SAND2015-9795PE

Exceptional service in the national interest

Sandia National Laboratories

Sandia National Laboratories' Wind and Water Power Programs

Presented to the Danish Technical University's Wind Energy Department (DTU Wind)

MOU Collaborative Discussion

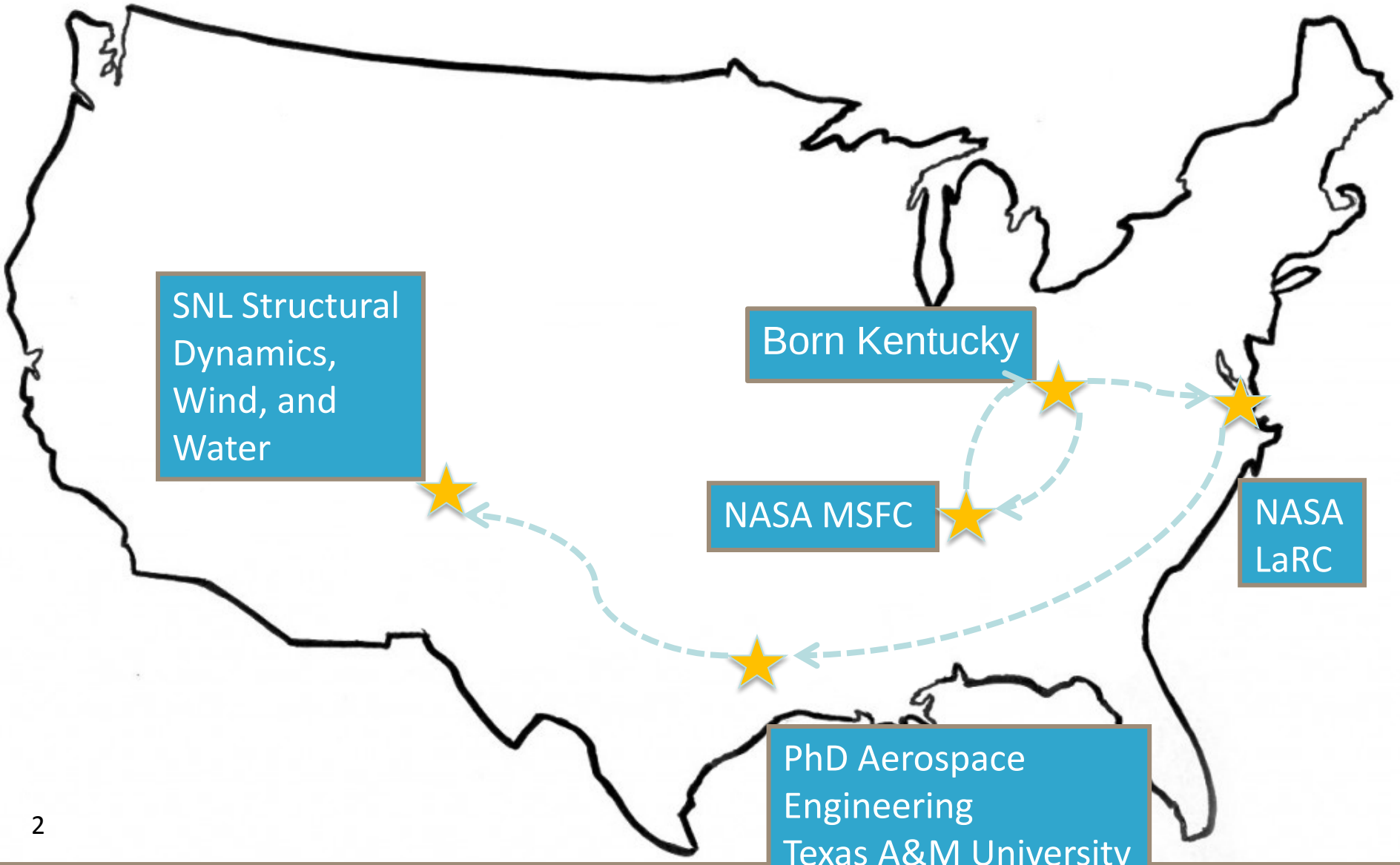
November 11, 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 20XX-XXXXP

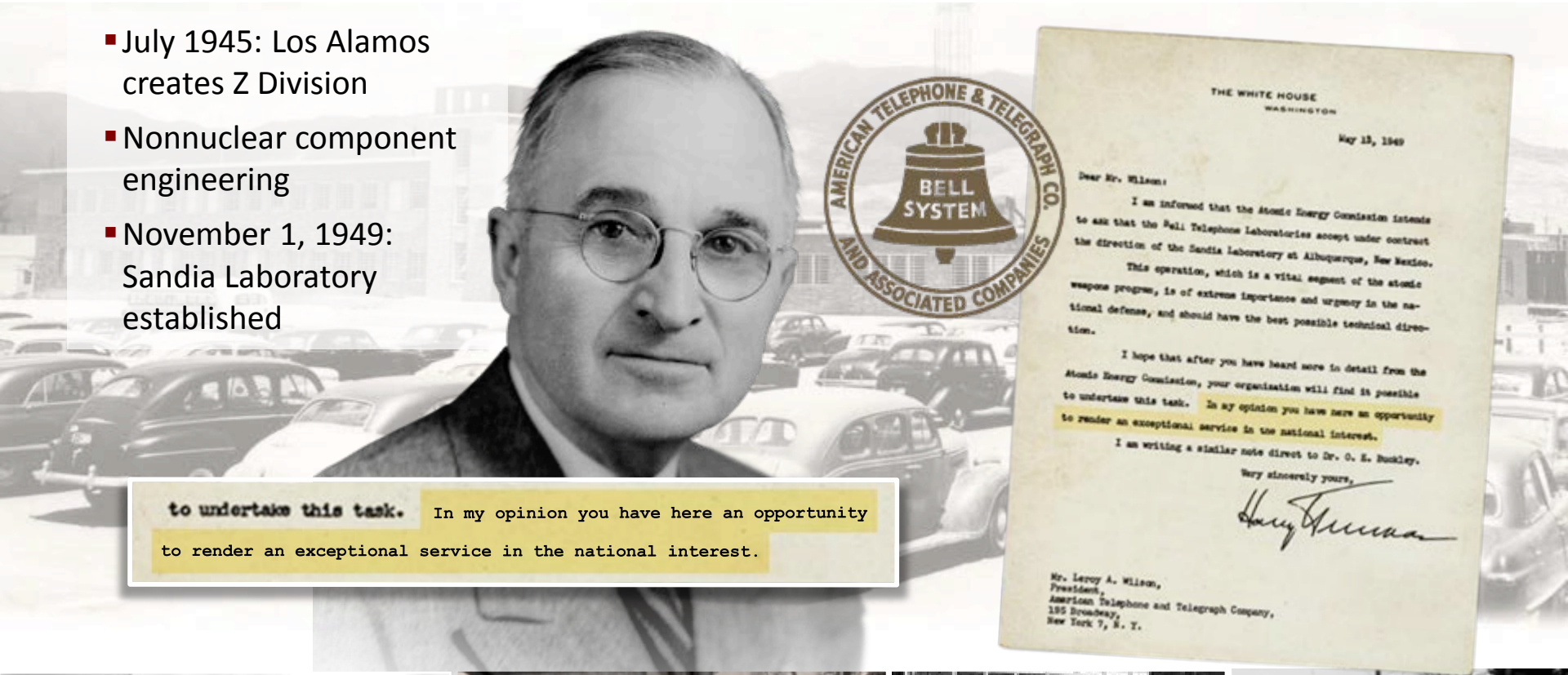
Personal Background – D. Todd Griffith (presenter)

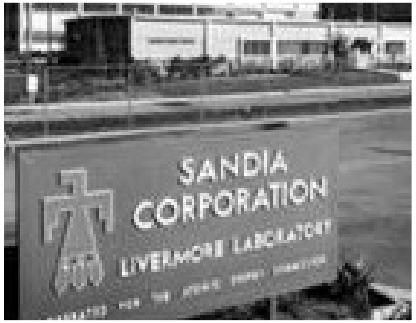


Sandia's History

Exceptional service in the national interest

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

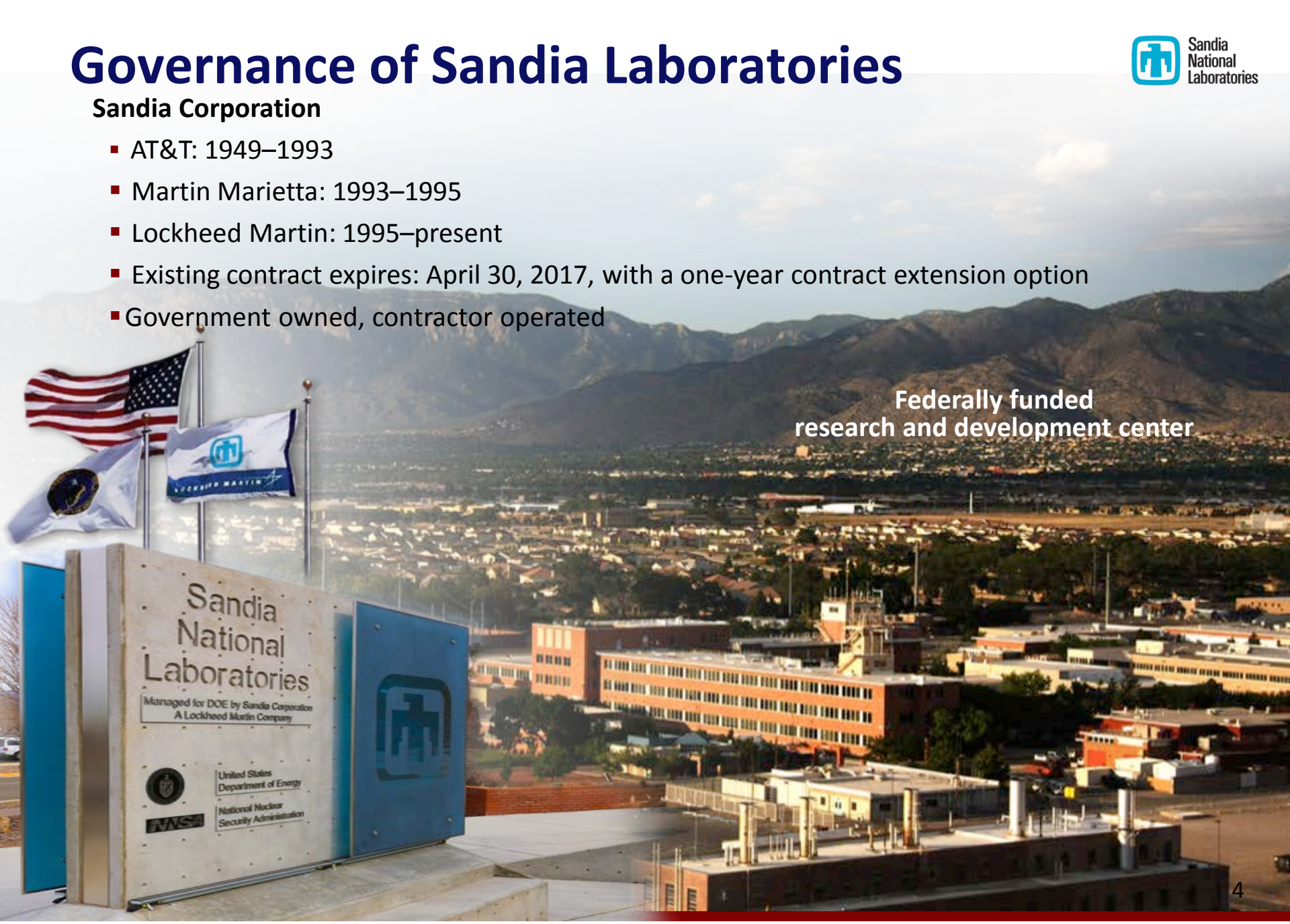




Governance of Sandia Laboratories

Sandia Corporation

- AT&T: 1949–1993
- Martin Marietta: 1993–1995
- Lockheed Martin: 1995–present
- Existing contract expires: April 30, 2017, with a one-year contract extension option
- Government owned, contractor operated



Federally funded research and development center

Sandia Sites

Albuquerque, New Mexico

Livermore, California

Kauai, Hawaii

Waste Isolation Pilot Plant, Carlsbad, New Mexico

Pantex Plant, Amarillo, Texas

Tonopah, Nevada

Our Core Values

- Serve the nation
- Deliver with excellence
- Respect each other
- Act with integrity
- Team for great results

Sandia Addresses National Security Challenges

Sandia National Laboratories

1950s	1960s	1970s	1980s	1990s	2000s	2010s
Nuclear weapons	Development engineering	Multiprogram laboratory	Missile defense work	Post–Cold War transition	START Post 9/11	LEPs Cyber, biosecurity proliferation
Production and manufacturing engineering	Vietnam conflict	Energy crisis	Cold War	Stockpile stewardship	National security	Evolving national security challenges

Energy & Climate

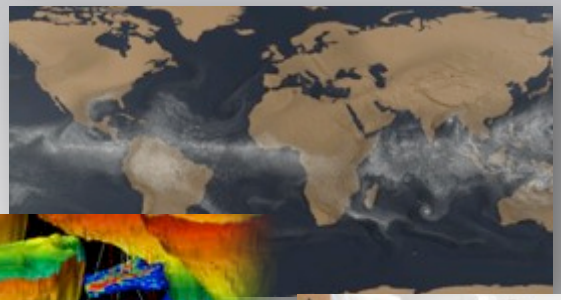
Sandia National Laboratories

Energy Research

ARPAe, BES Chem Sciences, ASCR, CINT, Geo Bio Science, BES Material Science

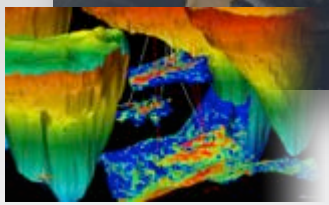
Climate & Environment

Measurement & Modeling, Carbon Management, Water & Environment, and Biofuels



Nuclear Energy & Fuel Cycle

Commercial Nuclear Power & Fuel, Nuclear Energy Safety & Security, DOE Managed Nuclear Waste Disposal



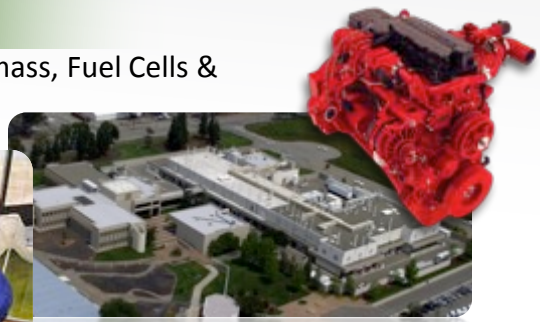
Renewable Systems & Energy Infrastructure

Renewable Energy, Energy Efficiency,

Grid and Storage Systems

Transportation Energy & Systems

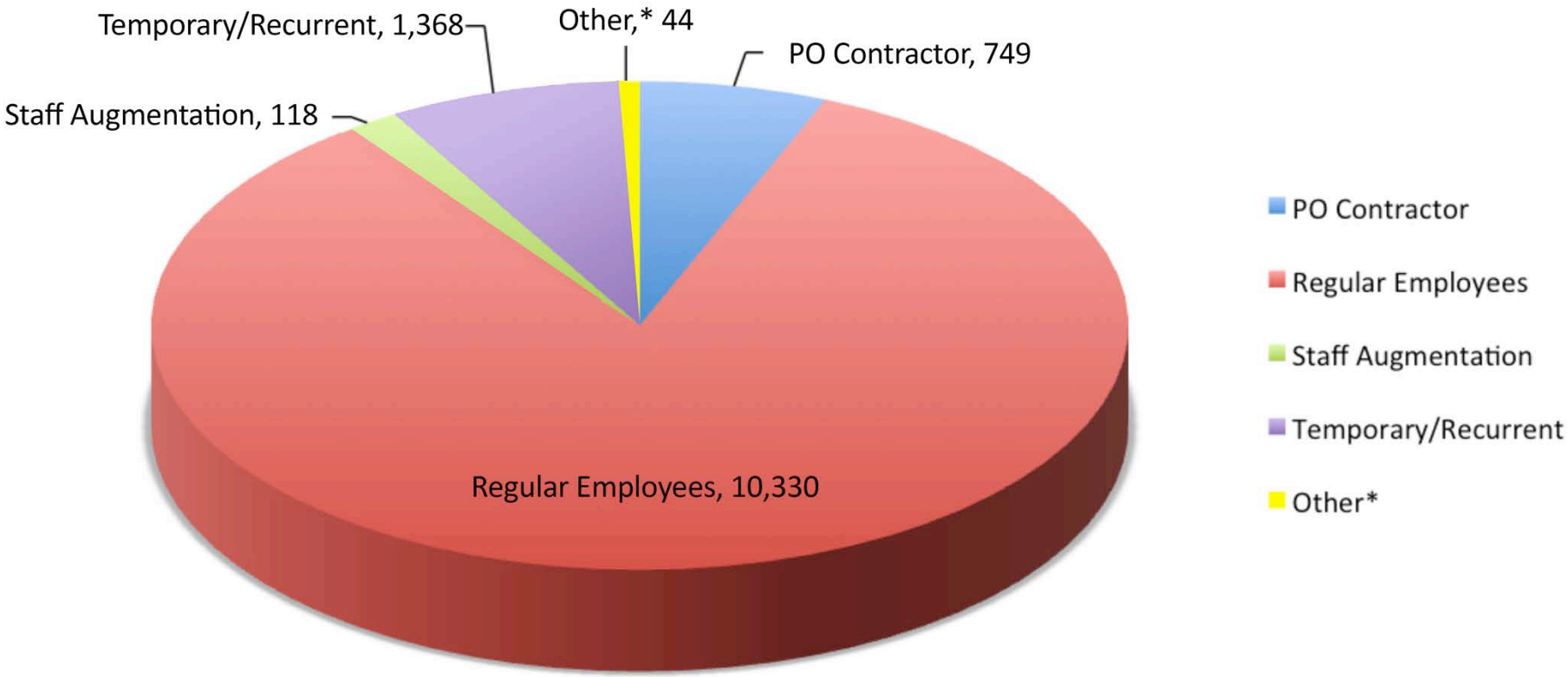
Vehicle Technologies, Biomass, Fuel Cells & Hydrogen Technology



Our Workforce

- Total Sandia workforce: 12,609
- Regular employees: 10,330
- Advanced degrees: 5,790 (56%)

Data as of July 20, 2015

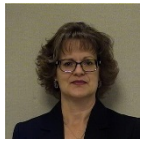


** Other badged personnel*

SNL Wind Team

Dave Minster - Manager

Carolee Wheeler– OAA



Natalie Pitcher – OAA Student Asst

Jon Berg – R&D
MS Mechanical Eng

Wes Johnson – R&D
BS Mech Eng (Tech)

Ben Karlson – R&D
MS Electrical Eng

Bruce LeBlanc – R&D
MS Mechanical Eng

David Maniaci – R&D
PhD Aeronautical Eng

Brandon Ennis – R&D
PhD Mechanical Eng

Todd Griffith– R&D
PhD Aerospace Eng

Brian Naughton – R&D
PhD Materials Science

Josh Paquette – R&D
MS Mechanical Eng

Brian Resor – R&D
MS Mechanical Eng

Jon White – R&D
PhD Mechanical Eng

Chris Kelley – R&D
PhD Mechanical Eng

Tommy Herges – R&D
PhD Aeronautical Eng

David Mitchell
SWiFT Operations Mgr
BS Electrical Eng

Financial Team Members

Arlene Sanchez - Financial - Dept 10661
Sunni Moore- Financial - Dept 10661

Matrixed Team Members

Brian Owens– ME/Modeling - Dept 1523
Matt Barone- AE/Modeling - Dept 1515
Dennis Roach- NDI – Dept 6620

Student Team Members

Phillip Chiu – ME Year-round PhD Student

Contractor Team Members

Bryan Miller– Radar/Siting
Carsten Westergaard- Wind Expert/Mentor
Joshua Bryant- Wind Expert/Turbine Ops
Eric Mallett- Control Systems/Software
Dale Berg- Wind Expert/Mentor
Miguel Hernandez- TTU/SWiFT Ops

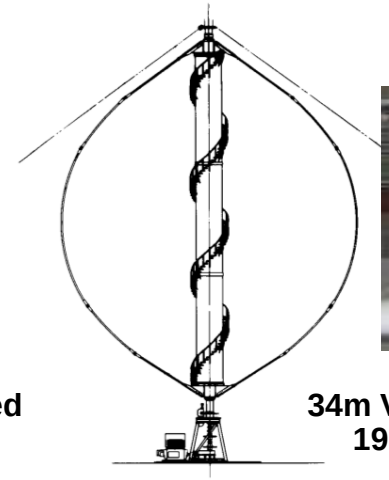
Partnerships

SWiFT: TTU, Vestas, NIRE
Universities: U Minn, UC Davis, MSU, UT Austin, Texas A&M

SNL Wind Program History

28 Years of wind turbine rotor development

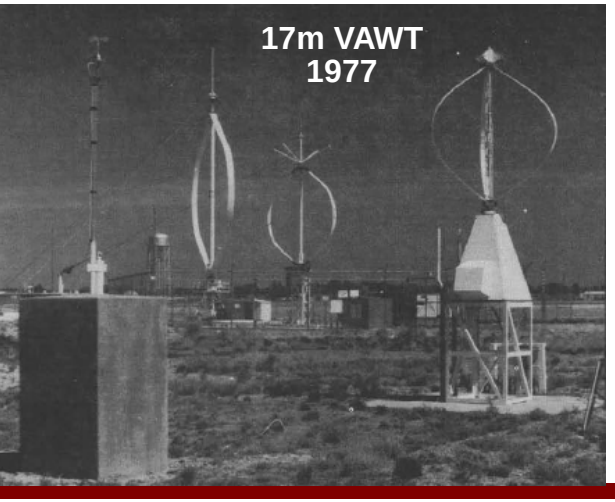
Wind Program Established 1975



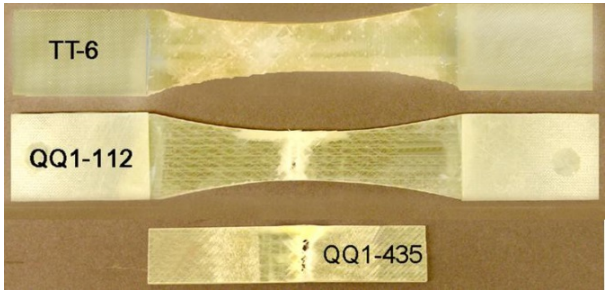
34m VAWT 1984

Blade Program 1994

SWiFT Facility 2013



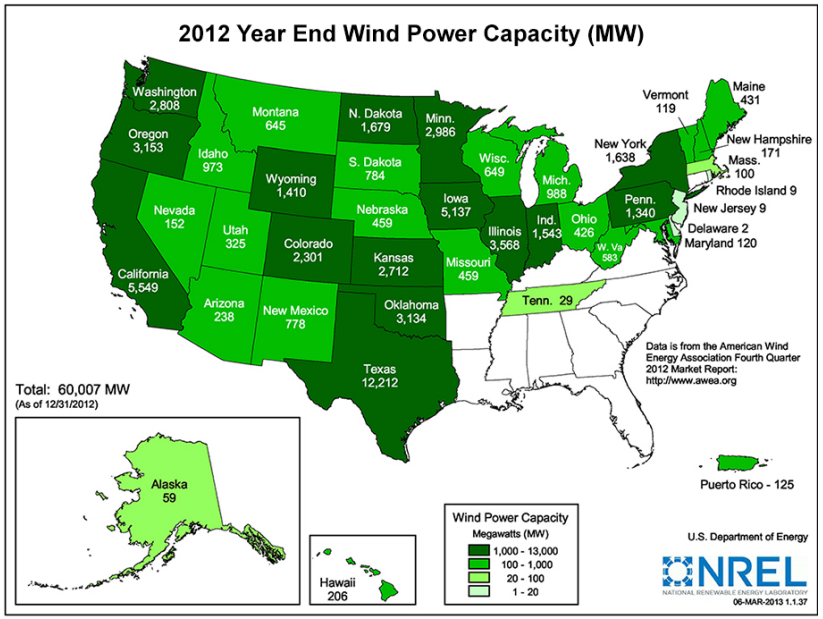
Composite Materials Database 1988

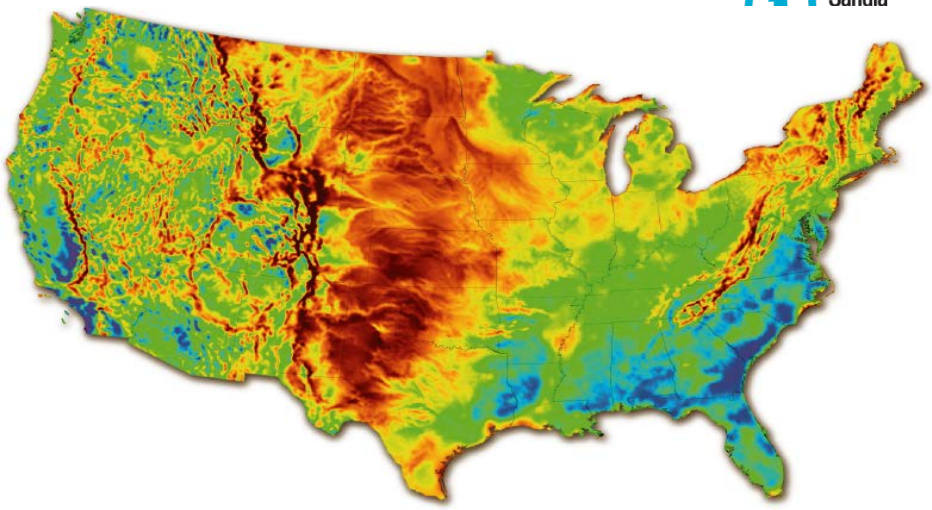


Advanced Manufacturing Initiative 2008

Overview of Project Areas

- Rotor Research
  - National Rotor Testbed at SWiFT
  - 100-meter blades, passive load alleviation
- Wake measurement and wake steering experiments
- Meso-scale/micro-scale coupling
- Offshore wind
  - Offshore VAWT
- Materials and structures for wind systems
- Sensors and Health monitoring





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Sandia's Wind Program

Projects

CREW Reliability Database

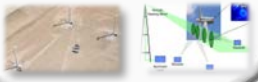
SWiFT Testing Facility

Core Competencies

Grid Control & Modeling

Reliability

Wind farm performance



Wake Measurement & Modeling

RADAR Impact Mitigation

Wind plant Integration

Innovative Energy Capture Technology

Sensors and Actuation

Smart rotors controls

Composite Materials Database

Materials & Manufacturing

Innovative rotor design

Rotor PHM

Blade Reliability Collaborative

Rotor Performance & Innovation

Large Offshore Rotor

National Rotor Testbed

Exceptional service in the national interest

Sandia National Laboratories

Rotor Research @ Sandia

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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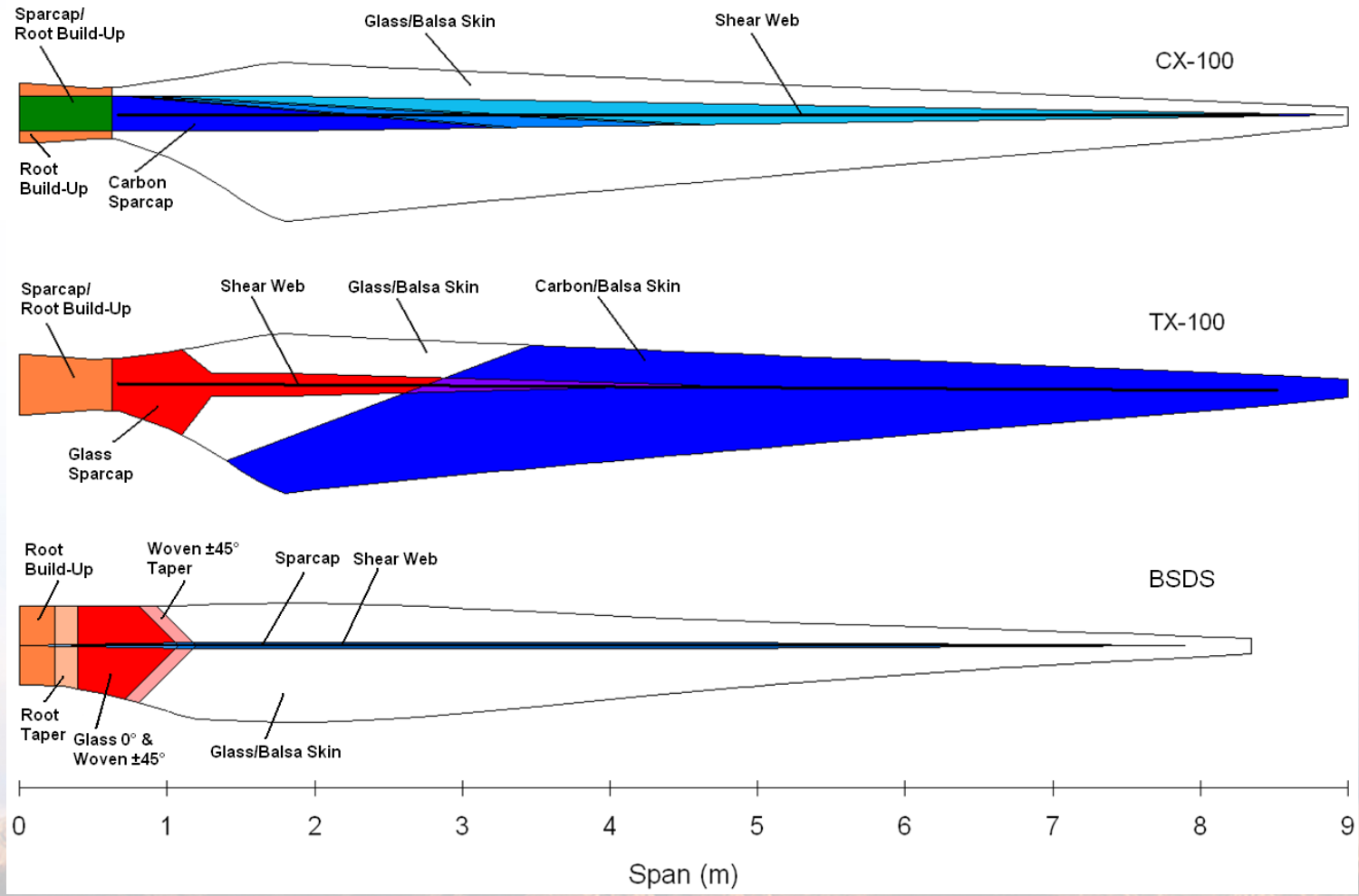
SNL Research Blade Designs
Late ’90s to Recent Past

Research Goal

Carbon: Strategic use of carbon for weight reduction

Bend-twist coupled: Passively coupled aero-structural load mitigation

Thick, flatback airfoils: Structural efficiency improvement



Sandia Blade Programs (1)

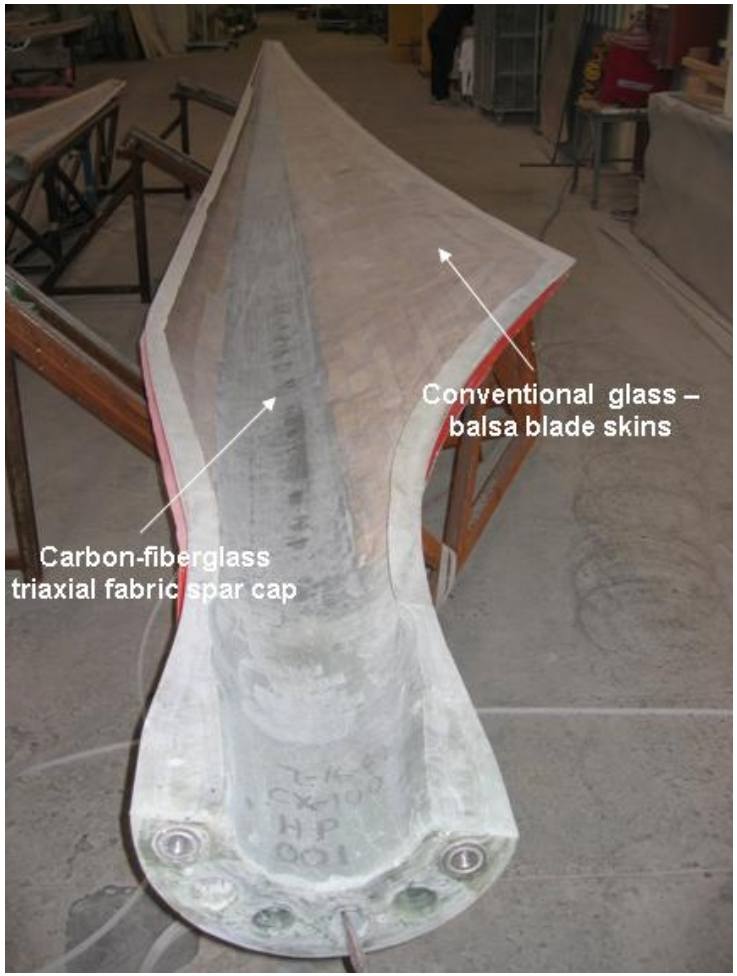
Carbon Fiber Spars

Advantages:
- High stiffness/strength
- Low weight

Challenges:
- Higher cost
- Difficult to infuse
- Sensitive to flaws

Sandia Research:
- CX-100 Blade: Demonstrated method for producing infused carbon spar

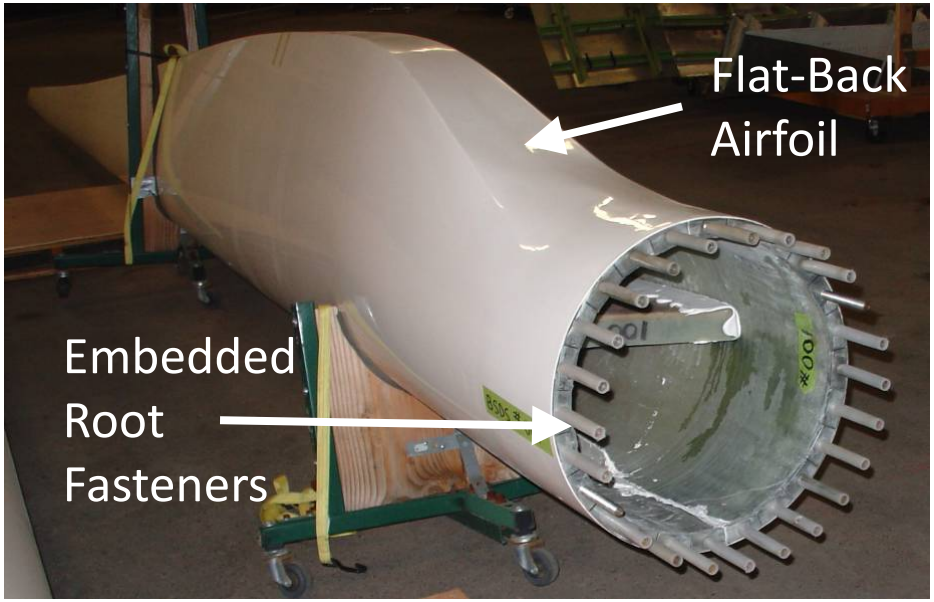
- Industry impact: Carbon fiber spars widely used on large blades



Carbon Experimental 100kW (CX-100) Blade Skin

Sandia Blade Programs (2)

Aero-Structural Optimization



Blade System Design Study
(BSDS) Blade

- Impact: Common in current production blades

Passive Load Alleviation

Twist-Bend Coupled
Experimental 100kW (TX-100)
Blade Skin Blade Skin

Sweep Twist Adaptive Rotor
(STAR) Blade

- Industry impact: Several current production and concept blades use this technology

Sandia Blade Programs (3)

Active Aerodynamic Load Control

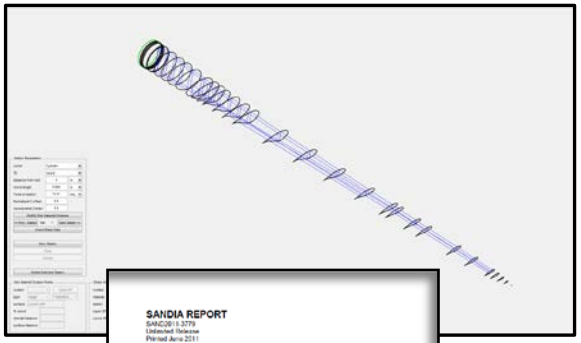
- Quicker, more controllable response to shed gust loads
- Allows for longer blades and higher energy capture
- Possible performance enhancement
- Sandia Research:
  - SMART Blade: first full rotor with active controls
  - Utilized ailerons and patented blade displacement sensing system

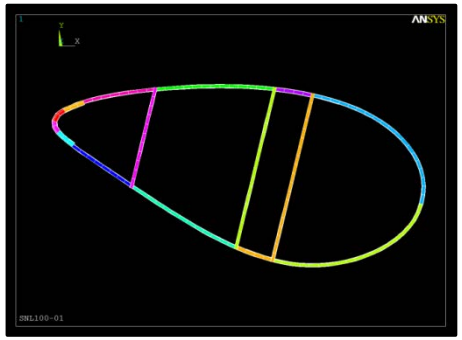
- Impact: Consistent industry interest, but no blades built to date

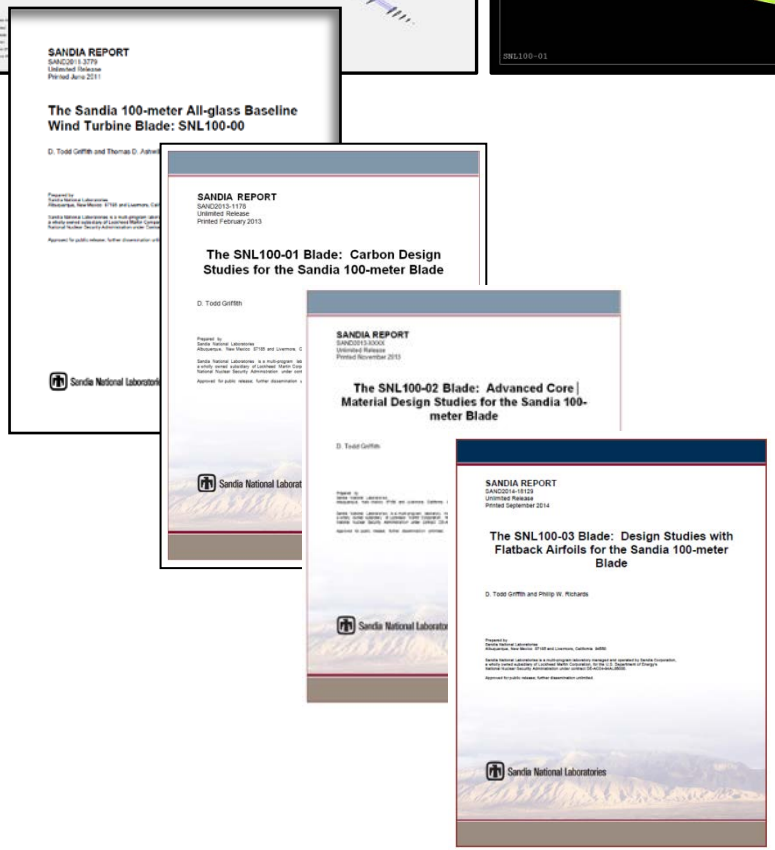
Large Offshore Rotor Development (100-meter Blade Project)

- **Summary**
  - Large blade design studies
  - **Public domain blade project**
  - **Reference Models**
- **Objectives & Results**
  - Identify trends and challenges
    - High weight and cost
    - Transportation
    - Shell/panel buckling
    - Gravitational Fatigue loading
    - Flutter
  - **Targeted follow-on studies**: **advanced concepts, materials**, flutter, manufacturing cost trends, **thick airfoils**, CFD, optimization
- **Products**
  - 100-m blade and 13.2 MW turbine reference models

http://largeoffshorerotor.sandia.gov

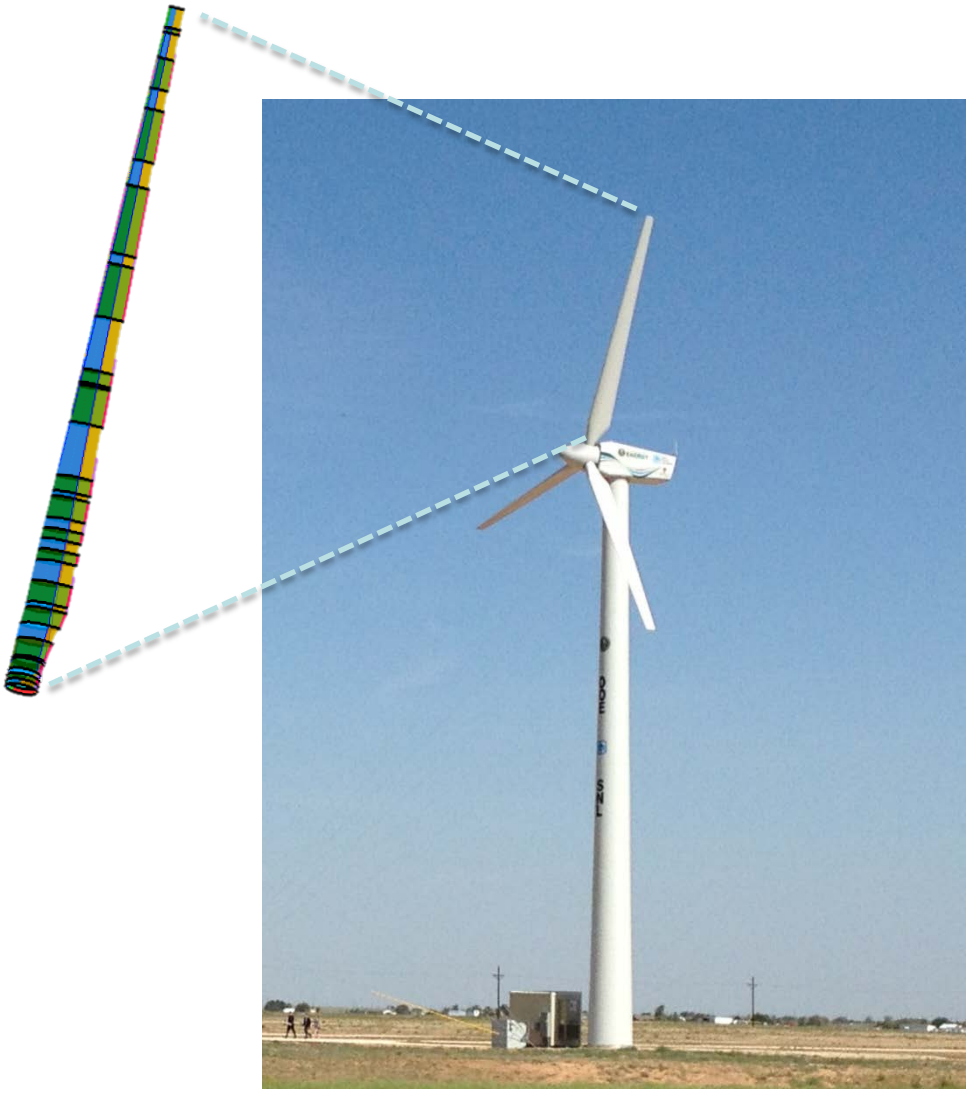






National Rotor Testbed (Current)

- Design and manufacture sub-scale rotors for the SWiFT turbines to emulate a modern, megawatt scale rotor.
- Enables low-cost field testing of new rotor technologies.
- Public rotor design



Wakes

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SWIFT Test Site

Scaled Wind Farm Test (SWiFT) Facility

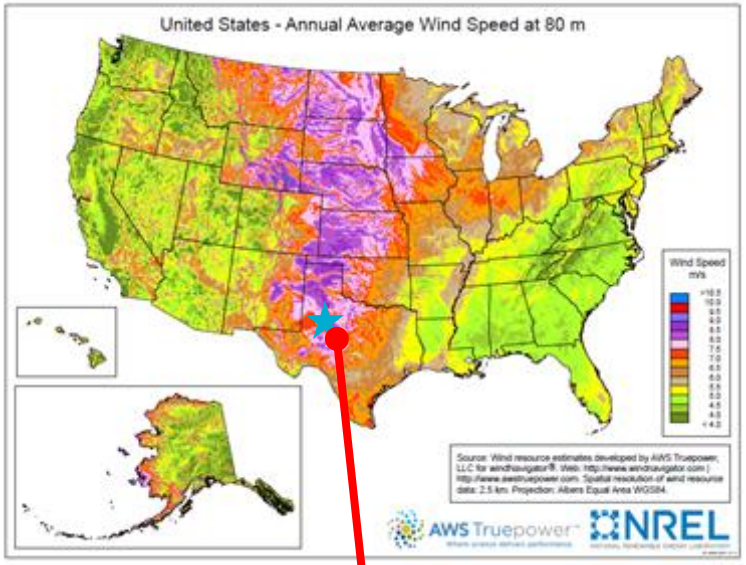
Cost-effective wind plant testing facility to transition basic research to commercialization

- Lubbock, Texas
- 3 x 225 kW Turbines
- ~14 m blades
- Highly instrumented site and turbines
- Modern technology

TEXAS TECH UNIVERSITY

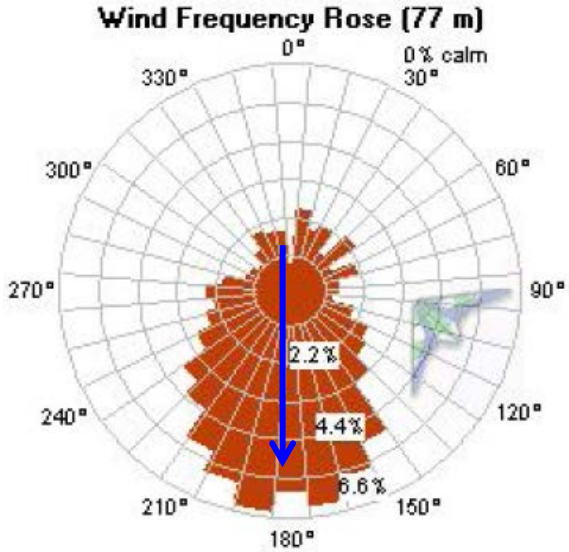
Source: Sandia National Laboratories

SWiFT: High, Consistent Wind



Consistent high data rate and efficient research execution due to:

- High winds (7.5 m/s at 50 m) with low variability
- Narrow wind rose, which provides consistent data for chosen array configuration
- Current and historical data from unique, site-adjacent 200 m meteorological mast
- Flat terrain, which allows reduced validation uncertainty and the opportunity to add man-made terrain effects in the future



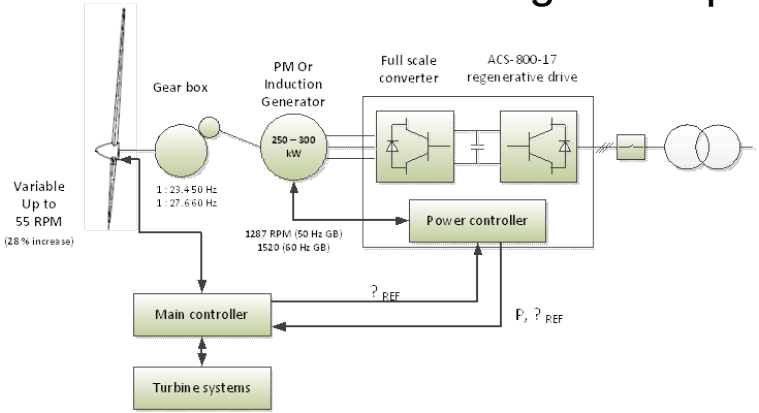
Location is in the best part of the US wind corridor—with favorable weather year-round and the most US wind installations: 12 GW and continued growth.

TEXAS TECH UNIVERSITY

Open-Source Wind Turbines

Fully documented open source hardware, developed in collaboration with Vestas

- Solid, proven machines with collective-pitch system that allows almost any type of research to be performed
- 300 kW variable-speed generator
- AC-DC-AC full-scale convertor designed with ABB, Inc.
- Open-source controllers based on National Instruments
- Complete turbine/rotor state instrumentation including fiber-optics



Types of SWiFT Facility Experiments

- **Tech demonstration**: Perform subscale technology demonstration tests, but do it with rotors which meet full-scale similitude requirements

- **Model validation:** Accurately predict, assess and optimize wind plant performance utilizing High Fidelity Modeling (HFM) tools to understand and accurately predict the fundamental physics and complex flows of:
  - the atmospheric boundary layer
  - interaction with the wind plant
  - the response of individual turbines to the complex flows within that plant

- Other types of experiments include calibration, phenomena discovery, mathematical model development, or phenomena exploration

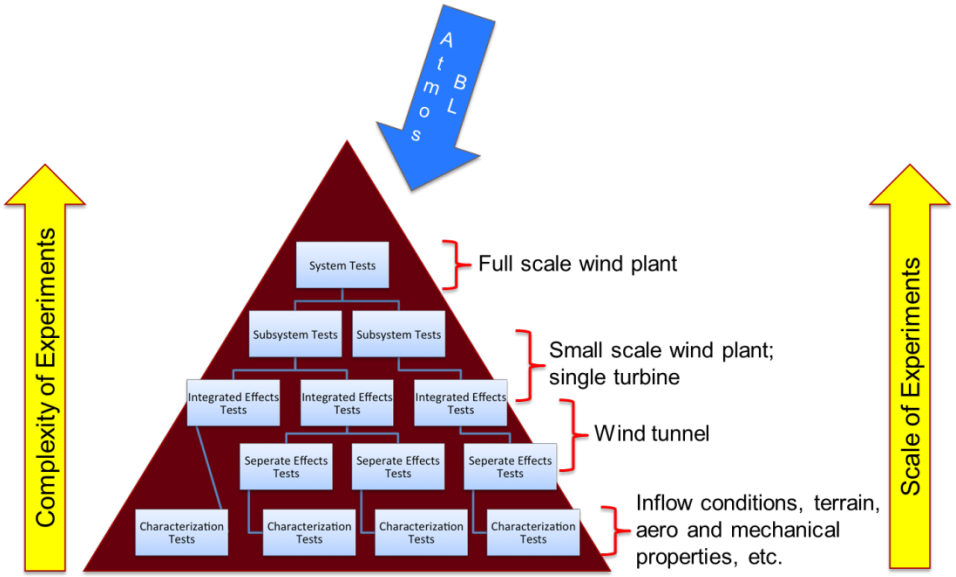
PIRT → Model Validation Hierarchy

PIRT

Phenomenon Importance Ranking Table

Phenomenon	Importance at Application Level	Model Adequacy		
		Physics	Code	Val
Turbine scale flow phenomena				
Blade Aero / Wake Generation				
Blade load distribution effects and rotor thrust	H	M	L	L
Tip and root vortex development, and evolution and merging	H	M	L	L
Vortex sheet and rollup (in addition to tip/root vortex)	M	M	M	L
Blade generated turbulence characteristics (energetic scales)	H	L	L	L
Root flow acceleration effect ('hub jet')	Unknown	M	L	L
Boundary layer state on turbine performance (roughness, soiling, bugs, erosion)	H	L	L	L
Boundary layer state (Re)	L	M	L	L
BL details near TE and LE	H	M	L	L
Rotational augmentation	H	L	L	L
Dynamic stall	H	L	L	L
Unsteady inflow effect (turb. intensity, spectra, coherence; veer, shear)	H	L	L	L
Blade flow control	M	L	L	L
Tower/rotor/nacelle wake interactions	H	M	L	L
Icing	L	L	L	L

Hierarchy



Validation Hierarchy Leads to Validation Experiments

Validation is a process of characterizing model error, not a binary statement of model validity

Characteristics of a successful validation programs

- Highly collaborative – team includes experimentalist, modelers, V&V specialist
- Models are used during the design phase to
  - Assure that the experiments are sensitive to the phenomena of interest
  - Help optimize the experiments, i.e. define sensor location, density, sampling rates, …
  - Assure that the experiments can be unambiguously modeled (failure to do this is the most common reason for the failure of a validation exercise)
- Estimates of data uncertainty and model prediction uncertainty play a key role model validation process
- Model credibility is established by following a formal verification and validation process

Model Assessment Areas

- Inflow to rotor and blade loads
- Initiation of wake by rotor
- Wake skew and meander
- Wake advection, instability, and dissipation
- Wake impingement on downwind turbine

Model Assessment Objectives

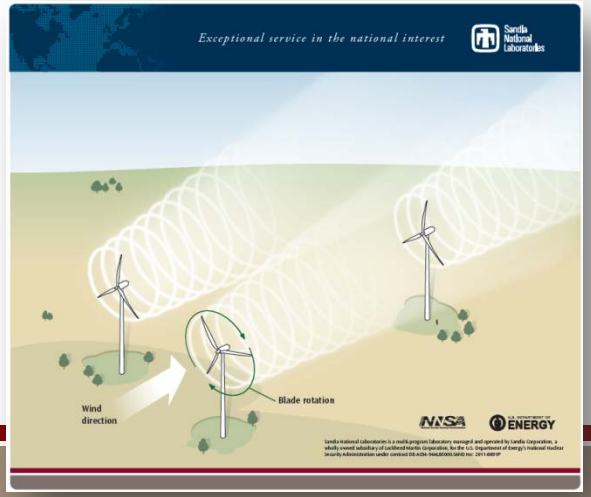
- Inflow to rotor and blade loads
  - Measure inflow to the wind turbine model domain for model assessment. Assess accuracy of existing rotor aerodynamics models in predicting rotor loads due to uniform, stationary random, and unique, non-stationary inflow structures
- Initiation of wake by rotor
  - Assess accuracy of existing rotor models for use in predicting the time rate of change of the near wake structures
- Wake skew and meander
  - Assess accuracy of existing wake steering models for use in guiding R&D for wind farm flow control to minimize wind farm LCOE
- Wake advection, instability, and dissipation
  - Assess the accuracy of existing near and far wake models in predicting the inflow to a downstream rotor
- Wake impingement on downwind turbine
  - Assess the accuracy of existing near and far wake models in predicting the inflow to a downstream rotor

SWiFT Site Layout and Capabilities

DOE/SNL Scaled Wind Farm Technology (SWiFT) facility hosted by Texas Tech University (TTU)

SWiFT exists to:

- Reduce turbine-turbine interaction and wind plant underperformance
- Public, open-source validation data
- Advance wind turbine technology



Facilities:

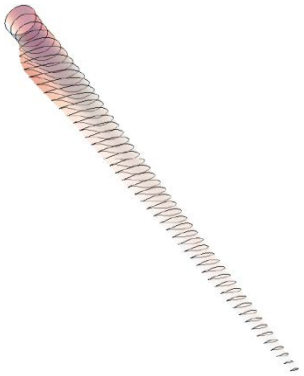
- Three variable-speed variable-pitch modified wind turbines with full power conversion and extensive sensor suite
- Two heavily instrumented inflow anemometer towers
- Site-wide time-synchronized data collection

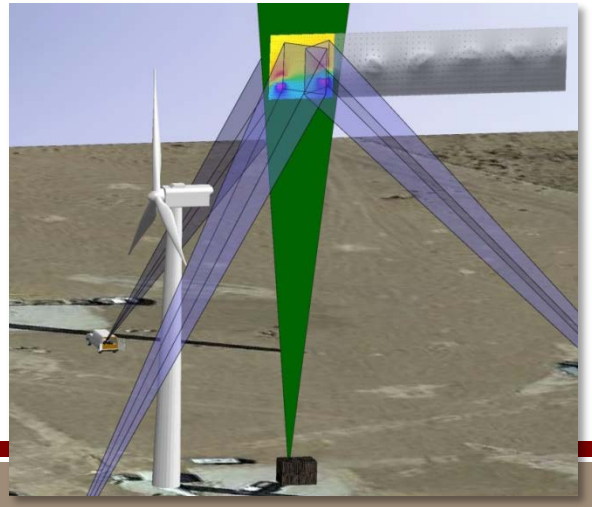
SWiFT-X1: Wake Skew and Meander

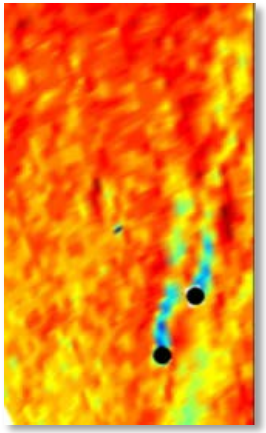
Goal: Validate HFM ability to predict blade loading and wake skew and meander given ABL and inflow measurements

