



Blade Reliability Collaborative  
Targeted Effects of Manufacturing Defects  
Aerodynamics and Aeroacoustics

**Joshua Paquette**

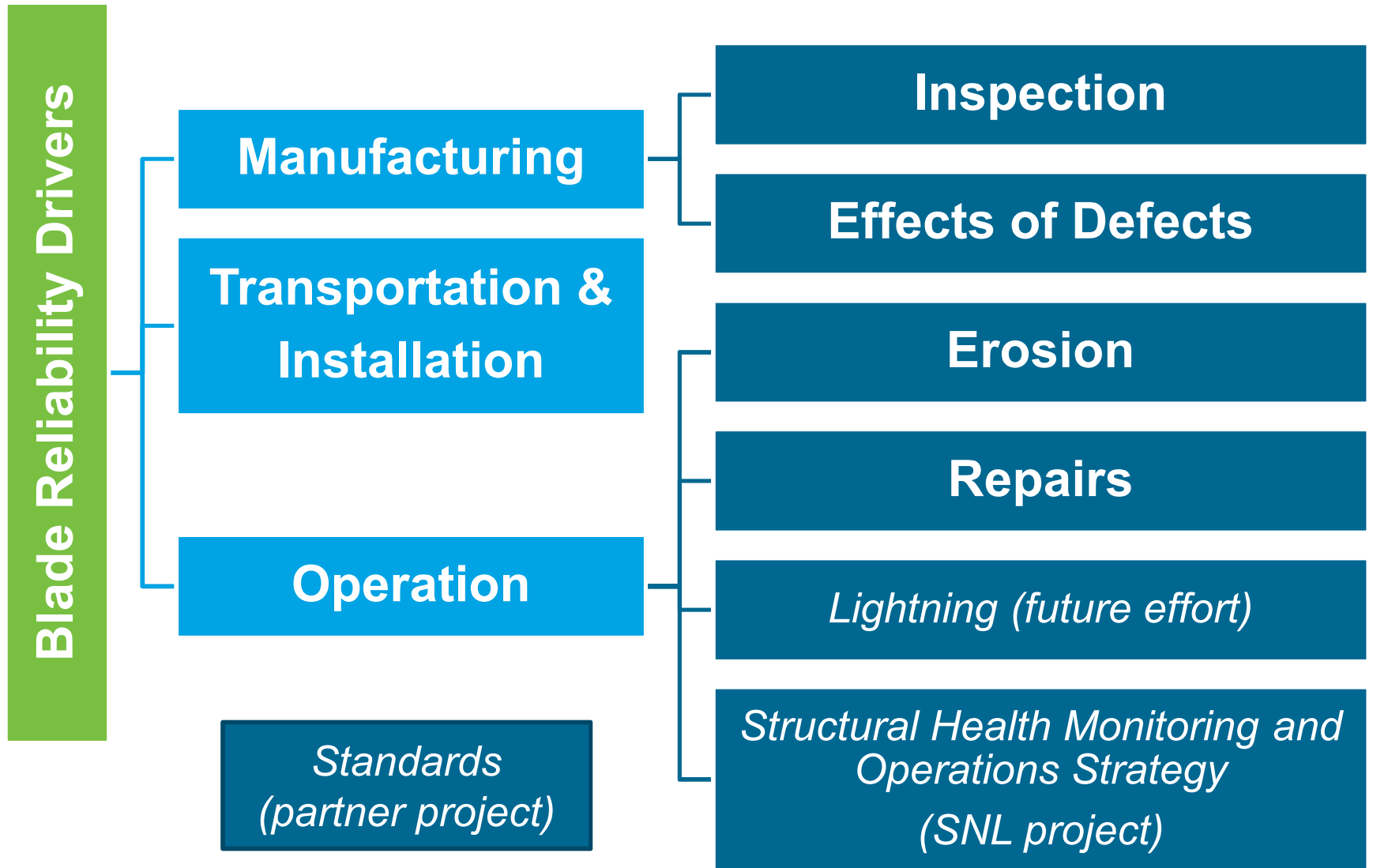
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**Problem Statement:** Blade failures can cause extensive down time and lead to expensive repairs, which increase both cost and cost-uncertainty for OEMs and operators.

**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

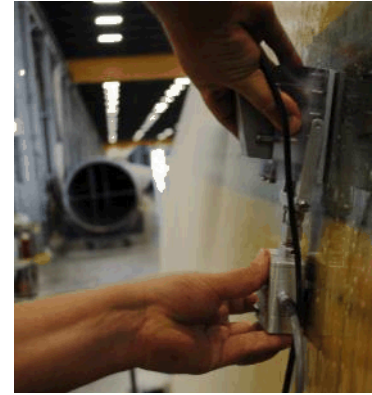


# Technical Approach (Manufacturing Flaws & Structural Damage)

**Standards**



**Mfg. Process**  
How are they  
created?



**Repair**  
Can you fix  
them/resulting-  
damage?

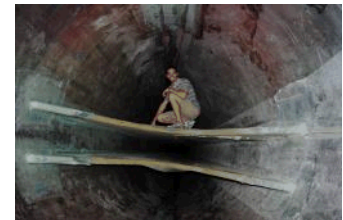
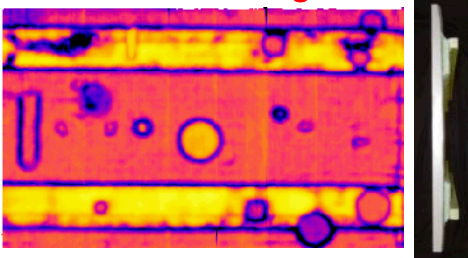
**Flaws/  
Damage**

**Inspection**  
How do you find  
them?

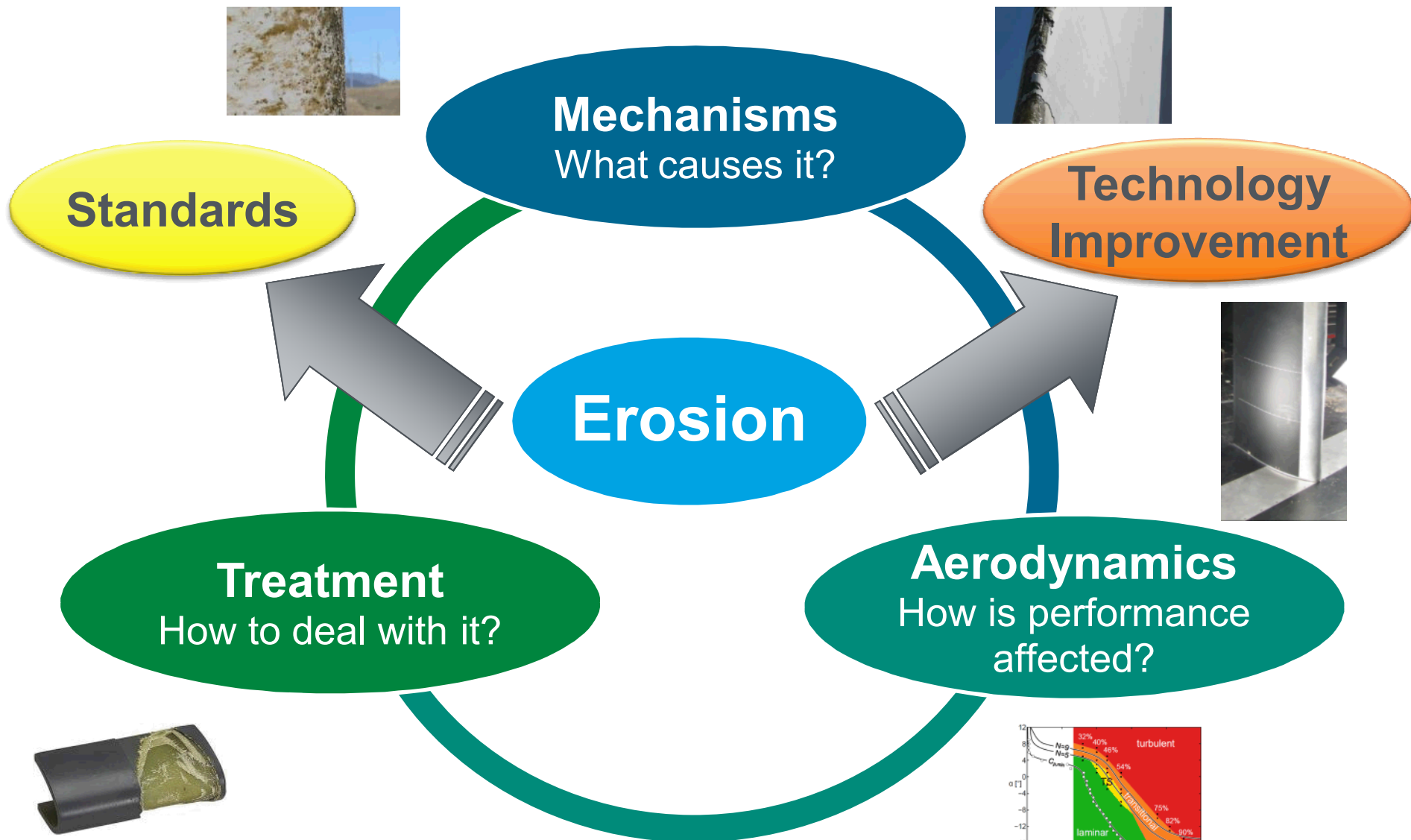
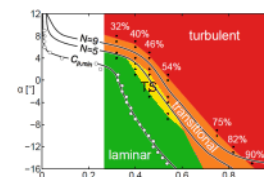
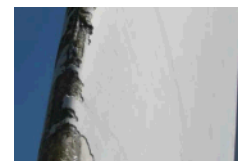
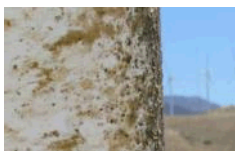
**Effects of  
Defects**  
What do they  
do?

**Technology  
Improvement**

**UT Flaw Image**

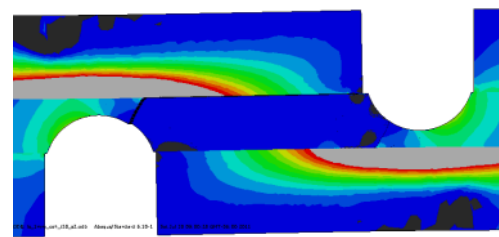
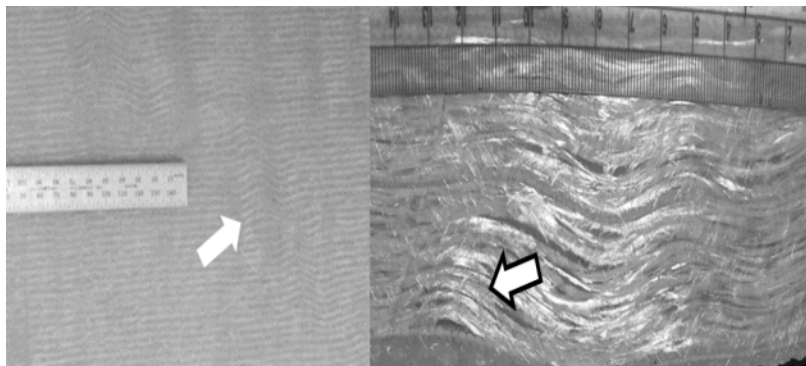
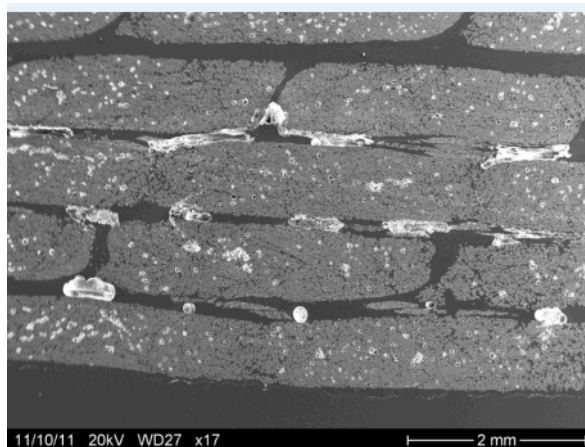


# Technical Approach (Leading Edge Erosion)



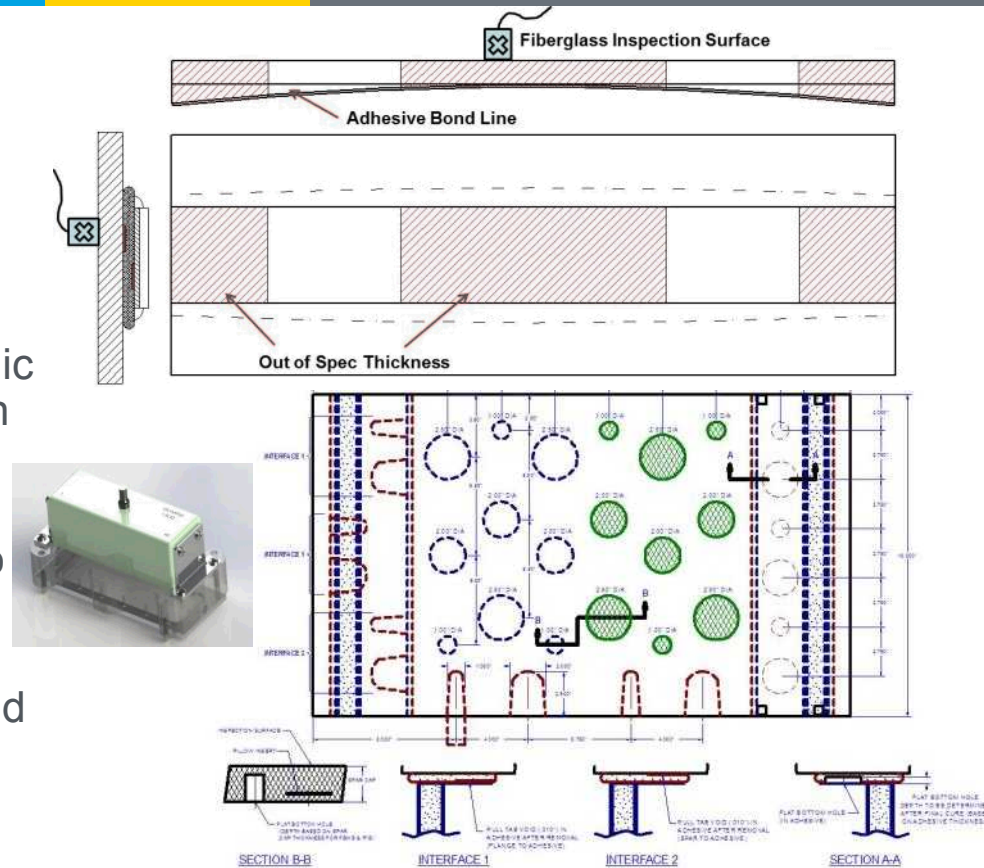
# Accomplishments (Effects of Defects)

- 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

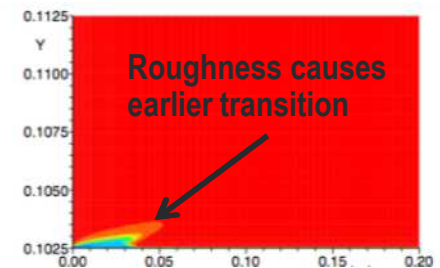
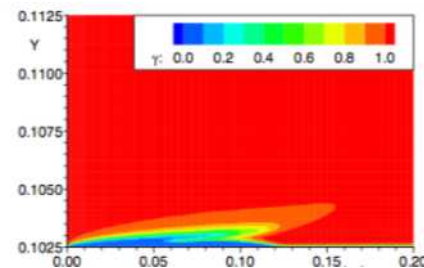
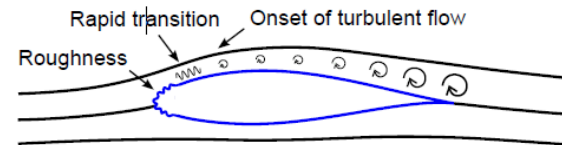


# Accomplishments (Inspection)

- 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



- 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

| Summary                                                                        |               |              |              |              | Legend                                    |              |              |              |               |              |              |              |
|--------------------------------------------------------------------------------|---------------|--------------|--------------|--------------|-------------------------------------------|--------------|--------------|--------------|---------------|--------------|--------------|--------------|
| WBS Number or Agreement Number                                                 | 2.3.0.2       |              |              |              | Work completed                            |              |              |              |               |              |              |              |
| Project Number                                                                 |               |              |              |              | Active Task                               |              |              |              |               |              |              |              |
| Agreement Number                                                               | 26909         |              |              |              | 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) |
| <b>Project Name: Blade Reliability Collaborative</b>                           |               |              |              |              |                                           |              |              |              |               |              |              |              |
| Q1 Milestone: Publish round 2 effects of defects report                        |               |              |              |              |                                           |              |              |              |               |              |              |              |
| Q2 Milestone: Expand reliability database to include operator/manufacture 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 manufacturing 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                               |               |              |              |              |                                           |              |              |              |               |              |              |              |
| <b>Current work and future research</b>                                        |               |              |              |              |                                           |              |              |              |               |              |              |              |
| 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         |              |              |              |               | Milestones & Deliverables (Original Plan) |              |              |               |              |              |              |
|                                                                                              |  |  |  |  |               |              |              |              |               | Milestones & Deliverables (Actual)        |              |              |               |              |              |              |
|                                                                                              |  |  |  |  | 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) |
| Task / Event                                                                                 |  |  |  |  |               |              |              |              |               |                                           |              |              |               |              |              |              |
| <b>Project Name: Aerodynamicsand Aeroacoustics</b>                                           |  |  |  |  |               |              |              |              |               |                                           |              |              |               |              |              |              |
| 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      |  |  |  |  |               |              |              |              |               |                                           |              |              |               |              |              |              |
| Q4 Milestone: Fabricate an LE erosion airfoil model for wind tunnel testing                  |  |  |  |  |               |              |              |              |               |                                           |              |              |               |              |              |              |

## Comments

- Project ended in FY12

# Project Plan & Schedule

| Summary                                                                                     |               |              |              |              | Legend        |                                           |              |              |               |              |              |              |
|---------------------------------------------------------------------------------------------|---------------|--------------|--------------|--------------|---------------|-------------------------------------------|--------------|--------------|---------------|--------------|--------------|--------------|
| WBS Number or Agreement Number                                                              | 2.6.0.1       |              |              |              |               | Work completed                            |              |              |               |              |              |              |
| Project Number                                                                              |               |              |              |              |               | Active Task                               |              |              |               |              |              |              |
| Agreement Number                                                                            | 22721         |              |              |              |               | 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) |
| <b>Project Name: Targeted Effects of Manufacturing Defects</b>                              |               |              |              |              |               |                                           |              |              |               |              |              |              |
| 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   |               |              |              |              |               |                                           |              |              |               |              |              |              |
| <b>Current work and future research</b>                                                     |               |              |              |              |               |                                           |              |              |               |              |              |              |
| 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.

## Budget History

|                                           | FY2012 |            | FY2013   |            | FY2014 |            |
|-------------------------------------------|--------|------------|----------|------------|--------|------------|
| Project Title                             | DOE    | Cost-share | DOE      | Cost-share | DOE    | Cost-share |
| Blade Reliability Collaborative           | \$800k | -          | \$1,000k | -          | \$500k | -          |
| Targeted Effects of Manufacturing Defects | \$650k | -          | \$500k   | -          | \$500k | -          |
| Rotor Aerodynamics & Aeroacoustics        | \$400k | -          | \$0k     | -          | \$0k   | -          |

- Current Project Expenditures (as of Feb. 2014)
  - Blade Reliability Collaborative: \$207k (40%)
  - Targeted Effects of Defects: \$159k (31%)

## 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

## 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

## 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