U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Reliability and A2e

March 24-27, 2014

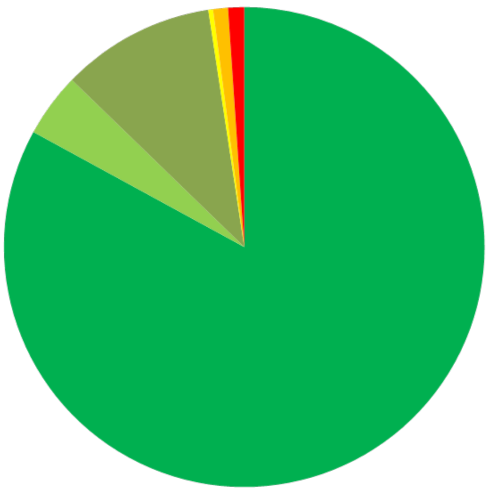
Wind Energy Technologies

PR-5000-62152

Contents

CREW Highlights:

- Identifies reliability technology improvement opportunities
- Provides industry benchmarking
  - Serves both operating fleet and next generation plants



	2013 Benchmark	2012 Benchmark
Operational Availability	97.6%	97.0%
Utilization	83.0%	82.7%
Capacity Factor	36.1%	36.0%
MTBE (hrs)	39	36
Mean Downtime (hrs)	1.3	1.6

CREW (Continuous Reliability Enhancement for Wind) Database & Analysis Program

Reliability, Operations and Maintenance (O&M), Standards Reliability, Availability and Maintainability

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March 26, 2014

Budget, Purpose, & Objectives

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Total DOE Budget[1]: $3.100M

Total Cost-Share[1]:$0.000M

Problem Statement: To identify technology improvement opportunities and benchmark performance of the fleet, unbiased characterization of reliability and operations and maintenance (O&M) performance is needed. Special challenges include rare events and the impact of aging.

Impact of Project:

- Supports DOE in prioritizing technology improvement opportunities
- Provides the industry with predictions and ability to benchmark individual plants against the fleet, to support O&M and financial decisions
  - Improves business case certainty for both new and existing plants
  - Supports owner/operators with limited engineering resources
- Capitalizes on CREW data to analyze wind plant performance

This project aligns with the following DOE Program objectives and priorities:

- Optimize Wind Plant Performance: Reduce Wind Plant Levelized Cost of Energy (LCOE)
- Accelerate Technology Transfer: Lead the way for new high-tech U.S. industries
- Mitigate Market Barriers: Reduce market barriers to preserve or expand access to quality wind resources
- Advanced Grid Integration: Provide access to high wind resource areas, and provide cost effective dispatch of wind energy onto the grid
- Testing Infrastructure: Enhance and sustain the world-class wind testing facilities at Universities and national laboratories to support mission-critical activities
- Modeling & Analysis: Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

Industry needs unbiased assessment of unreliability drivers

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

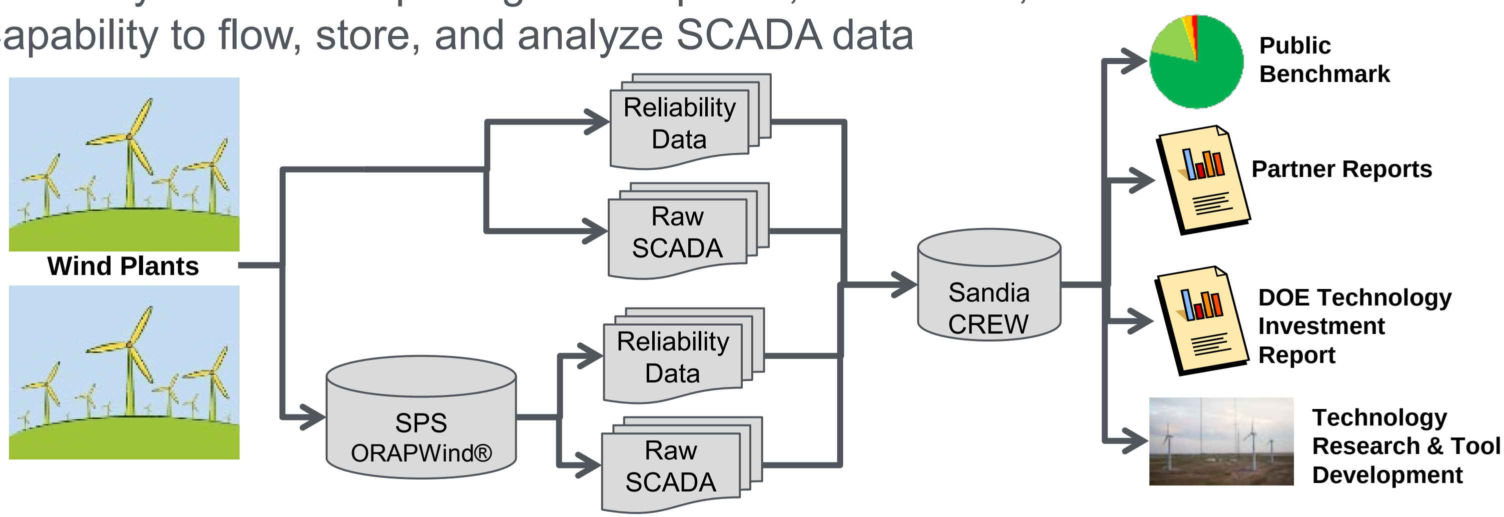
Technical Approach

Approach: Data from individual plants feeds plant-level reliability models, which Sandia aggregates into a fleet-level model. Fleet model is the basis for reliability analysis, public Benchmark, and DOE reporting. Currently, data pathway via 3rd party data partner (Strategic Power Systems) is the primary pathway. As of FY14, there is a summarized data pathway, which captures information directly from owner/operators.

Key Issues: Growth in benchmark participation and fleet representation has been slow; new summarized pathway approved by DOE to address this.

Unique Aspects

- Reliability and O&M reporting that is: public, continuous, & US-based
- Capability to flow, store, and analyze SCADA data



CREW data serves double-duty for research: reliability <u>and</u> plant-level performance

FY2012-FY2013 Accomplishments and Progress

- Published 2nd and 3rd Wind Plant Reliability Benchmark
  - Over 1900 downloads (as of Jan 2014) http://energy.sandia.gov/crewbenchmark
  - Created multi-year datasets for trending and prediction
- Published industry reports to support work order data collection
  - Work Order survey report, summarizing current use
  - Work Order value propositions report, emphasizing value of work orders to various segments of industry
  - Work Order System reference and best practices, documenting other industries' experience and tips for the Wind industry

CREW Reliability Benchmark is now embedded in wind industry

FY2013 Re-evaluation

- Conducted full evaluation of opportunities, including interviews with 11 owners (representing 37% of the US fleet), plus DOE, NREL, NERC, OEMs, and consultants
- Feedback Highlights
  - Owners are developing in-house reliability monitoring and data mining
  - Owners find benchmarking highly desirable
    - Owners very willing to participate if Sandia is collecting & auditing the data
  - Owners see need for tech. development (i.e. new data mining algorithms, performance optimization, data gap filling methods)
  - OEMs hard to motivate, though they are interested in impact of aging on predictions
- Two research approaches identified
  - Expand reliability data collection; owners provide reliability summaries directly
    - Supports expansion of national benchmark that better represents the US fleet
    - Supports component-level reporting by including more operator knowledge
  - Progress as a technology platform to develop tools with and for stakeholders
    - Combination of summarized reliability data and detailed SCADA data provides ability to explore detailed analysis with big picture context

Owners want expanded Benchmark – more plants, more detail

Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	2.3.0.1
Project Number	
Agreement Number	22527

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

Task / Event	FY2012				FY2013				FY2014			
	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: CREW Database & Analysis Program												
2012-Q1: Reliability Report, with Speed Exploration												
2012-Q2: Reliability Report, with Fleet Representation Assessment												
2012-Q3: Database Sharing Update; CMMS Software Review												
2012-Q4: 2012 Benchmark Presentation and Technical Report												
2013-Q1: Report on CMMS and Predictive Analytics												
2013-Q2: Reliability Report, Mid-Year Update												
2013-Q3: Updates on CMMS Efforts and Data Sharing												
2013-Q4: 2013 Benchmark Presentation and Technical Report												
Current work and future research												
2014-Q1: Review of current Project and Opportunities; Proposed Path Forward												
2014-Q2: Report on Turbine-to-Turbine Interaction												
2014-Q3: Report on CREW future plans and data strategies												
2014-Q4: 2014 Benchmark with details on plan to integrate summarized data												

Project Dates: FY2008-2010: Development of Infrastructure
FY2011-13: Stabilization and Data Exploration
FY2014 & beyond: Expanded Benchmark; Plant Performance Exploration

Go/No-Go : December 2013 = Go

Expanded Benchmark with Summarized Data
Plant Performance Analysis

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

- **Subcontractors**: Strategic Power Systems, Inc.
  Muir Data Systems
  Management Resources Group, Inc.
- **Partners**: Shell Wind Energy, EDF-re, Xcel Energy, Wind Capital Group, NREL

Communications and Technology Transfer:

Presentations: AWEA WindPower Conference (6/2012), AWEA O&M Seminar (1/2012, 1/2013), PowerGen / Renewable Energy World Conference (12/2012), Optimizing Wind O&M Conference (9/2012, 9/2013), Wind Energy Update O&M Summit (4/2012, 4/2013), Sandia Wind Plant Reliability Workshop (8/2013), Sandia Blade Workshop (5/2012), OSIsoft Renewable Users Group (4/2012), IEC 61400-26 Meeting (11/2012), Sandia DataCon (10/2011), DOE Wind/Water Brown Bag (12/2011), GRC Annual meeting (2/2013), DOE Peer Review (6/2012)

Publications:

- "Wind Plant Reliability Benchmark" Presentation & Technical Report; 2012 & 2013
- "CMMS In the Wind Industry" SAND2012-10617
- "Wind Industry Work Order Information Flow Survey"
- "Wind Industry Segments and CMMS Value Propositions"

Presenting results frequently keeps industry ties thriving

Next Steps and Future Research

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FY14/Current research:

- Developing methods for summarized data pathway, including data, analysis, and reporting
  - Creating owner/operator Steering Committee to provide input beyond past learnings
  - Developing Non-Disclosure Agreements to protect participants
- Utilizing detailed data in CREW database to perform plant-level performance analysis, including the exploration of turbine-to-turbine interaction

Proposed future research:

- Expand Benchmark by incorporating summarized reliability data from advanced owner/operators
  - Goal: Represent 25%+ of US Fleet to support overall benchmark and analysis of important subsets (geography, wind profile, technology/design, etc.)
    - Steering Committee owner/operators already cover 15%
- Partner with stakeholders to build tools based on plant-level performance analysis and insights

GOALS: Industry reliability benchmarking.
Technology improvement opportunities. Assess plant-level performance.

Blade Reliability Collaborative
Targeted Effects of Manufacturing Defects
Aerodynamics and Aeroacoustics

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May 26th , 2014

Budget, Purpose, & Objectives

Total DOE Budget[1]: $3.350M

Total Cost-Share[1]:$0.000M

Problem Statement: Blade failures can cause extensive down time and lead to expensive repairs, which increase both cost and cost-uncertainty for OEMs and operators.

Impact of Project: Thorough understanding of the issues that affect blade reliability from design through operation, and how mitigate them.

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities at Universities and national laboratories to support mission-critical activities

[1]***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

Blade Reliability Drivers

- **Manufacturing**
  - **Inspection**
  - **Effects of Defects**
- **Transportation & Installation**
- **Operation**
  - **Erosion**
  - **Repairs**
  - *Lightning (future effort)*
  - *Structural Health Monitoring and Operations Strategy (SNL project)*

Standards (partner project)

Technical Approach (Manufacturing Flaws & Structural Damage)

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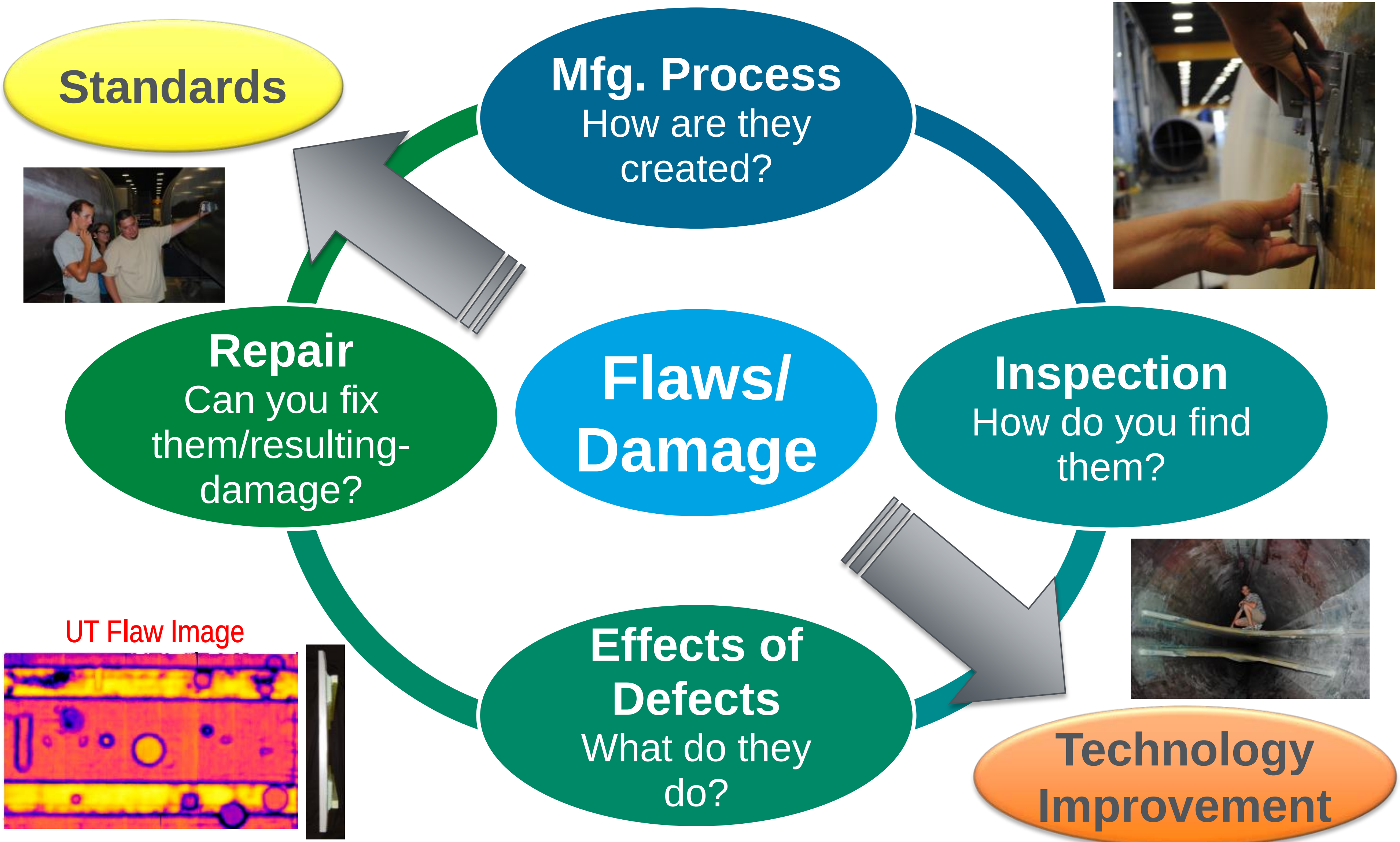


Technical Approach (Leading Edge Erosion)

Mechanisms
What causes it?

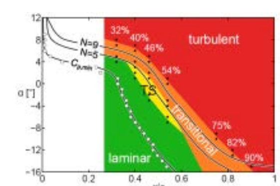
Standards

Technology Improvement

Erosion

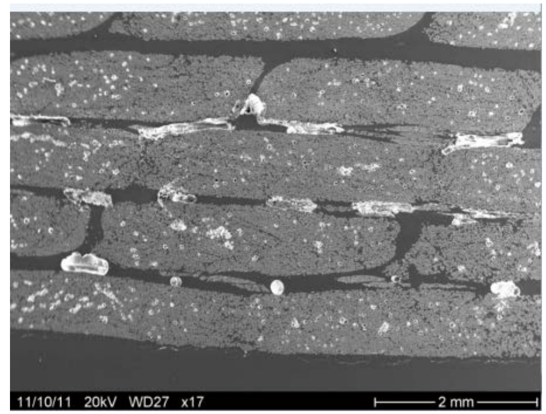
Treatment
How to deal with it?

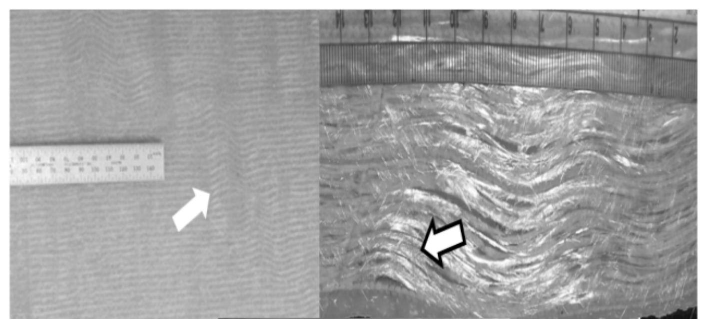
Aerodynamics
How is performance affected?

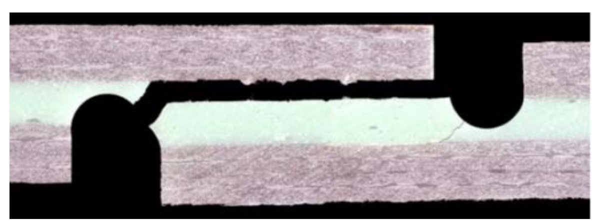


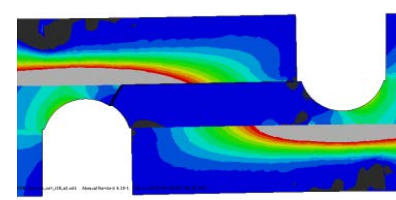
Accomplishments (Effects of Defects)

- Tested coupon samples containing prominent types of blade flaws
- Developed probabilistic flaw and damage model for blade design
- Created/validated new cohesive zone modeling procedure to analyze fiber waviness and adhesive crack growth



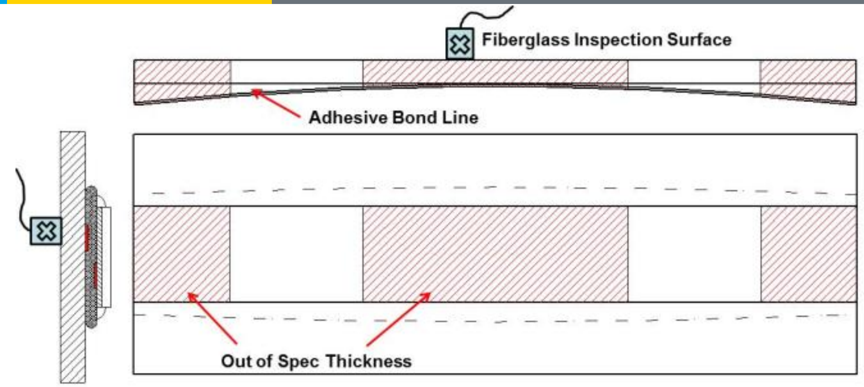


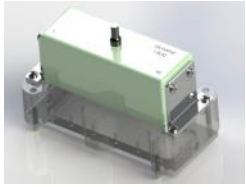


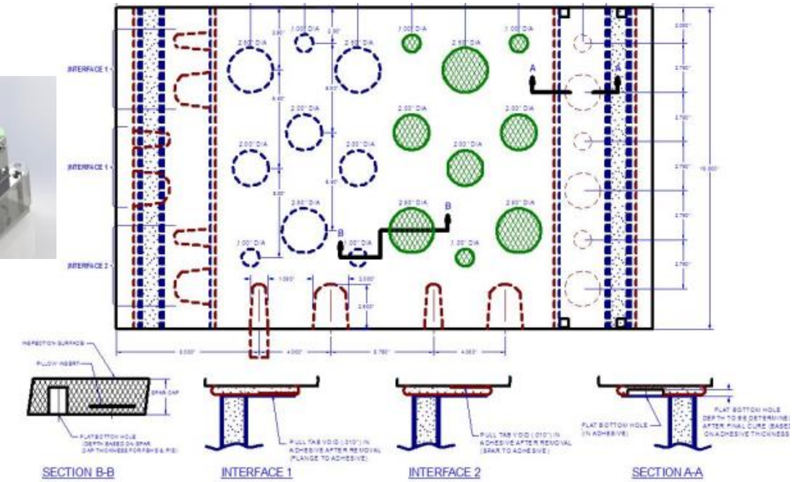


Accomplishments (Inspection)

- Developed initial set of wind-blade-specific panels with flaws and tested with over 20 equipment developers
- Completed inspection of sub-scale validation blade with 5 equipment manufacturers
- Developed improved hardware for ultrasonic inspection, allowing for sensitive inspection of thick composites
- Developed methods to detect flaws in both the spar cap and bond line and methods to quantify bond line thickness
- Designed/fabricated fiberglass and carbon NDI Reference Standards for setting up and verifying the proper function of inspection equipment
- Completed manufacturing plant visits to assess applicability of lab-based inspection methods

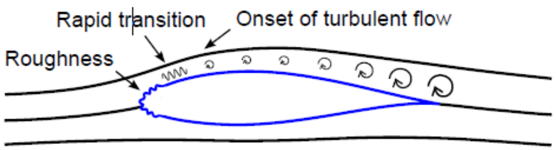


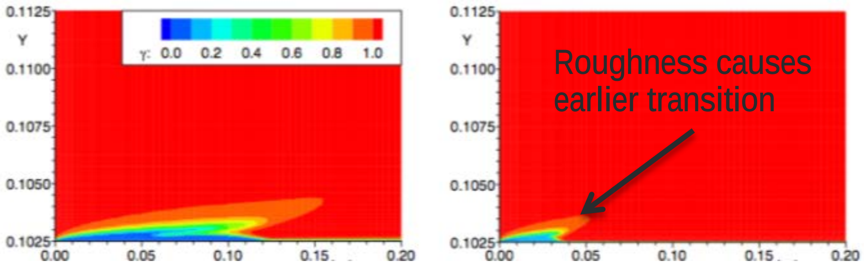




VISTA Engineering Technologies · GE · Sonatest · Iowa State · Resodyn Corporation · Olympus · Toshiba Leading Innovation · Boeing · Physical Acoustics Corporation · Dantec Dynamics · Mistras Group, Inc. · Evisive Microwave NDE Technology · MoviMED custom imaging solutions · Thermal Wave Imaging

- Gathered detailed LE erosion measurements from utility scale wind farm
- Built and tested LE erosion wind tunnel models
- Created CFD model of leading edge erosion
- Tight interaction between modelers and experimentalists
- Detailed calibration and validation of model





Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	2.3.0.2
Project Number	
Agreement Number	26909

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Blade Reliability Collaborative												
Q1 Milestone: Publish round 2 effects of defects report												
Q2 Milestone: Expand reliability database to include operator/manufacturer data												
Q3 Milestone: Complete lab evaluation of NDI techniques												
Q4 Milestone: Status update on round 3 effects of defects testing												
Q4 Milestone: Manufacture BRC validation blade Set												
Q1 Milestone: Test plan for BRC validation blade Set												
Q1 Milestone: Project plan for manufacuring floor NDI work												
Q1 Milestone: Update BRC project plan and budget												
Q2 Milestone: Publish BRC Phase I summary report												
Q3 Milestone: Test plan for wind tunnel testing of airfoil with LE erosion												
Q3 Milestone: Prototype of blade reliability tracking system												
Q4 Milestone: Report on validation of initial CFD model for LE erosion												
Q4 Milestone: Update BRC project plan and budget												
Current work and future research												
Q1 Milestone: Complete long range BRC project plan												
Q2 Milestone: Report on BRC NDI screening												
Q3 Milestone: Report on calibrated LE erosion model												
Q4 Milestone: Report on results of wind tunnel testing of LE erosion airfoils												
Q4 Milestone: Report on current state of wind turbine blade repair practices												

Comments

- BRC Phase I summary report was delayed to focus on other tasks

Project Plan & Schedule

Summary		Legend	
WBS Number or Agreement Number	2.3.2.1		Work completed
Project Number			Active Task
Agreement Number	22527	◆ (grey)	Milestones & Deliverables (Original Plan)
		◆ (black)	Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Aerodynamics and Aeroacoustics												
Q1 Milestone: Complete a conference paper on wind turbine rotor loads predictions	◆											
Q2 Milestone: Modeling strategy for prediction of aerodynamic rotor losses due to LE erosion		◆										
Q3 Milestone: Develop a model for parameterization of blade roughness due to LE erosion			◆ (original plan)	◆								
Q4 Milestone: Fabricate an LE erosion airfoil model for wind tunnel testing				◆ (original plan), ◆								

Comments

- Project ended in FY12

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	2.6.0.1
Project Number	
Agreement Number	22721

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Targeted Effects of Manufacturing Defects												
Q3 Milestone: Completion of Preliminary Facility Design												
Q4 Milestone: Complete Installation of Test Equipment												
Q1 Milestone: Complete preliminary assessment of candidate NDI methods												
Q2 Milestone: Design NDI probability of detection POD experiment and produce specimens												
Q3 Milestone: Draft interim Effects of Defects summary report												
Q4 Milestone: Publish "Effects of Defects for the Blade Reliability Collaborative" report												
Current work and future research												
Q1 Milestone: Report on defects as a function of processing parameters												
Q2 Milestone: Complete design of 2nd set of probability of detection (POD) specimens												
Q3 Milestone: Complete manufacturing of 2nd set of probability of detection (POD) specimens												
Q4 Milestone: Complete POD experiment protocols												

Comments

- Sub-scale test facility installation was delayed by site infrastructure and part supplier issues.

