Past, Present and Future Wind Research Efforts at Sandia Laboratories

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Sandia National Laboratories
“Exceptional Service in the National Interest”

- National Security Laboratory

- Broad mission in developing science and technology applications to meet our rapidly changing, complex national security challenges

- Safety, security and reliability of our nation’s nuclear weapons stockpile

Our highest goal is to become the laboratory that the U.S. turns to first for technology solutions to the most challenging problems that threaten peace and freedom for our nation and the globe.
Exceptional Service in the National Interest

I am informed that the Atomic Energy Commission intends that the Oak Ridge Laboratory accept under contract direction of the Sandia Laboratory at Albuquerque, New Mexico. This operation, which is a vital segment of the atomic energy program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have had time to install the necessary equipment and facilities atSandia National Laboratories, you will be ready to render an exceptional service in the national interest.

Harry S. Truman
May 13, 1949

Harry S. Truman
Sandia’s Sites

- Albuquerque, New Mexico
- Livermore, California
- Yucca Mountain, Nevada
- WIPP, New Mexico
- Kauai, Hawaii
- Pantex, Texas
- Tonopah, Nevada
People and Budget

- FY07 permanent workforce: 8,478
- FY07 budget: $2.4B

Technical Staff (3,921) by Degree (Start of FY08)

- Mechanical Engineering 15%
- Electrical Engineering 17%
- Other Engineering 15%
- Other Fields 16%
- Computing 16%
- Chemistry 5%
- Math 3%
- Physics 6%
- Other Science 7%
- Other Engineering 15%

FY07 Operating Revenue

- Nuclear Weapons: 7.5%
- Defense Systems and Assessments: 20.3%
- Energy, Resources and Non-proliferation: 29.2%
- Homeland Security and Defense: 43.0%

Operating Budget: $2.3 B
U.S. Department of Energy’s Wind Energy Program

Technology Application:

Technology Acceptance
- Wind Powering America
- Wind Siting
- Environmental Impact

Systems Integration
- Wind Integration
- Transmission
- Interconnection and operation

Technology Viability:

Distributed Wind Technology
- Residential & Businesses
- Industrial & Commercial
- Community-Based Wind Power

Large Wind Technology
- Utility Scale Wind Farms
- Turbine Productivity and Reliability Enhancements
- Emerging Wind Applications

Sandia National Laboratories
Sandia Lab’s Wind Energy Program

- **Blade Technology**
  - Materials and Manufacturing
  - Structural, Aerodynamic, and Full System Modeling
  - Sensors and Structural Health Monitoring
  - Advanced Blade Concepts
  - Data Acquisition Systems
  - Lab and Field Testing

- **System Reliability**
  - Industry Data Collection
  - Improve reliability of the existing technology and future designs

- **System Integration and Outreach**
  - Wind/RADAR Interaction
  - Integration and Outreach
Sandia Wind Department Background & Accomplishments

- Established in Mid 1970’s
  - Primary focus VAWT’s
  - Industry partnerships
- Transitioned to Blades in early 1990’s
- 15 Full-Time Employees
- Several Contractors and Students

Mission:
To provide a knowledge-base expertise in the design and advancements of composite wind turbine blades and turbine reliability, in order to accelerate the penetration of wind energy into the electric utility grid.

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>Sandia National Labs (SNL) Wind Program Established</td>
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<tr>
<td>1977</td>
<td>17m VAWT Fabricated</td>
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<tr>
<td>1981</td>
<td>1st Wind-Turbine Specific Airfoils</td>
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<tr>
<td>1982</td>
<td>FloWind Technology Transfer</td>
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<tr>
<td>1984</td>
<td>34m VAWT Test Bed</td>
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<tr>
<td>1988</td>
<td>SNL/MSU Material Database Established</td>
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<tr>
<td>1994</td>
<td>SNL Blade Program Started</td>
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<tr>
<td>1998</td>
<td>Blade Manufacturing Initiative</td>
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<tr>
<td>2003</td>
<td>Incorporation of Carbon in Blades</td>
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<tr>
<td>2005</td>
<td>K&amp;C Swept Blade Contract</td>
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<tr>
<td>2006</td>
<td>Reliability Program Started</td>
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<tr>
<td>2007</td>
<td>Renewable System Integration (RSI) Program Started</td>
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<tr>
<td>2008</td>
<td>Advanced Manufacturing Initiative (AMI) Program Started</td>
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Sandia’s Program Focus

Program Focus is on Industry Needs

- **Higher fidelity modeling**
  - Blade structural modeling
  - Aerodynamics
  - Full system dynamics

- **Improve blade design to eliminate upcoming barriers**
  - Transportation (segmented blades)
  - Strategic use of advanced materials
  - Embed sensors in blades to enable advance control

- **Increase energy capture**
  - Active aerodynamic control
  - Advanced control research (adaptive architecture)

- **Improve turbine availability**
  - Condition-Based Maintenance (CBM)
  - Prognostic & Health Management (PHM)

- **Increase system reliability**
  - Improve turbine O&M strategy
  - National reliability database
System analysis identifies research initiatives with increasing industry involvement as it gets closer to the commercial product.
Wind Industry Trends & Challenges

- Costs (traditional)
  - System ~ $3/lb
  - Blades ~ $5/lb
  - ~ $1.00/Watt (2002)
  - $0.04-$0.06/kWh (2002)