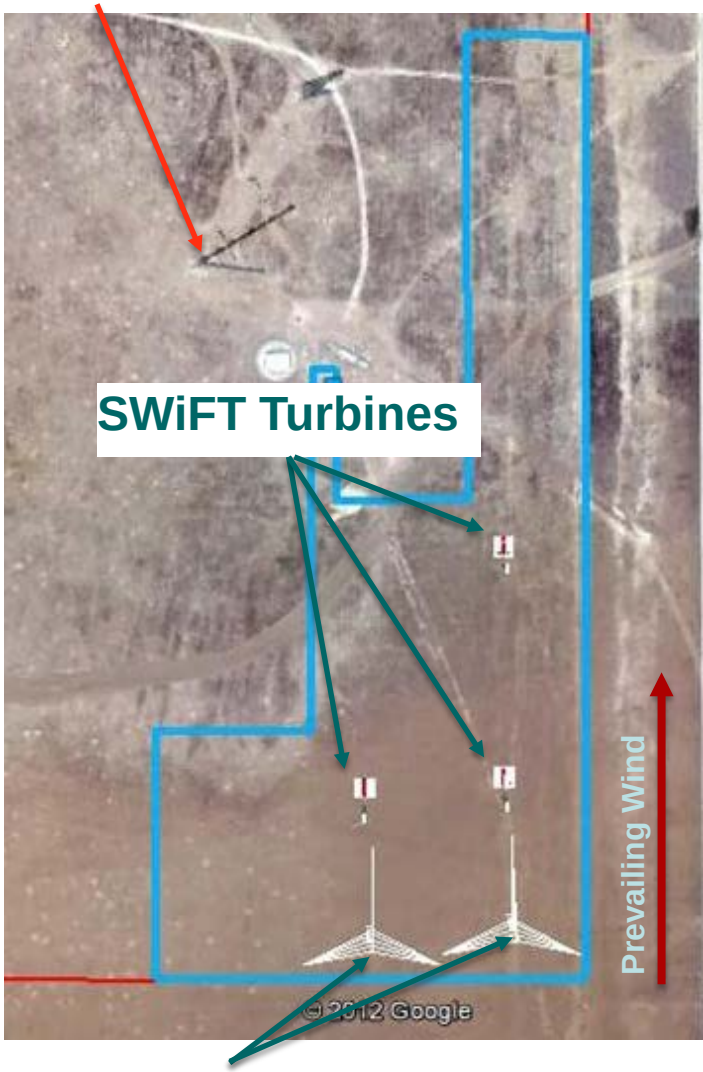
Measurements:

- ABL Conditions: 200m MET, Sodar, and Radar Profiler
- Inflow: Dual 58.5m MET towers, Lidar
- Rotor and Tower Strains and Accels.
- Rotor loading: Distributed strain measurements and/or pressure taps
- New rotors functionally scaled from utility turbine
- Wake Flow Diagnostics: SWIS, Lidar, MET, Dual-Doppler Radar









SWiFT-X2+: Wake Meandering and Turbine-Turbine Interaction

Goal: Validate HFM ability to predict downstream rotor loading and wake movement given inflow measurements

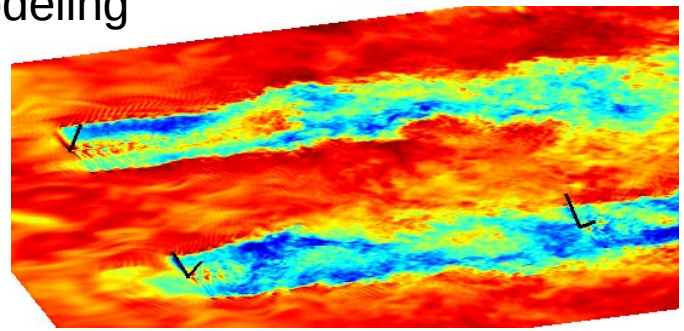
Measurements:

- Far Wake
  - Re-deployable MET tower(s)
  - Scanning Lidar
  - TTU Ka-band mobile Doppler radars
  - Flow-angle sensors on downstream turbine
- Downstream turbine loads
- Correlation with ABL observations

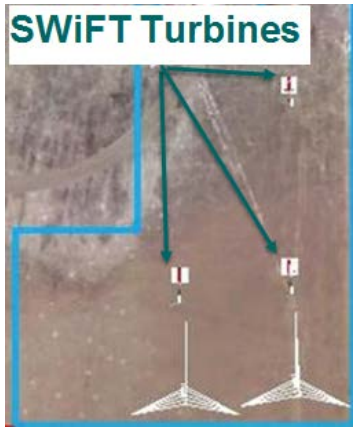
Models are used in the planning stages to determine

- Conditions that will be most useful for model assessment
- Optimum measurement location and resolution

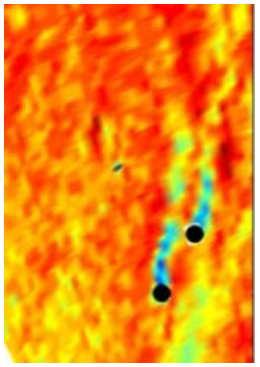
Modeling



Site-specific Data



Expected Measurements

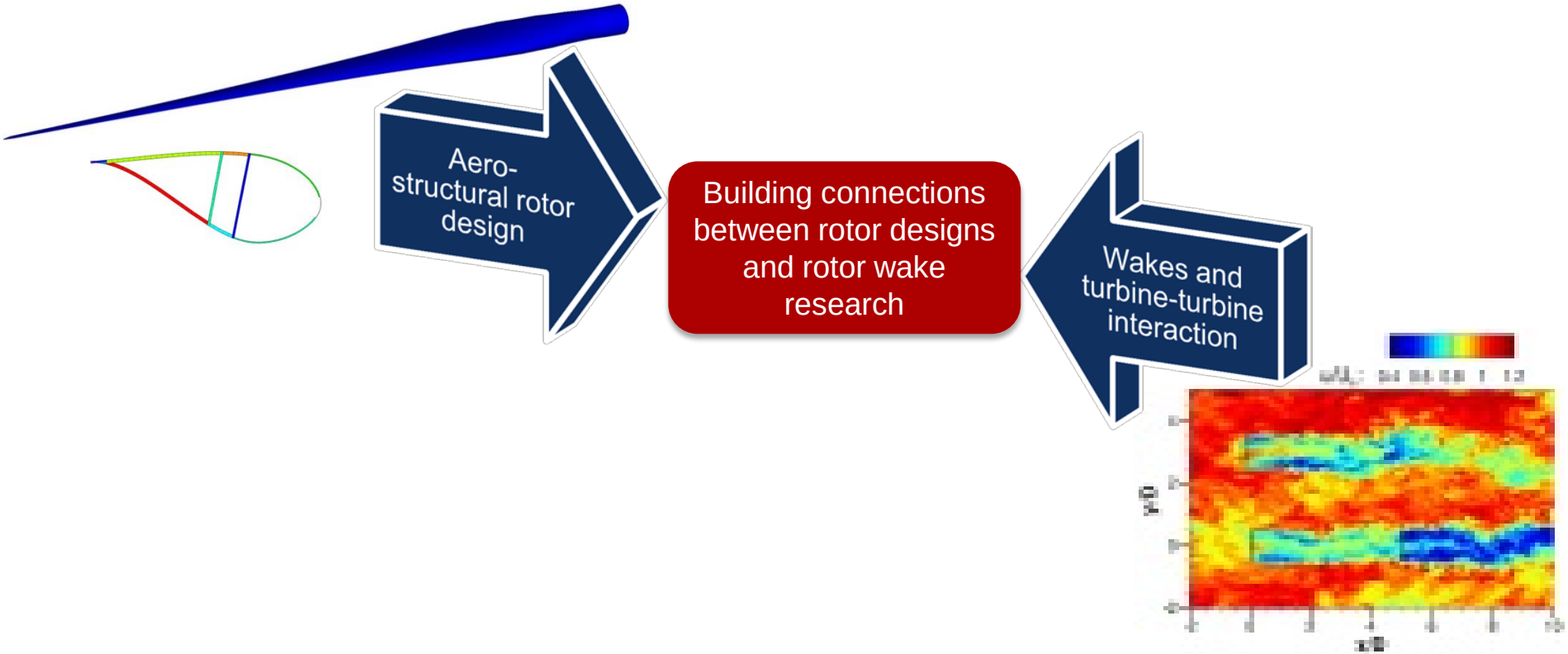


SWiFT Baselining

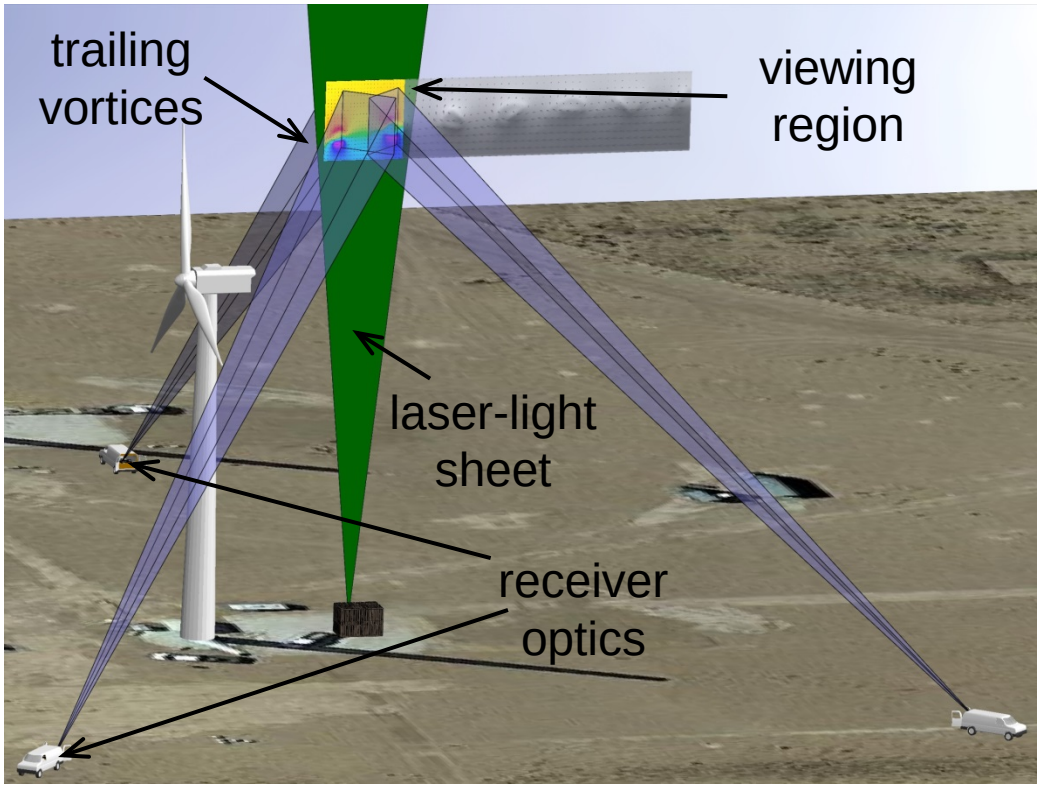
- Detailed analysis of fundamental turbine-turbine interaction
- Calibration and verification of public open-source wind turbine / plant model
- Data quality analysis and troubleshooting

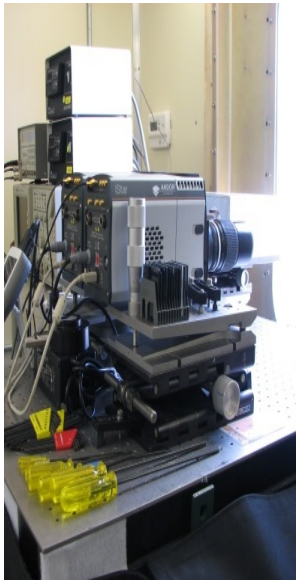
National Rotor Testbed

- Baseline blades represent functionally scaled-down aerodynamics of a modern megawatt-scale rotor
- Baseline blade design is public and open
- Focused on research in wake interaction and control



Sandia Wake Imaging System

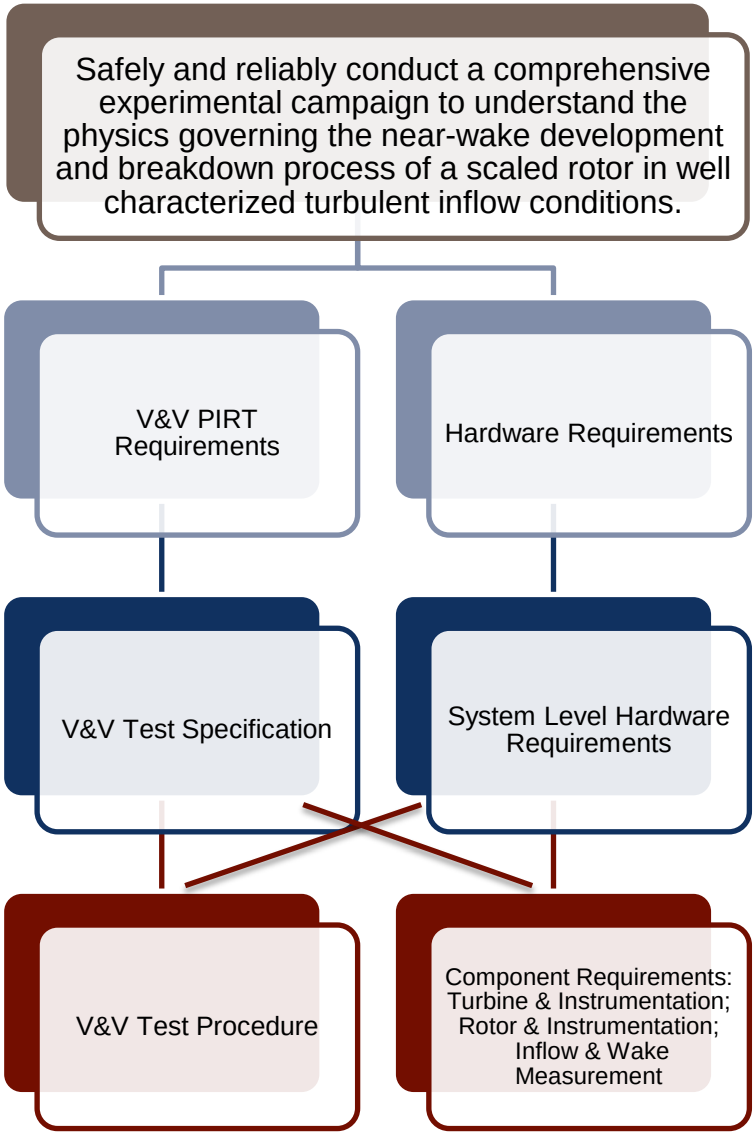




- Imaging allows for fast scanning sufficient to capture sub-rotor scale turbulent flow structures
- High spatial resolution: 16,000 data points per sample
- Enables direct comparison with high-fidelity and engineering level models

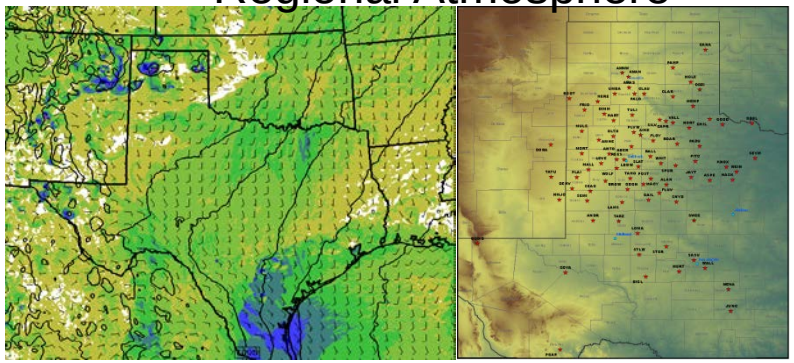
SWiFT Test Requirements Schema

- Design of new test hardware for SWiFT could be done based on known operational envelopes and using standard rotor design practices and standard farm flow measurements
- At the same time, design of a V&V test campaign begins with the PIRT process, which determines a test campaign specification, which leads to a test procedure
- Interdependency 1: The test campaign specification drives aspects of test hardware and test instrumentation
- Interdependency 2: The hardware operational requirements drives aspects of the V&V test procedure



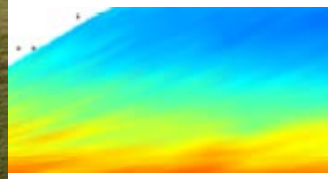
SWiFT Integrated Experiment Planning

Regional Atmosphere

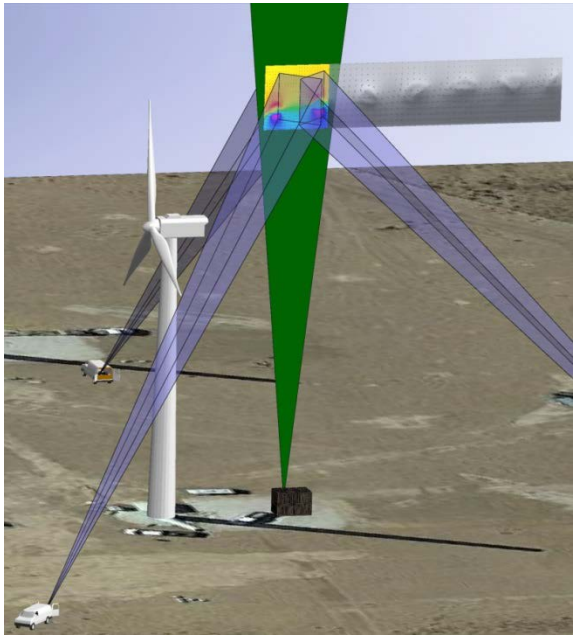


Atmospheric Boundary Layer

Wind Farm Flow



Array Flow



Wake Flow Structures

Exceptional service in the national interest

Sandia National Laboratories

Meso- to Micro-scale Research

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Exceptional service in the national interest

Sandia National Laboratories

Offshore Wind

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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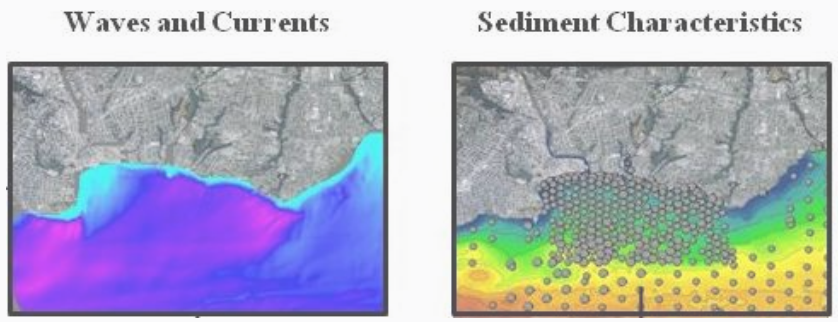
Characteristics of Offshore Wind

- Opportunities
  - Proximity to population centers
  - Better winds
  - Vast resource
  - Scale-up opportunity

- Challenges
  - High LCOE
  - High BOS costs
  - Accessibility
  - Inexperience, Immaturity

Offshore Wind @ Sandia

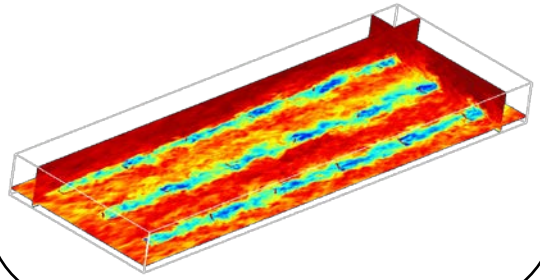
- **Vision**: Promote & accelerate the commercial OW industry and **reduce costs** through **technical innovation:**
  - Siting/Permitting: Sediment Transport & Radar
  - Large offshore HAWT rotors
  - Deepwater VAWT system
  - Structural health and prognostics management
  - Offshore wind farm modeling

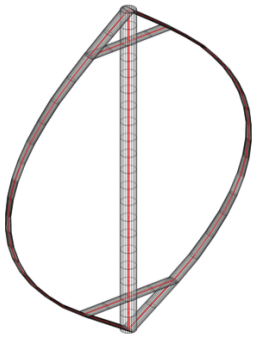


Offshore Siting Analysis

Sensing, Structural Health, and Prognostics

High-resolution Offshore Wind Farm Modeling



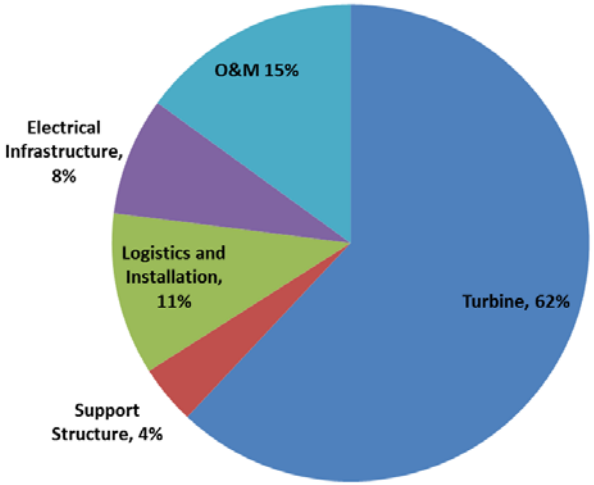


Deepwater Offshore VAWT

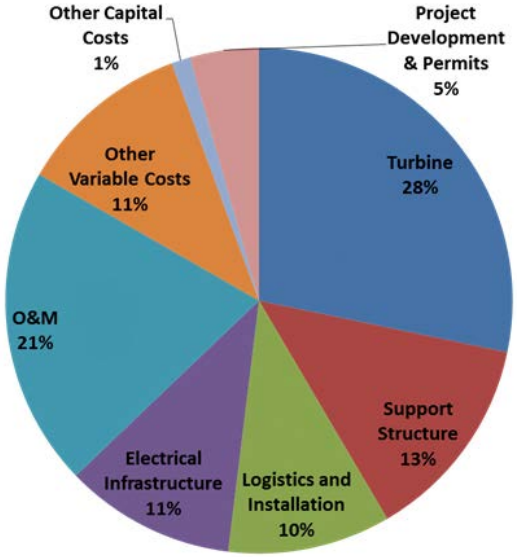
Large Offshore Rotors

Land-based vs Offshore Wind Costs

Land-based Project

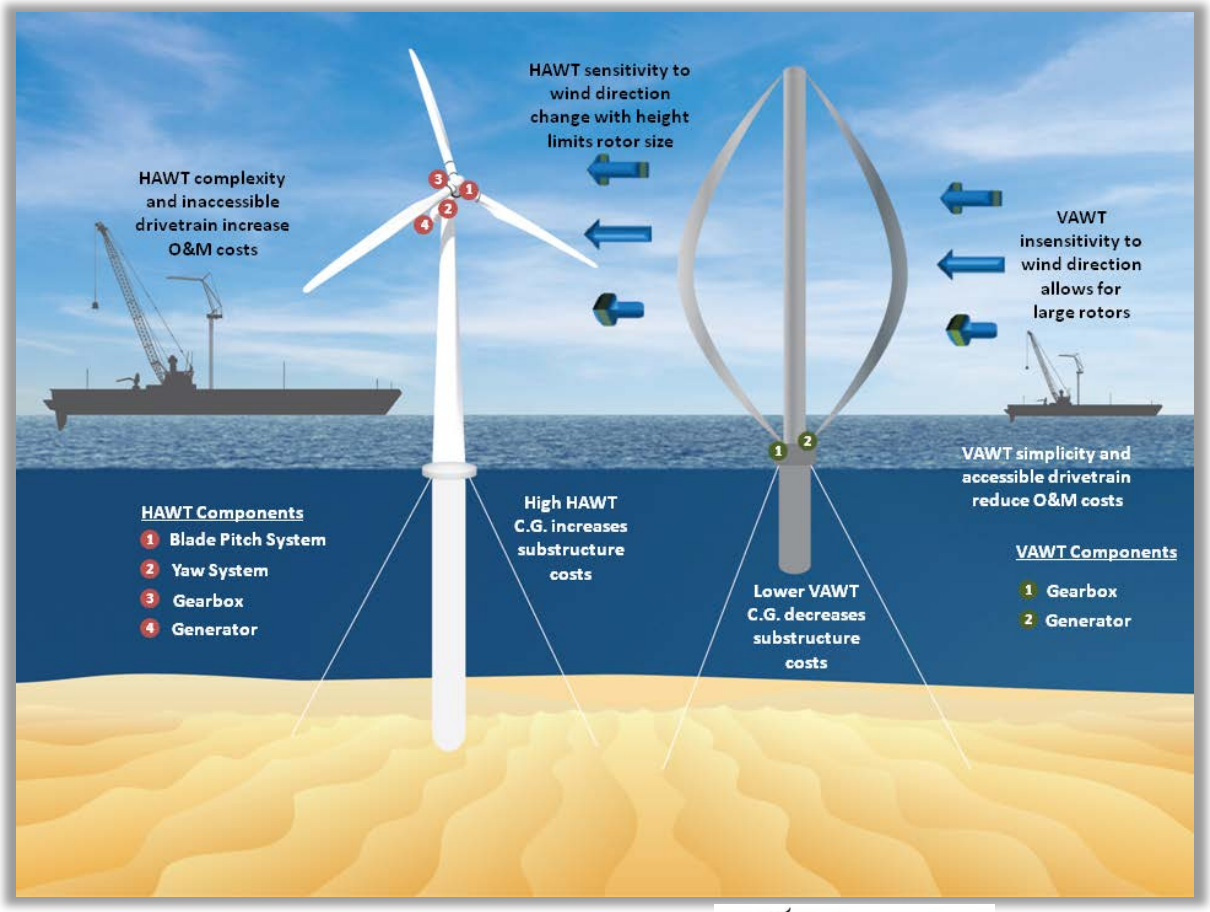


Shallow Water Offshore Project

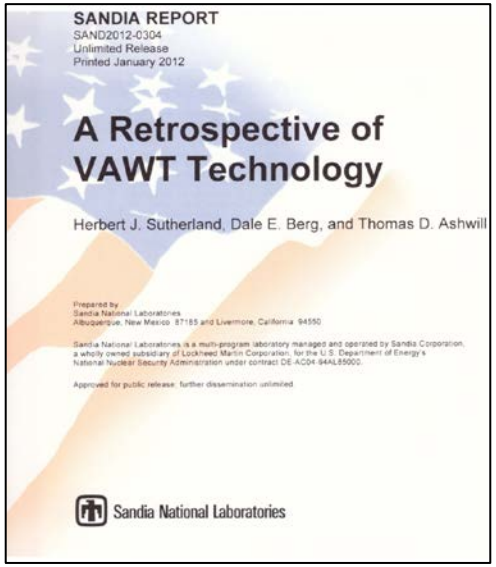


Floating VAWTs

Large reduction in Deepwater Offshore COE may require non-incremental system solutions



Available at www.sandia.gov/wind


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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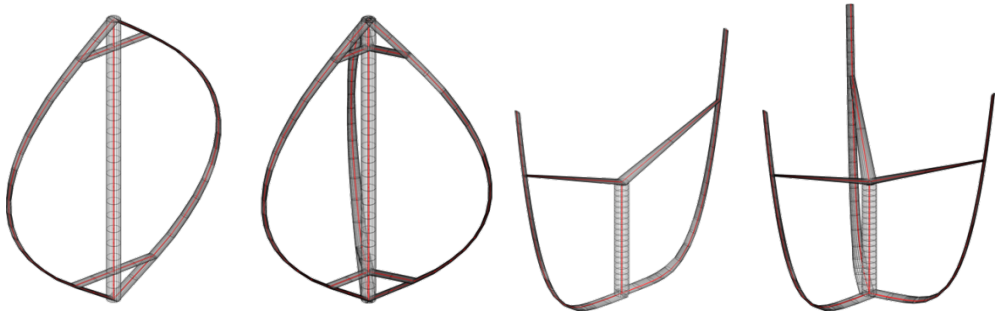
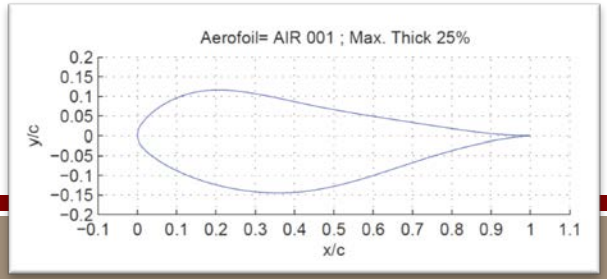
Major Accomplishments (To Date)

1) Design codes development for floating offshore VAWT systems
2) Identification of wind and wave design conditions and standards
3) Design studies for floating VAWT design concepts
4) Innovations and analysis to mitigate barriers and design challenges

In addition, cost models were developed and used to perform an LCOE analysis to better understand opportunities and tradeoffs in the design space.