Partners, Subcontractors, and Collaborators:

Over 40 participants including

- **3 Research Institutions:** Sandia National Laboratories, National Renewable Energy Laboratory, Electric Power Research Institute
- **1 Academic Institution:** Montana State University
- **30 Companies:** TPI Composites, MFG, Rope Partners, GE, Vestas, Gamesa, Seimens, Iberdrola, EDPR, over 20 NDI Equipment Manufacturers

Research Integration & Collaboration (cont.)

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Communications and Technology Transfer:

Conferences and Workshops:

- AIAA SDM 2012, 2013
- AIAA ASM 2013, 2014
- NAWEA Symposium 2013
- 2012 Sandia Blade Workshop
- 2013 Sandia Wind Reliability Workshop
- AWEA 2014

Publications:

- “Effects of Defects in Composite Wind Turbine Blades Round 2”
- “Effects of Defects in Composite Wind Turbine Blades Round 3”
- “Blade Reliability Collaborative: Development and Evaluation of Nondestructive Inspection Methods for Wind Turbine Blades” (pending DOE SAND report)
- M.S. Thesis and Ph.D. Dissertation in preparation

Project Review Meetings:

- March 2012, October 2012, February 2013, August 2013

Next Steps and Future Research

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FY14/Current research:

- Non-Destructive Inspection: Go to the manufacturing floor
- Effects of Defects: Quantify affect on fatigue damage at coupon and sub-structure level
- Blade Repairs: Survey current practice in wind and other industries
- Leading Edge Erosion: Develop validated aerodynamic engineering model for blades

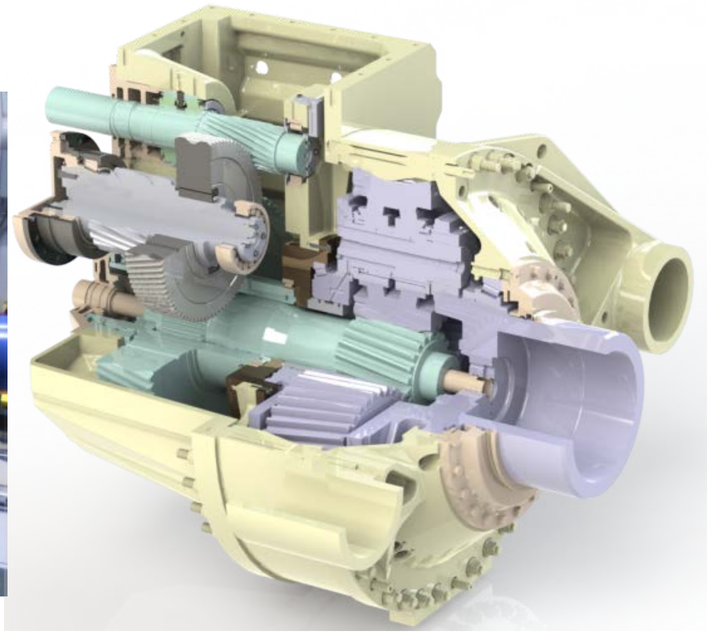
FY14 Milestones

- Q1: Submit update of multi-year Blade Reliability Collaborative (BRC) project plan (complete)
- Q2: Complete SAND report on Blade Reliability Collaborative (BRC) Phase I non-destructive inspection (NDI) Screening (March 2014)
- Q3: Report describing calibrated leading edge erosion roughness model (June 2014)
- Q4: Report detailing wind tunnel test results of wind blade airfoils with leading edge erosion (Sept. 2014)
- Q4: Report on wind blade repair technologies (Sept. 2014)

Proposed future research:

- Testing of blade repair methods and associated NDI of repairs
- Leading edge erosion mechanical testing
- Expand leading edge erosion tests to a range of airfoils
- Lightning-related damage to blades

GRC Drivetrain with existing gearbox in NWTC 2.5 MW Dynamometer



Improved gearbox under construction

Gearbox Reliability Collaborative

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March 26, 2014

Budget, Purpose, & Objectives

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Total DOE Budget[1]: $2.850M

Total Cost-Share[1]:$0.726M

Problem Statement

- Determine why gearboxes do not always achieve their expected design life and determine whether the cause is underspecified loads, inadequate part specification, inaccurate design analysis tools, and/or insufficient testing.

Impact of Project

- Project modeling, test data, and lessons learned are disseminated to the industry to facilitate improvements to gearbox designs and standards, resulting in more reliable wind-turbine gearboxes that lower O&M costs.

This project aligns with the following DOE Program objectives and priorities

- **Optimize Wind Plant Performance:** Reduce wind plant levelized cost of energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new, high-tech U.S. industries

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

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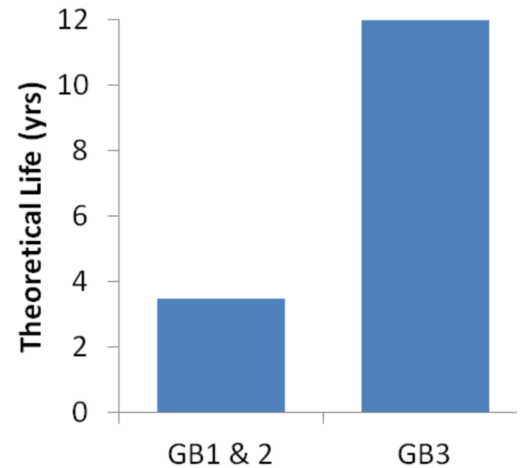
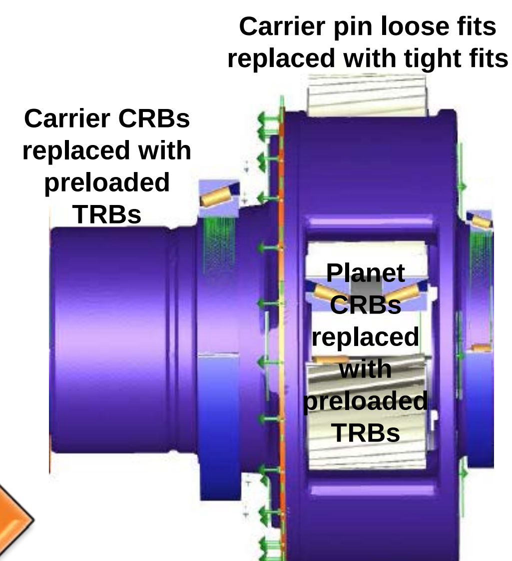
- Solution Process
  - Conduct field and dynamometer testing to measure responses (1000+ hours, 150+ signals)
  - Validate modeling approaches (multibody/FEA)
  - Investigate design deficiencies (CRB clearance)
  - Redesign gearbox to correct (preloaded TRBs)

- Propagate lessons learned to industry
  - Design and model best practices
  - Make recommendations to design standards



Gearbox Theoretical Life Comparison



Gearbox Planetary Section Changes

Accomplishments and Progress

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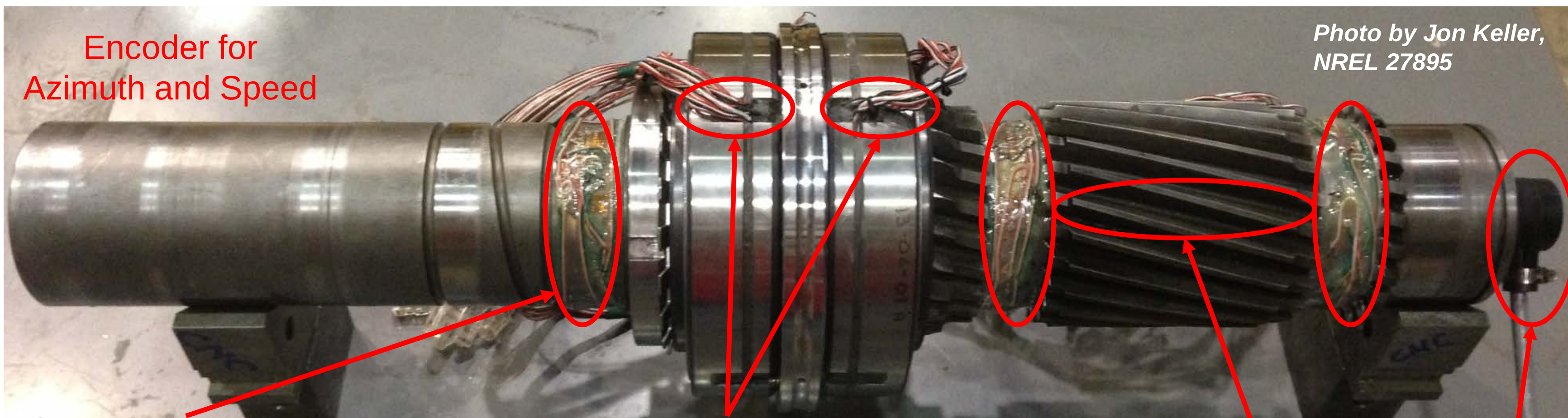
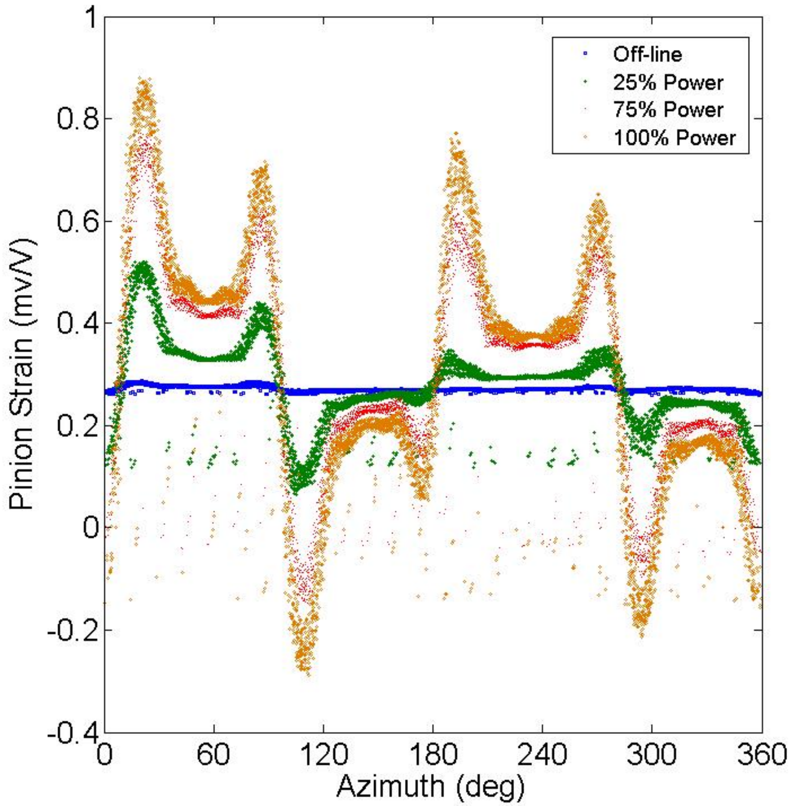
New Instrumentation

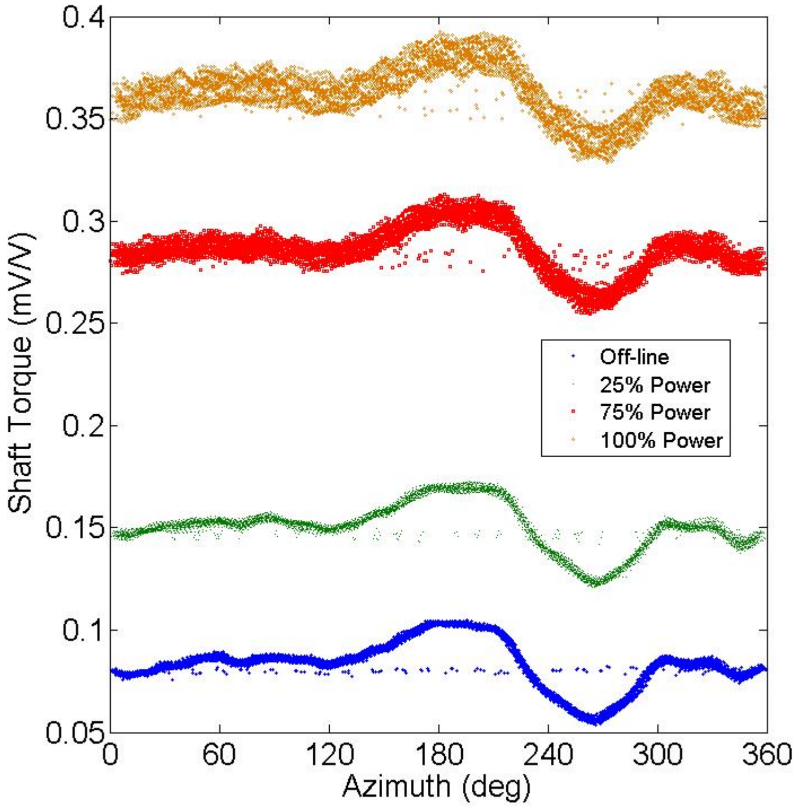
- Added new instrumentation and are performing tests for existing gearbox
  - Instrumentation to high-speed shaft, pinion and bearings, per industry suggestion for most failure-prone area of the gearbox
  - Dynamic and transient tests with new dynamometer capability (VFD and CGI), industry test suggestions such as generator misalignment



HSS Pinion Strain



HSS Torque



30 HSS Revolutions
5 kHz acquisition rate

Accomplishments and Progress

- Improved design—Designed, manufacturing, and will test improved gearbox
  - Replace CRBs with preloaded TRBs in planets and carrier
  - Integral planet gear/bearings and related manufacturing techniques

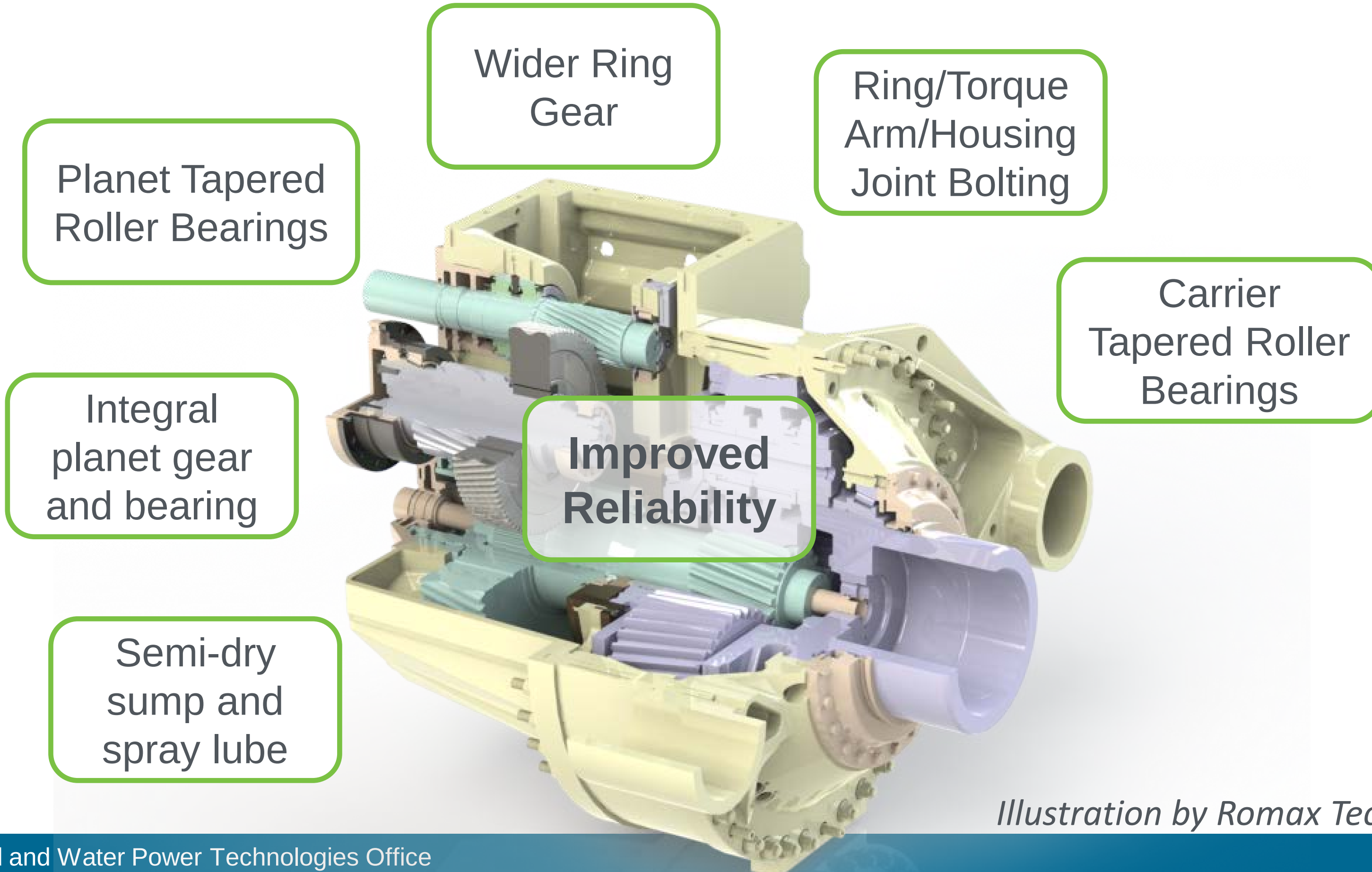
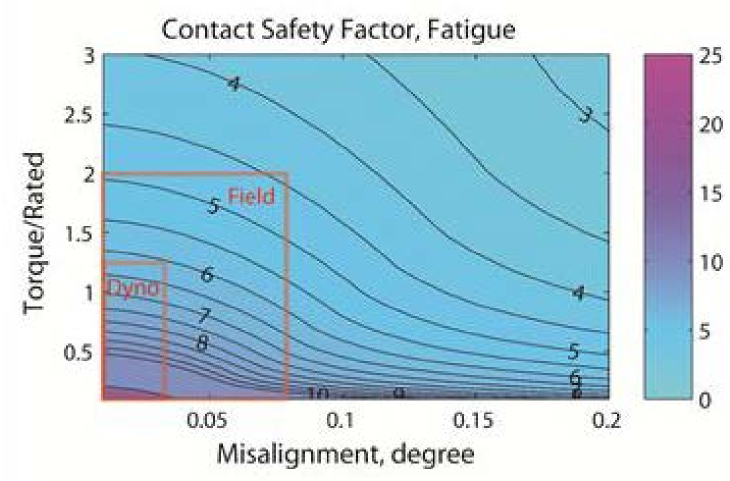
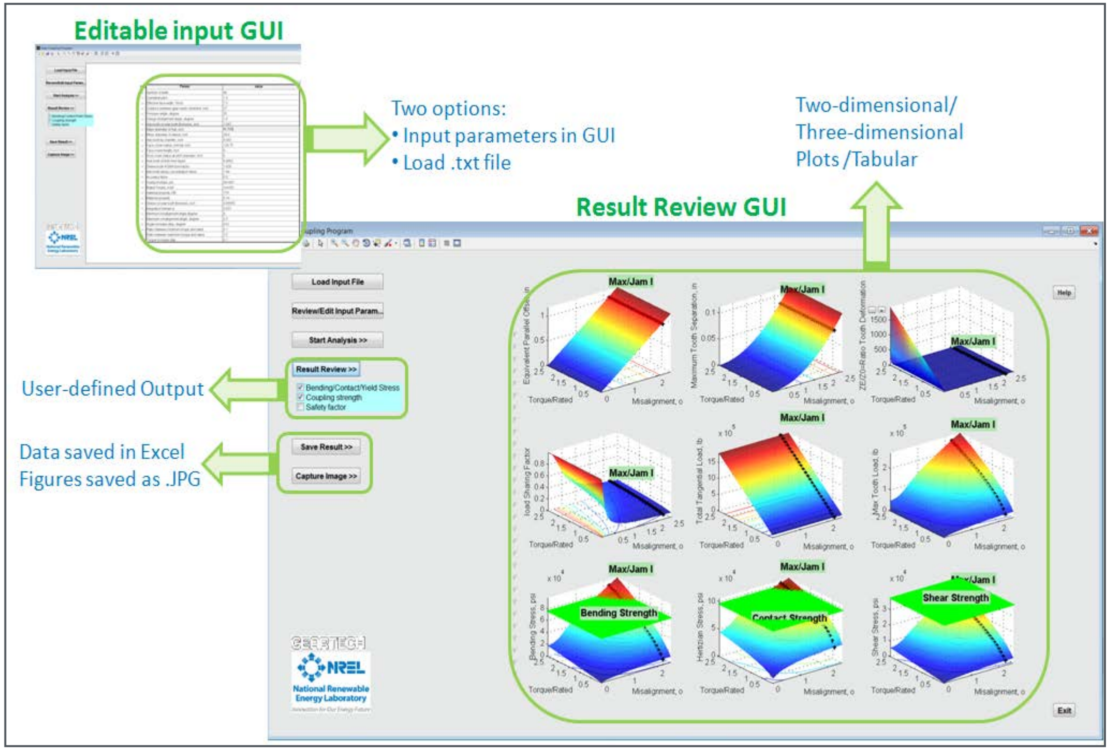


Illustration by Romax Technology

- Modeling—Developed and released sun spline rating “Gear-SCouP”
  - Validated against 2D and 3D commercial FEA codes
  - Uncertainty around spline design, lack of life rating in AGMA 6123
  - Specific recommendations made to AGMA 6123

https://pfs.nrel.gov





Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	3.1.1.1
Project Number	Reliability 4
Agreement Number	

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Gearbox Reliability Collaborative												
Q1 Milestone: Complete Tribology Seminar report												
Q4 Milestone: Complete gearbox 3 critical design review												
Q1 Milestone: Complete GB2 test plan												
Q2 Milestone: Begin GB2 dynamometer test												
Q3 Milestone: Complete GB3 parts manufacture												
Q4 Milestone: Publish recommendations to design standards												
Q1 Milestone: Complete GB2 static NTL test												
Current work and future research												
Q2 Milestone: Convene GRC meeting and publish presentations												
Q3 Milestone: Complete GB3 assembly												
Q4 Milestone: Complete instrumentation plan for GRC1.5												