- Recent cost of steel & copper increases have increased cost by 30 - 50%
- Currency exchange rate
- Limited Manufacturers & Suppliers

- Size
  - 1.5-5.0 MW
  - Towers: 65-100 meters
  - Blades: 34-50 meters
  - Weight: 150-500 tons

- High-end Military ~ $1000/lb
- Aerospace Industry ~ $100/lb

2008: ~$1.6 – $2.0/Watt

Currency exchange rate
Limited Manufacturers & Suppliers

Current state-of-the-art

- Altamont Pass WRA
  - 0.10 MW: 18 m, 60 ft
  - 0.75 MW: 50 m, 164 ft
  - 1.5 MW: 66 m, 216 ft
  - 2.5 MW: 85 m, 279 ft
  - 3.5 MW: 100 m, 328 ft
  - 5.0 MW: 120 m, 394 ft

Boeing B747-400
Wind Power Basics

Wind Power output is proportional to wind speed cubed.

WindPower = \frac{1}{2} \rho AC_P V_{\infty}^3

C_{P_{max}} \approx 0.3 \text{ (Drag)}

C_{P_{max}} \approx 0.59 \text{ (Lift)}

The Betz Limit

\[ V_i = \frac{1}{3} V_w \]

\[ P = \frac{16}{27} \left( \frac{1}{2} \rho AV_w^3 \right) \]
Performance Enhancement Options

**Power**

- Larger Rotor
  - Rotor *costs* increase with diameter *cubed*.
  - Rotor *power* grows with the diameter *squared*.

**Resource**

- Taller Tower
  - Tower costs increase with height to the *fourth* power.

We can only win this battle if we build rotors that are smarter and components that are lighter to beat the squared-cubed law.
Materials Research Goal & Impact

- **Goal:**
  - Engineer composites materials that can be manufactured to reduce the weight and increase the strength of wind turbine blades

- **Current Status:**
  - Materials
    - Investigating new configurations of carbon fibers
    - Characterization of materials
  - Design
    - Structurally efficient designs
    - Composite hybrid designs

- **Large Materials Database**
  - Material properties (10000+ tests for 175 materials)

**Collaboration with Montana State University**
Carbon in Blades

■ Advantages:
  • High stiffness/weight ratio
  • Excellent properties with straight fibers

■ Disadvantages:
  • Higher cost
  • Limited availability
  • Difficult to infuse
  • Poor properties with wavy fibers

■ Potential solution: SAERTEX glass/carbon triax fabric
  • Relatively inexpensive
  • Permeable
  • Dry fabric for conventional infusion techniques
  • Maintains excellent fiber straightness

SAERTEX Glass/Carbon Triax used in SNL 9 m Blades

* Study of carbon materials performed in collaboration with Global Energy Concepts and Montana State University
Goal: Increase the viability of wind energy and ensure the continued growth of the nation's fastest growing technology through advanced design concepts, automated manufacturing processes, and domestic job creation.

Program Focus
- Design for Manufacturability
  - Hard-tooling
  - Regional Manufacturing
  - Transportation

Better manufacturing processes

Opportunity:
- Increased suppliers, expansion of capacity, and job creation
  - Reducing cost
  - Creating a U.S. market
Design Tools and System Modeling

**Goal:**
- Enable the generation and widespread use of more advanced, more accurate numerical models which are capable of simulating new wind energy technology

**Current Efforts:**
- Blade Structural Modeling
- System Dynamics
- Leverage SNL’s high performance computing

**Motivation:**
Smaller turbines $\rightarrow$ Larger turbines
$\rightarrow$ $$$ Build, Break, $\rightarrow$ Advanced Redesign $\rightarrow$ Simulation
NuMAD - Structural FE Analysis
Will the blade break?

Pre-processor and post-processor for ANSYS® finite element analysis software

Standard MS Windows® application

Tailored to Design and Analyze wind turbine blade structures

Databases
materials
airfoils
loadings

• Analysis used to find weak spots in blades
• Development guided by industry input
• Beam Property Extraction capability
**Goal:**
- Evaluate and implement sensing technologies in blades to enable advance wind turbine controls

**Current Status:**
- Sensor Blade (Sblade) Project
- Evaluating NDT and SHM techniques for the lab
- Continue partnership with NREL/NWTC blade testing facility to test and evaluate new sensing technologies

**Industry Impact:**
- Improved wind turbine operations & maintenance strategy
- Enable control of localized active aerodynamics

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**Non-Destructive Inspection Methods**

- Visual photo
- Steady-state thermal image
- Thermoelastic stress image
- Fluorescent dye-penetrant
Purdue’s Involvement
Sandia’s Sensor Blade Project

Loads extraction, structural dynamics, damage detection and structural health monitoring

TX-100 blade fatigue test at National Renewable Energy Lab, Boulder, Colorado

Installation of sensors in Sensor Blade during blade manufacture, TPI Composites, Warren, RI

Modal testing Sensor Blade at Sandia field test facility, Bushland, Texas
Active and Passive Blade Control

Active Devices

Passive Bend-Twist Coupling

Geometry-based

Courtesy: NREL
Aerodynamic Tools & Aeroacoustics

Goals:
- Develop performance tools that are more accurate and easy to use
- Develop aeroacoustic database and predictive code

Current Status:
- