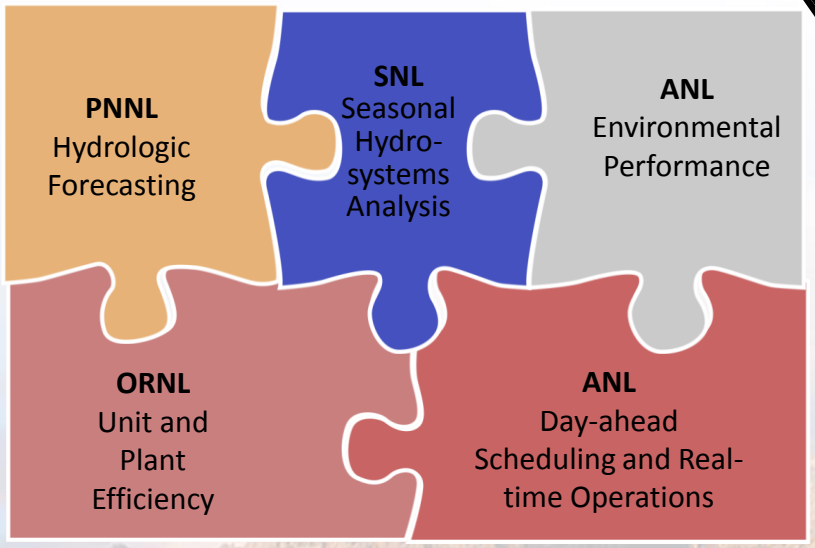
- **Purpose:** Develop and demonstrate a hydropower water use optimization tool set that links water supply, power generation and ancillary services and environmental performance for planning and operations
- **Challenge:** How to operate conventional hydropower plants in an increasingly uncertain and competitive water-constrained environment