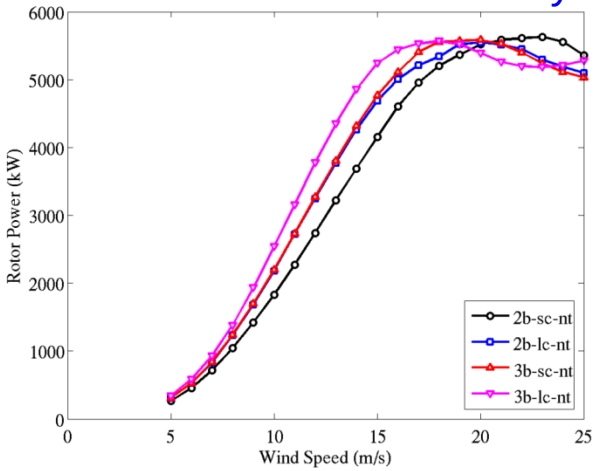


Rotor Design Studies



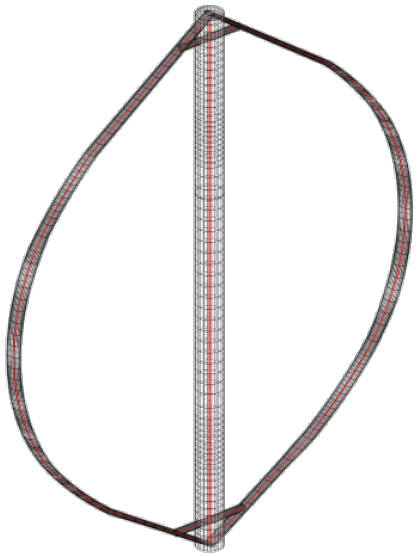
Novel VAWT Airfoils

AEP and LCOE Analysis



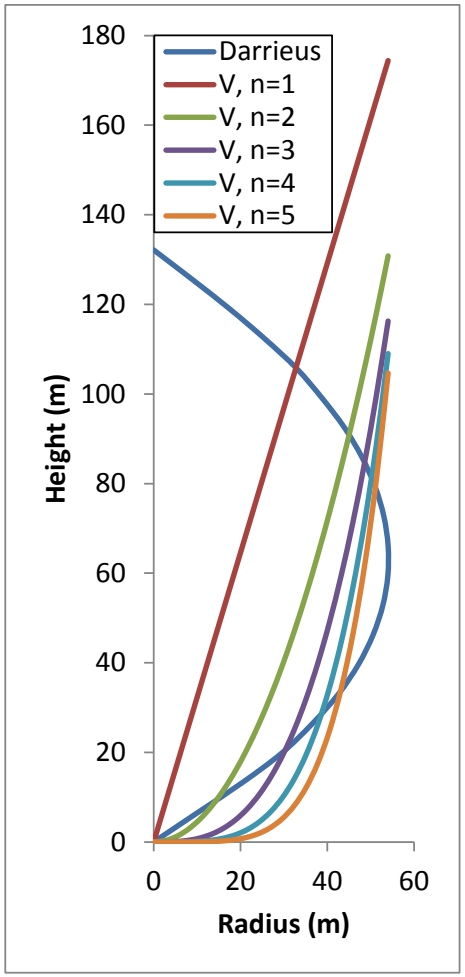
Sandia VAWT Codes List

- Geometry/Modeling & Post-processing
  - VAWTGen Code
- Aerodynamics
  - CACTUS code
- Structural Dynamics
  - OWENS code
  - Features: Modal, Transient, Static
- Hydrodynamics
  - WaveEC2Wire code
  - Notes: Coupled with OWENS

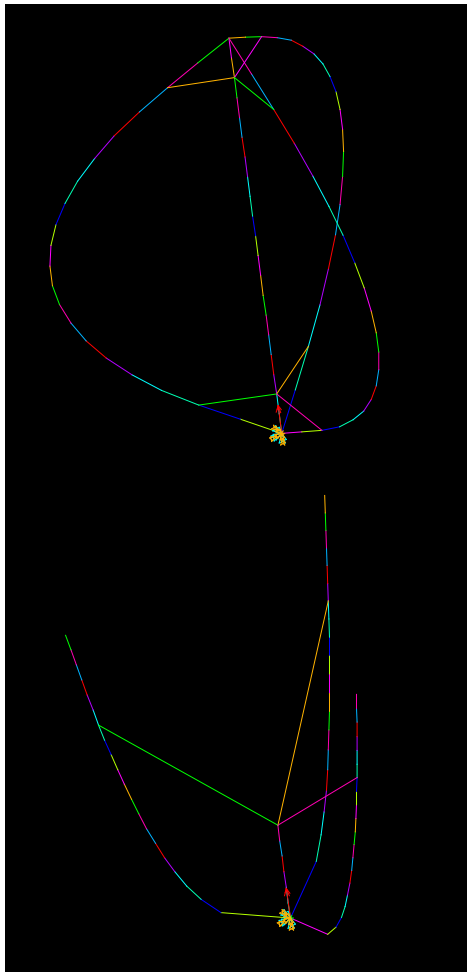


Rotor Structural Design Configurations

Parameter	Values Considered
Architecture	Darrieus, V
Number of Blades	2, 3
Tip Chord Length	2m, 3m
Composite Material:	Glass/Epoxy, Carbon/Epoxy
Tapering Scheme (Darrieus only, V-VAWTS used Single Taper)	No Taper, Single Taper, Double Taper
Curvature or Power Law Exponent (V-VAWT)	n=1, n=3, n=5



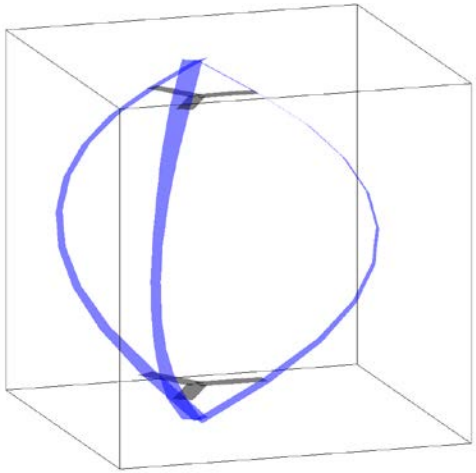
D and V VAWT Shapes

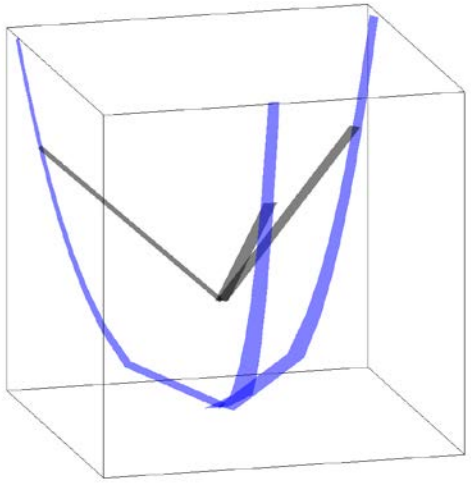


ANSYS Beam Models of D and V VAWTS

Rotor Aero Design Population

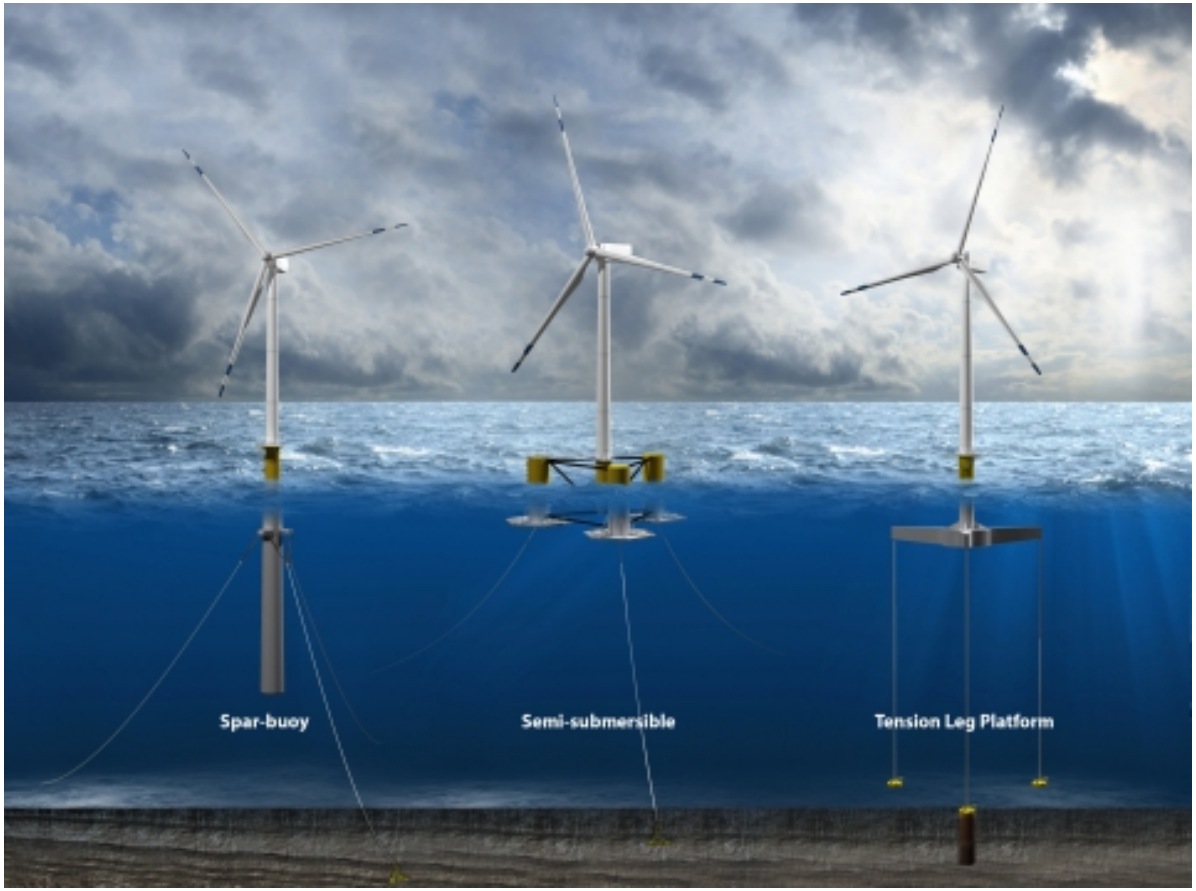
- 24 Candidate Rotor Design **External Shapes**
  - 12 Darrieus :
    - large/small chord
    - single/double/no blade taper
    - two/three blades
  - 12 “V”-Rotors :
    - large/small chord
    - power law shape exponent = 1/3/5
    - two/three blades
- Constraints
  - Max radius = 54 m
  - Same capture area
  - NACA 0021 airfoil section



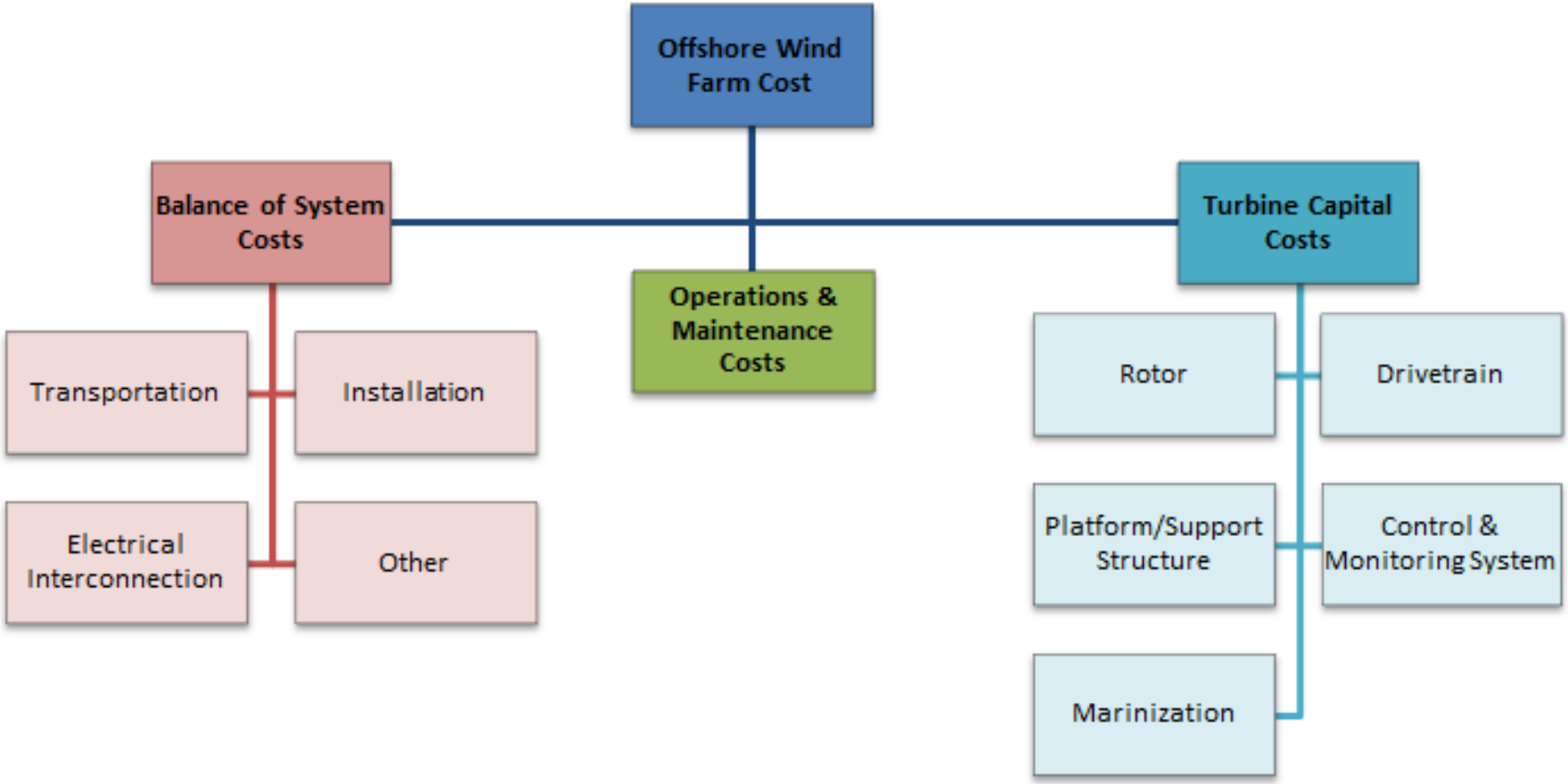


Platform Options

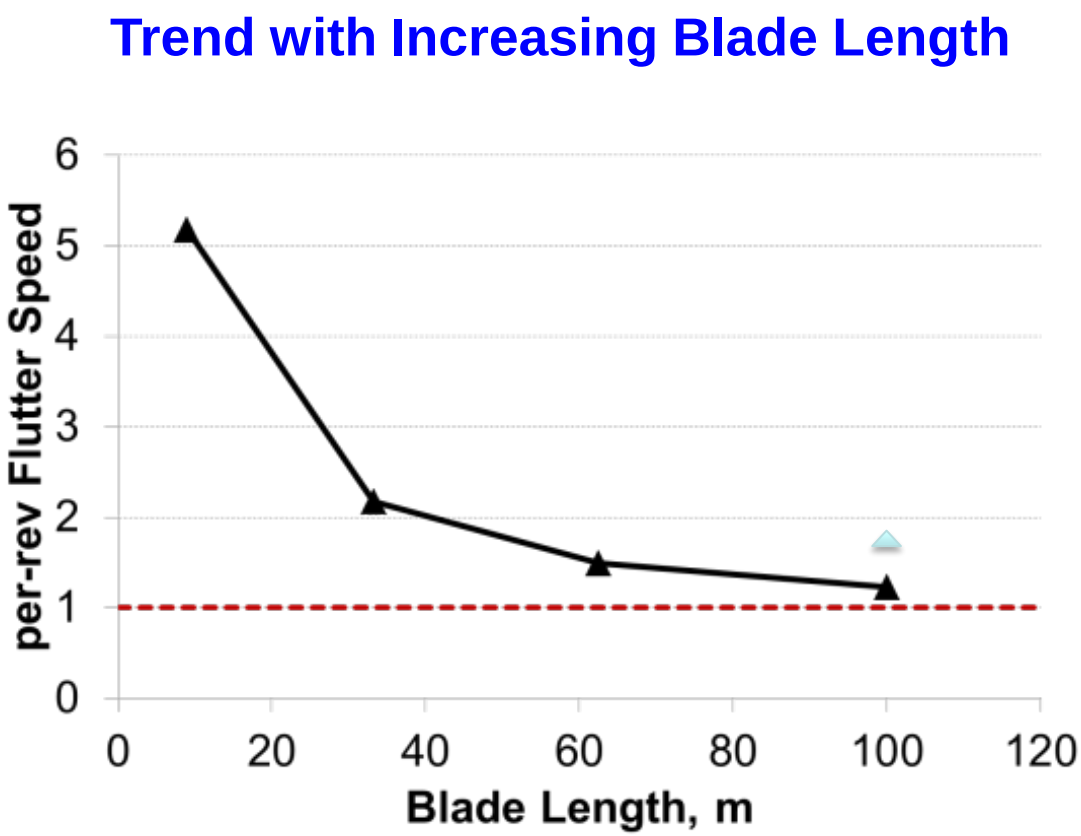
- Tailored solution to a floating VAWT



Cost Analysis Components

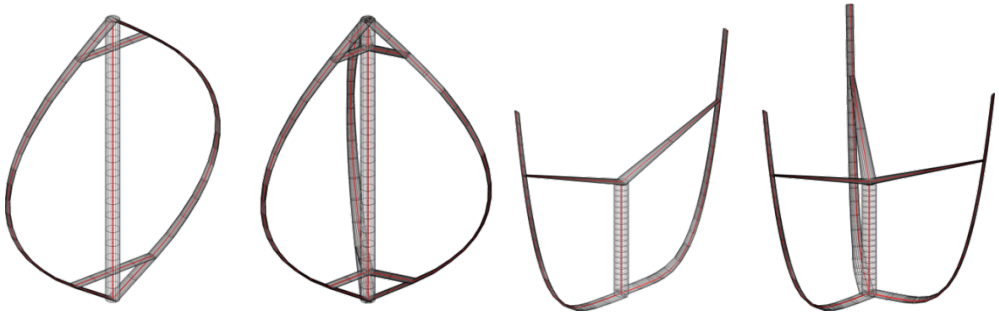


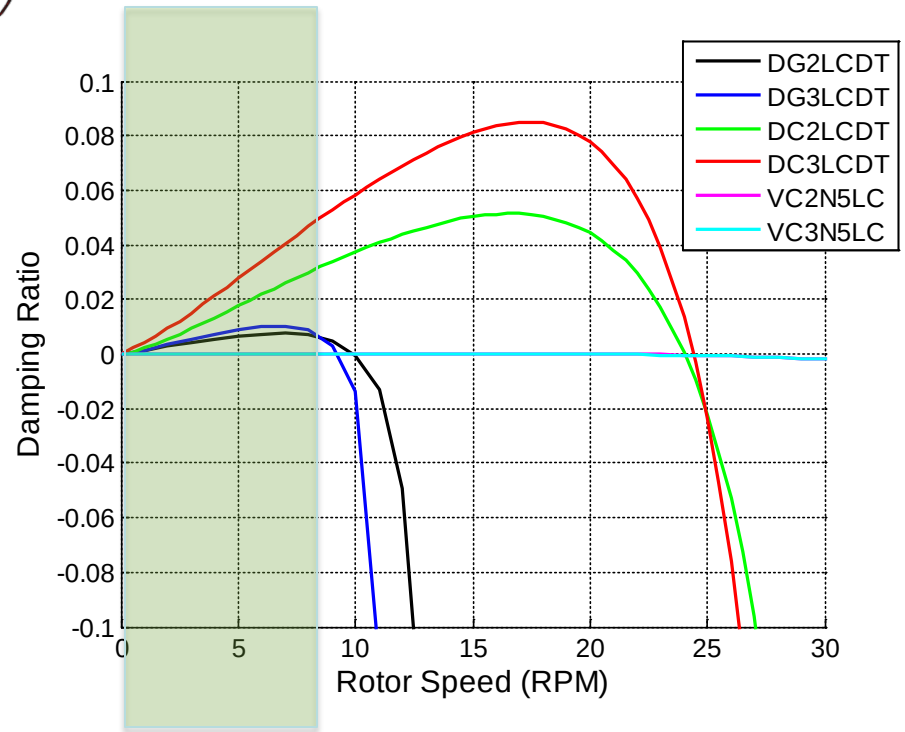
Is Aeroelastic Stability an issue for large-scale VAWTs?



Is Aeroelastic Stability an issue for large-scale VAWTs?

5 MW Design Studies





Owens B.C. and Griffith, D.T. “Aeroelastic Stability Investigations for Large-scale Vertical Axis Wind Turbines,” Science of Making Torque from Wind Conference, Copenhagen, Denmark, June 2014

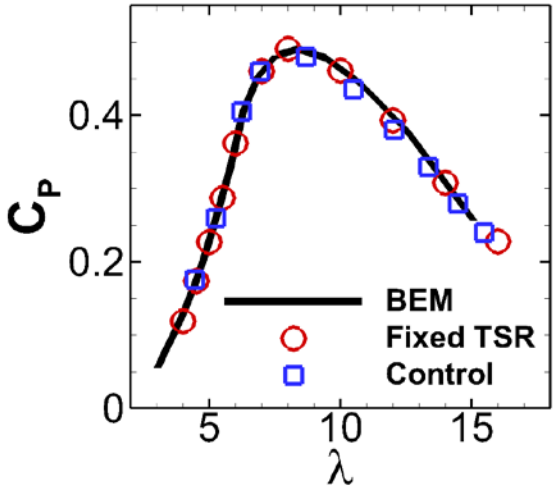
VAWT Flutter – Sandia 2-meter testbed

High-resolution modelling of offshore wind turbines and farms: Model development and validation

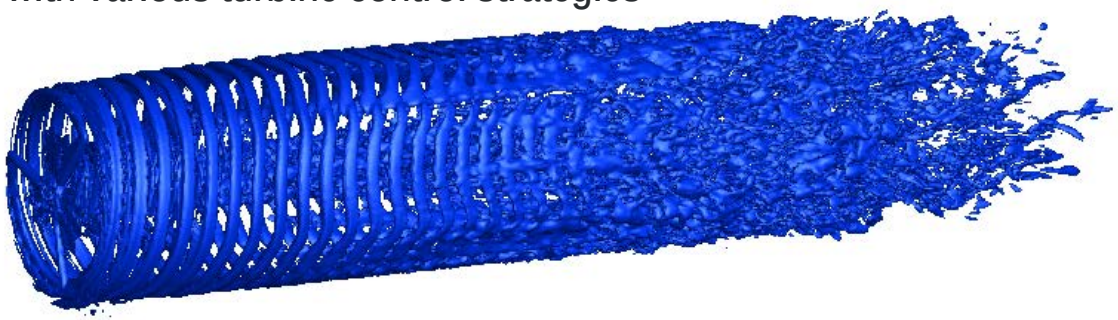
- FSI of floating turbines
  - Combined wind and wave loads
- Wind farm scale
  - Wake effects
- Coupling across scale
  - Mesoscale coupling

VWiS simulations of full-scale wind turbines using Sandia Supercomputers

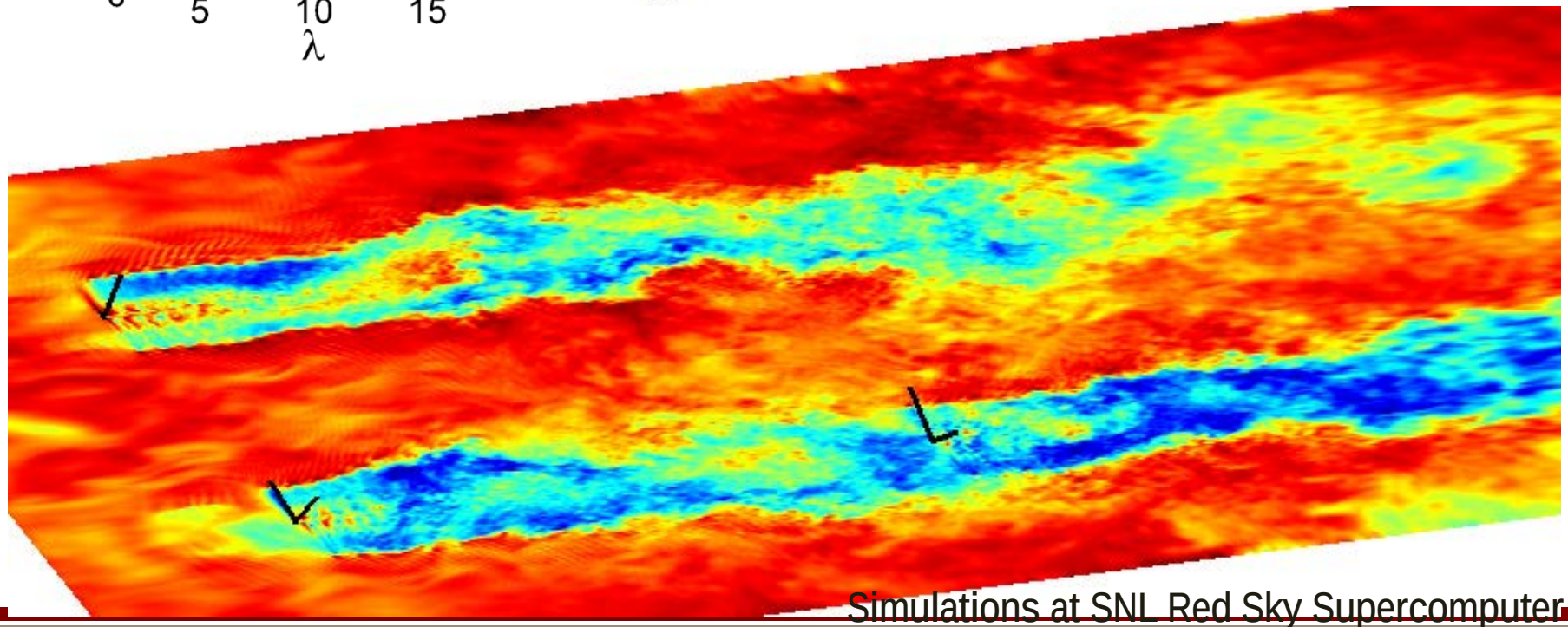
EOLOS turbine



Simulation of the University of Minnesota 2.5MW EOLOS turbine with various turbine control strategies



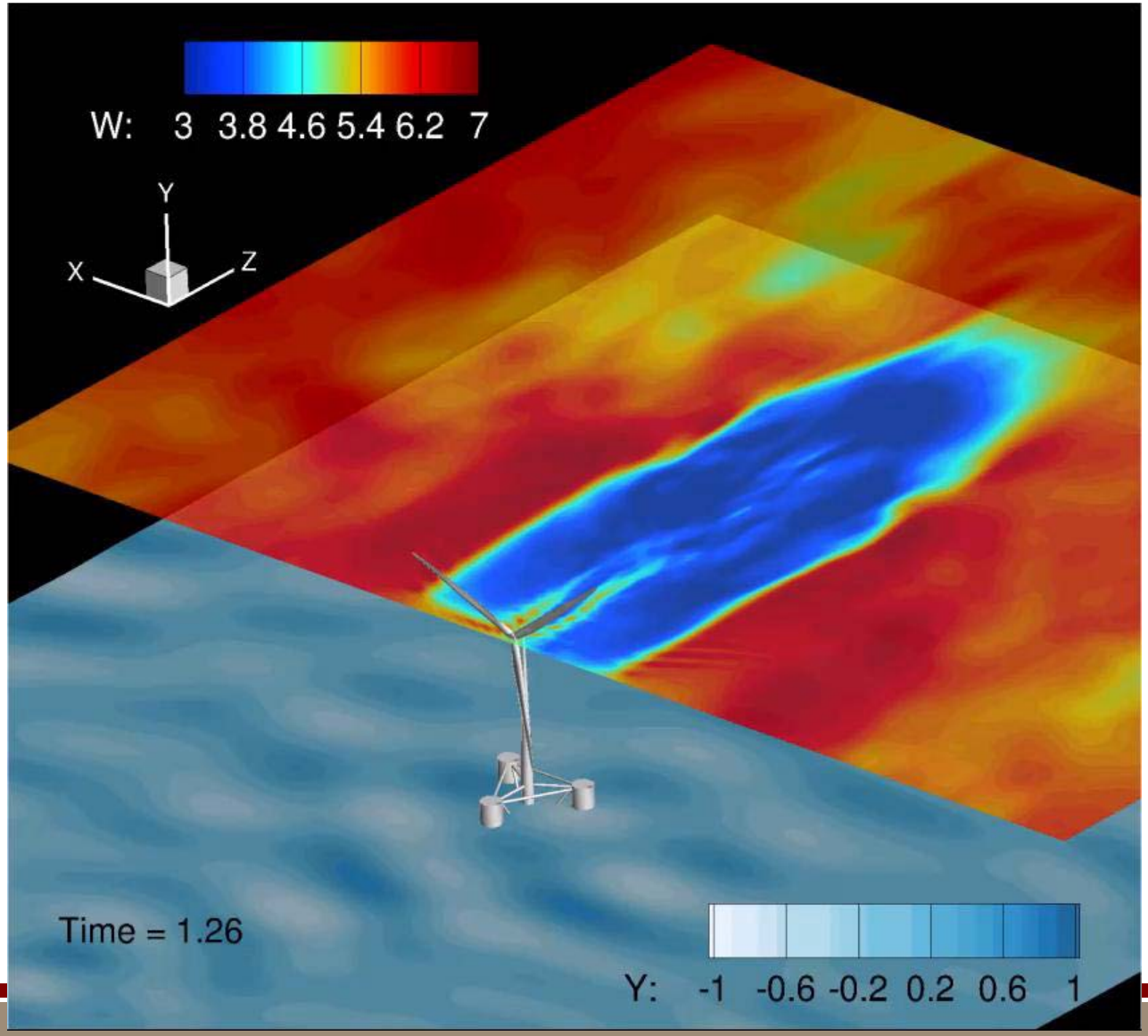
SWiFT turbines



Simulations at SNL Red Sky Supercomputer

Results for Floating 13.2 MW Turbine

http://cfdlab.safl.umn.edu/content/offshore-floating-wind-turbine-simulation



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Blade Materials and Manufacturing

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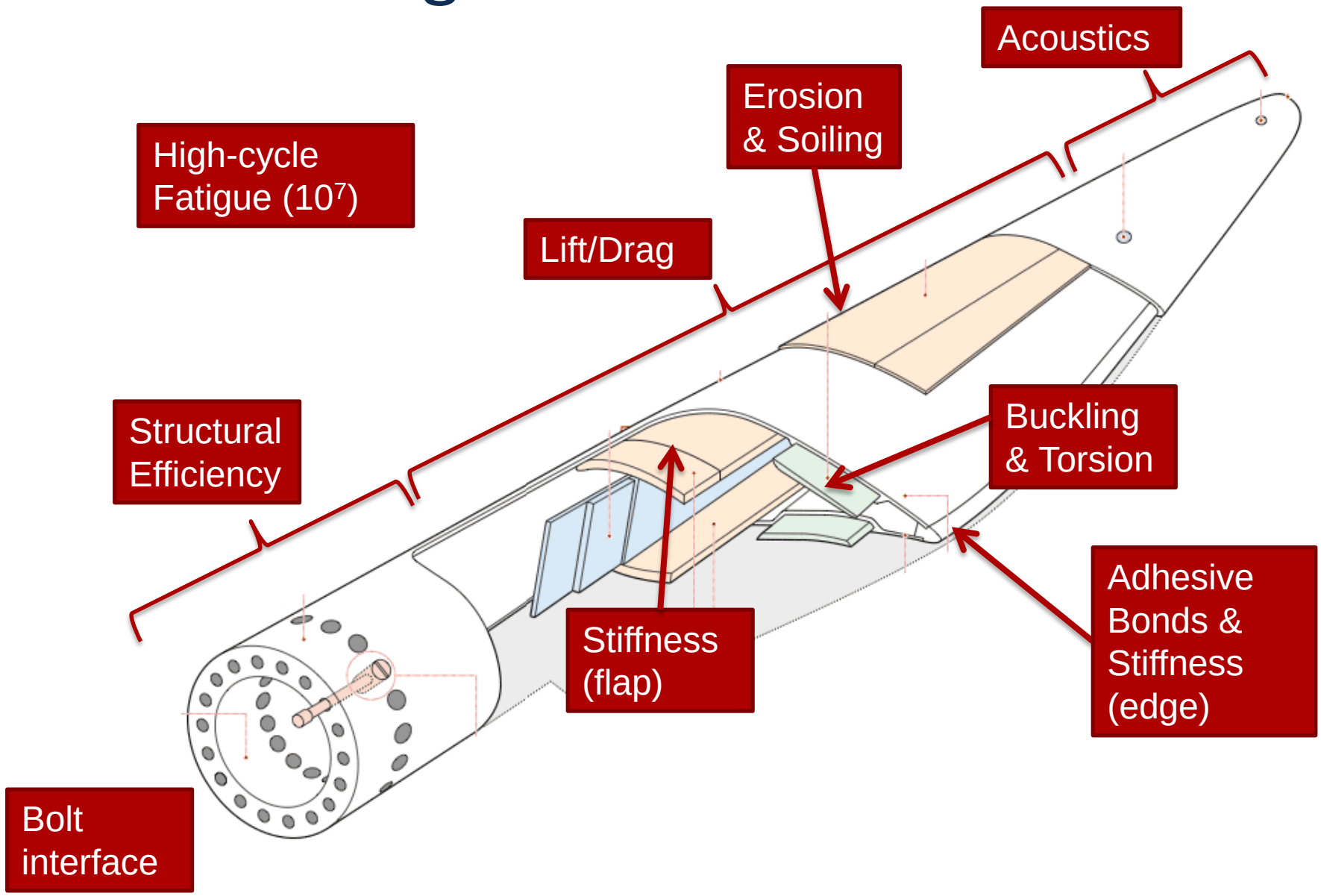
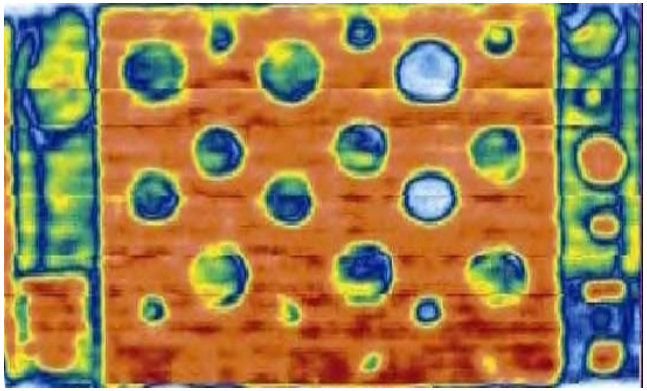
Blade Design Drivers

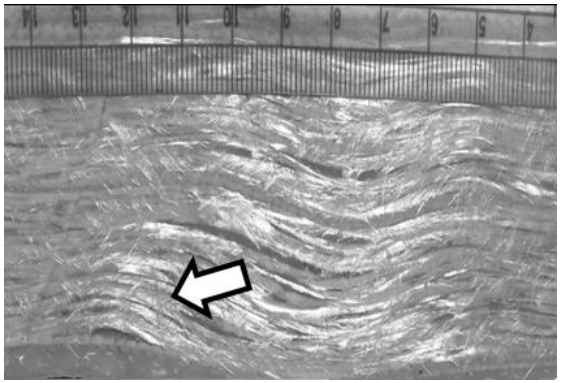


Source: Windpower Monthly July 2012

Blade Reliability Collaborative

Improve the reliability of blades through field investigations, inspection technology, evaluating effects of defects, and improved design, analysis and certification



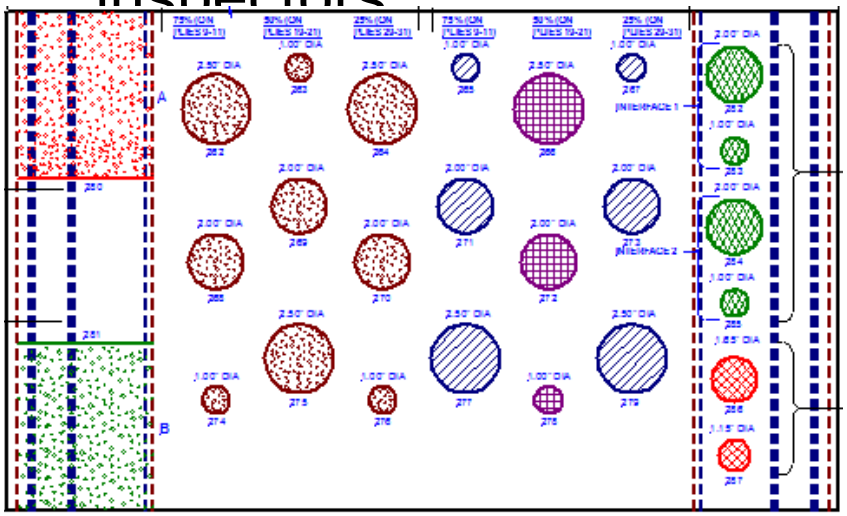


Many industry participants

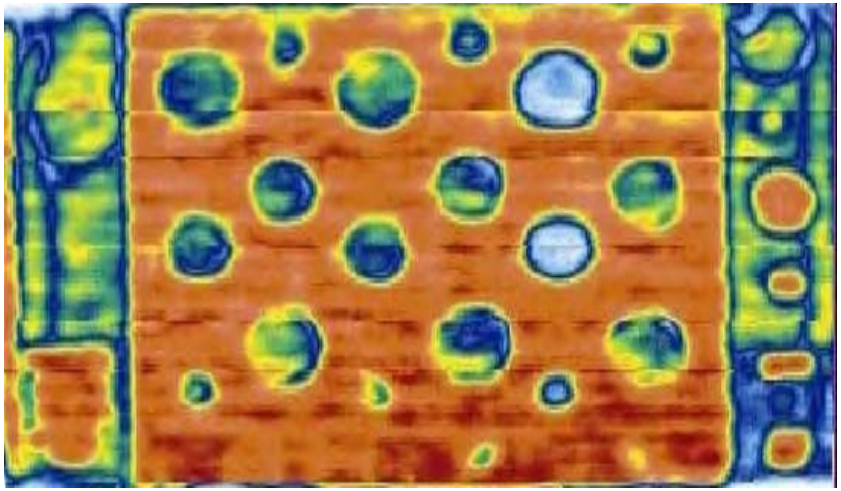
Inspection Technology

Inspection methods are need at the manufacturing plant and in the field to improve quality and reliability

- Test specimens with different flaw types and sizes
- Evaluation of non destructive inspection (NDI) methods to determine probability of flaw detection
- Operationalize methods for manufacturers and inspectors



Test Specimen of Known Flaws

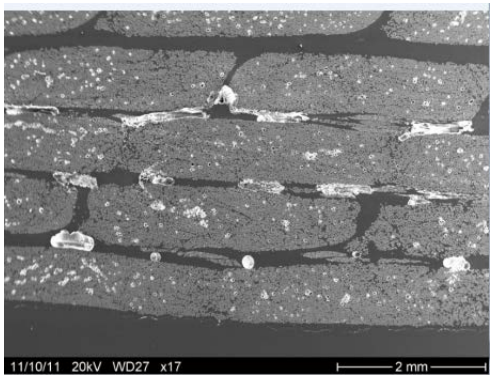


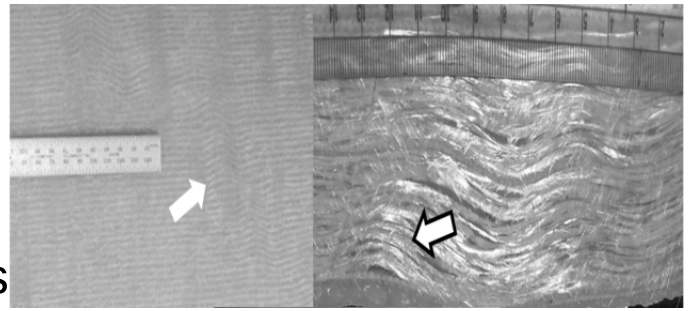
Ultrasonic Scan

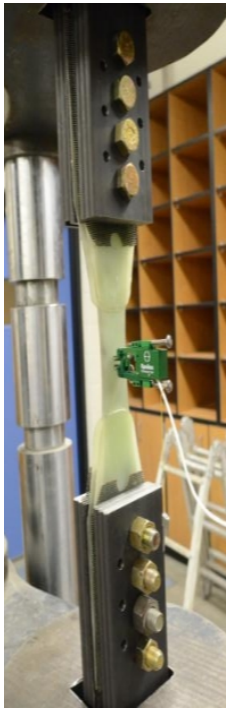
Source: SNL – Dennis Roach – Blade Reliability Collaborative

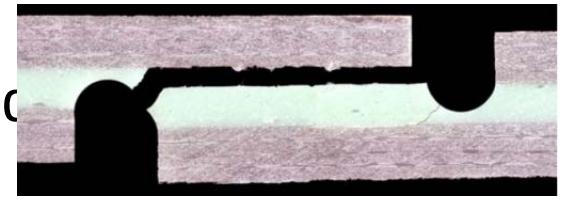
Effects of Manufacturing Defects

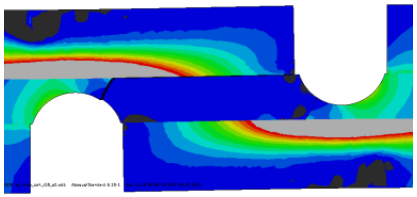
- Defects in wind laminates are unique due to scale/manufacturing
- Current standards are possibly both over and under conservative in terms of flaws
- Sandia Research
  - Build, test, model coupons and sub-structures with defects
  - Develop probabilistic models of impact on blades
- Industry impact: Quantify effect on blade strength and reliability for improved standards







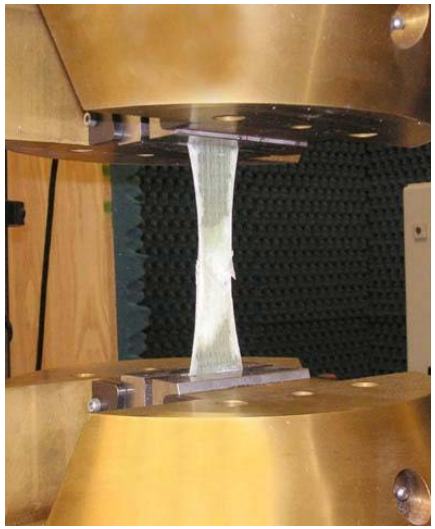


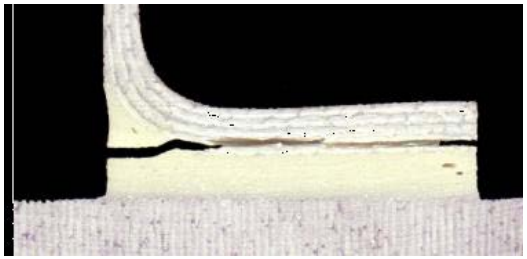


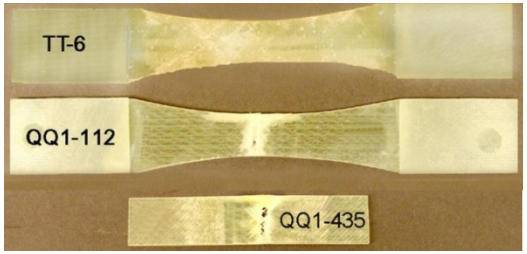
Coupon Testing

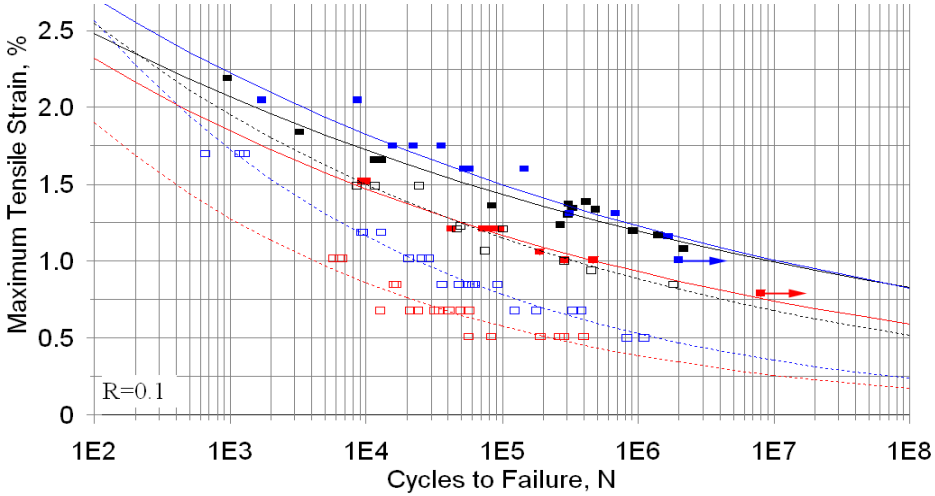
Characterize static and fatigue properties of blade materials from suppliers (resins, fabrics, adhesives, cores), and laminates and structural details from blade manufacturers.

Results published in Composite Materials Database since 1989





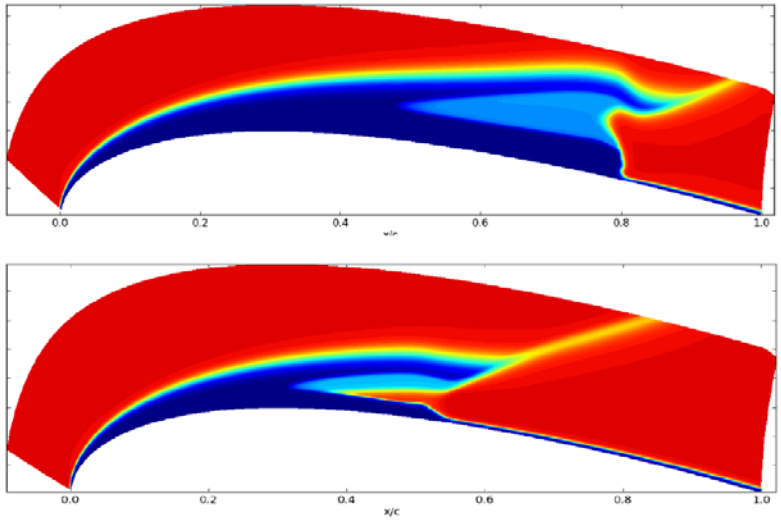




Source: Sandia National Laboratories

Leading-Edge Erosion

Characterization
Measurement
Modeling



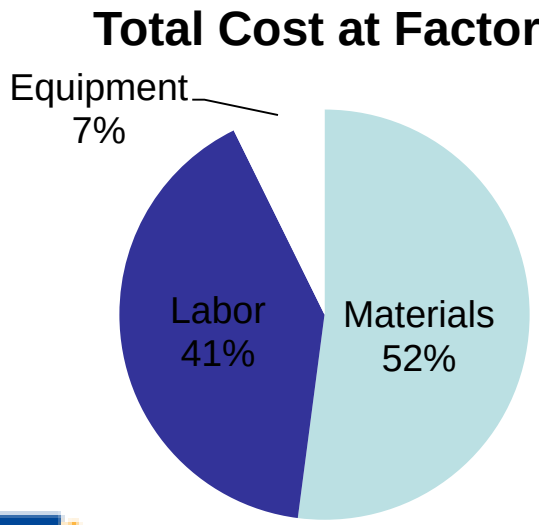
No Roughness

k_s = 350 μm

Oran W. Nicks Low Speed Wind Tunnel

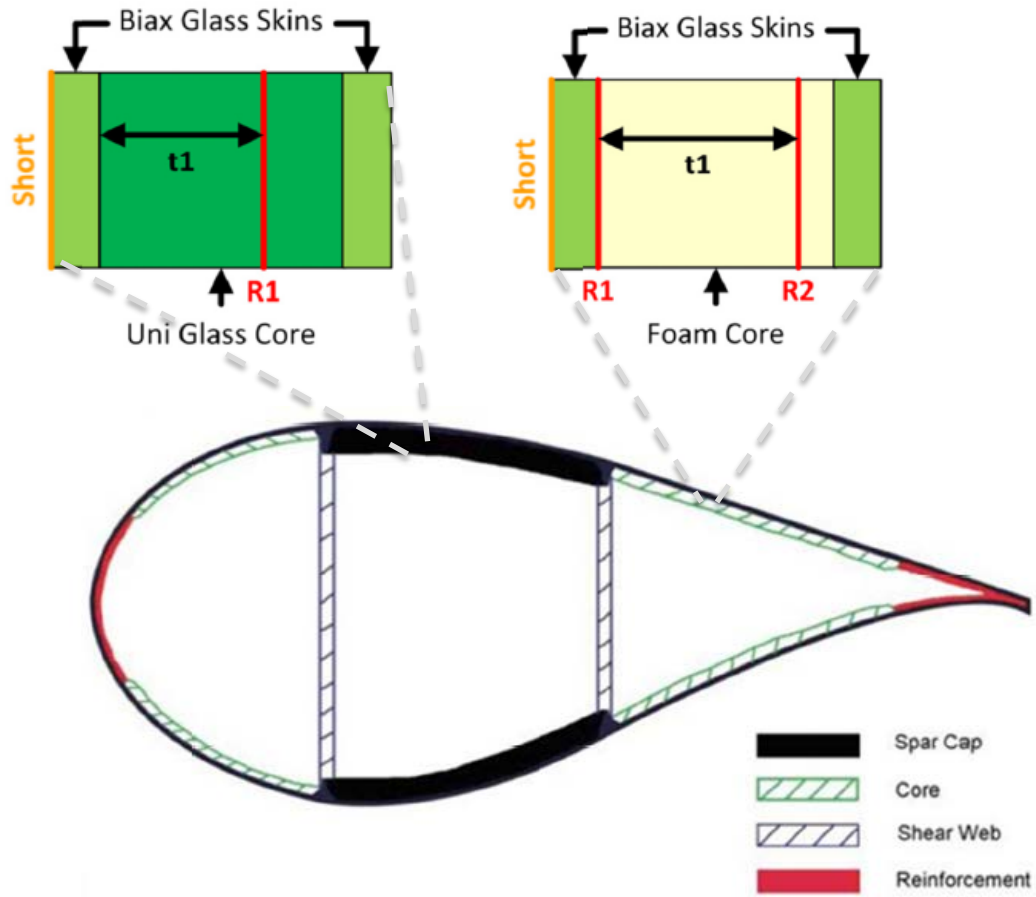
Advanced Manufacturing Initiative

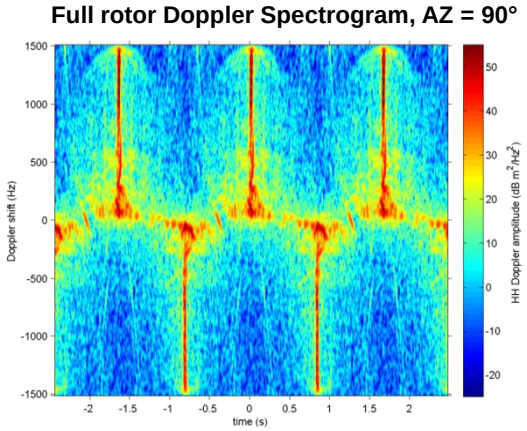
Increased labor productivity by ~14% and reduced cycle time by ~37% while maintaining or improving part quality (preliminary results).

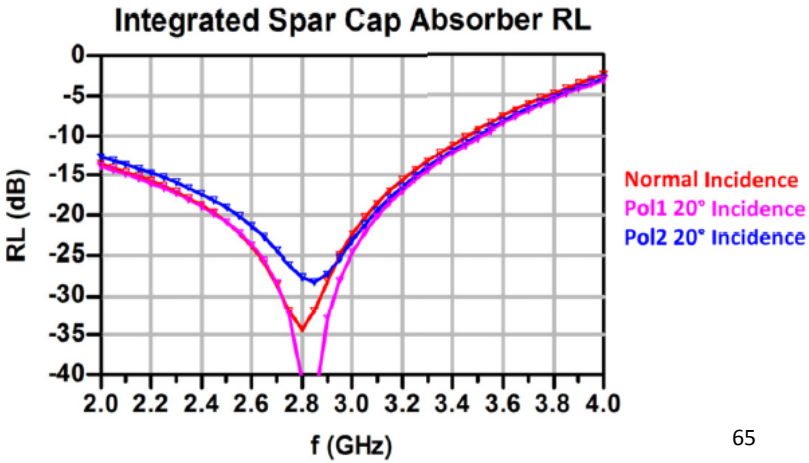


Radar friendly blade

Develop a low-cost material treatment compatible with current manufacturing processes that can reduce the RCS by 20 dB







Source: Sandia National Laboratories

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Sensors and Health Monitoring

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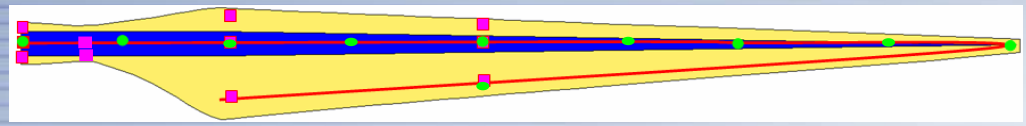
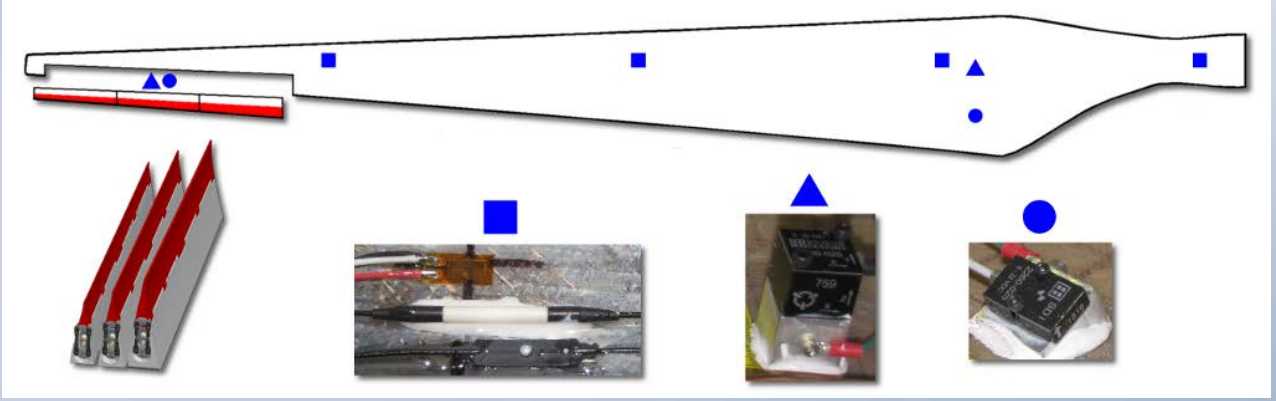
Sensor and Actuator Research

- **Research efforts are driven by advanced load control strategies and structural health monitoring**



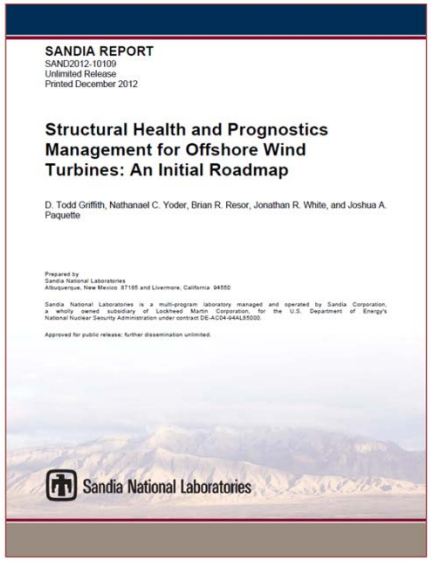
- **Address manufacturing issues**
  - Incorporation (egress/ingress, surface-mount/embed, manufacturing, maintenance accessibility, material compatibility, costs)
  - Reliability
- **Blade Projects Field Tested**
  - ✓ Sensor Blade 1
  - ✓ Sensor Blade 2
  - ✓ SMART rotor blade



Structural Health and Prognostics Management

- **Summary/LCOE Impact**
  - **Mitigate rising costs for offshore O&M** (estimated to be 2-5 times of land-based)
  - **Maximize energy capture** by increasing availability
- **Focus Areas**

  Simulation of Damage:
  1. Identify best operating signatures (sensors) : Damage Detection
  2. Analyze effects of damage (state of health and remaining life): Prognostics
- **Key Blade Downtime Issues**
  - Rotor imbalance
  - Trailing edge disbonds
  - Leading edge cracks
  - Edge-wise vibration
  - Erosion
  - Lightning
  - Icing



SANDIA REPORT
SAND2012-10109
Unlimited Release
Printed December 2012

Structural Health and Prognostics Management for Offshore Wind Turbines: An Initial Roadmap

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

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

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Approved for public release; further dissemination unlimited.

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Initial Roadmap Report

Motivations for a Structural Health and Prognostics Management System

A SHPM system that can be used to:

1. Ensure operations in a desired safe state of health
2. Avoid catastrophic failures through advanced warning
3. Aid in planning of maintenance processes versus more costly unplanned servicing
4. Improve energy capture by avoiding unnecessary shutdown

COE affected in 3 areas

$$COE = \frac{ICC*FCR + LRC}{AEP_{net}} + O\&M$$

COE- Cost of Energy ($/kWh)
ICC- Initial Capital Cost ($)
FCR- Fixed Charge Rate (%/yr)
LRC- Levelized Replacement Cost ($/year)
O&M- Operations and Maintenance Costs($/kWh)
AEP- Annual Energy Production (kWh/yr)

ICC ↑
O&M ⇓
AEP ↑↑↑

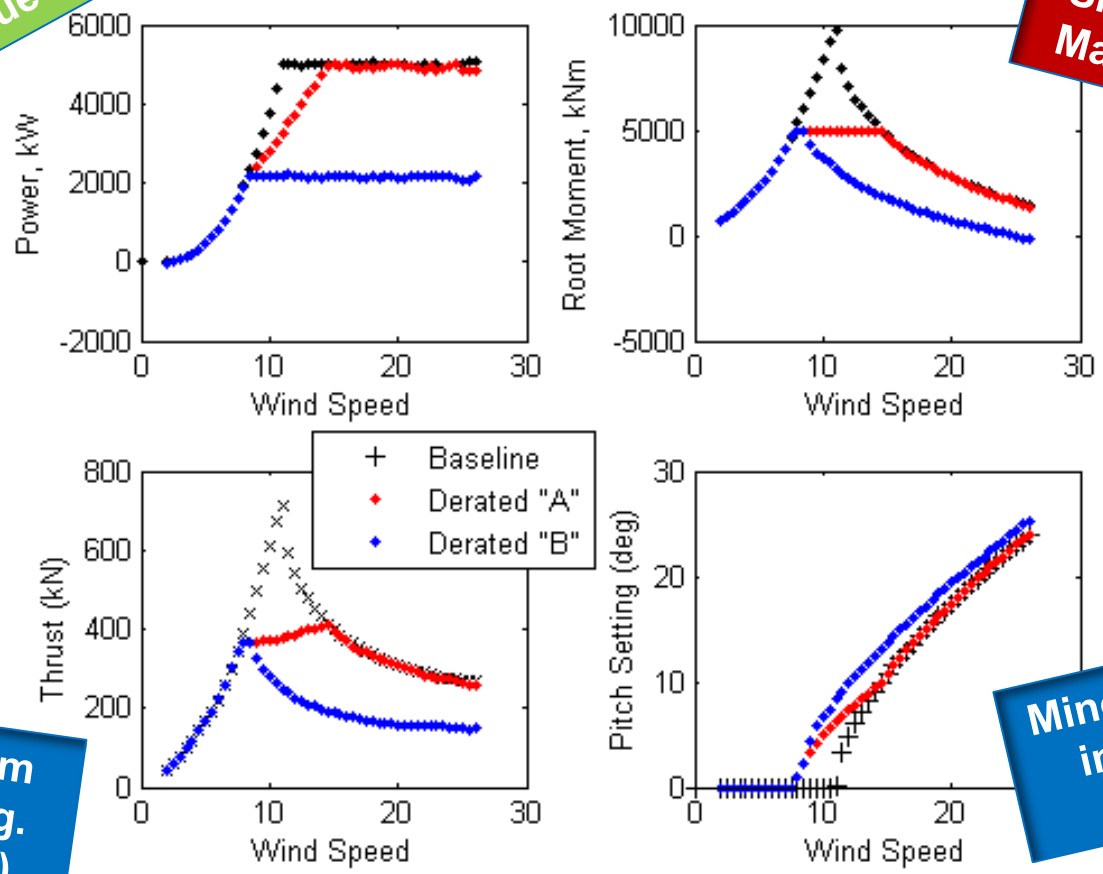
Greater motivation offshore with accessibility issues.
Reduce O&M costs and Maximize Energy Capture

Smart Loads Management

"derating", "prognostic control"

Revenue

Smart Loads Management



Secondary, System Level Benefits (e.g. support structure)

Minor Change in Control Strategy

Increase energy capture and reduce O&M costs with planned maintenance

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Design Codes and Tools

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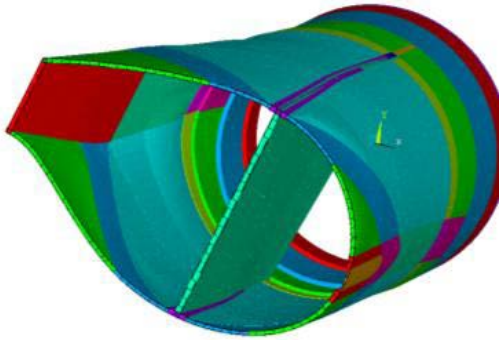
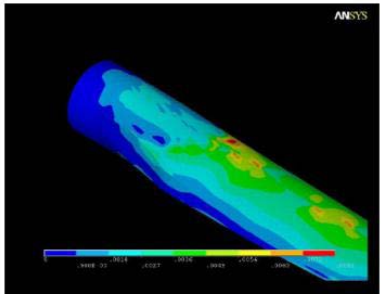
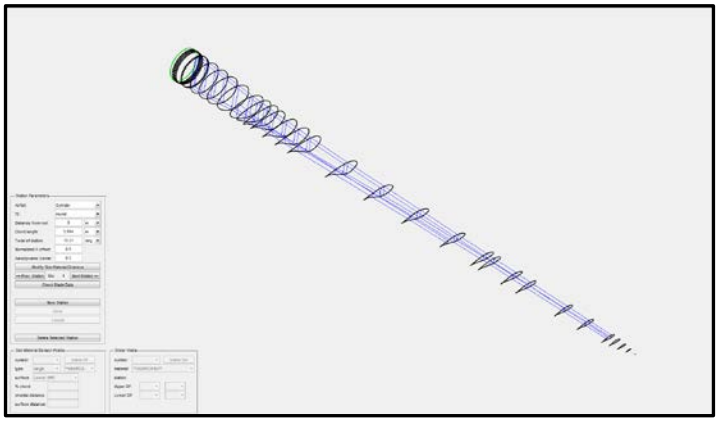
Blade Design Tools & System Modeling

- Design codes to analyze:
  - Structures
  - Aerodynamics
  - Control
  - Aero-servo-elastic stability
  - Manufacturing costs







Source: Sandia National Laboratories

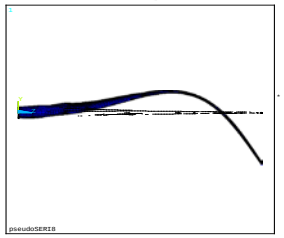
NuMAD Blade Design Tool

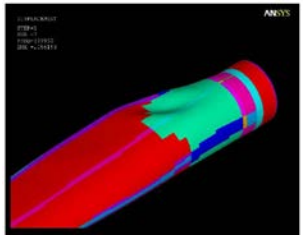
- Information manager for blade geometry, materials, and layup.
- Enables many types of analysis, including Finite Element Analysis in ANSYS

NuMAD is an example of complementing existing codes with needed capabilities.

ANSYS Analysis

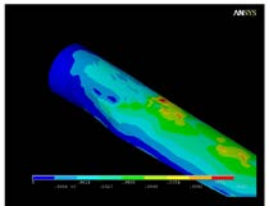
Modal



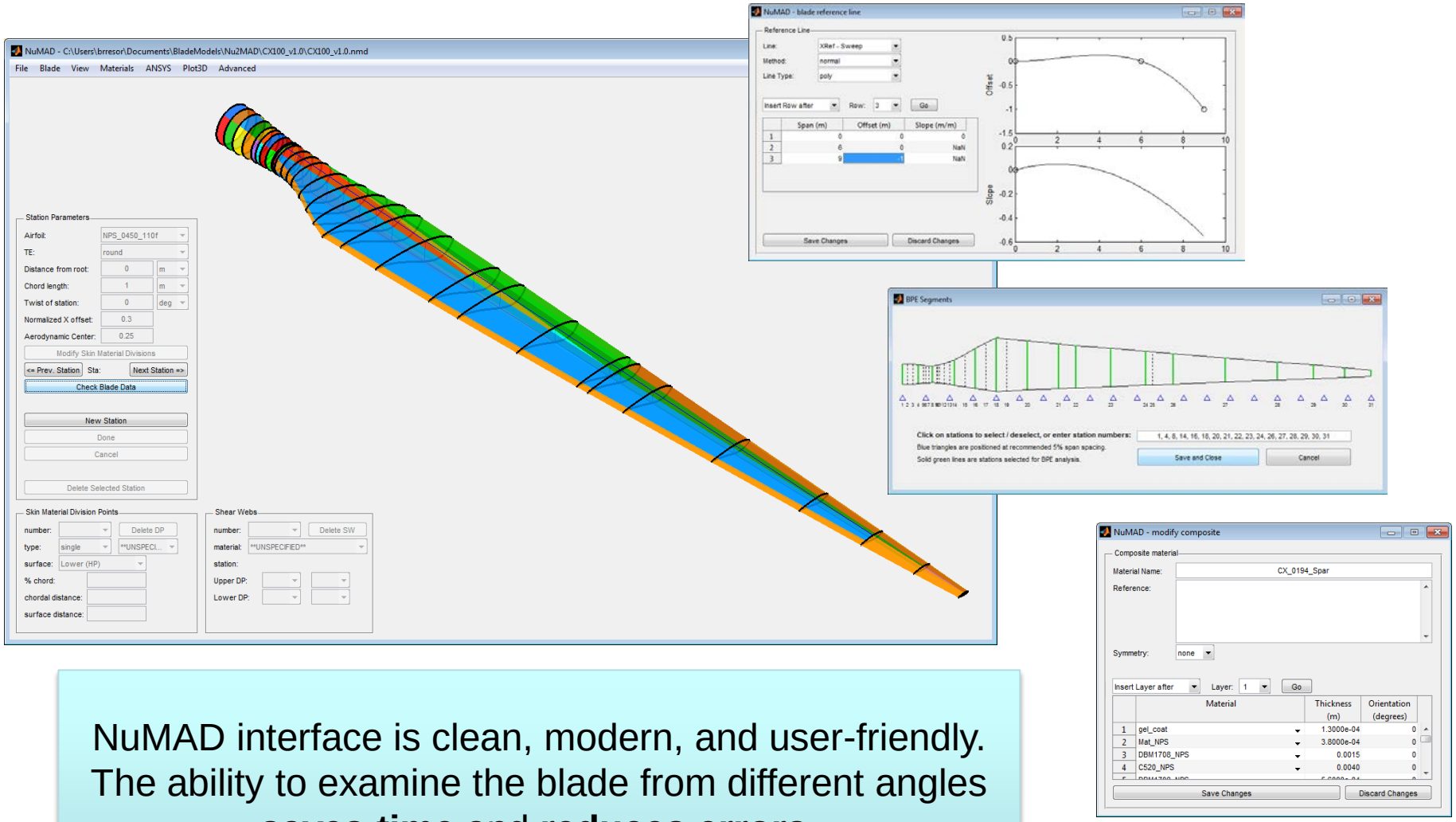


Buckling

Stress & Strain



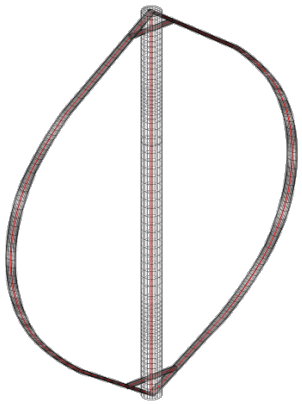
NuMAD v2.0 Interface



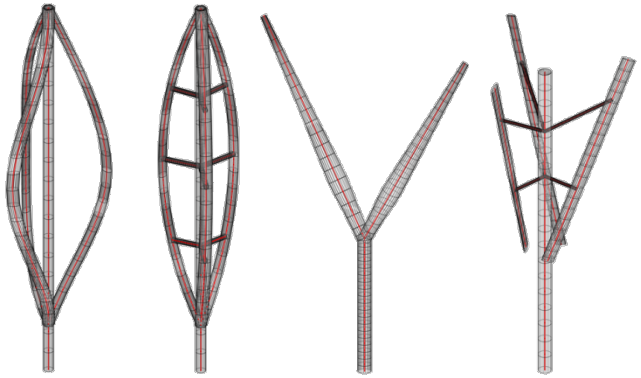
NuMAD interface is clean, modern, and user-friendly. The ability to examine the blade from different angles **saves time** and **reduces errors**.

Sandia VAWT Codes List

- Geometry/Modeling & Post-processing
  - VAWTGen Code

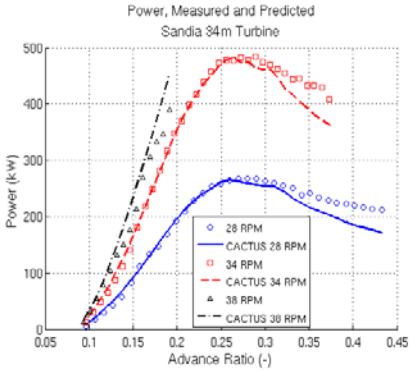


- Aerodynamics
  - CACTUS code

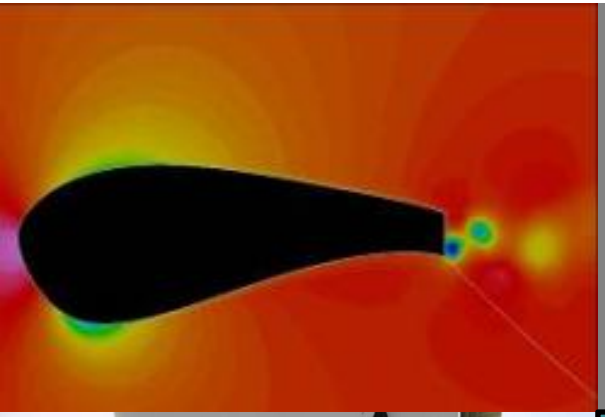
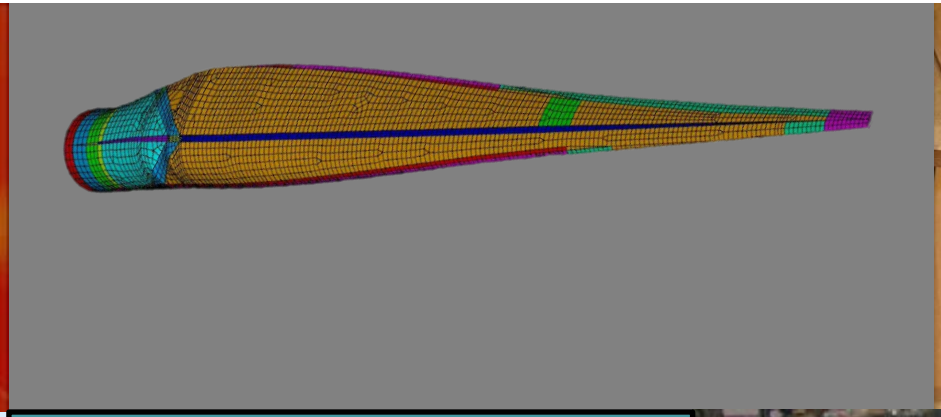


- Structural Dynamics
  - OWENS code
  - Features: Modal, Transient, Static

- Hydrodynamics
  - WaveEC2Wire code
  - Notes: Coupled with OWENS



Rotor Technology Integrators

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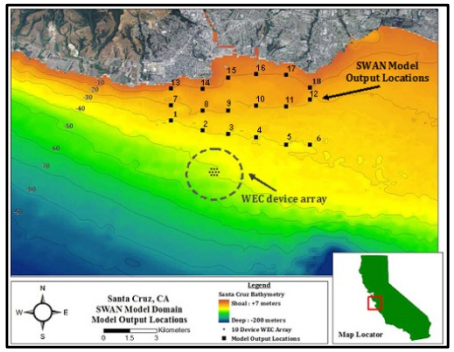

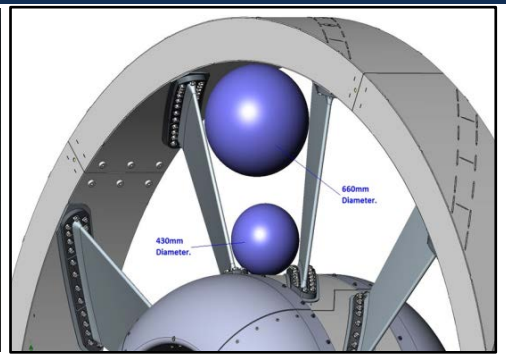

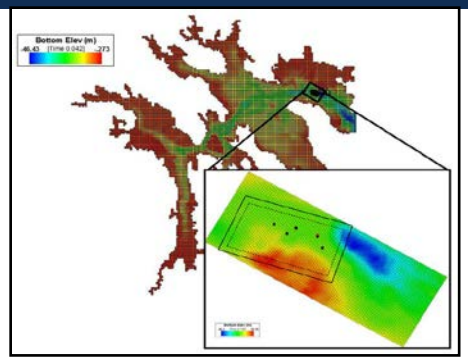

Water Power Technologies 6122

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Sandia National Laboratories

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ADVANCED WATER POWER TECHNOLOGIES PROGRAM

waterpower.sandia.gov

TECHNOLOGY FOCUS

- Wave Energy
- Current/Tidal Technologies
- Conventional Hydropower
- Offshore Wind Energy

OUR MISSION

"Enable and support an emerging water power technologies portfolio - *offshore wind, marine hydrokinetic, and conventional hydropower* through a systematic approach that develops and evaluates technology innovation and promotes environmental stewardship"

SANDIA'S CAPABILITIES

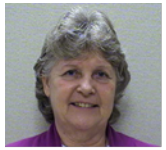
- Hydrodynamics
- Sediment Transport
- Materials and Coatings
- Economic Analysis
- Water Use Optimization
- Analysis, Lab & Field Testing
- Reference Model
- Sensor & Condition Health Monitoring
- Device Optimization
- Anchoring & Mooring

Sandia MHK Research Program

Sandia National Laboratories - Water Power Technologies Department:

- Performs research and development to improve performance, lower costs, and accelerate the deployment and commercialization of water power *and* offshore wind technologies.
- Responsible for investigating all aspects of marine and hydrokinetic (MHK) device design, performance, system reliability, system integration, resource characterization, and environmental evaluations, through basic and applied research.
- We develop tools and methods to improve device performance and reliability, understand and minimize environmental disturbance, and effectively classify and characterize resources.

Water Power Technologies



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Tim Crawford – Manager (acting)

Mario Pino – Financial

Sunni Moore – Admin Support

Diana Bull – R&D S&E, MHK

Tim Crawford – Program/Project Manager

Guild Copeland – R&D Laboratory Support Technologist

Todd Griffith – R&D S&E, Offshore Wind

Chris Chartrand– R&D LTE, MHK

Carlos Michelen – R&D LTE, MHK

Vincent Neary – R&D S&E, MHK

Jesse Roberts – R&D S&E, MHK/Offshore Wind

Kelley Ruehl – R&D S&E, MHK

David Wilson – R&D S&E, MHK/Wind/DoD

Ann Dallman – PostDoc

Budi Gunawan – PostDoc

Ryan Coe – PostDoc

Matrix Staff

Bernadette Hernandez-Sanchez – Materials
Tom Lowry – CH Optimization
Rich Jepsen – MHK

Student

Natalie Pitcher – Clerical

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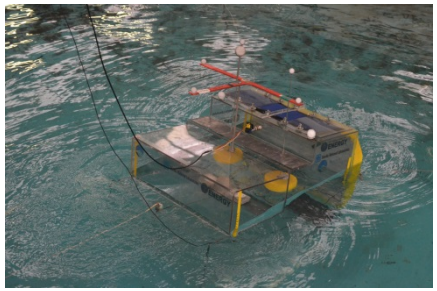

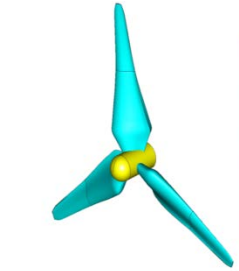

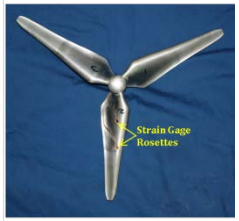

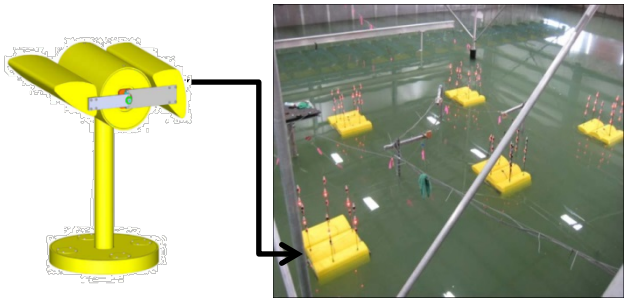

MHK Technology Development

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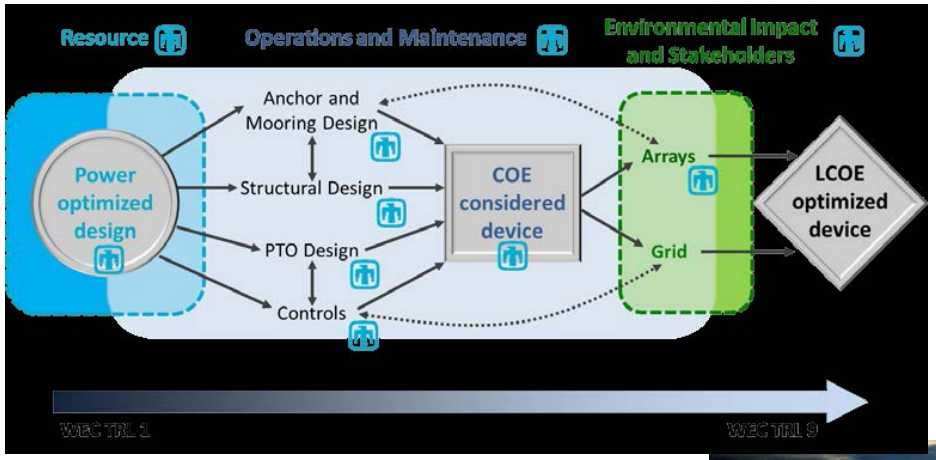
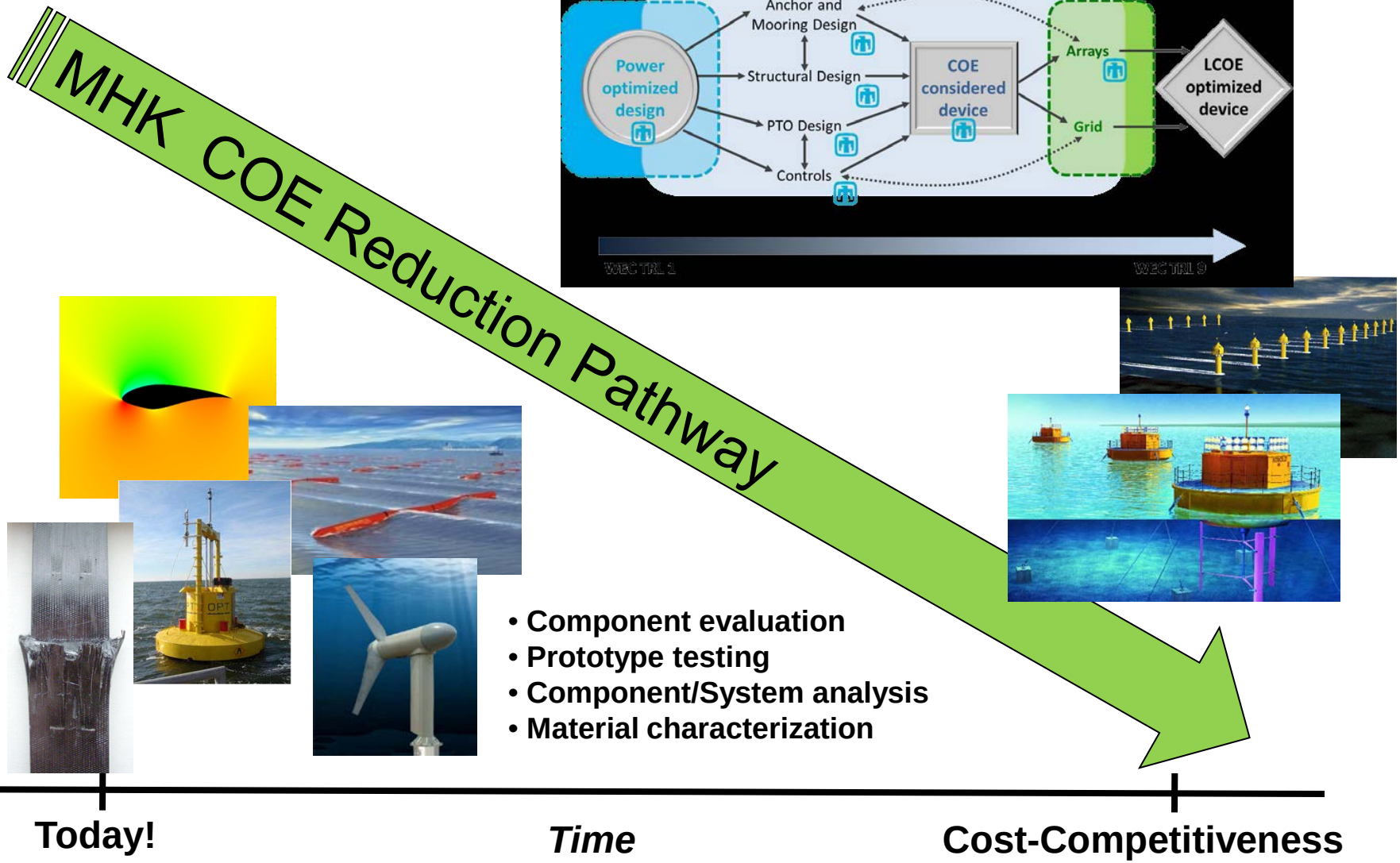
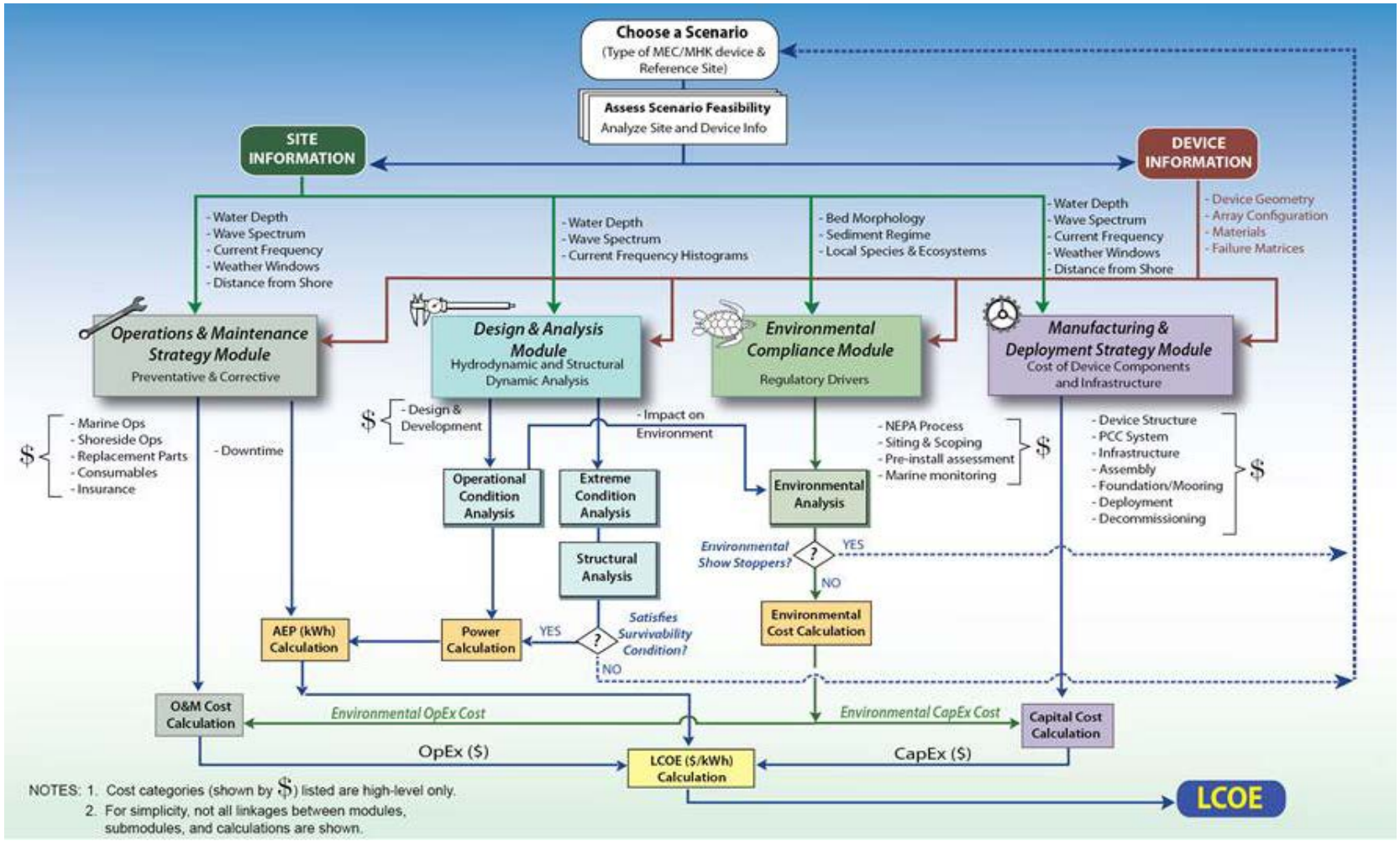
MHK Industry COE Strategy





- Component evaluation
- Prototype testing
- Component/System analysis
- Material characterization

Open-source methodology for design, analysis, and LCOE estimation



Reference Models

Accomplishment: Developed 6 public domain designs incorporating:

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

Released report on four of the completed designs highlighting the philosophy behind LCOE derivation and experimental verification.