Comments

- Drawing toward conclusion of 750 kW platform research in FY15
- Extensive machining and calibration of high-speed shaft instrumentation
- 9-month contracting process for manufacture of improved gearbox

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners, Subcontractors, and Collaborators

- Subcontracted—Romax Technology, McNiff Light Industry, Brad Foote Gearing, The Timken Company, and Geartech
- Many additional unfunded partnerships exist through the larger collaborative

Communications and Technology Transfer

- Feb. 2014 GRC meeting drew 120 attendees
- Recent journal papers:
  - "Three-dimensional bearing load share behavior in the planetary stage of a wind turbine gearbox" in IET Renewable Power Generation
  - "Planetary gear load sharing of wind turbine drivetrains subjected to non-torque loads" in Wind Energy
  - "Nonlinear dynamics and stability of wind turbine planetary gear sets under gravity effects" in European Journal of Mechanics, Part A
  - Many conference and NREL publications

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research

- May 2014 (approx.)—Dynamometer testing of newly instrumented gearbox will conclude
- July 2014—Improved gearbox will be completed and subsequently tested to same test plan
- Comparison of planetary load sharing between gearboxes will validate design improvements
- Transient modeling round robin will validate industry modeling approaches

Proposed future research

- Field measurement of end-to-end drivetrain loads for commonly used 3-stage gearbox in a pitch-regulated, variable-speed, 1.5 MW wind turbine as part of A2e initiative. Objective is to provide publicly available operational loading data → "reference load set"

NREL 2.5 MW Dynamometer/PIX16913

Gearbox Failure Database, Condition Monitoring, and Operation & Maintenance Research

Shawn Sheng

NREL

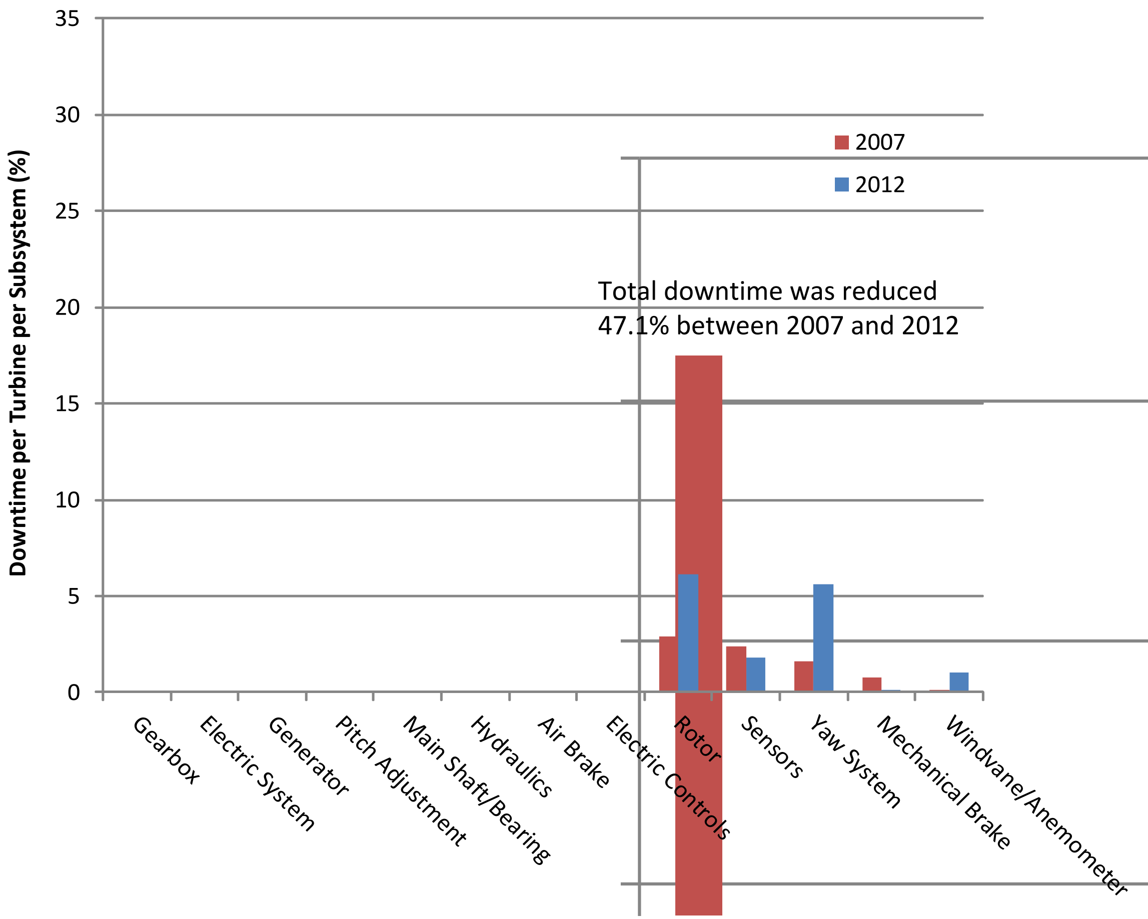
Shuangwen.Sheng@nrel.gov; 3033847106

3/26/2014

Budget, Purpose, & Objectives

Problem Statement:

- Globally:
  - Premature component failures, led by gearbox, increase O&M costs, downtime, and COE
- In the United States:
  - No available industry-wide failure statistics on gearboxes and other major components / subsystems
  - Condition monitoring systems are not commonly employed



Wind Stats Data in Europe: Downtime per Turbine Subsystem

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $0.940M

Total Cost-Share[1]:$2.900M

Project Objectives:

- Improve turbine reliability, availability, maintainability, and plant performance, and reduce O&M cost
- Support validation / verification and recommended practices or standardization efforts

Impact of Project:

- Provide public domain gearbox and other major subsystem failure statistics for the U.S. wind fleet
- Identify cost-effective condition monitoring techniques, and investigate improved O&M strategies and management systems

This project aligns with the following DOE program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce wind plant levelized cost of energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries

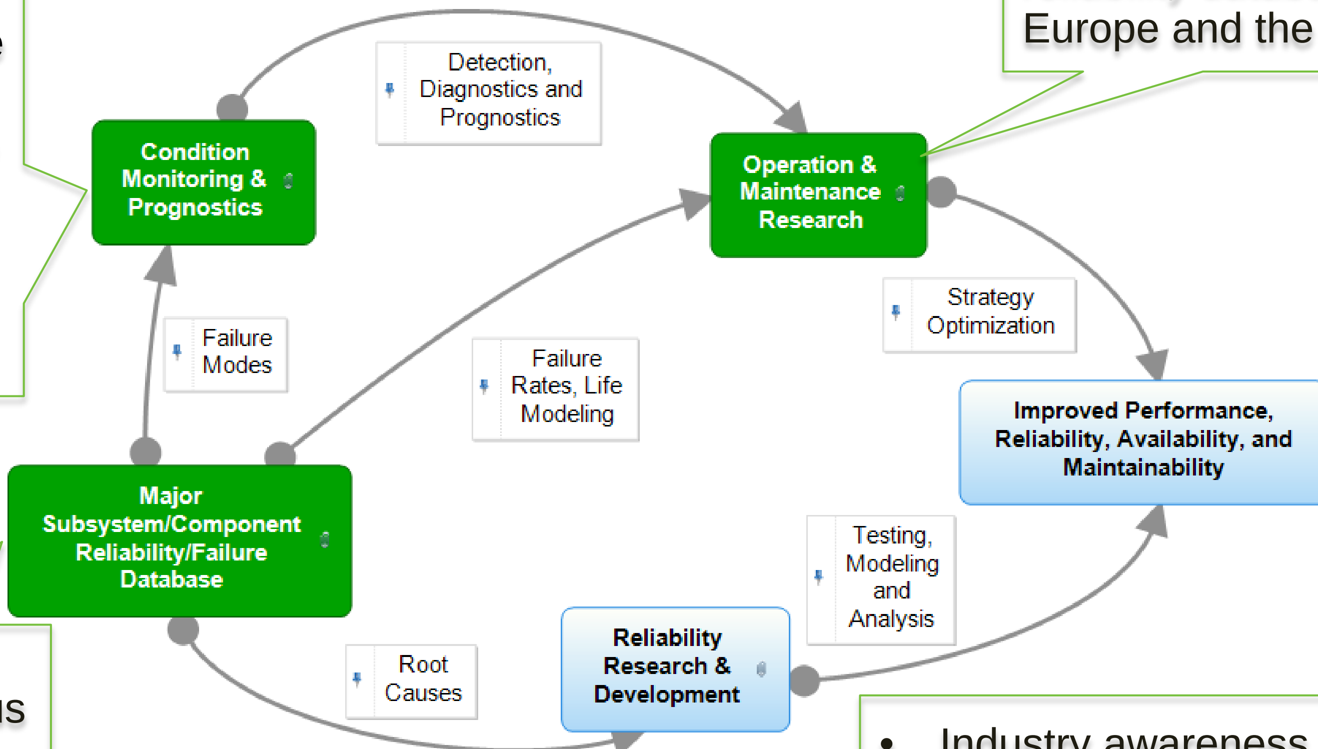
[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Evaluation of different condition monitoring techniques using the Gearbox Reliability Collaborative (GRC) 750-kW drivetrain in the dynamometer and the DOE 1.5-MW turbine

Survey of wind turbine subsystem/component reliability databases in Europe and the U.S.



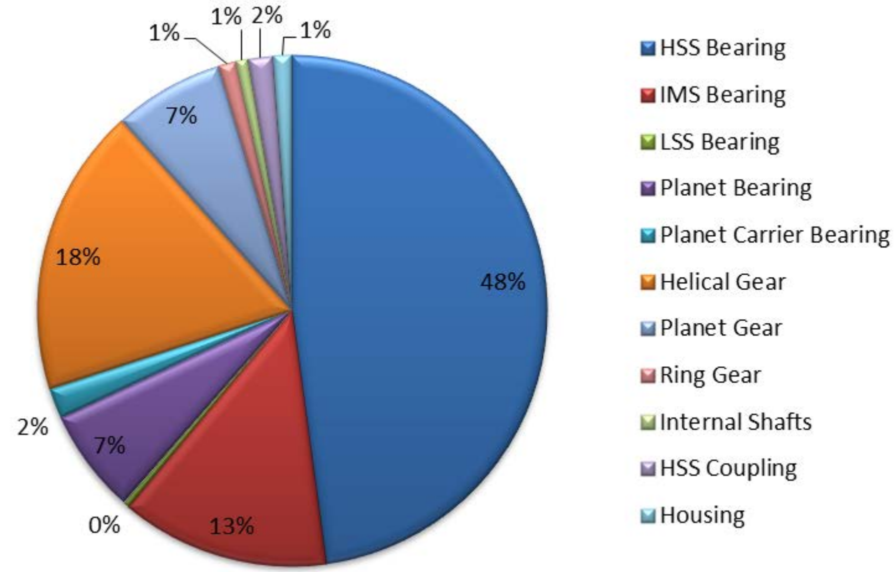
Gearbox Failure database with a focus on top failure modes and possible root causes; detailed rebuild events and high-level summary

- Industry awareness and recommended practices
- Public domain information dissemination and in-kind collaboration

Accomplishments and Progress
Gearbox Failure Database

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Released gearbox failure statistics on 289 gearbox failure incidents, a ten-fold increase from 2012
- Increased to 22 partners, representing more than ~34% of end of 2012 U.S. installed capacity
- Inquiries from gearbox OEMs, bearing suppliers, owner/operators, and other stakeholders demonstrate the need and value of public domain failure statistics



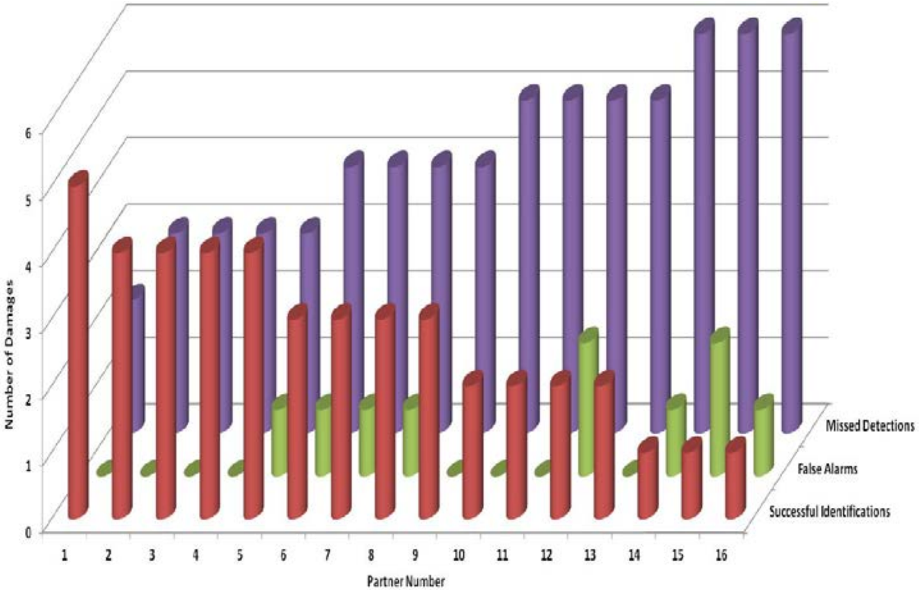
- Bearings: 70%; gears: 26%; others: 4%
- Both bearing and gear failures are concentrated in the parallel section
- Top failure mode is bearing axial cracks in high-speed shaft (HSS) or intermediate-speed shaft (IMS), confirming the importance of instrumenting HSS stage in the GRC.

Accomplishments and Progress
Condition Monitoring

- Published the *Wind Turbine Gearbox Condition Monitoring Round Robin Study – Vibration Analysis* report
- Demonstrated there is still room for improvement with the current techniques so as to make vibration analysis more beneficial to wind turbine condition monitoring
- Estimated in-kind cost-share to be ~$1.8 million, demonstrating how a national laboratory can leverage expertise from around the globe and can conduct focused research to make a big impact

Wind Turbine Gearbox Condition Monitoring Round Robin Study – Vibration Analysis

S. Sheng, Editor
National Renewable Energy Laboratory



Accomplishments and Progress
Condition Monitoring

- Investigated potential economical and effective approach for gearbox damage evaluation through compact filters:
  - Limitations of traditional oil sample analysis
  - Analysis about 1/10 of the cost for a system filter
  - Filter element reusable
- First round of testing results were presented at the 2013 Society of Tribologists and Lubrication Engineers (STLE) annual meeting
- Discussions ongoing to further test this technology on more field turbines

Compact Filter

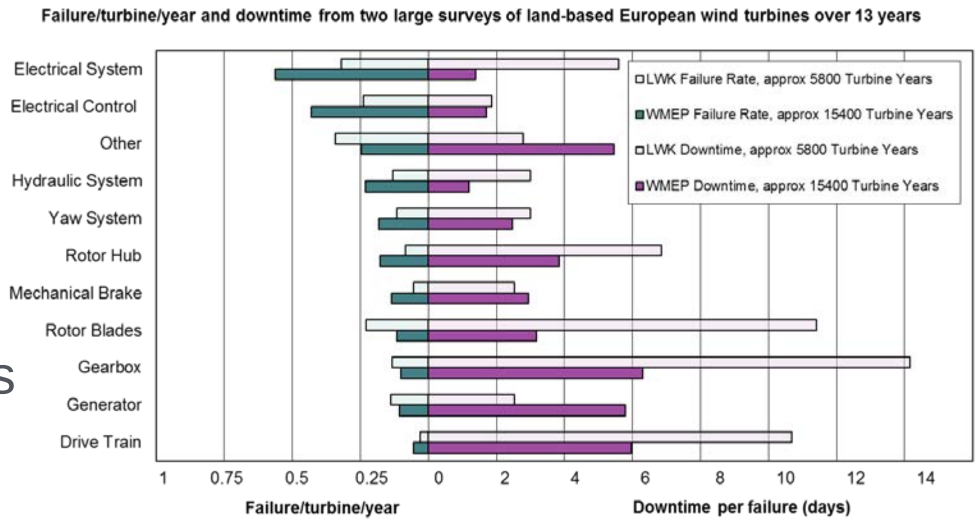
System Filter

Photo Credits: Don Roberts (Left) and Bill Herguth (Right)

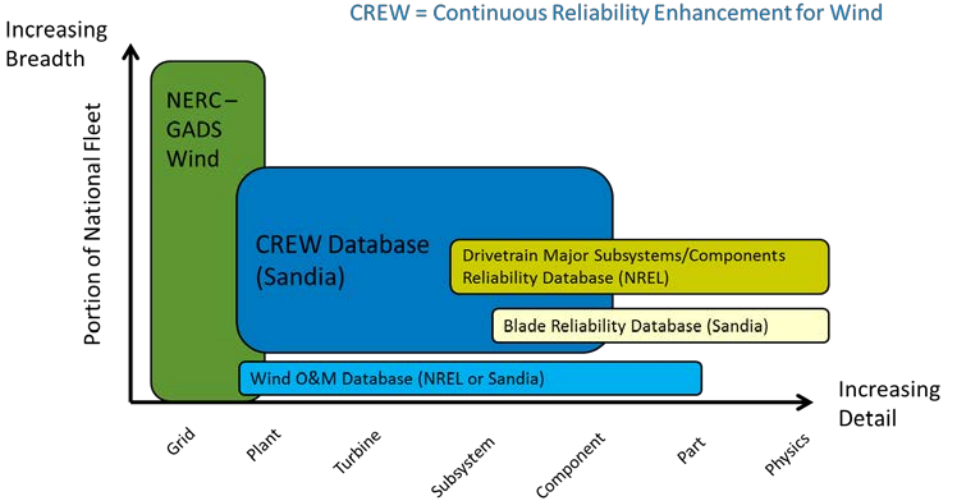
Accomplishments and Progress
O&M Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Published a survey of various reliability databases
- Observations based on most European databases:
  - Most frequently failed subsystem is power electronics or power module.
  - Gearboxes caused the highest downtime per failure.
  - Benefits of direct-drive turbines not conclusive.
- Provides a centralized location for updated reliability statistics and identifies the lack of reliability data collection efforts in the United States



NERC = North American Electric Reliability Corporation
GADS = Generating Availability Data System
CREW = Continuous Reliability Enhancement for Wind



Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	3.1.1.2 and 3.1.3
Project Number	Reliability 5
Agreement Number	

Legend	
(light blue bar)	Work completed
(blue bar)	Active Task
(grey diamond)	Milestones & Deliverables (Original Plan)
(black diamond)	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Gearbox Failure Database, Condition Monitoring and O&M												
Q2 Milestone: Draft a report on wind turbine gearbox condition monitoring												
Q1 Milestone: Submit a journal article on gearbox design evaluations												
Q2 Milestone: Complete a report on the evaluation of various CM systems												
Q3 Milestone: Complete a survey of various reliability databases												
Q4 Milestone: Collect and release vibration CM data												
Q1 Milestone: Organize a Wind Energy Workshop												
Current Work and Future Research												
Q2 Milestone: Submit a journal article on oil condition monitoring												
Q3 Milestone: Submit a journal article on modeling of main shaft bearing												
Q4 Milestone: Update statistics from gearbox failure database												

Comments:

- In FY 2012, the project was part of the GRC; the first fiscal year for this task to run as a standalone project was 2013
- All planned milestones so far are on track for FY 2014

Partners, Subcontractors and Collaborators:

- ## Testing:
  1) Castrol Industrial North America Inc.
  2) CC Jensen Inc.
  3) GasTOPS
  4) Herguth Laboratories, Inc.
  5) Parker Kittiwake Americas
  6) The Lubrizol Corporation
  7) Poseidon Systems
  8) SKF

- ## Other Related Research:
  1) Durham University in the UK
  2) Nanyang Technological University in Singapore
  3) NASA Glenn Research Center
  4) National Renewable Energy Centre in the UK
  5) University of Michigan
  6) Wichita State University
  7) University of Newcastle in the UK

- ## Failure Database:
  1) 11 wind plant owner/operators:
     - AES
     - Duke Energy
     - EDF
     - EDPR
     - Exelon
     - Iberdrola
     - Infigen
     - Invenergy
     - Oklahoma Gas & Electric Company
     - Puget Sound Energy
     - Terra-Gen Power
  2) 5 rebuild shops
  3) 3 turbine OEMs
  4) 2 gearbox OEMs
  5) 1 consulting company

- ## Subcontractor:
  1) D.A. Roberts, LLC

Communications and Technology Transfer:

Technical Workshop:

1. FY2013: 2013 Wind Energy Workshop, Oct. 6-8, New Orleans, LA.

Selected Publications and Presentations (~30 in total):

1. Yampikulsakul, N.; Byon, E.; Huang, S.; Sheng, S.; You, M. "Condition Monitoring of Wind Power System with Non-parametric Regression Analysis," *IEEE Transactions on Energy Conversion*. DOI: 10.1109/TEC.2013.2295301.
2. Luo, H.; Hatch, C.; Kalb, M.; Hanna, J.; Weiss, A.; Sheng, S. "Effective and Accurate Approaches for Wind Turbine Gearbox Condition Monitoring," *Wind Energy*, DOI: 10.1002/we.1595.
3. Tamilselvan, P.; Wang, P.; Sheng, S.; Twomey, J.; (2013) "A Two-Stage Diagnosis Framework for Wind Turbine Gearbox Condition Monitoring" , *International Journal of Prognostics and Health Management,* Vol. 4 (Special Issue Wind Turbine PHM), pp. 11-21.
4. Greco, A.; Sheng, S.; Keller, J.; Erdemir, A. (2013) " Material Wear and Fatigue in Wind Turbine Systems," *Wear*, Vol. 302, Issues 1-2, April-May, 2013, pp. 1583-1591. [http://dx.doi.org/10.1016/j.wear.2013.01.060]
5. Yang, W.; Tavner, P; Sheng, S.; Court, R. (2012) "Information Entropy: An Effective Approach for Wind Turbine Condition Monitoring," presented at EWEA Annual Conference, Copenhagen, Denmark, April 16-19, 2012.
6. Dempsey, P. J.; Sheng, S. (2013) "Investigation of Data Fusion Applied to Health Monitoring of Wind Turbine Drivetrain Components," *Wind Energy*. Vol. 16(4), May 2013; pp. 479-489.
7. Errichello, R.; Sheng, S.; Keller, J.; Greco, A. (2011) *Wind Turbine Tribology Seminar – A Recap,* NREL Report No. TP-5000-53754.

Inquiries or Interviews around the Globe:

1. Data on failure statistics and condition monitoring: tracked are more than a dozen, such as AWEA, gearbox OEMs, bearing suppliers, owner/operators, research institutes, and so on. Majority are not tracked.
2. Interviews and inputs to technical articles/reports by different professional societies: ~ half a dozen, such as STLE, Gear Technology, Wind Energy Update, Lubrication International, and so on.

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research

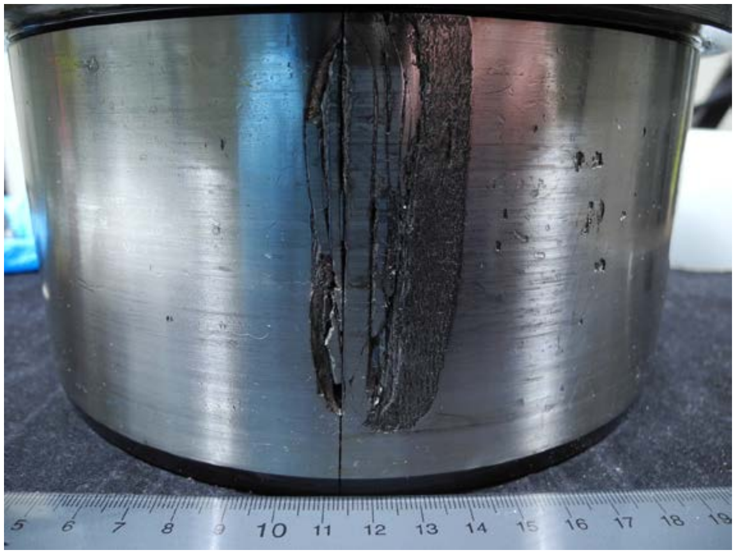
- Continue gearbox failure data collection and release updated statistics, expand data collection fields to enable failure rates and life modeling analysis
- Release vibration condition monitoring data collected from both a healthy and a damaged GRC test gearbox
- Evaluate representative and new monitoring techniques and release results based on resumed GRC tests, other test turbines on the NREL wind site, and wind plant owner/operator partners: compact filter, oil debris, and vibration, etc.
- Submit journal manuscripts on oil condition monitoring, main shaft dynamics modeling; and publish a *Wind Energy* journal special issue on wind turbine condition monitoring

Next Steps and Future Research

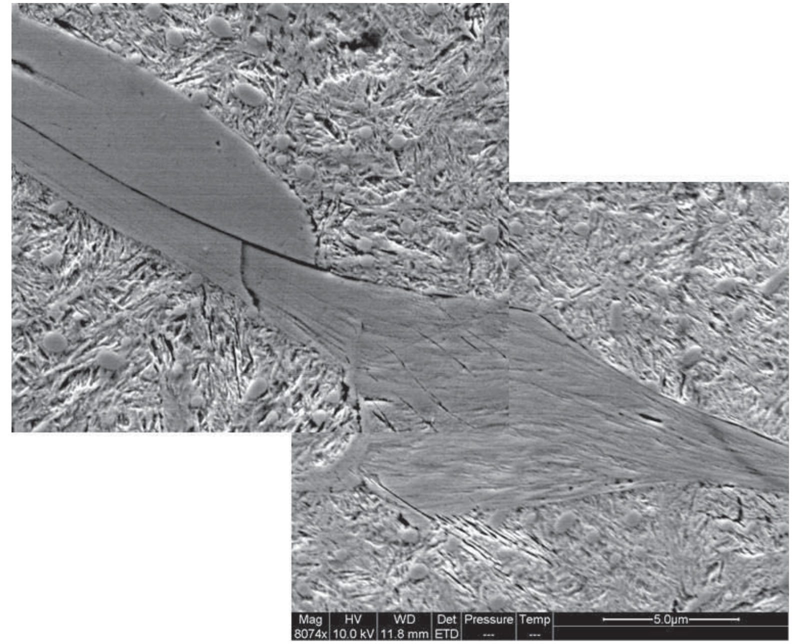
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Proposed future research

- Support the A2E initiative on improving component reliability, turbine availability and plant performance by:
  - Facilitating failure event data collection on major components/subsystems and generating public statistics
  - Helping industry understand cost effectiveness of condition monitoring through long-term field trial projects
  - Providing insights in O&M strategies through life modeling of major turbine components, starting with gearboxes
  - Participating in standards for failure event data reporting, O&M data collection, and condition monitoring systems techniques



White-Etching Crack Bearing Failure



Electron Microscopy Image White-Etching Crack Microstructure

Reliability Improvement of Tribological Contacting Components

Gearbox Reliability Collaborative

Aaron Greco

Argonne National Laboratory

Greco@anl.gov | 630-252-5869

March 26th, 2014

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $0.625M

Total Cost-Share[1]:$0.000M

Problem Statement: A leading cause of early drivetrain failures (1-10% of design life) across the industry is attributed to an ‘irregular’ bearing cracking/pitting known as white-etching cracks (WECs). The root cause of failure and appropriate mitigation has not yet been determined.

Impact of Project: A mechanistic approach to determine the cause of WECs is underway using failure analysis and bench-top testing. With the aim to develop a test methodology to replicate the failure and test various mitigation techniques to improve existing drivetrain reliability.

This project aligns with the following DOE Program objectives and priorities

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries

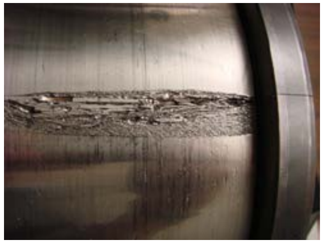
[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Bearing Failure Analysis

- Examine bearings with premature cracking/flaking
- Conduct a metallurgical analysis to characterize microstructural alteration to the bearing material (WEC)
- Collect and analysis used oil from wind turbine gearboxes

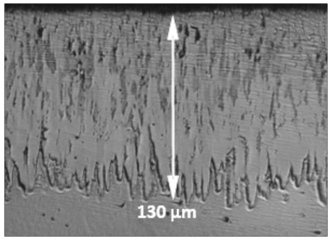


Bench-Top Test Development

- Develop accelerated ‘coupon-level’ bench-top tests to mimic WEC failures
- Conduct a sensitivity study on operational parameters (load, slip, etc.)
- Match lab generated WEC failures with field failures

Mitigation Testing

- Test commercially available mitigation approaches (materials, coatings, lubricants, etc.)
- Consider advanced material approaches (lubricant additives, advanced coatings, etc.)
- Conduct bearing component testing for validation

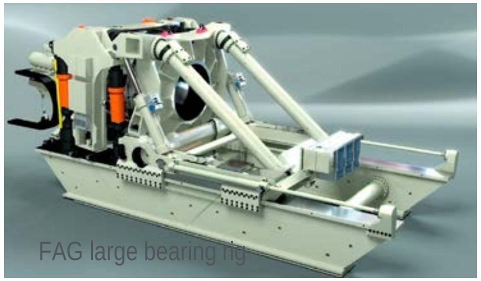


Technical Approach

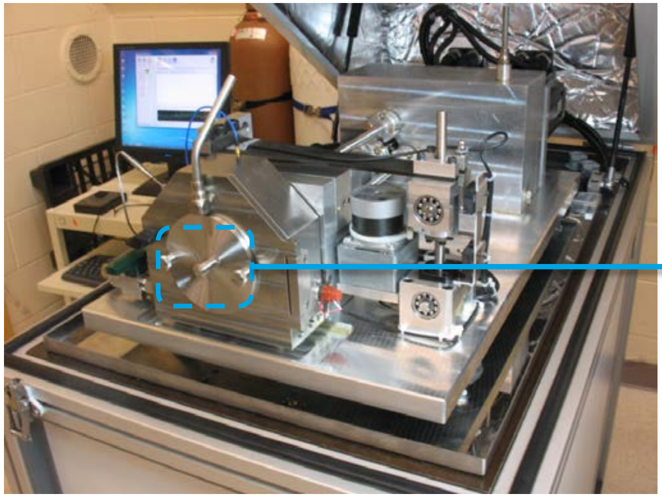
Turbine/Field

Dynamometer

Bearing Test



Tribometer- *3 ring-on-roller*

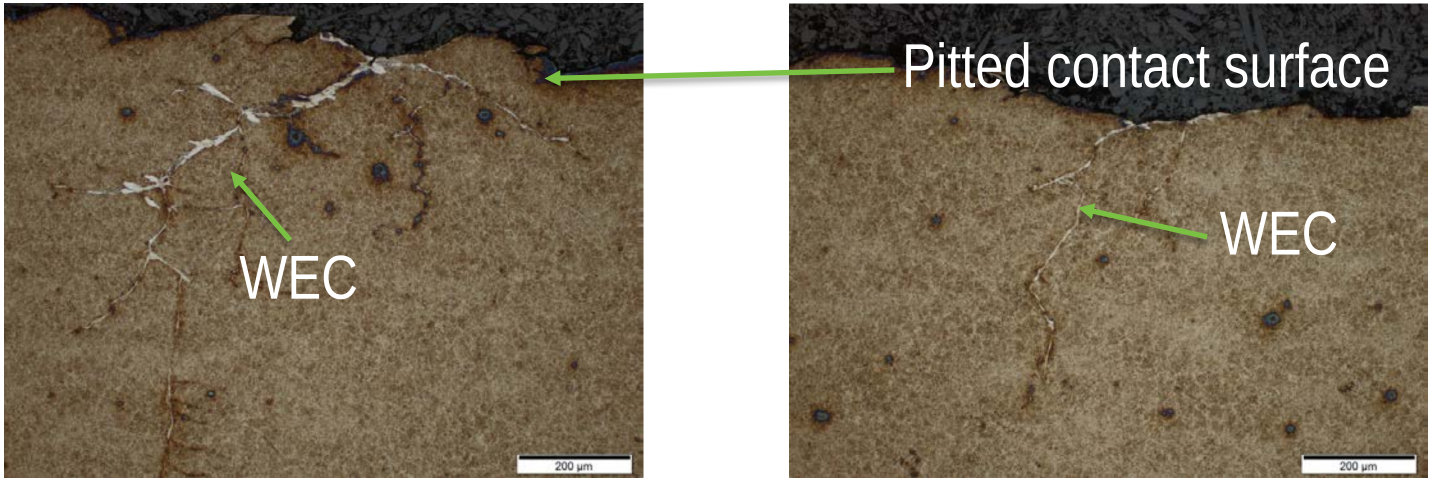


- Replicates surface failures:
  - *Micropitting*
  - *Fatigue spalling*
  - *Scuffing*
  - *Wear*
- Controlled operating conditions
- Enables a mechanistic evaluation of surface failure

Bearing Failure Analysis

- 15 failed bearings of different type, manufacturer, and material were analyzed, including: surface, cross-sections, and metallurgical analysis
- Characterized subsurface microstructure with surface failure
- Correlated cracks and spalls with altered microstructure

Etched circumferential cross-section

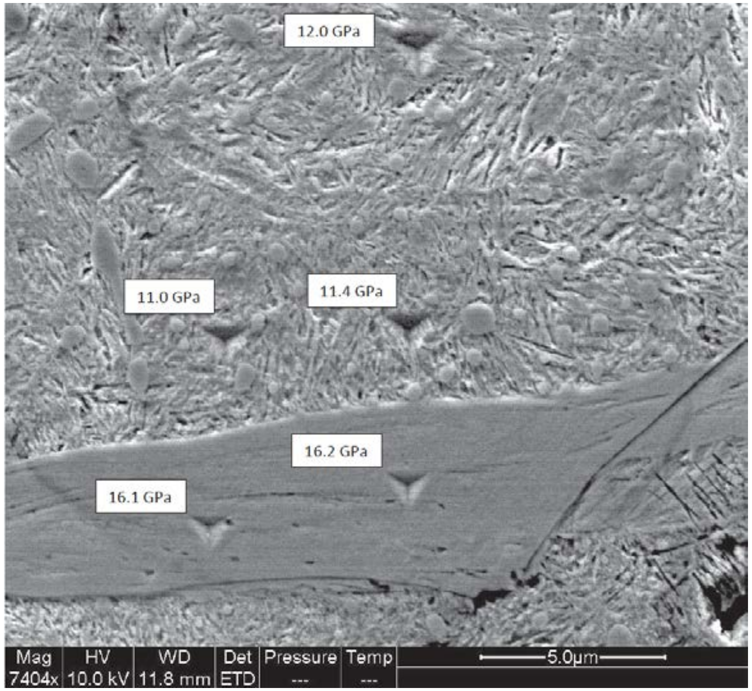


Greco, A., S. Sheng, J. Keller, and A. Erdemir. "Material Wear and Fatigue in Wind Turbine Systems." *Wear* 302, no. 1–2 (April 2013): 1583–1591. doi:10.1016/j.wear.2013.01.060.

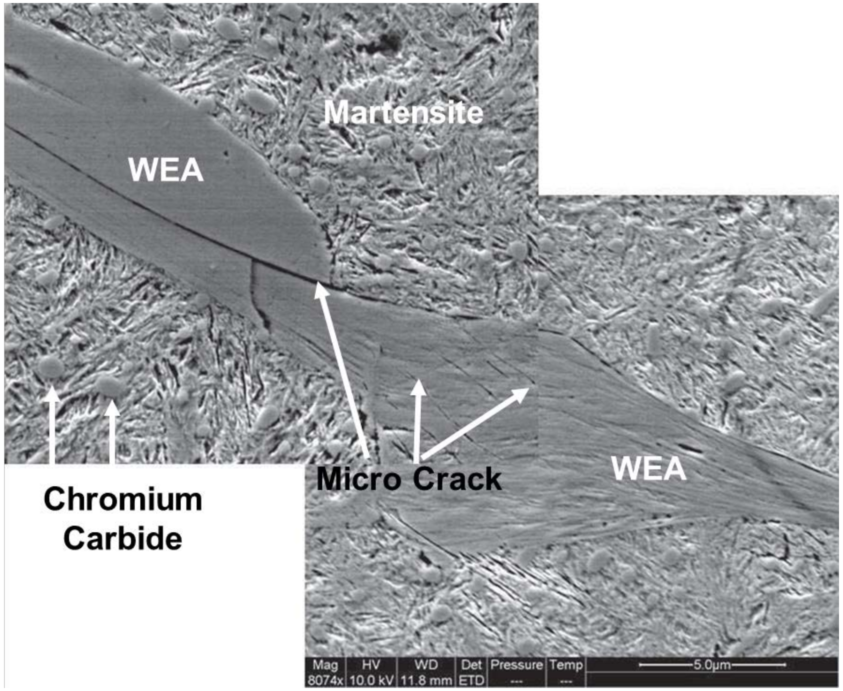
Accomplishments and Progress

WEC material characterization

Nano-Hardness Measurement



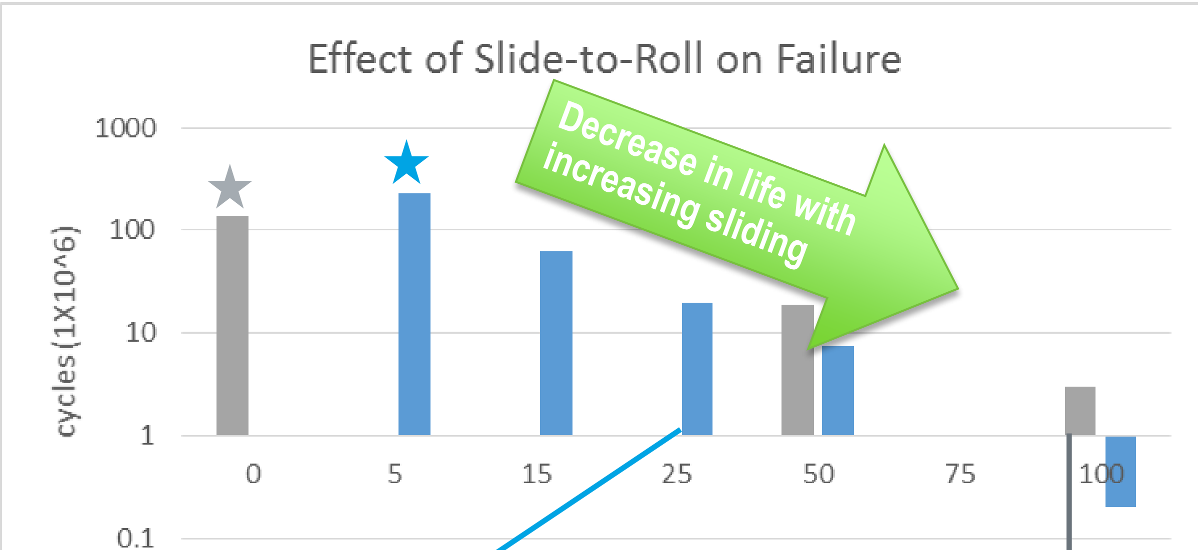
Microstructural Analysis



- 44% increase in hardness between the WEA and surrounding martensitic matrix
- Micro-cracks formation along matrix and altered microstructure

Greco, A., S. Sheng, J. Keller, and A. Erdemir. “Material Wear and Fatigue in Wind Turbine Systems.” *Wear* 302, no. 1–2 (April 2013): 1583–1591. doi:10.1016/j.wear.2013.01.060.

- Tribometer tests were performed to replicate bearing skidding/sliding
- Significant decrease in run time till pitting with increased slide-to-roll ratio (SRR)
- Surface macropitting was the leading mechanism of failure

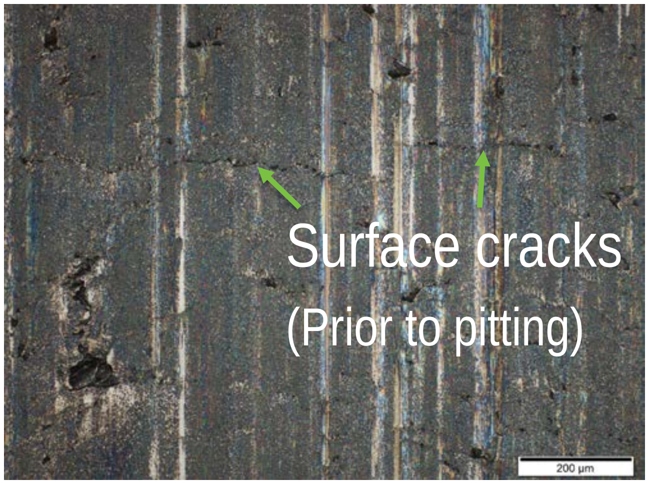


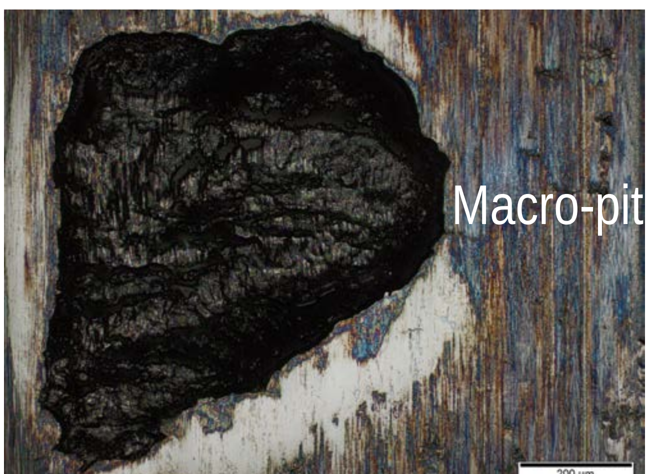
Conditions:

- Two commercial lubricants
- AISI 52100 steel
- 3 GPa contact pressure
- 80° C
- 2.5 m/s speed

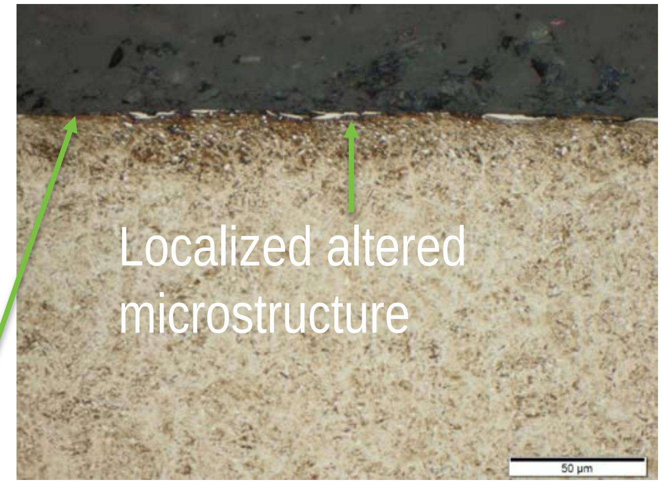
★ No failure observed
200% SRR= pure sliding

Examples of surface damage on test samples

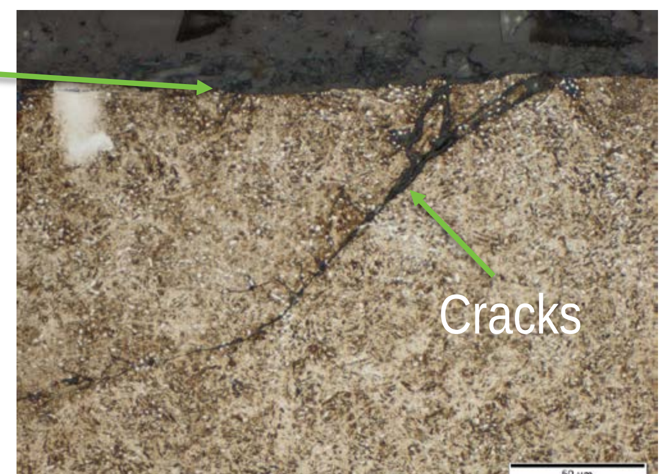




Examples of etched circumferential cross section



Contact surface



Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	Legend	
WBS Number or Agreement Number		Work completed
Project Number: WBS 3.1.2		Active Task
Agreement Number: 23733		Milestones & Deliverables (Original Plan)
		Milestones & Deliverables (Actual)

	FY2012	FY2013				FY2014			
Task / Event	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Bearing and Gear Material Reliability									
Q4 Milestone: Initial WEC characterization of failed bearing									
Q1 Milestone: Material analysis of 10 failed bearings									
Q2 Milestone: Establish WEC bench-top test method									
Q3 Milestone: Test WEC failures at 3 operational and contamination levels									
Q4 Milestone: Test WEC failures of 3 coatings, 2 materials, and 3 lubes									
Q1 Milestone: Bench test at range of sliding conditions									
Q2 Milestone: Bench test at range of load conditions									
Current work and future research									
Examine WEC propogation using developed methodology									
Test material and lubricant mitigation approaches									
Development of bearing test protocol									
Fabricate and test bearings									

Comments

- Project began in Q4 of FY12 with overtarget funds
- Delay in establishing a test method to replicate WEC failures resulted in missed milestones of subsequent quarters in FY13

Partners, Subcontractors, and Collaborators:

- NREL: Gearbox Reliability Collaborative: *Partner*
- University of Akron (Prof. Gary Doll): *Subcontractor (pending)*
- SKF (bearing OEM): *Collaborator*
- Afton Chemical (lubricant additive company):*Collaborator*
- Moventas (gearbox OEM): *Collaborator*
- Wind farm owner/operator: *Collaborator*
- Turbine OEM: *Collaborator*

Communications and Technology Transfer:

- Publication: Greco, A., S. Sheng, J. Keller, and A. Erdemir. "Material Wear and Fatigue in Wind Turbine Systems." *Wear* 302, no. 1–2 (April 2013): 1583–1591. doi:10.1016/j.wear.2013.01.060.
- Presentations:
  - Wear of Materials Conference, 2013
  - Society of Tribologist and Lubrication Engineers Annual Meeting, 2013
  - American Gear Manufacturers Association (AGMA) technical meeting, 2013
  - NREL GRC meeting, 2013 & 2014

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research:

- Further bench-top testing methodology development with load, material, and lubricant chemistry testing
- Small scale dynamic bearing test development to confirm mechanistic bench-top study
- Further examination of WEC failed bearings with high energy X-ray tomography (ANL APS, pending proposal) as an NDA method to investigate WEC failure origins

Proposed future research:

- Further validation of potential mitigation technologies with bearing testing
- Provide further tribological based evaluation and mitigation testing of critical surface failure mechanisms in wind turbine drivetrain and/or pitch/yaw drives (scuffing, fretting, micro-pitting, wear, etc.)