Optimization Tool Set Testing & Demonstration





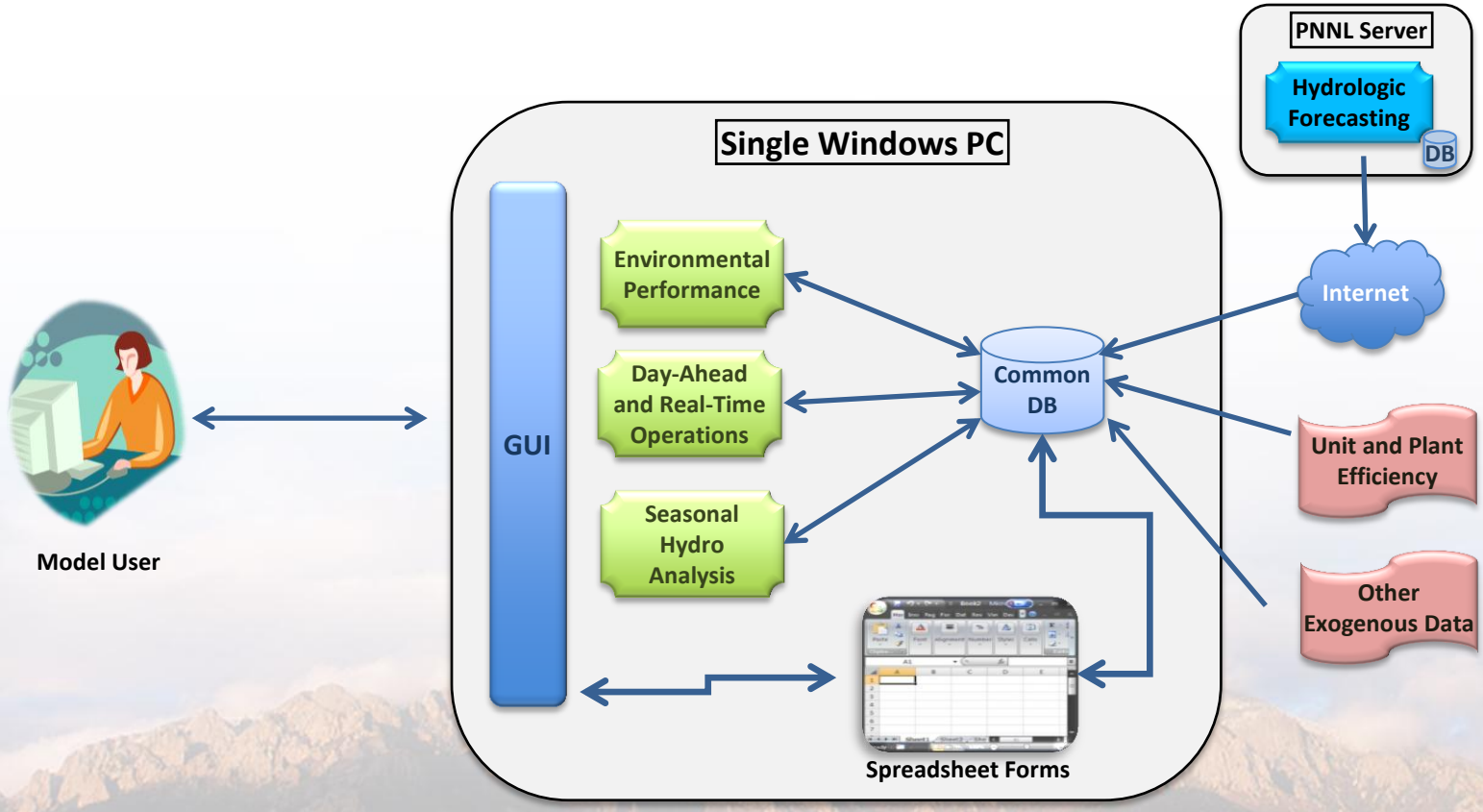
Optimization Toolbox Development



Hydropower Best Practices Identification, Assessment, Demonstration	Hydrologic Forecasting Enhancement	Asset Scheduling Enhancement	Unit and Plant Optimization
Increase Hydropower Production	✓	✓	✓
Improve Environmental Performance	✓	✓	✓
Increase Hydropower Flexibility	✓	✓	✓
Enhance Hydropower Economics	✓	✓	✓

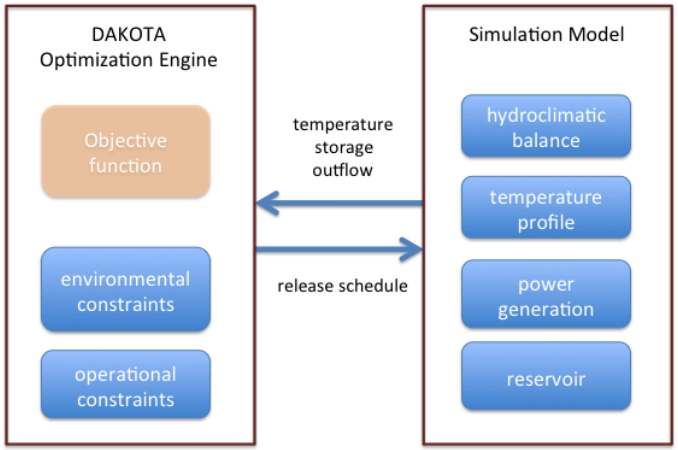
Integration with Full Project

- Argonne National Laboratory: Project coordination, Project lead for Day-Ahead and Real Time Scheduling, Environmental Performance.
- Sandia National Laboratory: Project Lead for Seasonal Hydrosystems Analysis
- Pacific Northwest National Laboratory: Project Lead for Hydrologic Forecasting
- Oak Ridge National Laboratory: Project lead for Unit and Plant Efficiency



Sandia's Seasonal Hydrosystems Analysis
***Hydro-SCOPE*:**
Hydropower Seasonal Concurrent Optimization for Power and the Environment tool

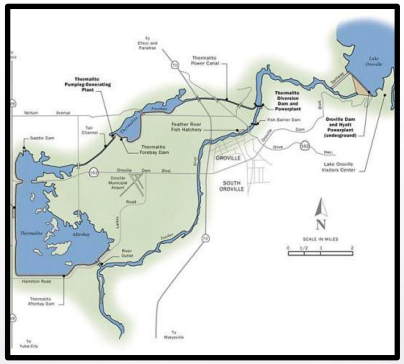
- **Simulate in reservoirs and rivers**
- **Multiple Systems**
- **Optimize to:**
  - Meet environmental standards
  - Maximize power production / revenues, recreational, etc.
  - Meet competing water needs (agriculture, flood control, etc.)



Demonstration sites

Key technical accomplishments to date include:

- **Tool Set Development**
  - Development of tool set component model frameworks and designs
  - Development of initial design for component integration software
- **Tool Set Demonstration**



Future CH research at Sandia Water Power Technologies

- **Improvement of Seasonal Model:**
  - Application to low head hydro
  - Pumped storage
- **CH transfer technology from South America**

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Thank You

Questions???

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