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

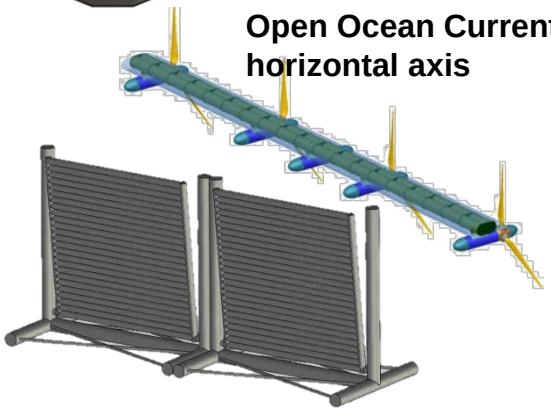
Project Impact:

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

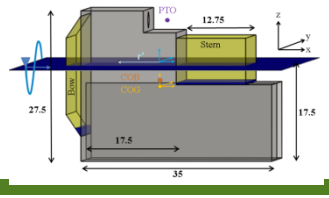
Current Work:

Launch public web site to disseminate:

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



Floating OWC
BBDB

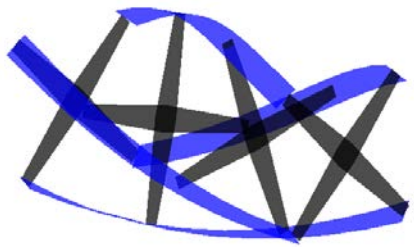


Technical Support of MHK Technology Industry Support

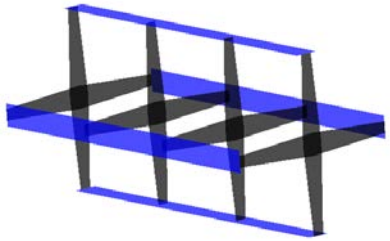
CACTUS (Code for Axial and Cross-flow Turbine Simulation) to perform a preliminary design-space search to evaluate rotor design hydrodynamic (power) performance.

<u>The numerical modeling test matrix considered the following parameters:</u>

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



CACTUS model of ORPC TidGen™ turbine



CACTUS model of straight blade turbine

Objective:

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

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

Ocean Renewable Power Company (ORPC) TidGen Turbine

Industry Support: Controls & Advanced Structures - New

Advanced Controls Projects

- Dehlsen Associates
  - Develop Advanced Controls for Multi-Pod Centipod Wave Device
- Ocean renewable Power Company
  - Investigate, Analyze, & Model a Control System
- Resolute Marine Energy
  - Develop Feedback Control Algorithm for Wave Energy Converter Device

Advanced Structures Projects

- Ocean Energy USA
  - Develop & Conduct Wave-Tank Testing on Cost-Effective Hull Design for Deep Water Wave Energy Device
- Ocean Power Technologies
  - Develop the Float-Spar, or Cylindrical Body Components of Power Buoy Wave Energy Converter

WEC Device Modeling, WEC-Sim

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

Objective:

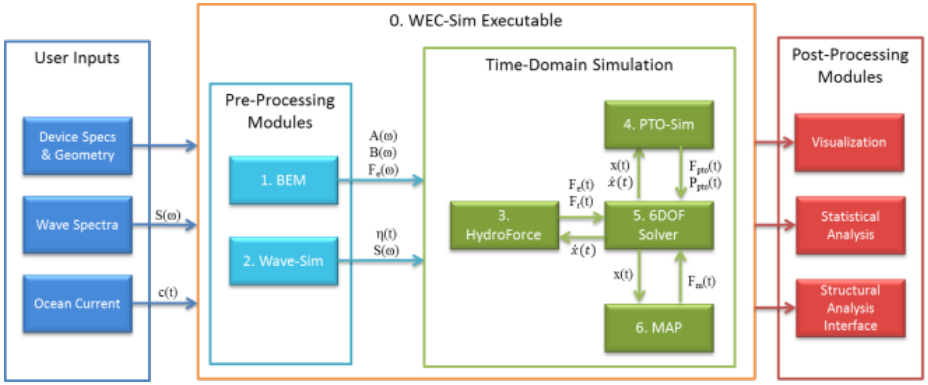
The long term objective, develop a cost effective suite of open source code modules containing a computer aided engineering tool for the development and optimization of wave energy conversion devices.

Project Impact:

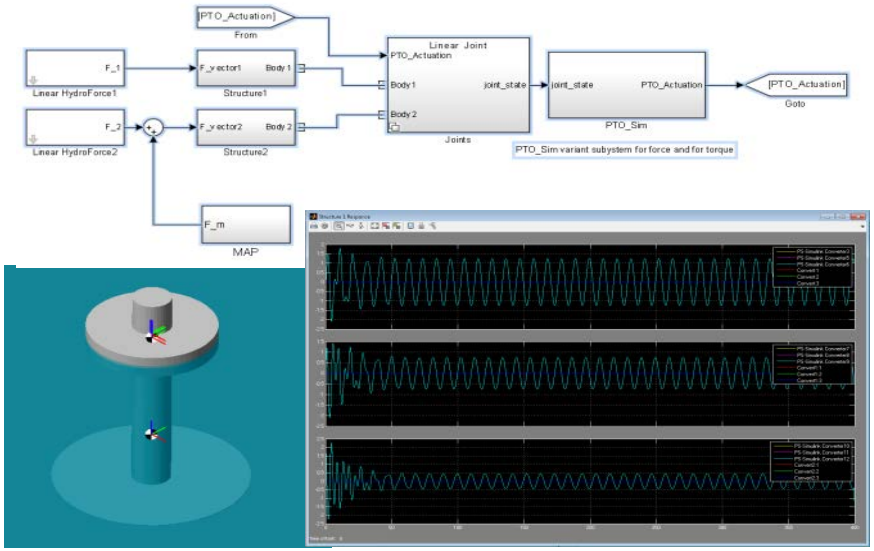
- WEC-Sim will provide the wave energy community a low cost alternative to commercial WEC modeling tools
- Allow early stage developers to optimize their design using the easily customizable open source code.

Future Work:

- SNL and NREL will work together to perform verification of WEC-Sim through a code-to-code comparison to the commercial codes WaveDyn and AQWA.
- Numerical model results will also be compared to experimental data, and a Beta version of WEC-Sim will be released in FY14.



WEC-Sim Module Structure



WEC-Sim Implementation in SimMechanics

Extreme Conditions Modeling

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

WECs are vulnerable to large waves for a number of reasons:

- Mooring lines and connection points
- Over-excitation and over-extension of components within the power conversion chain (PCC).

Objective:

- Develop an ECM Procedure that can help the WEC industry design WEC devices to withstand extreme events (i.e. extreme seas).
- Demonstrate & validate the ECM procedure by designing and testing three devices in an extreme events experimental testing campaign.

Current Work:

ECM workshop to identify and direct research to advance the wave energy industry towards commercial viability.

Workshop Objectives:

- Review current design methodologies
- Understand offshore oil & gas and shipping methodologies
- Identify conditions that result in extreme loads on WEC devices
- Identify existing numerical and experimental design methods and tools
- Determine how experimental and numerical design methods and tools need to be improved and identify research to meet the goals

Images courtesy of Columbia Power

survival *- "the ability of a marine energy system to avoid damage, during sea states that are outside of intended operating conditions, that results in unplanned down time and the need for service." – Brown et al., 2010*

Wave Array Performance and Optimization

Accomplishment:

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

Objective:

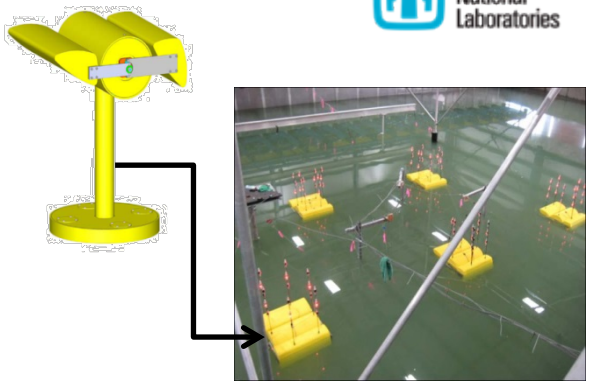
- The SNL-SWAN WEC Module incorporates frequency- and directional-dependent energy extraction terms that better model Wave Energy Converters (WECs).
- Validation of SNL-SWAN will based on the Oregon State University (OSU) Tsunami Basin array power performance data collected from the OSU wave tank tests.

Project Impact:

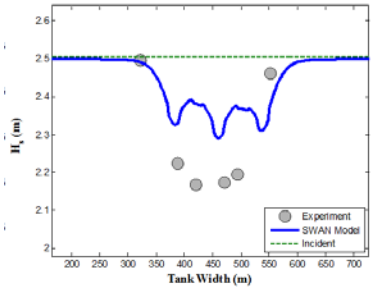
SNL-SWAN will provide a fast solving array modeling tool, allowing developers to perform preliminary array layout optimization and determine potential environmental impacts of deploying wave farms.

Future Work:

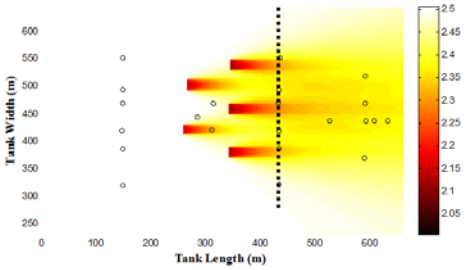
SNL will continue to perform comparison to experimental data from the Oregon State Tsunami Wave basin array tests. A Beta version will be released in FY14.



OSU Wave Farm Tank Tests



SNL-SWAN Experimental, Numerical Comparison



RCW based WEC power absorption

SWAN Application - Wave Modeling for Far-field Environmental Effects

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

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

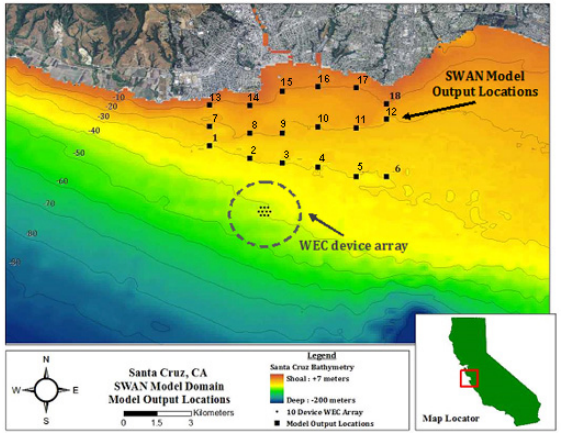
Incorporated eight different WEC device types, four array sizes, and three device spacing's into the validated Monterey Bay model domain at three different locations and performed sensitivity analysis of wave propagation and obstruction parameters.

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

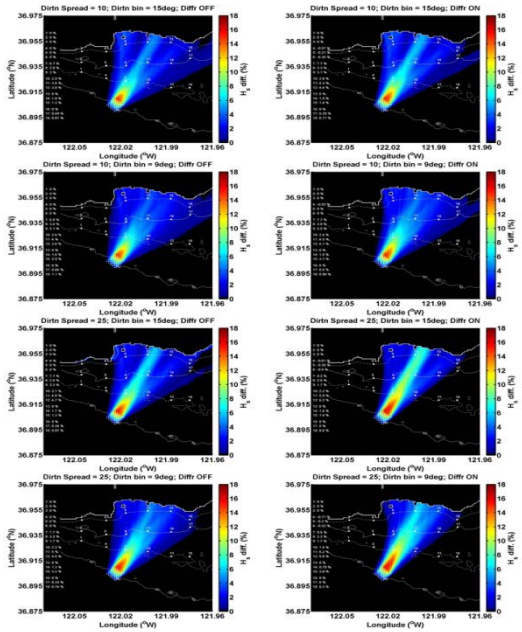
Project Impact:

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

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



SNL-SWAN model domain with example 10-WEC array



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

Open Source and Outreach for Current and Tidal Turbine Models

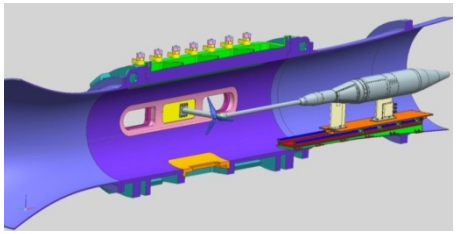
CACTUS code User's Manual has been developed and released.

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

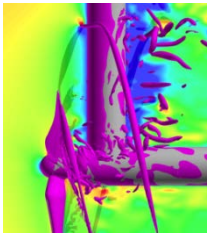
Objective: Improve MHK industry modeling capabilities for hydrokinetic turbine design and analysis and provide developers and researchers an open source CACTUS model that incorporates techniques unique to a single package and allows for rapid design turnaround.

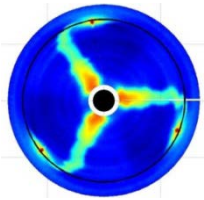
Project Impact: This simulation capability will improve the performance of the next generation of axial-flow and cross-flow hydrokinetic turbines. Many researchers and industry developers are actively using this code.

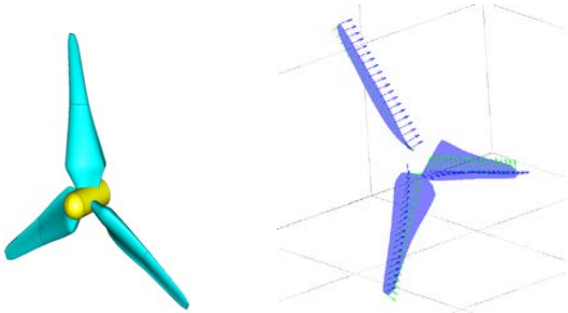
Future Work: Experimental performance data collected from scaled model testing of the Reference Model 2 cross-flow turbine at The St. Anthony Falls Laboratory Main Channel, at the University of Minnesota, will be used to evaluate CACTUS model performance simulating a cross-flow hydrokinetic turbine.



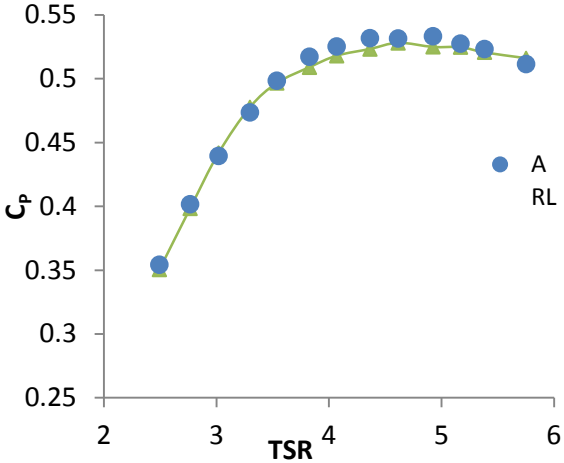
Experimental set-up at ARL water tunnel





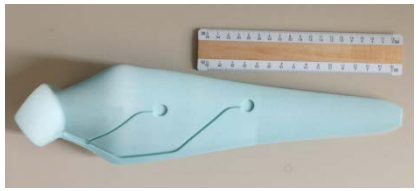


Sandia hydrokinetic turbine (left) and CACTUS model of turbine (right)



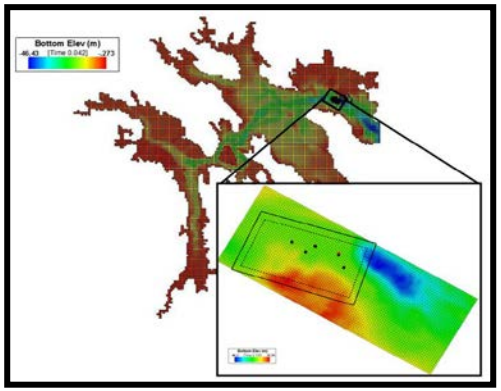
CACTUS predicted power curve (green) compared to experimental measurements from ARL

Rapid prototype foil showing location of strain gages



MHK Device Performance Modeling and Analysis

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



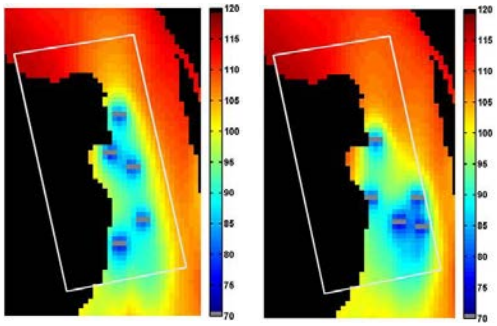
Cobscook Bay, ME regional and local model domains

Objective:

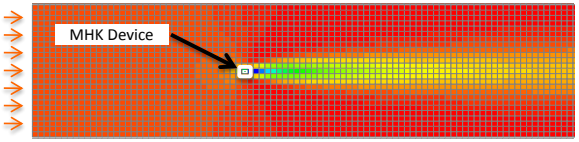
- To reduce cost of energy through strategic deployment of MHK devices
- Enhance and apply simulation tools to investigate optimal array spacing

Project Impact:

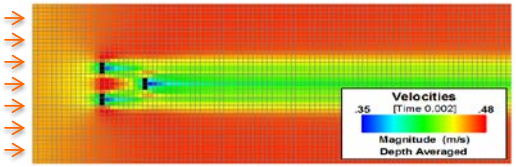
- Application of SNL-EFDC at key industry sites will help maximize power and minimize potential environmental effects. (Sediment Transport)
- Mature the simulation modeling to become more highly technically defensible
- Increase confidence in its use as it becomes the industry standard tool.



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



SNL-EFDC simulation of single turbine in a test flume



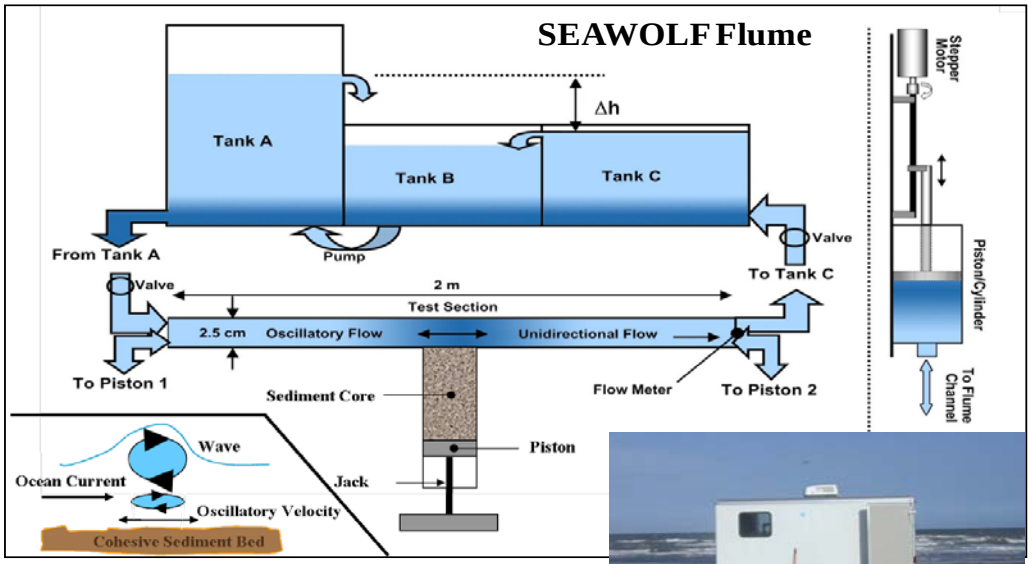
Simulation of actuator disk array in a test flume

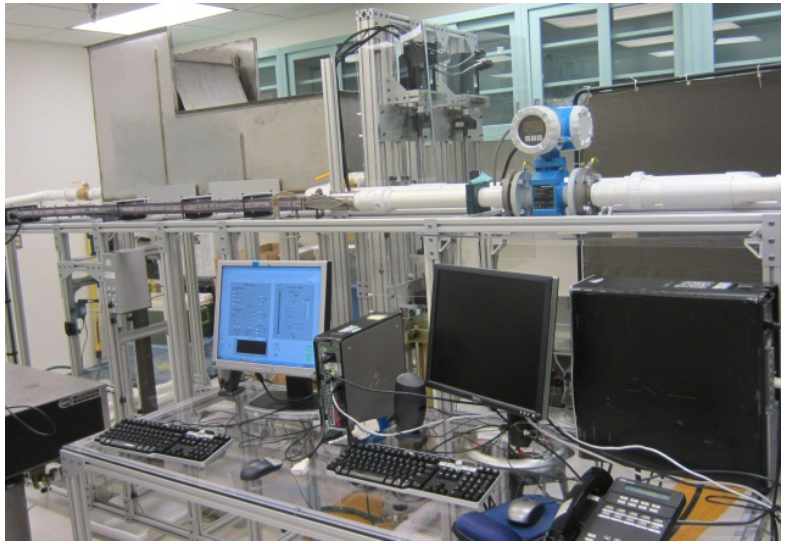
Schematic of the ORPC TideGen™ turbine.

Sediment Field Measurements & Dynamics Lab

ASSET and SEAWOLF Flumes

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



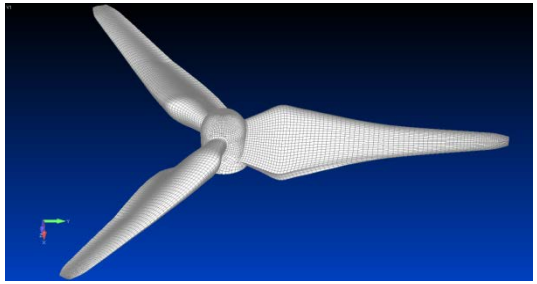


Sediment Dynamics Laboratory

Acoustics

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

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



Finite element mesh of reference CEC turbine

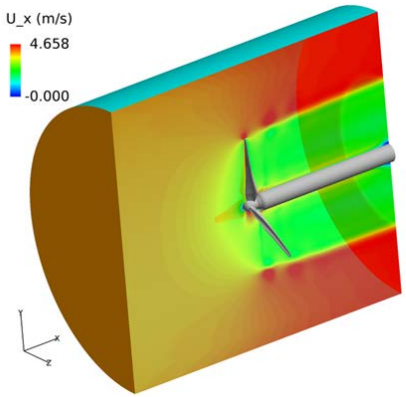
Objective:

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

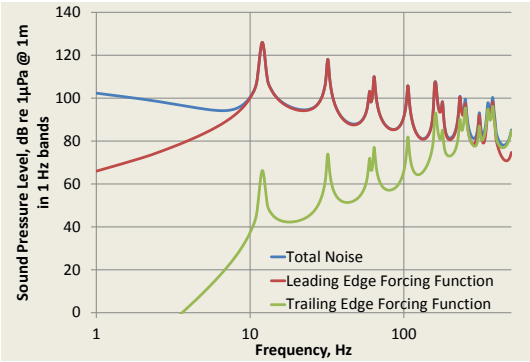
Project Impact:

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

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



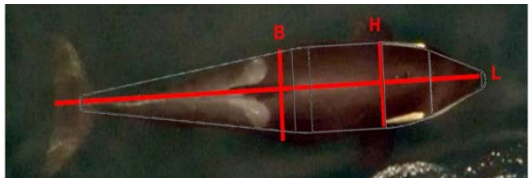
Flow computational domain with axial velocity contour



Predicted sound pressure levels from reference CEC turbine

Strike Analysis

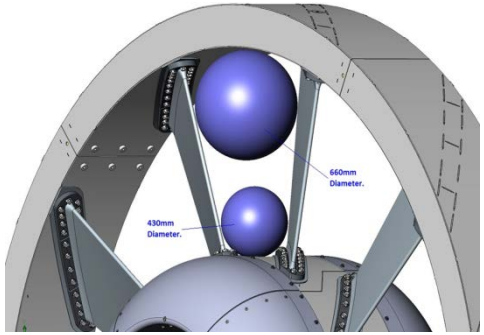
- Analysis for the Southern Resident Killer Whale (SRKW) with the new material properties has also been accomplished.
- Sandia and PNNL developed & executed test plan to determine whale skin and blubber material properties from two SRKW carcasses.
- The new simulations use a refined model that includes the more realistic blubber and skin data from recent tests.
- Simulation results are completed and will help biologists determine whether this particular device could cause significant injury to killer whales.



Southern Resident Killer Whale (SRKW)

Objective:

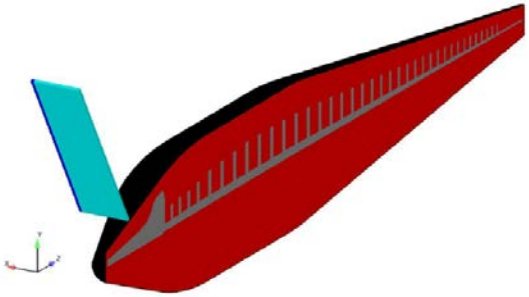
- Reduce regulatory concerns about marine mammal interactions with CEC devices by simulating marine mammal blade strike and identifying the type and extent of tissue damage.
- Specifically, SNL will determine, via computational simulation, the structural dynamic impact such as force and material deformation during the strike event and PNNL will use these results to assess the tissue response.