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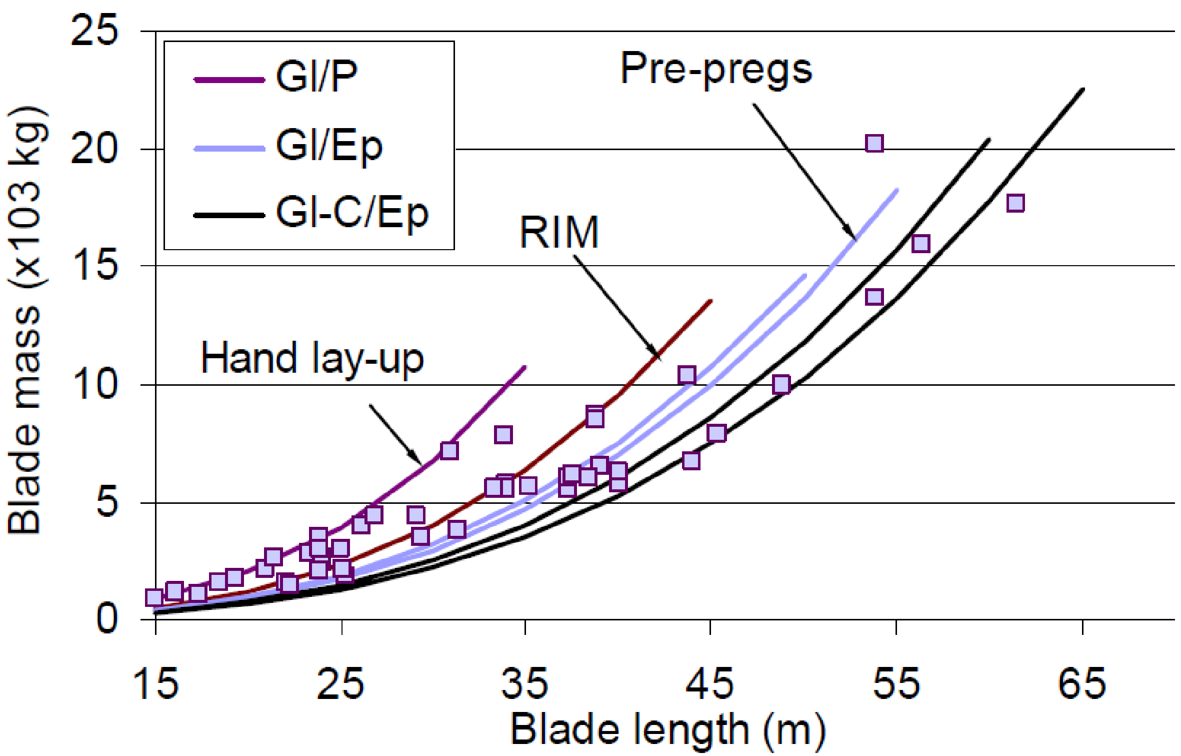

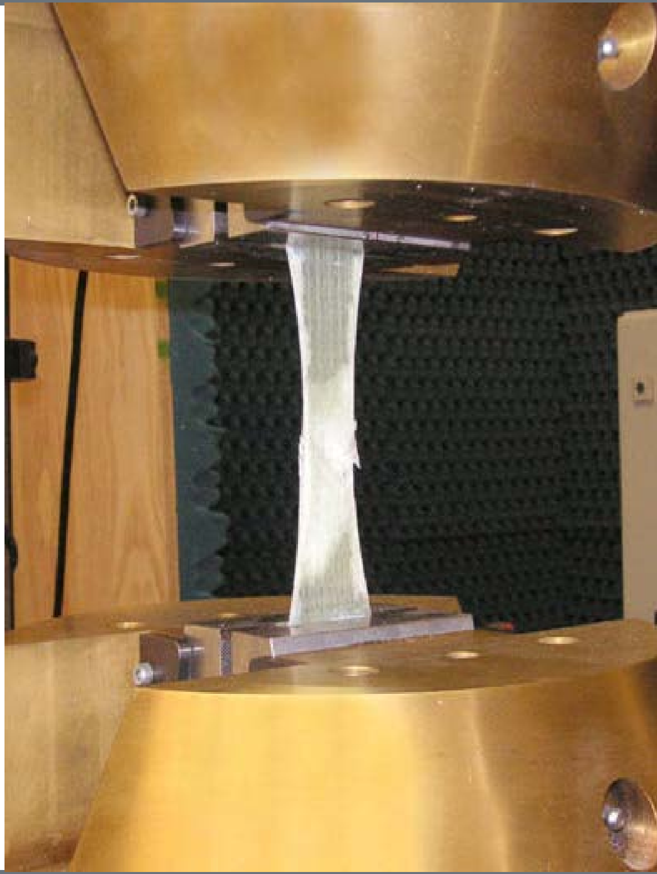

Composite Materials Database

Reliability, O&M, Standards Composite Materials Database

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March 27th, 2014

Budget, Purpose, & Objectives

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Total DOE Budget[1]: $0.600M

Total Cost-Share[1]:$0.000M

Problem Statement: Cost-effective blade design requires an understanding of multi-scale composite material parameters and manufacturing processes

Impact of Project: Characterization of new and existing wind blade materials improves blade design, manufacturing, and reliability by reducing the gap between expected and actual performance and cost

This project aligns with the following DOE Program objectives and priorities

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities at Universities and national laboratories to support mission-critical activities

[1]***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Independent, blade material testing for:

- **Research** to improve materials performance and lifetime prediction in blades
- **Direct support of US industry**: Characterization of current and potential blade materials from **suppliers** (resins, fabrics, adhesives, cores), and laminates and structural details from **blade manufacturers**
- **Public data:** SNL/MSU/DOE Fatigue of Composite Materials Database

Technical Approach

Decision Process: Which issues to address?

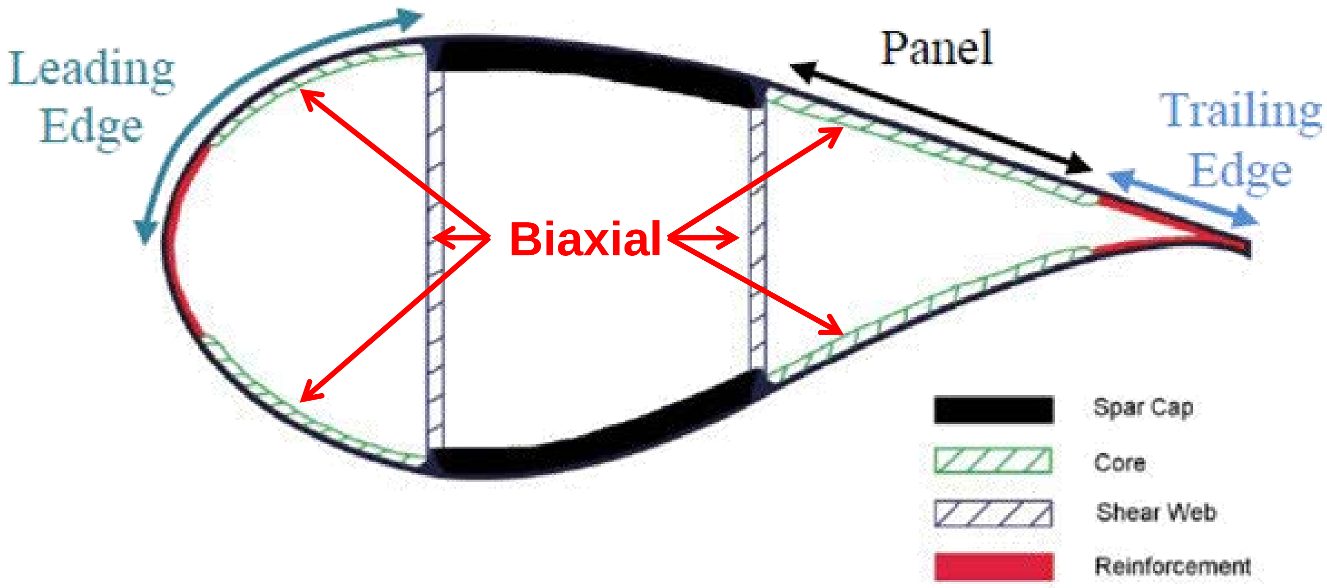
1. Suggestions from blade/turbine manufacturers
2. Experience of program participants at MSU and SNL in composites and composite structures
3. Requests from materials suppliers to test specific materials for inclusion in database (under program guidelines)
4. Needs to complete datasets for parametric studies, etc., like resin or fabric structure effects

Example Accomplishments:

1. Biaxial laminate study (Research focus)
2. Epoxy vs urethane resin study (Direct industry support)
3. Substructure test fixture (New testing capability)

Biaxial Laminate Study:

- Prompted by industry observation of damage initiation in biaxial materials progressing into other primary structures
- More common in larger, heavier blades that experience more edgewise gravity fatigue loading
- Biaxial laminates in the panels carry associated shear loads
- Very little research has been performed on biaxial laminates



Accomplishments

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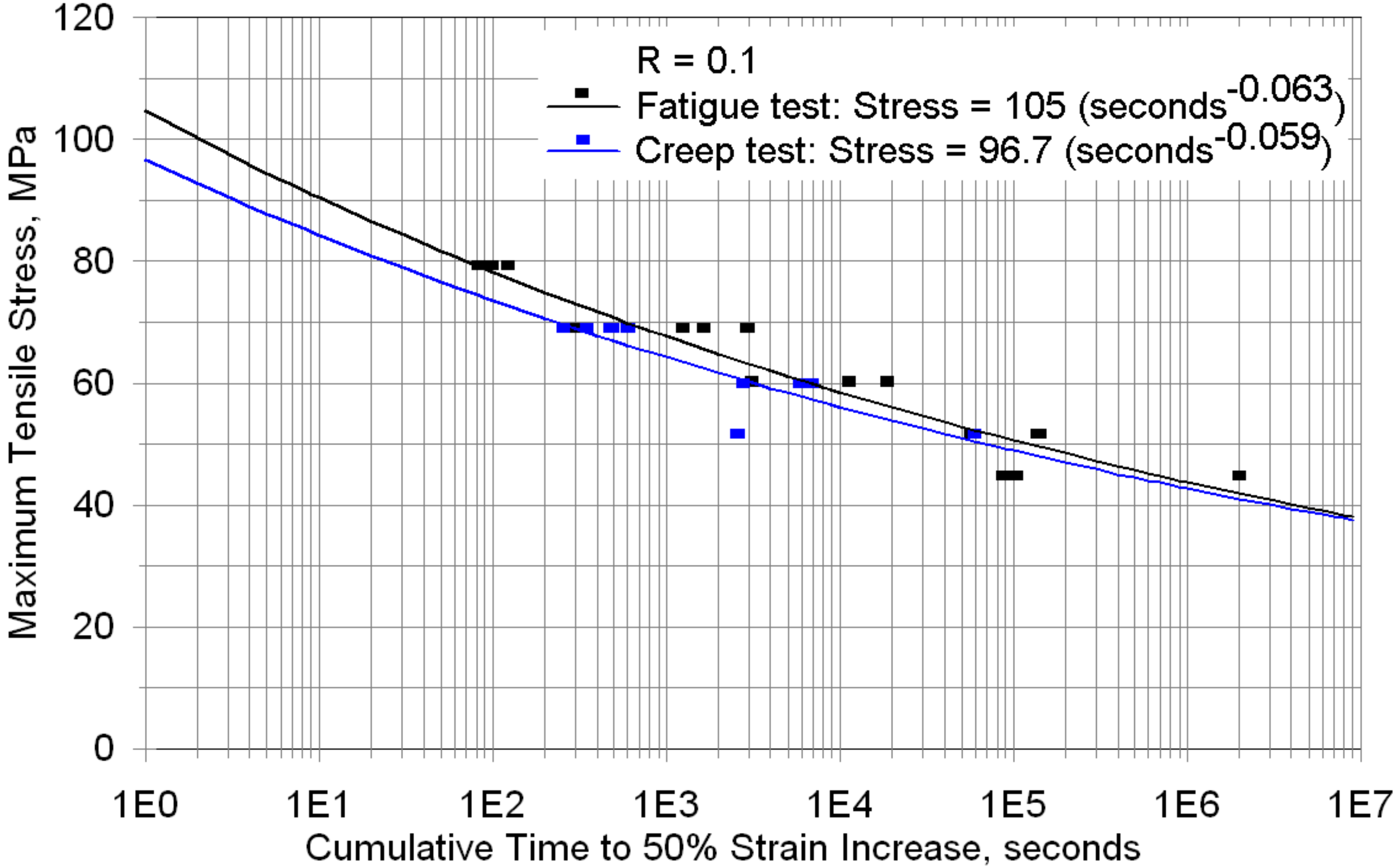
Damage in biaxial laminates depends on **cumulative time** under load, not cycles (the opposite of fiber dominated laminates)



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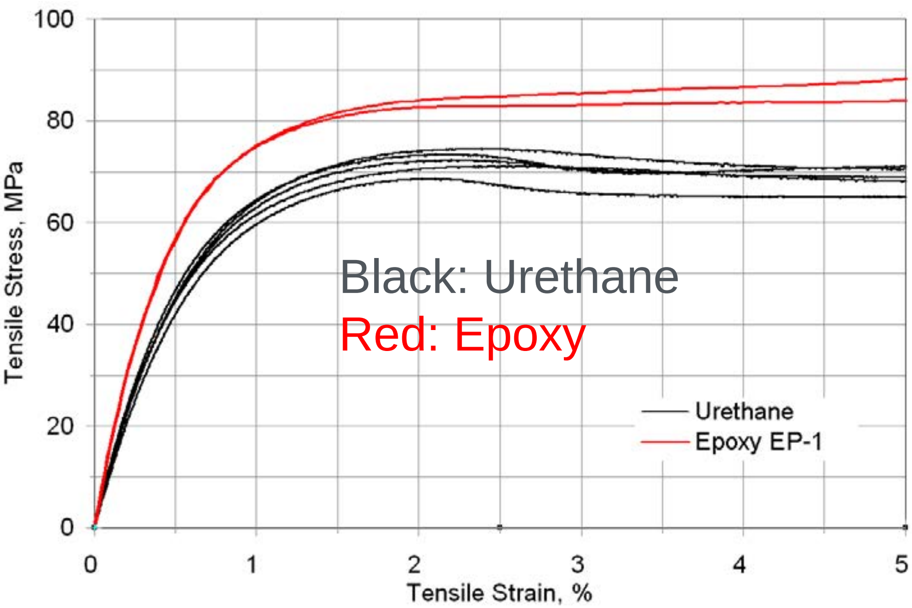
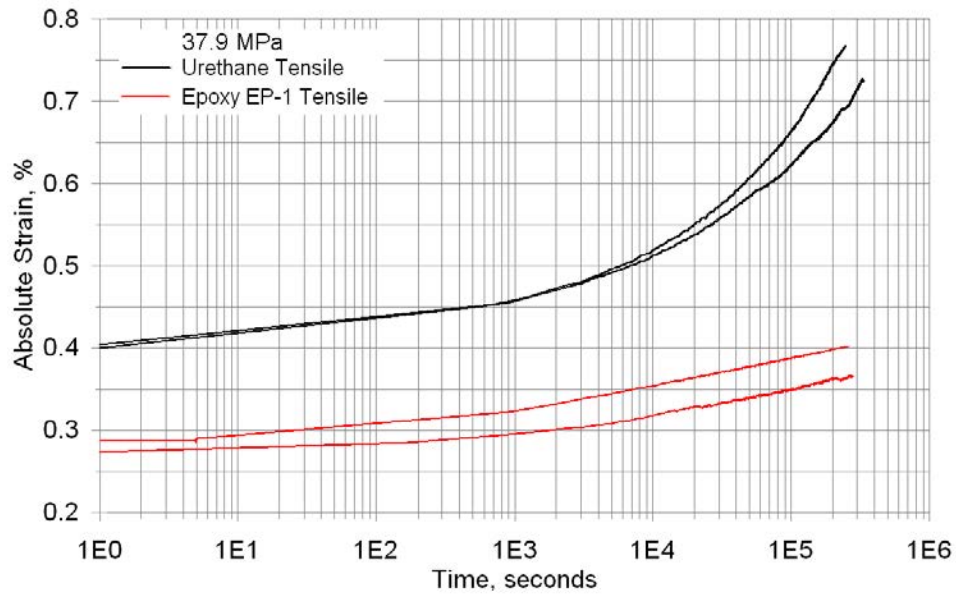
For ±45 laminates with same fabric, Urethane compared to Epoxy has:



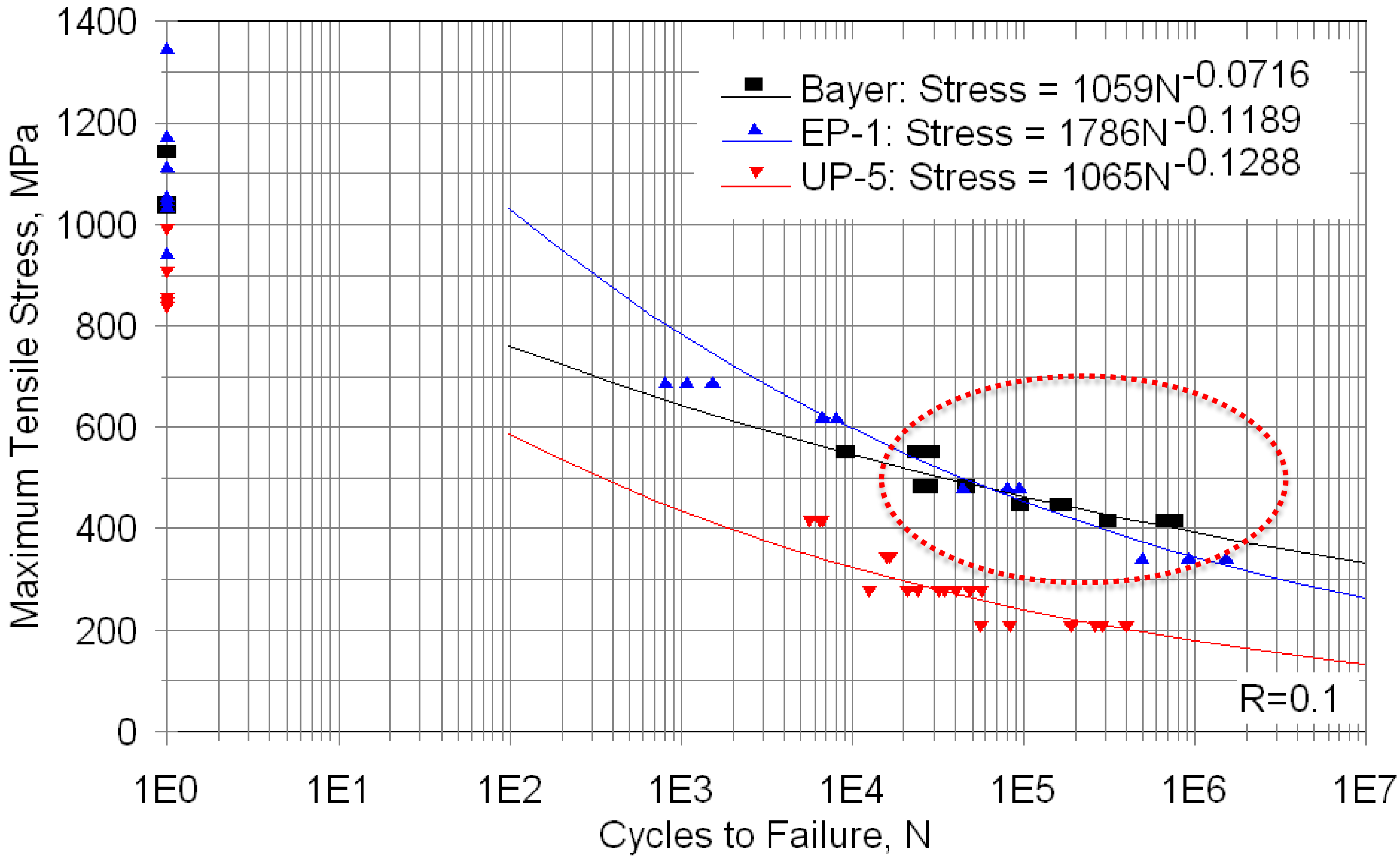


- Reduced Stiffness
- Reduced Strength

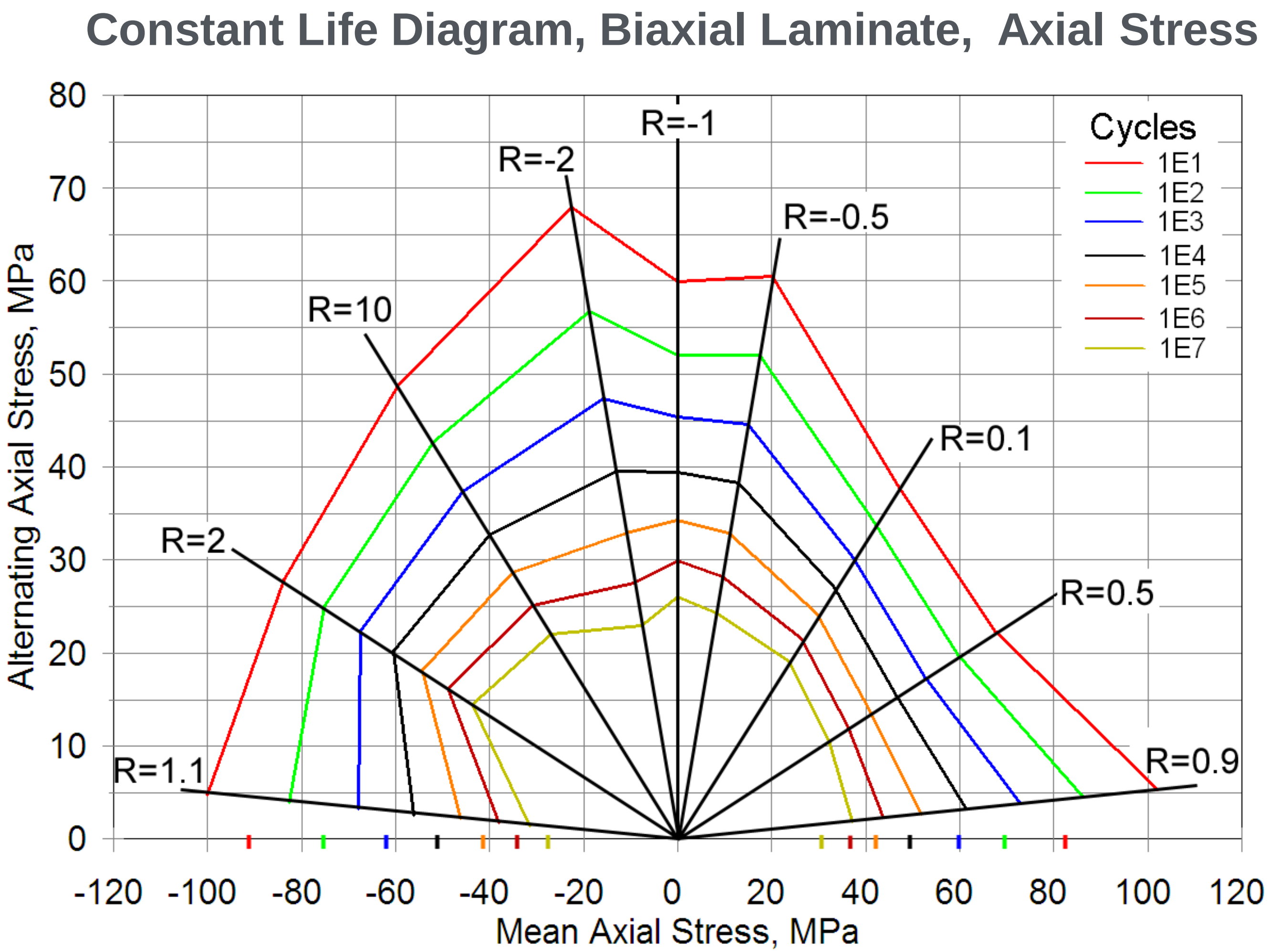
- Reduced Creep Resistance

Accomplishments

Bayer urethane matches epoxy performance in spar cap applications with potential cost and processing advantages



Composite material characterization for wind application requires hundreds of samples tested over thousands of hours to obtain the required design information.



Accomplishments

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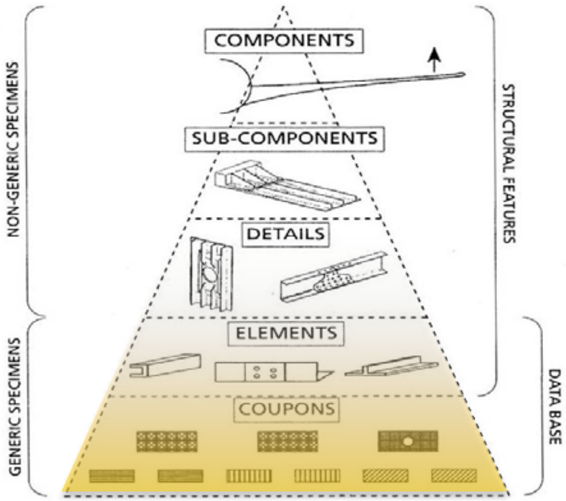
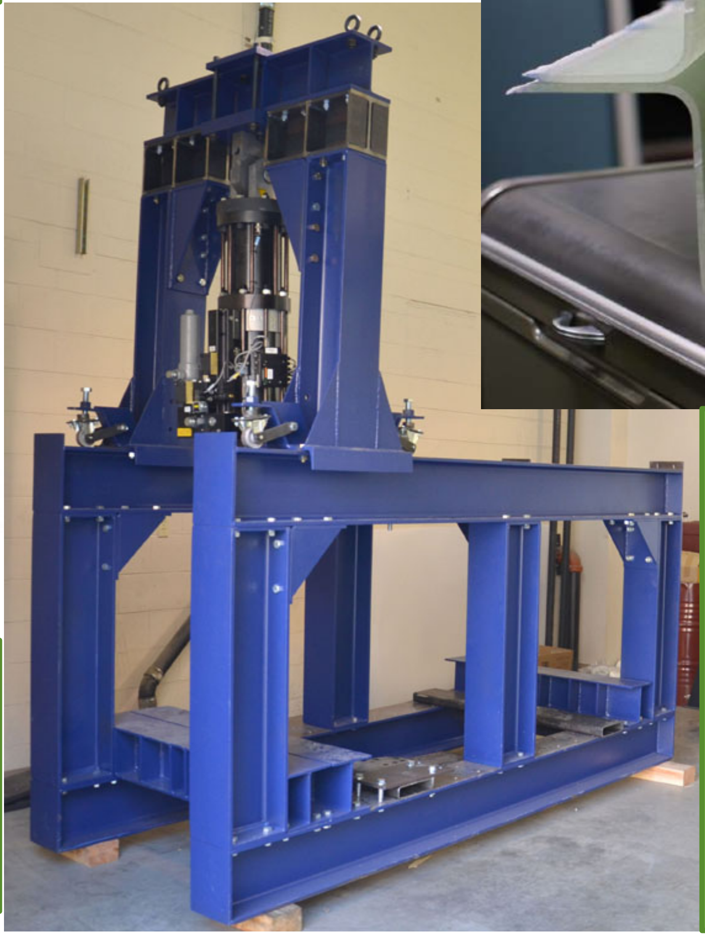
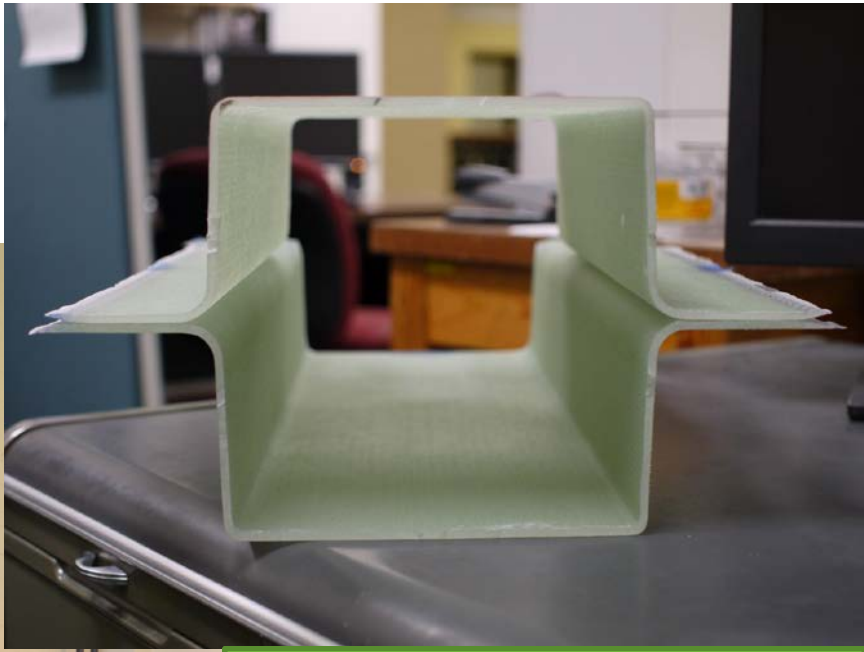
Expensive, Proprietary, Fewer tests, more certainty



Cost effective, generic, many tests, statistical





More representative blade structures and loadings can be investigated

Project Plan & Schedule

Summary	
WBS Number or Agreement Number	2.3.0.4
Project Number	N/A
Agreement Number	22527(FY13) 26909(FY14)

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q1 Milestone: Deliver CY12 Test Plan												
Q2 Milestone: Publish Conference Paper on recent testing trends												
Q3 Milestone: Publish 2012 Edition of DOE/SNL/MSU Materials Database												
Q4 Milestone: Complete annual MSU contract review meeting and report												
Q1 Milestone: Deliver CY13 Test Plan												
Q2 Milestone: Publish Conference Paper on recent testing trends												
Q3 Milestone: Publish 2013 Edition of DOE/SNL/MSU Materials Database												
Q4 Milestone: Complete annual MSU contract review meeting and report												
Current work and future research												
Q1 Milestone: Deliver CY14 Test Plan												
Q2 Milestone: Publish Conference Paper on recent testing trends												
Q3 Milestone: Publish 2014 Edition of DOE/SNL/MSU Materials Database												
Q4 Milestone: Complete annual MSU contract review meeting and report												

Comments

Database and MSU contract started in 1989 and is currently budgeted through 2014.

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

- Montana State University
- Oak Ridge National Lab (low cost carbon fiber)
- Supports Blade Reliability Collaborative & other Sandia projects

Communications and Technology Transfer:

Publications: 2013 AIAA SDM Conference, 2014 SciTech Conference
Book Chapter: Advances in Wind Turbine Blade Design and Materials (2013)
Presentations: SNL Blade Workshop 2012, AIAA 2013,2014
Composite Materials Database:
2013 Version 22 available at www.coe.montana.edu/composites/

Over 250 Materials,12,000+ test results, Excel based

Outcome: 53,593 visitors to composites page from Jan 2012 through Nov 2013.

286 downloads of database in 4 months in 2013

Industry Collaborations

- **Momentive (Hexion):** Epoxy resin variations, adhesives, environmental effects
- **Gurit:** carbon prepregs; aligned strand materials
- **Neptco:** RodPack aligned strand material
- **Hexcel:** Carbon prepreg
- **Dow:** Adhesives
- **Milliken:** Core materials and laminates
- **REPower:** Blade test damage prediction
- **Bayer:** Urethane Resins
- **Materia:** pDCPD resin

Next Steps and Future Research

FY14/Current research:

Task Areas:

1. Baseline laminates
2. New Materials
3. Adhesives
4. Core materials
5. Substructures

→ Blade Materials and Structures

Proposed future research: A 2-year effort to investigate the techno-economic feasibility of low-cost carbon fiber for wind applications.

Oak Ridge National Laboratory | Sandia National Laboratories | Montana State University

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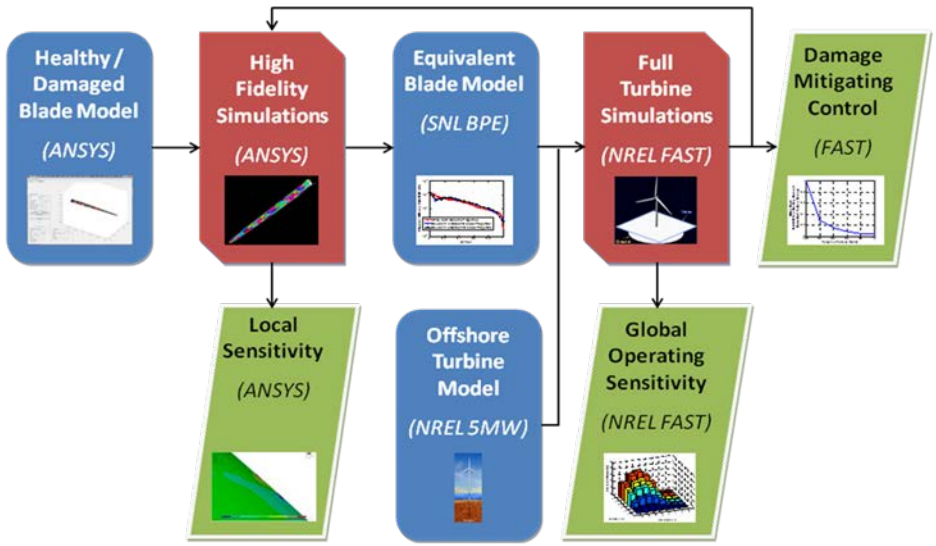

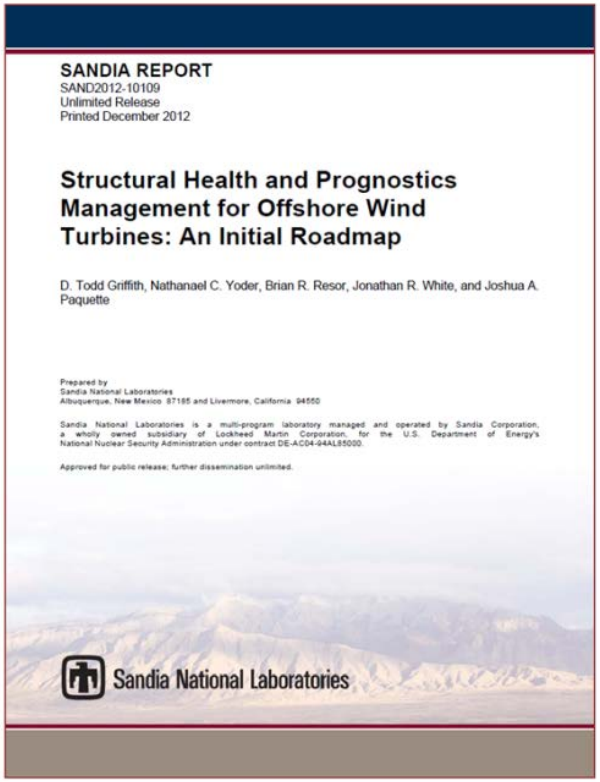
SANDIA REPORT
SAND2012-10109
Unlimited Release
Printed December 2012

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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Sandia National Laboratories

WE 5.1.1 Offshore Wind RD&T: Structural Health and Prognostics Management

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March 27, 2014

Budget, Purpose, & Objectives (1/2)

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Total DOE Budget[1]: $0.480M

Total Cost-Share[1]:$0.000M

Problem Statement: Address high costs of O&M, un-reliability, and downtime by developing and evaluating structural health and prognostics management (SHPM) techniques.

- Address higher offshore O&M costs that arise due to difficulty of access, high sea states, etc.
- Increase availability and maximize AEP
- Ensure applicability to land-based and offshore

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Budget, Purpose, & Objectives (2/2)

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Impact of Project:

Developed a roadmap to a cost-effective structural health and prognostics management (SHPM) system that reduces O&M costs and maximizes AEP.

Enable 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	↑↑↑

Technical Approach (1/3)

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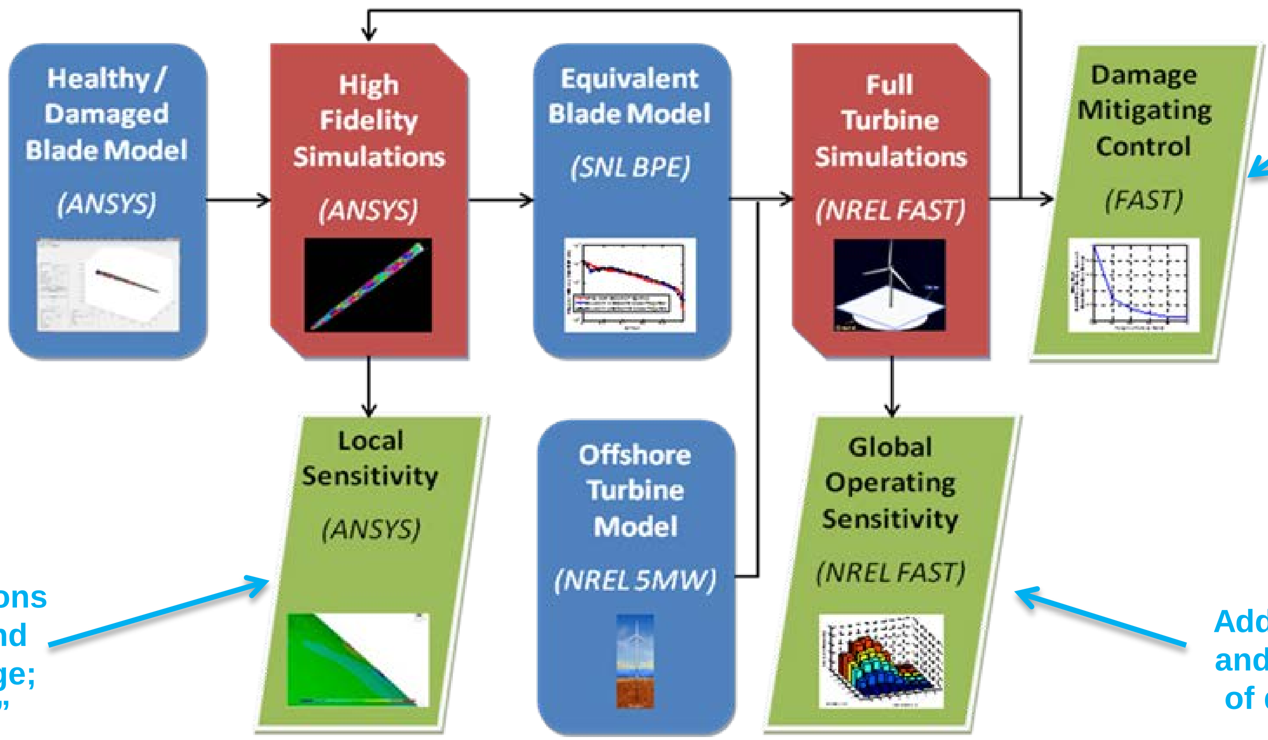
In the first year, FY11, the approach was to:

- Identify the major causes of turbine downtime in the rotor
- Perform a simulation of damage case study for one type of damage to determine the extent to which blade damage could be detected using sensors and operational monitoring
- An initial roadmap for structural health and prognostics management technology was developed
  - A case study of blade trailing edge disbond damage demonstrated the simulation-based approach and illustrates the elements of the initial roadmap.

Technical Approach (2/3)

Multi-scale simulation of damage methodology



Decisions regarding operating strategy

Addresses questions about severity and impacts of damage; "state of health" assessment

Addresses detection and characterization of damage/faults in operation; "sensing"

Broadly applicable and cost-effective simulation-based methodology

Technical Approach (3/3)

- In FY12, additional blade downtime issues were identified and a detection strategy was developed for each
  - Shear web disbond
  - Mass imbalance
  - Pitch error aerodynamic imbalance
- In FY13, an updated technology roadmap was produced to map-out the multi-year strategy and objectives for the research.
- In FY13, the technical work focused on sensitivity of damage studies in the presence of variable inflow conditions

Accomplishments and Progress (1/5)

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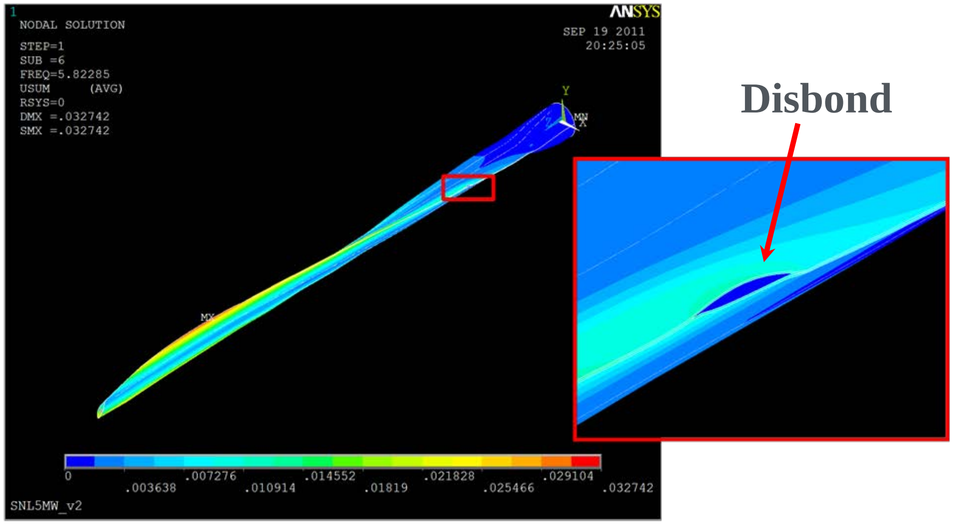
		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Thrust Area 1	**Identify Relevant Damage Features**	• Identify single damage feature #1 • Define criterion for selection: rank based on impact on revenue	• Identify additional important rotor damage features	• Quantify and validate collective effects of these features on revenue loss	• Implement approach for experimental simulation of damage	• Identify and demonstrate the method for non-blade components (e.g. tower)
Thrust Area 2(a)	**Model and Characterize Damage Features: *Global Operating Sensitivity***	• Develop methodology to model and simulate damage globally • Identify sensor needs for blade and non-blade sensing for feature #1 • Identify detection strategy for feature #1	• ID sensor needs for multiple features (blade and non-blade) • ID detection strategies for additional features (blade and non-blade) • Comprehensive survey of industry sensor products (turbine and general)	• Mature detection robustness to uncertainties and multiple simultaneous damage features • Mature the damage model (linear versus nonlinear models) of operating sensitivity	• Mature the damage model (progressive damage model) for operating sensitivity • Laboratory demonstration of detection strategies	• Demonstrate detection in field tests on utility-scale rotor
Thrust Area 2(b)	**Model and Characterize Damage Features: *Local Damage Effects***	• Develop methodology to model and simulate damage locally • Develop a plan to quantify the blade state of health • Perform targeted load case analysis	• Perform complete set of load case analyses to quantify damage effects on state of health tied to IEC/GL blade design standards	• Mature the damage modeling (linear versus nonlinear models) for buckling and strain calculations	• Mature the damage model (progressive damage model) for effect on local sensitivity	• Demonstrate localized damage effects and their progression in full-scale blade test
Thrust Area 3	**SHPM Economics Analysis**	• Initial cost model defined for SHPM system assessment (ID inputs/outputs)	• Refine the fidelity of the SHPM cost model • Perform input/output sensitivity studies	• Integrate with simulations in Thrust Areas 2(a) and 2(b) in end to end case study of SHPM system cost and performance	• Field demonstration project to validate SHPM system model performance and economics	• Distribute validated SHPM cost and decision tools to industry
Thrust Area 4	**SHPM Operations Decisions: Controls**	• Define conceptual prognostic (damage mitigating) control modes	• Refined loads management strategy to avoid catastrophic failure/total loss	• Refined loads management strategy to maximize revenue; to mitigate damage growth	• Model and test/validate the impact of upstream turbine(s) wake on downstream SHPM	• Field demo of prognostic control in utility-scale rotor
Thrust Area 5	**SHPM Operations Decisions: Maintenance**	• Define conceptual maintenance states for blade SHPM • ID the information needed from sensor/SHM system for maintenance decisions	• Refine/expand model to include other information (vessels, weather, etc.) • Refine the blade repair/replacement cost information • Exercise SHPM cost model with new inputs	• Review loads management strategies in the context of optimal maintenance planning	• End to end simulations that demonstrate the effect of SHPM system on maintenance process economics	• Field test validation of SHPM-based maintenance operations for utility-scale wind farm

Technology Integration

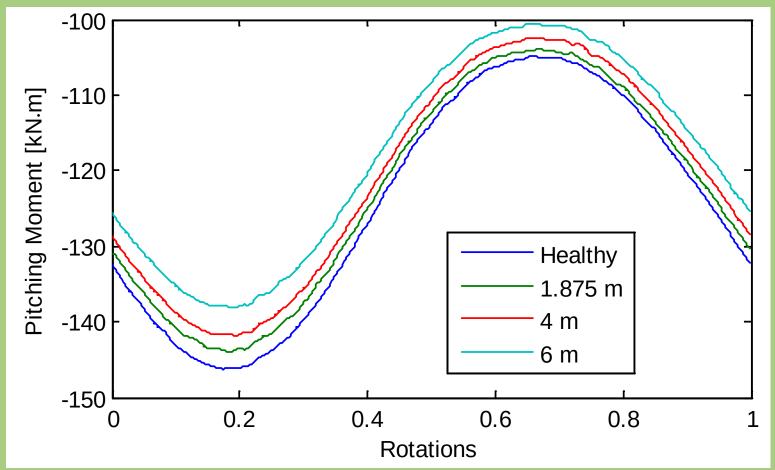
Technology Thrust Maturation Path

Developed a detailed SHPM Technology Maturity Roadmap.

Sensitivity of damage results: Example for Trailing Edge Disbond



Blade and Non-blade sensing approaches considered for all damage/fault types



Root pitching moment is sensitive to trailing edge disbond

Location and number of sensors affects both cost and performance

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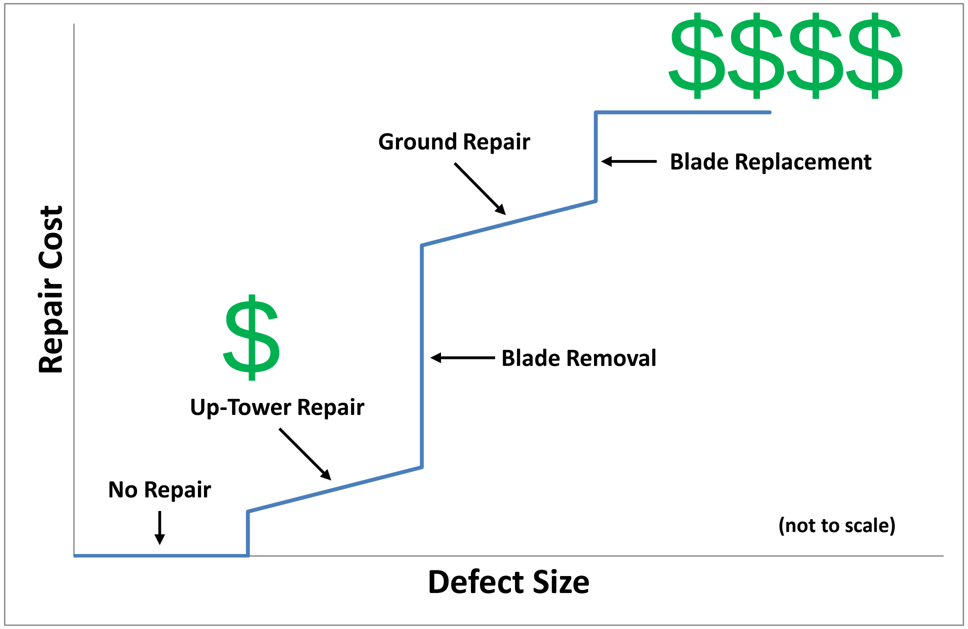
Recognizing the dependence of repair costs on extent of damage and ease of accessibility.

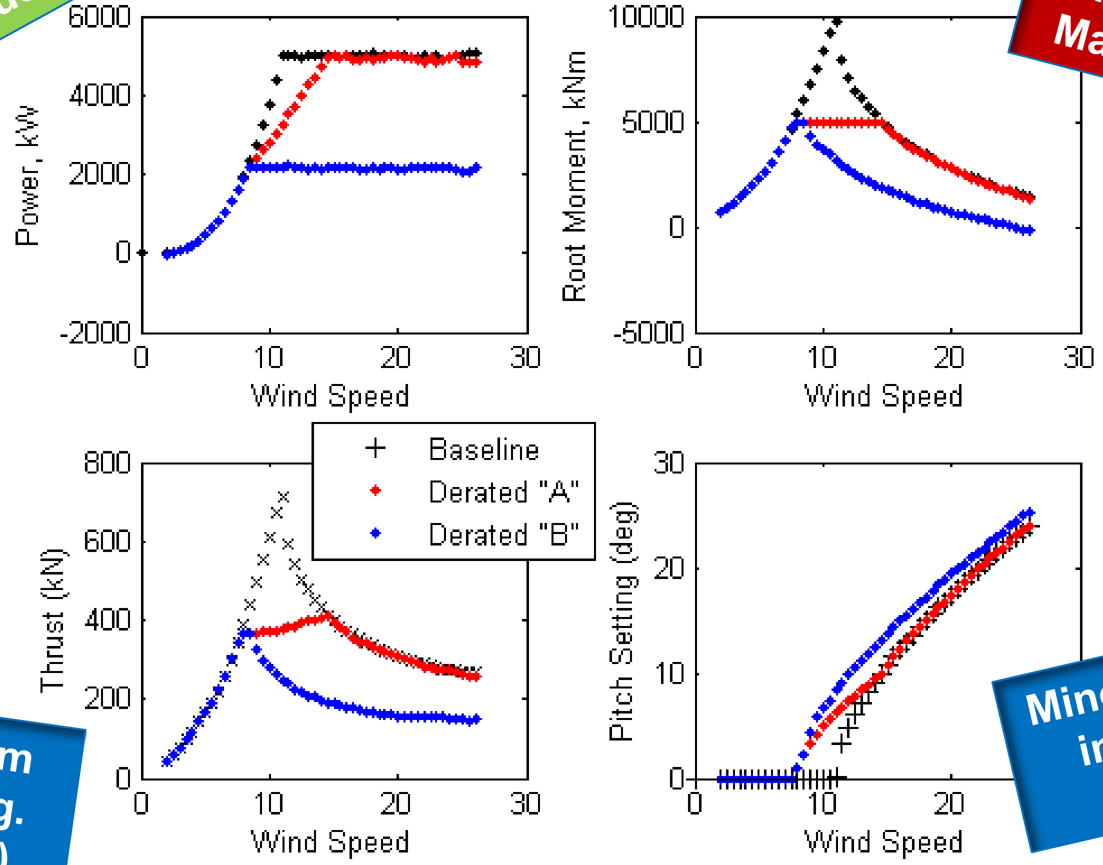


Opportunity to plan for cheaper repairs, optimize O&M processes

Smart loads management (“derating”, “prognostic control”)

Revenue

Smart Loads Management



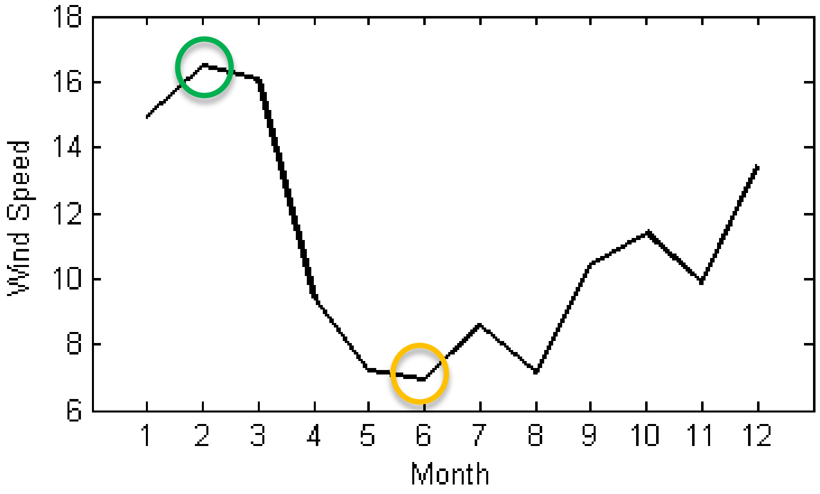
Secondary, System Level Benefits (e.g. support structure)

Minor Change in Control Strategy

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

Accomplishments and Progress (5/5)

SHPM Economics: Effects of Monthly Wind Resource Variation and level of derating



Strong opportunity for return on investment of monitoring system

The increased energy capture of derating ranges from 1.5% to 10.7% depending on level of derating and monthly variation in the wind resource

Derated in Month 6

Derated in Month 2

Table 2: Variations due to monthly wind speed variation in possible revenue increases (using 5 c/kWh), when derating for 1 month instead of shutdown.

Derating Level	Low Speed (7 m/s)	High Speed (16.5 m/s)
75% (A)	+\$63,800 (+4.9%)	+\$140,000 (+10.7%)
75% (B)	+\$53,400 (+4.1%)	+\$99,100 (+7.6%)
50% (A)	+\$55,800 (+4.3%)	+\$131,000 (+10.0%)
50% (B)	+\$44,500 (+3.4%)	+\$73,800 (+5.6%)
25% (A)	+\$35,300 (+2.7%)	+\$96,800 (+7.4%)
25% (B)	+\$19,200 (+1.5%)	+\$23,900 (+1.8%)

Results for a single turbine

Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	WE 2.5.0.1
Project Number	
Agreement Number	26915

Legend	
(light blue bar)	Work completed
(blue bar)	Active Task
◇	Milestones & Deliverables (Original Plan)
◆	Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: WE 5.1.1 Offshore Structural Health and Prognostics Management												
Q1 Milestone: Identify additional probable damage mechanisms	◆											
Q2 Milestone: Simulate additional damage mechanisms		◆										
Q3 Milestone: Prepare draft report on dynamic simulations of damaged turbines			◆									
Q4 Milestone: Draft final FY12 memo				◇	◆							
Q1 Milestone: Finalize disbond and imbalance report; AWEA Offshore Poster					◆							
Q2 Milestone: Updated SHPM Technology Roadmap document						◆						
Q3 Milestone: Document initial experimental plan to validate SHPM							◆					
Q4 Milestone: FY13 Final Report								◇	◆			
Current work and future research												
FY14/Q1 Milestone: Initiate SHPM Working Group									◆			

Comments

- All milestones on track with exception of FY12 and FY13 final reports delayed by 1 quarter each
- Initiation of SHPM Working Group in FY14 off to good start

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners, Subcontractors, and Collaborators:

Subcontracts: ATA, Inc., Purdue University, Vanderbilt University

Communications and Technology Transfer:

Publications:

1. Griffith, D.T., et al, "Prognostic Control to Enhance Offshore Wind Turbine Operations and Maintenance Strategies," **EWEA Annual Event** (Scientific Track), April 16-19, 2012, Copenhagen, Denmark.
2. Griffith, D.T., et al, "Structural Health and Prognostics Management for Offshore Wind Turbines: An Initial Roadmap," **Sandia National Laboratories Technical Report**, December 2012, SAND2012-10109.
3. Myrent, N., et al, "Structural Health and Prognostics Management for Offshore Wind Turbines: Case Studies of Rotor Fault and Blade Damage with Initial O&M Cost Modeling," **Sandia National Laboratories Technical Report**, April 2013, SAND2013-2735.
4. Myrent, N.J., et al, "Pitch Error and Shear Web Disbond Detection on Wind Turbine Blades for Offshore Structural Health and Prognostics Management," **54th AIAA Structures, Structural Dynamics, and Materials Conference**, April 8-11, 2013, Boston, MA, USA, AIAA-2013-1695.
5. Griffith, D.T., et al, "Structural Health and Prognostics Management for the Enhancement of Offshore Wind Turbine Operations and Maintenance Strategies," Wiley **Journal of Wind Energy**, September 2013.
6. Myrent, N., et al, "Aerodynamic Sensitivity Analysis of Rotor Imbalance and Shear Web Disbond Detection Strategies for Offshore Structural Health Prognostics Management of Wind Turbine Blades," **32nd ASME Wind Energy Symposium**, National Harbor, MD, USA, January 2014.
7. Kusnick, J., Adams, D.E., and Griffith, D.T., "Wind Turbine Rotor Imbalance Detection Using Nacelle and Blade Measurements," Wiley **Journal of Wind Energy**, January 2014.

Next Steps and Future Research

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FY14/Current research:

1. SHPM working group formation (in-person meeting at 2014 Sandia Blade Workshop)
2. Additional data analysis for inflow variability study
3. Impacts of smart loads management on damage growth
4. Experimental validation planning
5. Explore synergies with other program elements as outlined in SHPM Technology Roadmap

Proposed future research:

1. A more comprehensive techno-economic assessment of SHPM
2. Lab-scale experimental validation of SHPM
3. SWiFT-scale experimental validation of SHPM
4. Data sharing – public release of SNL damaged turbine simulations

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Standards Highlights:

- DOE and National Labs have long-term perspective needed for Standards development
  - Industry sees value in impartial contributors
- Current Sandia Standards work includes Availability/Reliability and Design Requirements
  - Sandia leverages existing expertise and facilities to create valuable contributions
- Both DOE and Sandia have benefitted from formal “Standards” task and its shared priorities

Reliability and O&M
Standards Development

[Offshore] Strategic Planning & Standards

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March 27, 2014

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $0.300M

Total Cost-Share[1]:$0.000M

Problem Statement: Industry needs unbiased 3rd parties engaging in discussions about technical and performance criteria to develop the most effective Standards. Standards that are developed by cross-cutting groups of dedicated experts provide the most benefit to market interactions.

Impact of Project: This work leverages the results of DOE research and Sandia's unique abilities, such as high-performance computing (HPC) and reliability analysis, to influence fact-based Standards and Best Practices that increase the performance of and knowledge of wind turbines and wind plants.

This project aligns with the following DOE Program objectives and priorities:

- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources

Impartial input into Standards is a market benefit

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

Approach:

- Utilize DOE research results and Sandia's expertise in HPC and reliability to inform relevant Standards and Best Practices, such as
  - IEC (International Electrotechnical Commission) 61400-1 Design Requirements Standard
  - IEC 61400-26 Availability Standard
  - IEA (International Energy Agency) Task 33 Reliability Data Best Practices
  - AWEA's (American Wind Energy Association) Operations and Maintenance Best Practices
- Jumpstart Offshore planning and standards, using Sandia's expertise

Key Issues:

- Best Practices need to remain in "Standards" work, as they are a key precursor

Unique Aspects

- Sandia's resources and expertise in HPC, along with a strategic partnership with UT Austin, creates a modeling competence used to evaluate Design Standards in an unbiased, fact-based environment
- Sandia's long history in reliability analysis and expertise from the CREW reliability project uniquely positions Sandia to contribute to Standards in reliability, operations, and data collection/reporting

Knowledge of Best Practices makes Sandia a key contributor to industry Standards

FY2012-FY2013 Accomplishments and Progress

- IEC 61400-1 Design Requirements:
  - Created and shared 100-year loads database for 5MW onshore turbine and 64-year loads database for shallow water offshore turbine
  - Developed new, simpler extreme load extrapolation procedure that reduces ambiguity from extrapolating a short term distribution to an extreme 50-year value
    - Currently under consideration for next revision of this Standard
- IEC 61400-26 Availability:
  - Time-Based Availability (Part 1): Published
  - Production-Based Availability (Part 2): Ready for publishing
  - Plant-Wide Availability (Part 3): In development
- IEA Task 33 Reliability Data:
  - Published report on all known international initiatives in Reliability data and analysis
  - Drafting report on Best Practices in Reliability Data Collection and Analysis
- AWEA O&M Best Practices
  - First edition published; significant Sandia authorship in “Data Collection & Reporting” chapter
- Offshore
  - Delivered Wind Supply Chain assessment to DOE

Sandia participation leads to concrete results in Standards development

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	2.3.0.5
Project Number	
Agreement Number	26929

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: CREW Database & Analysis Program												
2012-Q1:Update on IEC 61400-26 Availability												
2012-Q2: Identify appropriate metrics for IEC 61400-26												
2012-Q3: Contribute to AWEA O&M Best Practices												
2012-Q4: Update on all activities												
2013-Q1: Update on IEC 61400-26 Availability												
2013-Q2: Update on IEA Task 33 Reliability Data												
2013-Q3: Update on IEC 61400-1 Design												
2013-Q4: Update on all activities												
Current work and future research												
2014-Q1: Update on IEC 61400-26 Availability												
2014-Q2: Update on IEA Task 33 Reliability Data												
2014-Q3: Update on IEC 61400-1 Design												
2014-Q4: Update on all activities												

Comments

- Project initiation: FY2011
- FY14-Q2 milestone (due in March) will be deferred, as IEA Task 33 meeting was moved to May

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners, Subcontractors, and Collaborators:

- **Subcontractor**: University of Texas, Austin – Prof. Lance Manuel
- **Partners**: *Numerous US and international partners for each Standards body or Working Group, including OEMs, owner/operators, universities*

Communications and Technology Transfer

Standards Published

- IEC 61400-26-1, "Time-based Availability for Wind Turbine Generating Systems"

Papers

- Barone, M., Paquette, J., Resor, B., & Manuel, L. Decades of Wind Turbine Load Simulation. AIAA2012-1288, ASME Wind Energy Symposium. Jan 2012.
  - **Won "Best Paper" award**
- Manuel, L., Nguyen, H., & Barone, M. On the use of a large database of simulated wind turbine loads to aid in assessing design standard provisions. AIAA 2013-0197, ASME Wind Energy Symposium. Jan 2013.

Presentations

- AWEA Offshore Windpower (10/2012): Laird, D. DOE Offshore Wind Research.
- IEC 61400-1 Loads Subcommittee (2/2013): Manuel, L, H. H. Nguyen, and M. Barone. Alternatives to Load Extrapolation

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research:

IEC 61400-1 Design Requirements:

- Create model definition for 13.2 MW floating turbine, to generate large-scale loads databases for improvement of offshore design Standards
  - Could also benefit 61400-3 (Offshore) Standard

IEC 61400-26 Availability:

- Continue contributing to draft of Part 3 (Plant Availability), including reliability block diagram models of wind power stations with turbine and Balance of Plant components

IEA Task 33 Reliability Data:

- Continue contributing to Reliability Best Practices report on Data Collection and Analysis

Proposed future research:

Incorporate additional Wind Standards work into a single task, possibly including

- IEC TC 88, WG 27; Electrical Simulation Models
- IEC 614405; Rotor Blade Standard
- IEA T31; Wakebench (SWiFT test case)

Both DOE and Sandia have benefitted from formal "Standards" task, including clarity on priorities and budgets

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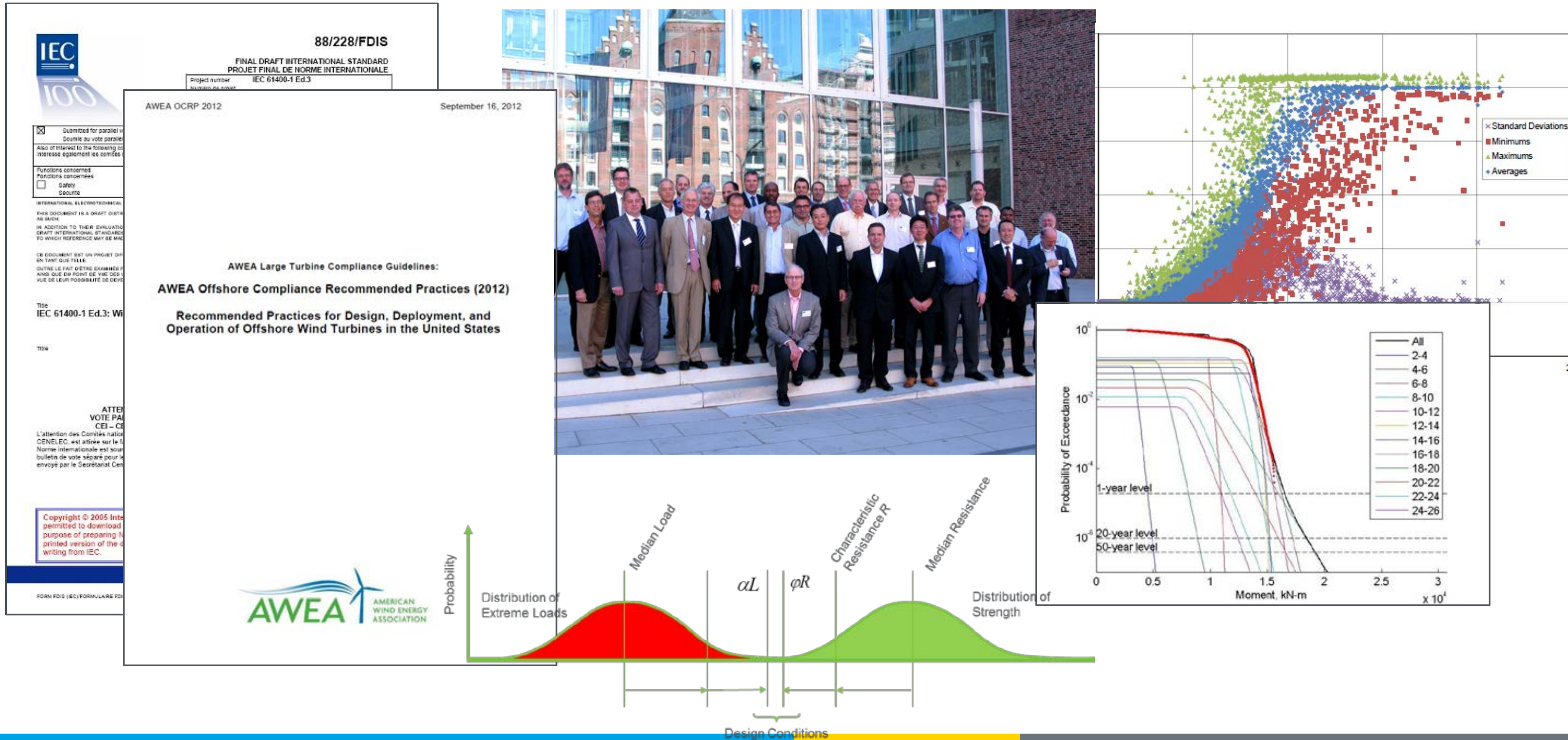


Standards

Jeroen van Dam

NREL

Jeroen.van.dam@nrel.gov, 303-384-7009

March 27, 2014

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $0.780M

Total Cost-Share[1]:$0.000M

Problem Statement: Standards need maintenance to reflect the state of the art in knowledge and technology. Knowledge developed in the DOE program can be used to inform appropriate requirements in standards.

Impact of Project: International standards resulting in reduced market barriers and lower Levelized Cost of Energy (LCOE) through reduced risk due to appropriate level of safety and high-quality test results.

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce wind plant LCOE
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

- Actively participate and have a leading role in the development of international and domestic standards related to wind turbines, including IEC, UL, and AWEA.
- Leverage knowledge developed in other parts of the program. DOE funding primarily covers preparation for, travel to, and attendance at meetings. The real knowledge is developed in other projects.
- Indirect benefit: Standards development meetings are a great platform to understand:
  - Issues the industry struggles with
  - Boundaries of our knowledge
  - How we can help define R&D needs

Technical Approach

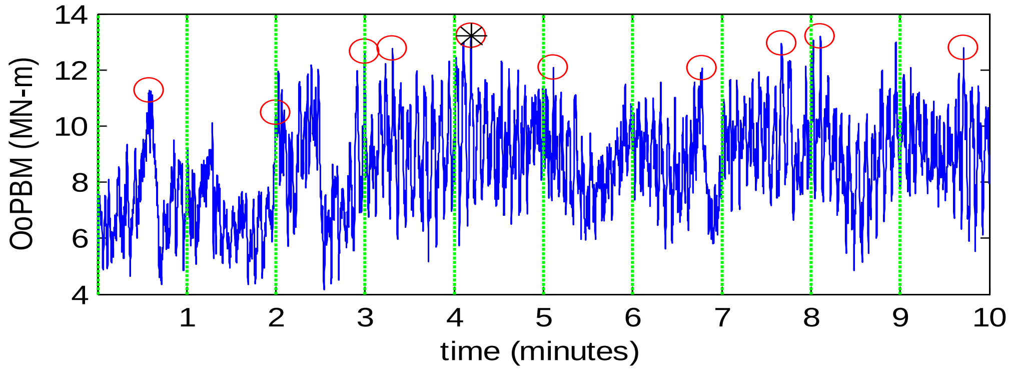
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Standard	Content
IEC 61400-1 (S)	Wind turbine design
IEC 61400-2 (S)	Small wind turbine design
IEC 61400-3	Offshore wind turbine design
IEC 61500-5 (S)	Blade design and manufacturing
IEC 61400-11 (S)	Acoustic noise testing
IEC 61400-12	Power performance
IEC 61400-13 (C,S)	Mechanical loads testing
IEC 61400-14 (S)	Noise declaration

Standard	Content
IEC 61400-21	Power quality testing
IEC 61400-23 (S)	Full-scale blade testing
AWEA –SWT1(C)	Small wind turbine safety and performance
AWEA RP (C)	Structural, Offshore wind, Electrical
UL6141	Large turbine electrical
UL6142	Small turbine electrical
(C), (S)	Marks where either we provide convener or secretary

Arlinda Huskey and Derek Berry received IEC1906 award for roles in MT11 and PT5

Example of direct impact of IEC 61400-1 on LCOE



Alternatives	Current IEC Ed.3	One proposal (MT1e4-6-18)
a) (Mean of extremes)	γ =1.875 = 1.25·1.5	γ=1.7 (~1.25·1.35)
b) (Extrapol. to 99%)	N. A.	γ=1.5 (=1.25·1.2)
c) (Extrapol. to 50 years)	γ=1.25	γ=1.25

- Load extrapolation uses many short operational simulations to estimate a long-term extreme through a statistical analysis (extrapolation)
- The extrapolation process is complex, computing demanding, and requires some engineering judgment
- Industry is demanding simpler alternatives with a similar reliability level

AWEA-Recommended Practice

Problem: No clear guidance on which local codes (structural, electrical, and offshore) apply in the U.S.