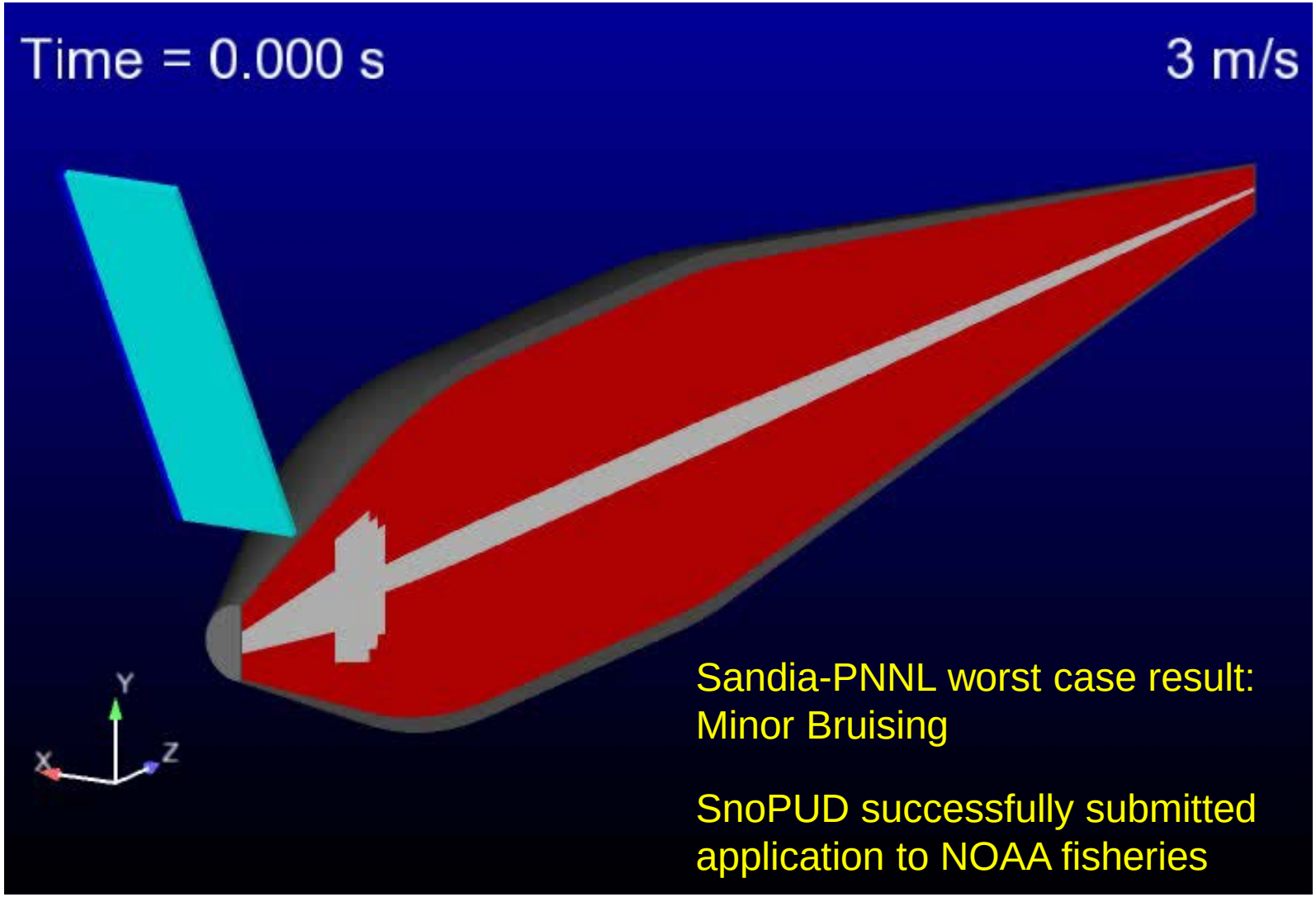
Schematic of Open Hydro turbine

Project Impact:

- This work leverages a unique structural dynamics code (PRESTO) developed by Sandia for weapons applications along with a collaborative effort by PNNL to obtain materials properties for marine mammal tissue.
- The results of this work will allow regulators to assess the potential for injury to marine mammals from various turbine designs & deployment areas.


Model representation of a SRKW showing skin, blubber, skeleton, and blade impact location

Impact Analysis



Model representation of a SRKW showing skin, blubber, skeleton, and blade impact location

Performance Testing for Hydrokinetic Canal Effects

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

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

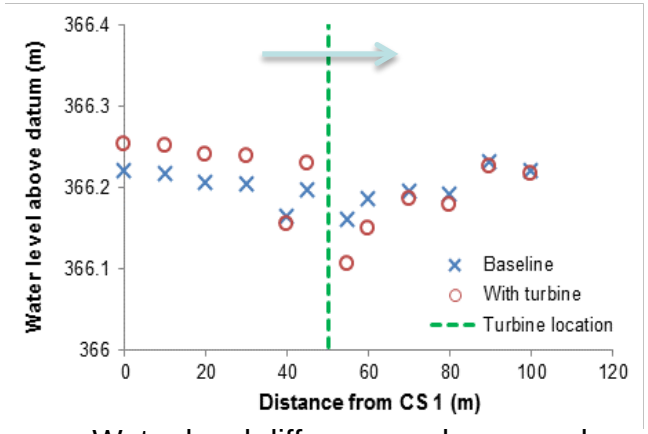
Objective:

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

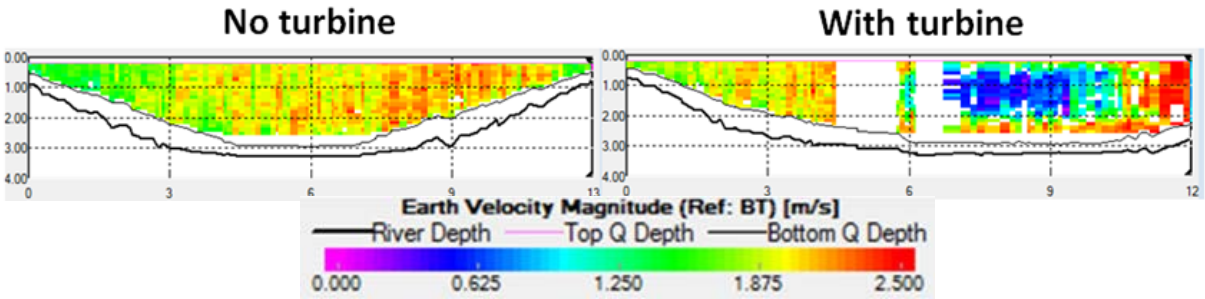
Study site near Pomona, WA

Performance testing and analysis

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



Water level differences along canal



Velocity magnitude downstream turbine utilizing Acoustic Doppler Current Profiler

Materials and Coatings

Materials & Coatings are not performing to industry expectations during deployment investigations.

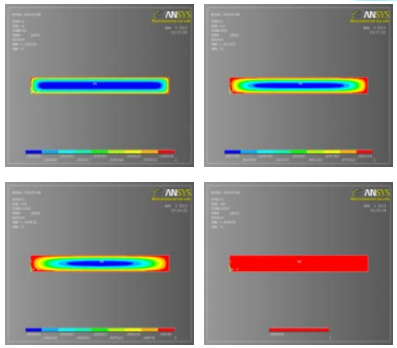
Novel solutions are needed to overcome barriers caused by commercial materials & coatings failures resulting from:

- Environmental degradation;
- Component materials reliability;
- Environmental impact (toxicity).

Objective:

Sandia's Water Power Technologies Advanced Materials Program conducts applied research and provides guidance on:

- Develop materials and coatings to Prevent Biofouling & Corrosion
- Materials & coatings issues that will impact manufacture, operation & maintenance, reliability and cost
- Development of environmentally friendly coatings
- Insight to marine effects on composites
- Salt Water Diffusion Effects on Composites
- Accelerate commercialization of marine & hydrokinetic technology
- Lower cost of energy



Simulation Models for Water Diffusion Effects on Composites

EFFECTS OF EXTERNALLY APPLIED TENSILE STRESSES ON THE MOISTURE DIFFUSION CHARACTERISTICS OF EPOXY GLASS COMPOSITES

by

Mark Thomas Steffels

A thesis submitted in partial fulfillment of the requirements for the degree

of

Master of Science

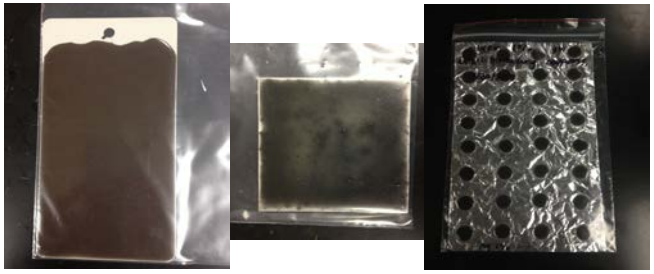
in

Mechanical Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 2013

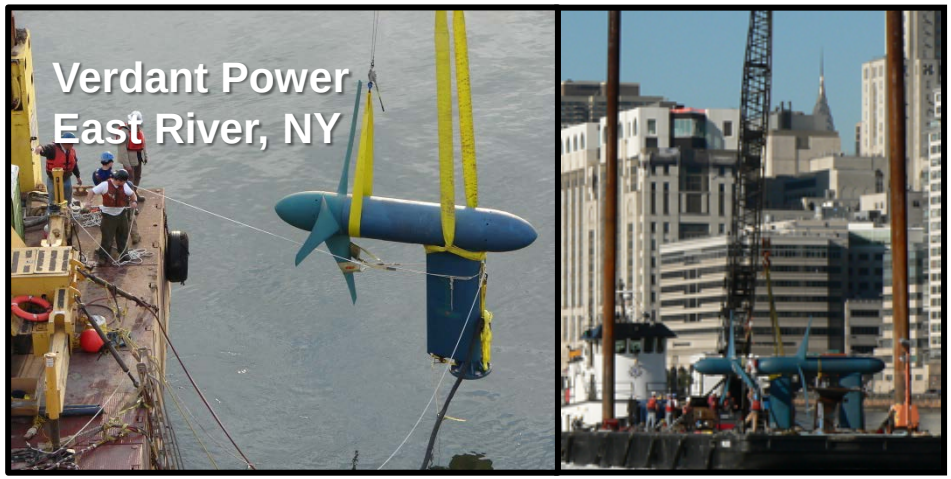
Moisture Effects on Tensile Strength for Epoxy Glass Composites



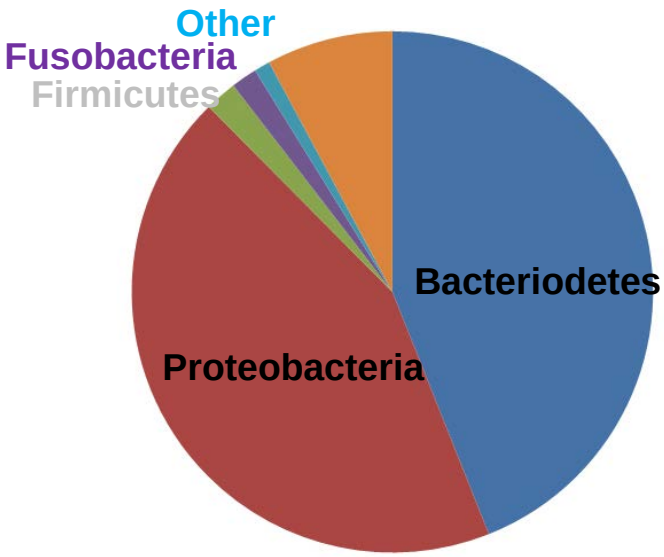
Coupons Coated with Antifouling and Anticorrosion Coatings For High-Throughput Characterization

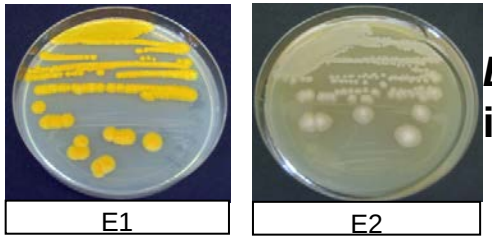
Accomplishments and Progress

Supporting MHK Industry:



2073 Operational Taxonomic Units Found





Bacillus sp. **identified**

16S rDNA Profiling

Identified bacteria in biofilms & water chemistry to help prevent future fouling.

Technical Approach

Industrial Guidance | Technology Transfer | Novel Materials & Coatings

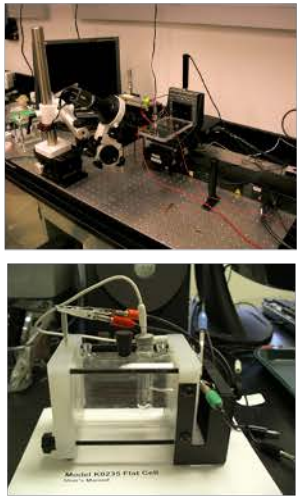
Novel Coatings Synthesis

SNL, BYU

Biofouling Testing

SNL, NDSU

Corrosion/Reliability Testing



SNL

Composite Fabrication & Performance Testing

SNL, MSU

Environmental Monitoring

ORNL

Instrumentation System Development

Fiber Bragg Grating (FBG) Bonding Test for MHK Composites

- Prepared and environmentally soaked samples and sensors
- Began static tensile tests for strength of sensor bonds and material

Objective: To support monitoring of material health and performance for MHK devices by investigating the bond strength of externally adhered fiber optic strain sensors under static and fatigue loading

Technical Approach:

- Strain sensors were bonded to coupons.
- Fiber-optic Fiber Bragg Grating sensors were selected
- Coupons were cut from a foil sample provided by Ocean Renewable Power Company (ORPC) and the FBGs adhered using methodology provided by MOI.

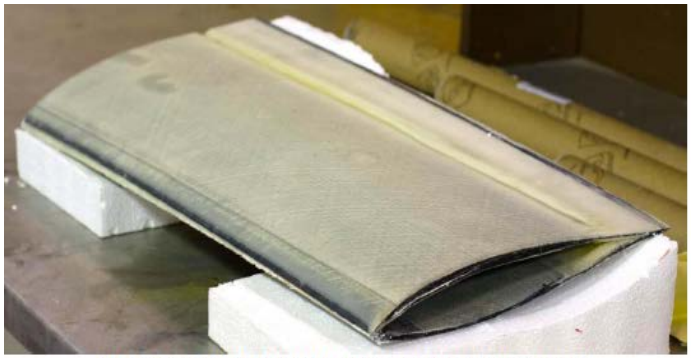


Figure 2 – Section of an ORPC-supplied foil,from which coupon substrates were cut.

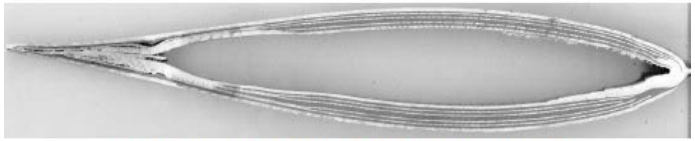


Figure 3 – Cross-section of the ORPC-supplied foil showing the laminate layup.

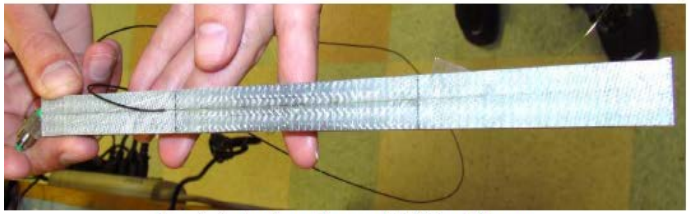
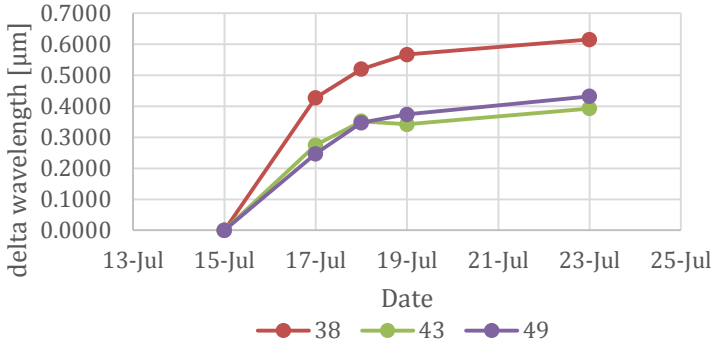


Figure 4 – Test specimen with a mounted MOI bare FBG sensor.

Figure 5 – Test specimen with a mounted MOI standard-package FBG sensor.



Temperature-compensated change in wavelength for the strain in fiber optic (Fiber Bragg Grating).

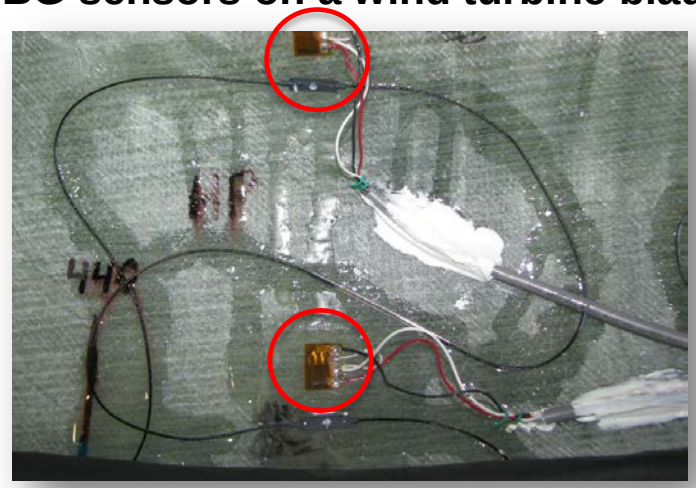
Future Steps:

- Non-Destructive Inspection & Structural Health Monitoring Program
- Developing MHK Smart Sensor (SNL) Technology and effect on resin additives

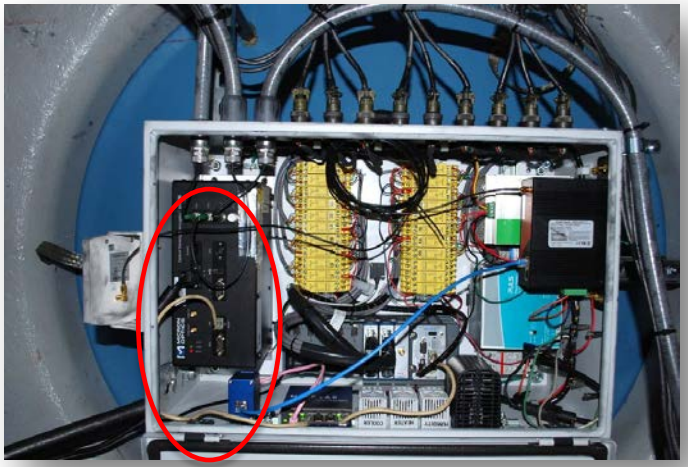
Field Measurements

Sandia's Wind Power Group: Installation of FBG sensors on a wind turbine blade

Sensor installation during blade manufacturing



Sensors surface-mounted using epoxy



FBG interrogator and other instruments installed at turbine nacelle

Field Measurements to Validate Tools

1. Design Fiber Bragg Grating instrumentation system based on turbine type and site condition
2. Bench top testing and calibration
3. System integration
   - FBG system integration with NREL's data acquisition (DAQ) system and other measurement instruments
4. Test turbine dry testing
   - FBG sensor installation at blade root
   - Various blade span lengths
   - Tower bottom to measure thrust

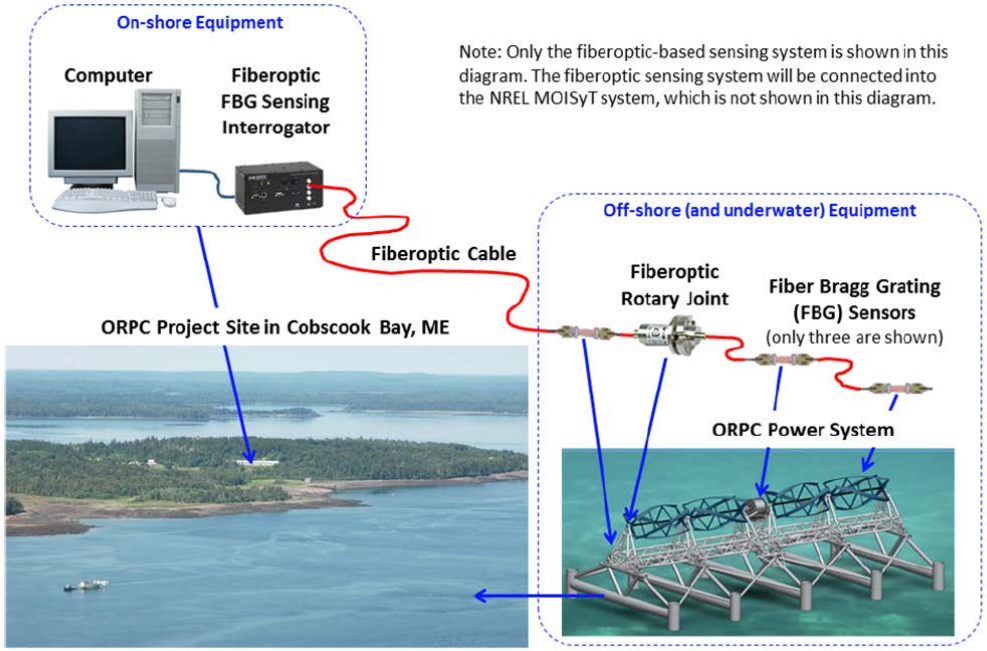


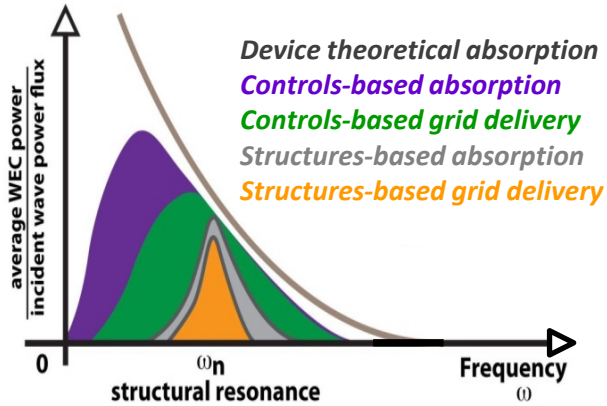
Figure 1 – Concept diagram of a fiberoptic-based sensing system for the ORPC MHK application.

Os3200 strain sensor

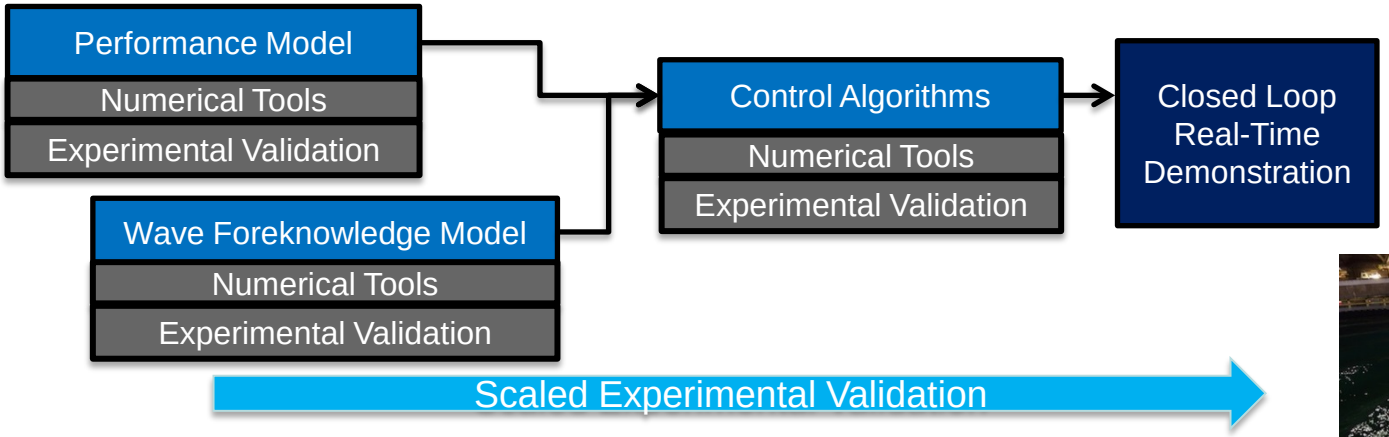
Advanced Controls

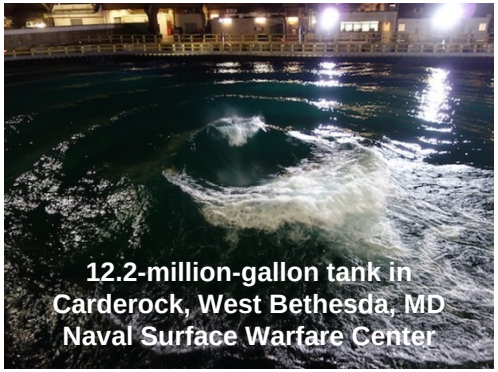
- Waves are very complex, they are spatial, temporally, and energetically variable
- They contain multi-frequencies, multi-amplitudes, and are multi-directional
- One of the objectives of this project is to understand how much of their available power can be converted and how well the WEC device can capture that power.

Program to expand the narrow band over which resonant WECs currently produce power by extending the structurally defined phase matched absorption to a real-time *controls-based* phase matched absorption.



Representative Capture Widths of a Point Absorber





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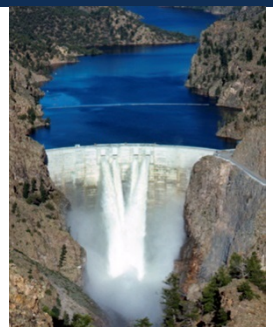

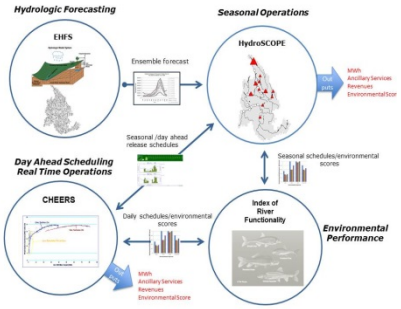

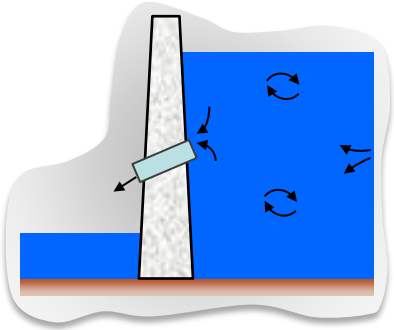

Hydropower Technology and Deployment

Water Use Optimization Toolset

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Toolset Development and Demonstration

Objective:

Improve the economic and environmental performance of hydroelectric power generating facilities by developing and demonstrating a set of numerical optimization tools that integrates hydrologic forecasting, environmental assessment, seasonal systems modeling, and day-ahead dispatching.

Project Impact:

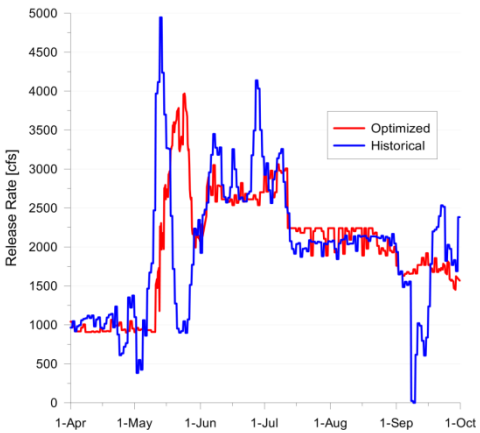
- Results for the first two demonstration sites have a 3-4% potential improvement on their power production.
- The demonstration analyses have also identified strategies and practices to potentially increase each sites flexibility and resiliency.

Future Work:

- Analysis of two additional demonstration sites, the Conowingo Dam on the Susquehanna River, MD and the Upper Skagit Dams on the Skagit River, WA.
- Development will continue to focus on toolset integration, algorithmic efficiency, as well as the user interface.

Technology Transfer:

- Refine the optimization toolset for application to each of the demonstration sites for its eventual transfer and use into each sites day-to-day operations and strategic planning activities.
- Additional demonstration sites and an increase of interest in using the toolset at various sites.



Plot showing the optimized releases against the historical releases for Blue Mesa reservoir from the Aspinall Cascade analysis.

Questions?

Concluding Remarks

- Many opportunities for cooperating in Wind Energy and Water Power research
  - Currently, cooperation in the areas of wake measurements and offshore VAWTs
- In near-term, Sandia interest to
  - Collaborate on current projects
  - Host DTU students at Sandia -- including EWEM Program students
  - Pursue joint projects, and work together in other ways of mutual benefit
- Interested to explore and discuss new areas of common interest and new ways to collaborate

Thank you