- Overall Lead: Paul Veers, NREL
- Structural (AWEA/ASCE): Rolando Vega, ABS
- Electrical (AWEA /UL), UL 6141 in final stages: Tim Zgonena, UL
- Offshore: Walt Musial, NREL
  - Structural Reliability
  - Fabrication, Construction, Installation and Qualification Testing
  - Operation, Maintenance, and Decommissioning
- Broad industry participation (government, OEMs, consultants, certification bodies, developers)

NREL chaired the IEC Certification Advisory Committee Test Laboratory subgroup

- 38 accredited labs participated
- 3 proficiency tests were completed
  - Power performance
  - Loads
  - Blade testing
- Addressing concerns about inconsistent level of quality

Accomplishments and Progress

- U.S. Wind Turbine Standards Summit: 27-28 Nov 2012
  - Informed industry about the direction standards are taking
  - Discussed some of the issues and formed a U.S. position on critical items
  - Solicited more involvement through shadow committees / TAGs
  - Developed ideas and identified gaps for national and international standards needs
  - ~70 participants covering a wide array of stakeholders

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	FY12: 3.1.1.6 FY 13: 3.1.6
Project Number	FY12: 21112
Agreement Number	22503

Legend	
	Work completed
	Active Task
◇	Milestones & Deliverables (Original Plan)
◆	Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Standards												
Q3 Milestone: complete offshore RP			◆									
Q1 Milestone: Organize US Standards Summit					◆							
Q2 Milestone: IEC CAC proficiency test						◆						
Q3 Milestone: AWEA SWT-1 meeting							◆					
Q4 Milestone: Activity summary report								◆				
Q1 Milestone: Comments on IEC 61400-12-1 CD									◆			
Q2 Milestone: Provide NREL votes to US TAG										◆		
Q3 Milestone: IEC 61400-13 CD											◆	
Q4 Milestone: Activity summary report												◆

Comments

- Limited control on timeline of standards development activities
- Standards developments are typically 3- to 5-year activities

Partners, Subcontractors, and Collaborators

- International industry stakeholders: OEMs, certification bodies, owner/operators, consultants, test laboratories, research laboratories, universities
- AWEA Standards Development Board Subcontract:
  Dr. Santos for convening IEC MT13
- Travel reimbursement:
  - Lance Manuel, TTU
  - Jim Manwell, UMass

Communications and Technology Transfer

- US Wind Turbine Standards Summit
- AWEA-Recommended Practice: www.awea.org
- U.S. merit/shadow committees

Next Steps and Future Research

FY14/Current research

- Standards development task is an ongoing activity
- FY14 activities are in line with prior years
- Assisting AWEA to take on a more active U.S. standards coordination/leadership role (e.g., handed off summit in 2014)

Proposed future research

- Shift focus from wind turbines to wind plant, both for design and testing
  - Waked inflow
  - Design load cases
  - Wind farm power performance

ATMOSPHERE TO ELECTRONS

U.S. DEPARTMENT OF ENERGY

Atmosphere to Electrons (A2e) Initiative Overview

Michael C. Robinson, PhD

DOE/WWPTO

mike.robinson@ee.doe.gov]

[Date of Presentation]

Project Budget

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Budget History ($K)	
National Laboratory:	**Budget***
Sandia National Laboratory (SNL)	$500
A2e Program Management & Planning	$500
National Renewable Energy Laboratory (NREL)	$2,000
A2e Program Management & Planning	$500
Wind Tunnel Wake Testing	$1,500
Pacific Northwest National Laboratory (PNNL)	$600
A2e Program Management & Planning	$500
Data Management	$100
	$3,100

* A2e Program front-funding provided for some activities late in FY-13 to begin program implementation in early FY-14

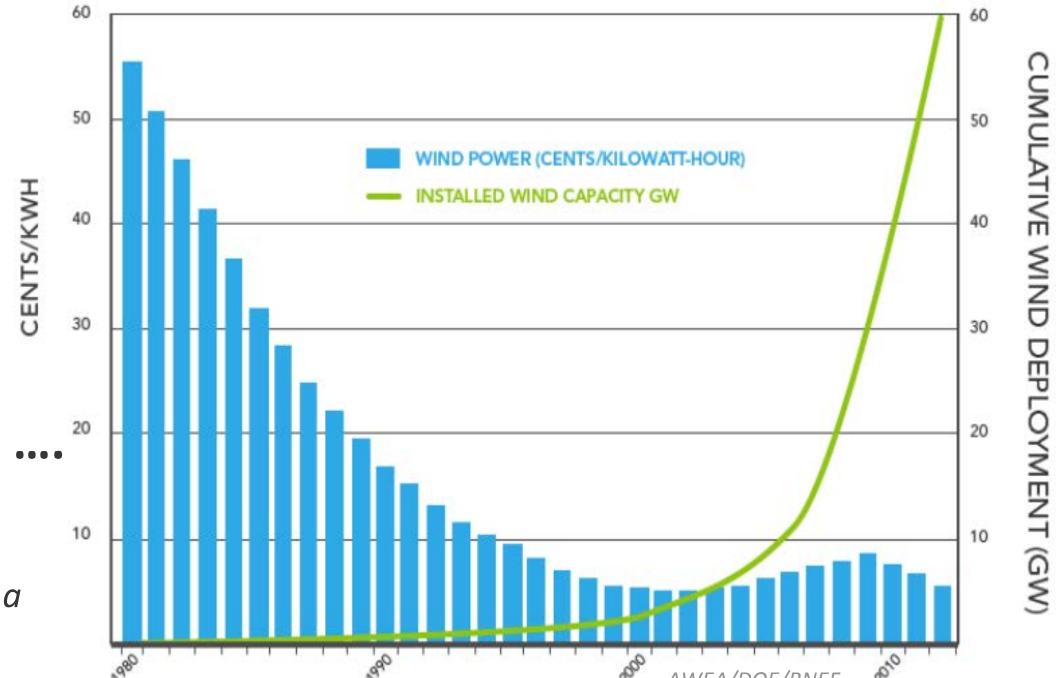
Wind Power Industry Overview

Wind energy today …..

- *Multi-Billion dollar industry with involvement of multi-national corporations*
- *60+ GW Deployed (~5% of U.S. Electricity)*
- *Land-based wind: 7-8 ¢/kWh (beating coal)*
- *Competitive wind turbine technology at multi-megawatt scales*
- *Leads all renewable technology deployment*

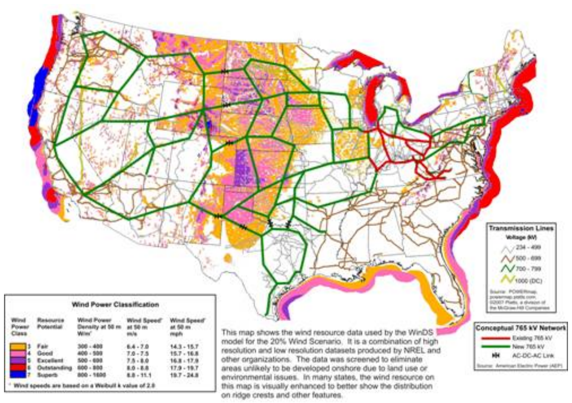
Tremendous opportunity remains ….

- *Achieve parity with natural gas @5-6 ₵/kWh*
- *Establish offshore wind deployment*
- *Provide foundational R&D to facilitate wind as a principal technology in the RE 30-80% Vision*



AWEA/DOE/BNEF

Getting to future, high penetration scenarios will require:



- *Federal R&D and operational oversight to ensure power availability, reliability, and stability from weather driven resources*
- *Engagement & participation by multiple government agencies (e.g. DOE, DOC, DOI, DOD, NASA, NSF), university & private sector stakeholders*
- *Defining the operational wind plant environment driving future technology development & innovation*
- *New generation of advanced HPC tools to achieve high fidelity modeling of integrated renewable power systems at national scales*

Motivation for a New Wind R&D Framework

Key Objectives:

I. Change the research paradigm from individual wind turbines to entire wind plant cost and performance optimization

II. Engage the national labs, universities, and industry in a collaborative consortia for the strategic planning and execution of comprehensive, high-value research initiatives

Strategic Approach:

I. Adopt an open "DOE/SC like" planning construct in establishing strategic goals, performance objectives and new initiatives

II. Collaboration with the international research community in advancing HPC to support technology evolution and high penetration deployment of renewable technologies

A2e Initiative Considerations

1. Performance, Cost and Risk Factors

- Wind Plant Power Losses can be as high as 20-30% in modern wind farms*
- $100-300M in annual operating costs can be saved through forecasting accuracy improvements of 10-20%*
- Unplanned maintenance and long term O&M uncertainty are a significant risk factor driving discount rates and project financing*
- Although turbine technology is mature, optimal wind plant performance potential has not been established*

2. Complicating Factors

- Wind resource characteristics remain poorly resolved, modeled and observed at plant scales
- Wind plant performance is a multi-scale and physics problem spanning many technical disciplines
  - Atmospheric science phenomena and weather patterns
  - Wind plant aerodynamics, turbulence, complex terrain, and wake dynamics
  - Fluid structure interactions and structural dynamics
- Required research investment is substantial, requiring multi-national stakeholder collaboration
  - Supercomputing resources for multi-scale high fidelity modeling and coupled simulations
  - Large-scale field experiments at operating wind plants
  - Partnerships will be necessary to leverage enough resources to solve the problem
- No single national lab, university, or industry participant has ALL the necessary expertise

3. The Atmosphere to Electrons Collaborative Approach Solution

- Seven (7) year "hub like" initiative, targeting specific wind plant cost and performance improvement objectives
- DOE/FFRDC led consortia leveraging national and international experts actively engaged in the planning process
- Formation of international science panels and external workshops in developing plans and approach
- Flexible funding framework inclusive of multiple execution methods (e.g. FOAs, AOPs, IAAs, International Agreements, etc.)
- Retain DOE oversight and control through active program management, project reviews

For references, please see Appendix

Introducing Atmosphere to Electrons (A2e)

A2e is a new, multi-year, multi-stakeholder DOE R&D initiative tasked with improving wind plant performance and mitigating risk and uncertainty to achieve substantial reductions in the cost of wind energy.

DOE Wind Program

- Federal Engagement & Oversight
- Integrated Program & Project Management
- Budgetary Control

National Labs & Universities

- Subject Matter Expertise
- Project Planning
- R&D Execution

Atmosphere to Electrons (A2e)

- ✓ DOE led partnership with National Laboratories, Other Federal Agencies, Universities, Industry, and International Stakeholders
- ✓ Integrated strategic research planning coordinated through lead National Labs & DOE
- ✓ Research conducted by appropriate organizations

Other Fed Agencies

- Leverage Strategic Programs
- Access to HPC Core Competencies
- Subject Matter Expertise
- Access to Facilities

Private Industry

- R&D Execution
- Operational Expertise
- End User Requirements
- Access to Operating Plants

Int'l Collaboration

- Coordinated & Collaborative Research Campaigns

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Need for a New Collaborative R&D Framework

Goals and Objectives for a lower cost, higher performance wind power plant paradigm …

1. Optimized Performance of Existing Wind Plants
- Increase Power Production
- LCOE Reduction
- Predicted Power Performance Probability Variance (P50/P99)

2. Wind Plant / Grid Interface
- Improve 24 Hour Ahead Forecasted Power Production Accuracy
- Reduce Annual Curtailment
- Prediction Certainty of Anomalous Ramping Events

3. Next Generation Wind Plant Technology Development
- CapEx Reduction
- Increase Capacity Factory (C_F)
- O&M Reduction
- Reduced Acoustic Emissions
- Reduce Discount Rate

… Require the following R&D cross cutting activities …

a. Quantify contributing factors to underperformance
b. Minimize array loss effect
c. Improve performance prediction confidence
d. Improve reliability and reduce major component failure rates
e. Improve production through flow resource active monitoring & control
f. Characterize physical atmospheric phenomena
g. Quantify gaps in boundary layer physics models
h. Improve high fidelity atmospheric models
i. Assess inter- and intra-array effects on macro and micro climatology
j. Integrate real-time forecast models into dispatch & operational control strategies
k. Explore optimal wind plant configurations
l. Incorporation of wake and flow control
m. Optimize turbine systems for next generation wind plant designs
n. Active incorporation of flow monitoring and resource characterization
o. Develop scaled prototypes of new technology
p. Develop pre-commercial prototypes at full scale
q. Full system integration and modeling

… Which require the following activities and capabilities:

- **Cross cutting and synergistic science & technology initiatives**
  - HPC, small- & large-scale experiments, field tests, design tools, etc.
- **Long-term integrated planning and execution**
  - Requires centralized planning and execution consisting of technical experts from multiple disciplines
  - Requires flexible, multi-year funding decisions
- **Multi-stakeholder engagement**
  - Must engage national labs, industry, international experts, & universities
- **Public dissemination of results**
  - Results must benefit the entire U.S. wind industry

Atmosphere to Electrons (A2e)
- ✓ Seven year strategic initiative managed as a "hub like" consortia in a DOE lead partnership with National Laboratories
- ✓ Integrated strategic research planning lead by National Labs & DOE engaging multiple domestic and international stakeholders
- ✓ Planning separated from research implementation
- ✓ Research activities conducted by most appropriate stakeholder using the most expeditious contract mechanism

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WWPTO Addresses these 3 R&D Topics in 2 Sub-Programs

WWPTO Director’s Office and Operations
(WWPTO Director: Jose Zayas)

Wind R&D
(Mike Derby)

Resource Characterization
(Joel Cline)

- Forecasting
- Complex terrain
- Meso-scale to LES coupling
- Long-term measurement
- Coupled wind/wave simulation

Wind Plant Technology
(Mike Derby)

- Wind plant and array aerodynamics
- Fluid structure interaction
- Advanced controls
- Component R&D
- Wind plant reliability
- Design & systems engineering tools

A2e Initiative
- Optimize Wind Plant Performance

Grid Integration
(Charlton Clark)

Market Barriers
(Hoyt Battey)

Water Program
- Resource Characterization
- Technology Development
- Grid Integration
- Market Barriers

- **A2e Combines These Two Sub-Programs into a jointly-planned Initiative.**
- **Currently, Grid Integration & Market Barriers Not Included in Scope**
  - Focus on wind plant performance, not full system performance
  - Limit planning impact on existing program
  - Have received some pushback

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A2e Executive Management Committee

Wind Power R&D
A2e Fiscal and Planning Oversight and Approval
(Mike Derby)

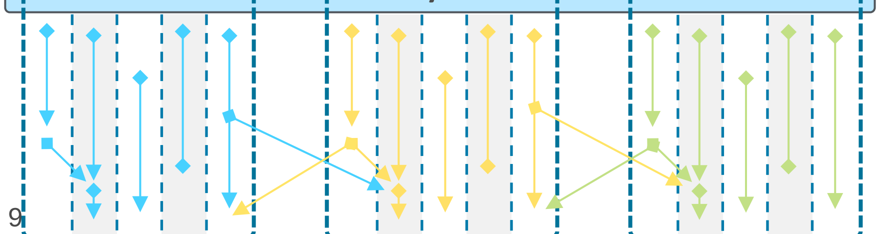
A2e Initiative
(Director: Mike Robinson, acting pending IPA)

Strategy Management Office
(John Meissner, Samantha Rooney, & Noel Bakhtian)

Executive Management Committee (EMC)
- A2e Director
- DOE Technology Feds (Derby, Cline, Ananthan)
- National Lab Subject Matter Experts (Veers, Shaw, Laird)

R&D Implementation Organizations
- ➢ EMC plan the R&D, does not execute
- ➢ Research conducted by best entity for the job

Atmospheric Science | **Wind Plant Aerodynamics** | **Technology Innovations**



External Merit Review Board

- External assessment of program performance and assessment of program impact on industry
- Chaired by Sandy Butterfield, CTO Boulder Wind Power, AWEA Board Liaison with R&D committee, Former Chief Engineer of the National Wind Technology Center
- Board constituency reflecting sector representation from industry, national laboratories, academia, government agencies, and international stakeholders

- The **EMC** provides A2e with vision & direction and coordinates the integrated program planning activities
- External Merit Review Board convenes on an annual basis
- EMC holds formal reviews of all R&D progress on a quarterly basis, with meetings rotating between DOE HQ, NREL, PNNL, and SNL

External Merit Review Team

Reviewer Name	Organization	Industry Role
Sandy Butterfield (Chair)	BWP / AWEA	OEM, standards, AWEA
Mark Jonkhoff	GE	OEM
Henrik Stiesdal*	Siemens	OEM
Dan Brake	NextEra	Owner/operator
Jim Lyons	NOVUS	Investor
Erik White	JPMorgan	Investor
Robert Poore	DNV	Service provider (Due diligence)
Bruce Bailey	AWS TruePower	Service provider (Forecasting)
Charlie Smith	UVIG	Utility integration
Peter Hauge Madsen*	DTU	Academic R&D (Wind Energy R&D)
Bill Mahoney	NCAR	Academic R&D (Atmospheric Science)
Steve Binkley**	Office of Science	ASCR
TBD **		Insurance Industry
TBD **		OEM

* International

** Pending Formal Discussions

EMC Membership Aligns with Technical Areas

Executive Management Committee (EMC)

Director: Mike Robinson (*acting, pending IPA approval*)

Joel Cline (DOE)

PNNL
- Field campaign testing experience
- Atmospheric science leadership
- Relationships with NOAA, NCAR, NSF, OS
- High performance computing expertise
- Reference Facility for Offshore Renewable Energy (RFORE)

Lab Rep: Will Shaw

Shreyas Ananthan (DOE)

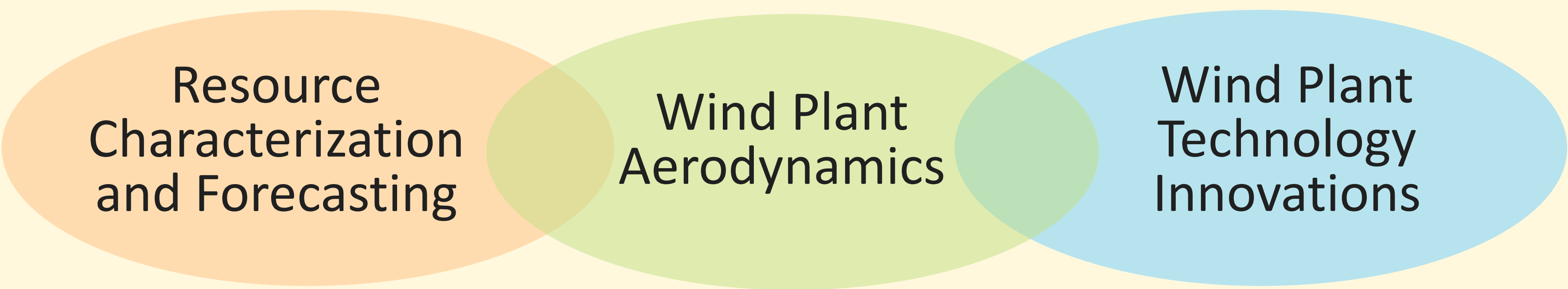
SNL
- Field campaign testing experience
- Scaled Wind Farm Facility (SWiFT)
- Performance & reliability leadership
- Instrumentation/sensor package dev.
- Wind Plant CFD (HPC simulations)
- U.S. fleet data collection relationships

Lab Rep: Daniel Laird

Mike Derby (DOE)

NREL
- Field campaign testing experience
- System design, standards, and analysis
- Utility-scale turbine testing facilities
- Turbine component test facilities
- NASA Wind tunnel test experience
- ESIF facility

Lab Rep: Paul Veers



Initial, High Priority Strategic Planning Areas

Strategic Planning Areas

1. Financial Risk, Uncertainty, and Portfolio Analysis
   – John Meissner (DOE Contractor)
2. High Fidelity Modeling
   – Dr. David Womble (SNL)
   – Dr. Steve Hammond (NREL)
3. Experimental Measurement Campaigns
   – Dr. Scott Schreck (NREL)
   – Dr. Jon White (SNL)
   – Dr. Jim Wilczak (NOAA)
4. Data Archive and Portal
   – Dr. Chitra Sivaraman (PNNL)
5. Integrated Wind Plant Control
   – Dr. Kathryn Johnson (Colorado School of Mines/NREL)
   – Dr. Dave Wilson (SNL)
6. Wind Plant Reliability
   – Dr. Carsten Westergaard (SNL Contractor)
   – Dr. Jonathan Keller (NREL)
7. Aeroacoustics and Propagation
   – Dr. Pat Moriarty (NREL)
8. Integrated Wind Plant Design and Analysis
   – Dr. Shreyas Ananthan (DOE), Acting Lead,

- **High priority R&D areas that need accelerated planning to align with A2e objectives**
- **Each area has an external topical expert planning group chaired by internationally recognized national lab experts**
  – Committees include expert stakeholder community
  – Working groups identify technology gaps and challenges
  – Recommended program plans vetted through open symposiums and workshops
- **Areas maintain a “wind plant performance centric” activity scope**
- **Cross-cutting activity planning is the key benefit of a consortia “wind plant systems” approach**

Prioritizing the Research Portfolio

Financial Risk, Uncertainty, and Portfolio Analysis

Validate System Plant Cost & Performance

- Identify & benchmark key system LCOE drivers
  - Knockdown Factors
  - Operational Availability
  - Downtime Statistics
  - Site Specific Power Curve
  - Plant and turbine energy production
  - O&M operation & balance of station
  - Component & system level cost ....
- Assessment methodologies & best practices
- Established Relationships with Owner / Operators
- Independent 3rd Party Protected Data & Statistics Repository

Align R&D portfolio to address greatest potential return on investment

Correlation of Project Financing to Modeling & Performance Uncertainty

- Dissect current project finance modeling approaches
- Identify key component drivers and assumptions
- Correlation of risk and reliability to performance confidence levels
- Identify and implement R&D initiatives to reduce discount rate drivers
- Requires building a much closer relationship with finance community

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Key Milestones Achieved

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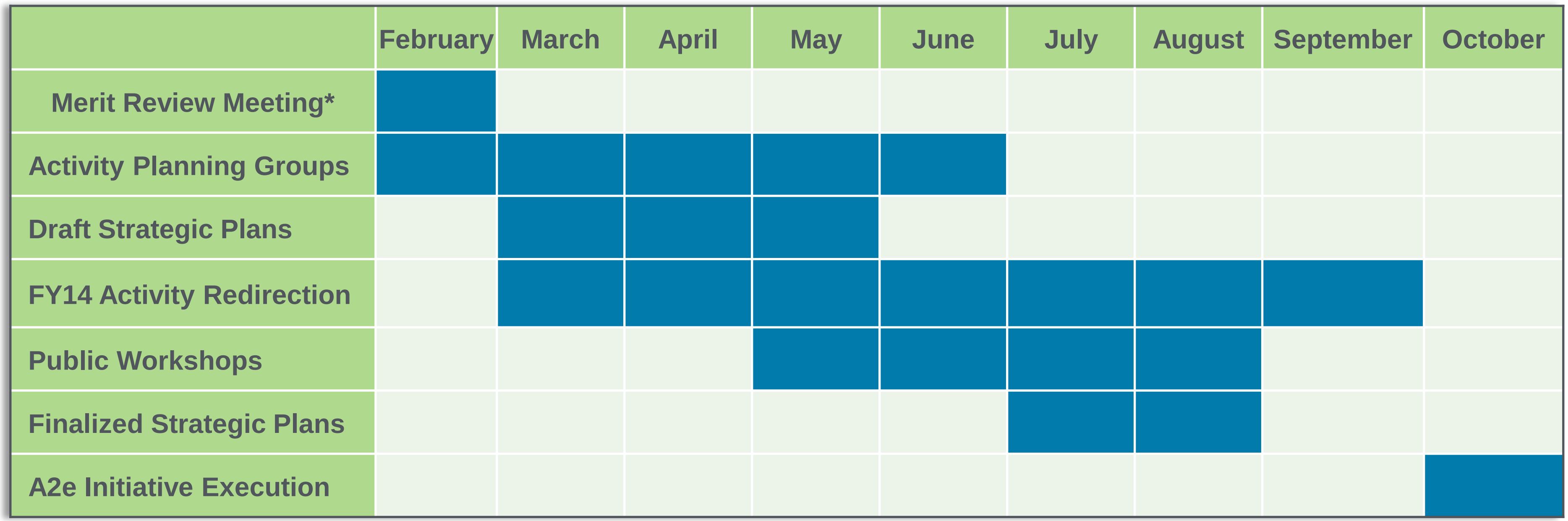
- ✓ **A2e Approved by EERE Assistant Secretary June 2013**
- ✓ **Formed Executive Management Committee (EMC)**
  - Convened three in-person meetings and many phone calls
  - Visited or invited to DOE a large swath of the international wind stakeholder community to establish support and solicit ideas. Organizations visited include Boulder Wind Power, GE, GH-GL, DNV-GL, AWS TruePower, Risoe/DTU, TU Delft, ECN, DOE/SC/ASCR, et.al.
- ✓ **Recruited Twelve (12) Member External Merit Review Committee**
  - External Merit Review planned for February 4-5 in Washington, DC
- ✓ **Defined Key R&D Priorities & Planning Areas**
  - Developed R&D Matrix and initial thrust areas
- ✓ **Established Eight (8) R&D Planning Groups with Chairs and co-Chairs**
  - Modeling & Analysis: High Fidelity Modeling, Experimental Measurement Campaigns, Data Archival and Dissemination, Performance Uncertainty Analysis
  - Four Technical: Wind Plant Reliability, Design Tools and Methodologies, Wind Plant Aeroacoustics, Wind Plant Controls
  - Active Strategic underway
- ✓ **Completed an initial FY14 Crosswalk of Existing Activities**
  - Developed R&D Matrix and initial thrust
- ✓ **Briefing Deputy Undersecretary of Energy & Science, Jan 15th, 2014**
- ✓ **External Merit Review February 4th, 2014**

The A2E meeting notes have been posted for public comment: http://energy.gov/eere/wind/events/submit-public-comment-atmosphere-electrons-a2e-external-merit-review-meeting

Key Activities Timeline

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Summary

- **DOE Program Refocusing R&D to Address Wind Plant Performance:**
  - Established the A2e multiyear initiative based on an open DOE/SC approach
  - National Laboratories leading the strategic planning process
  - Engaging industry, academia, and other agencies in an open planning process
  - Redirect FY14 projects to align with new strategic program priorities
  - Integrated A2e program execution to begin in FY15

ATMOSPHERE TO ELECTRONS
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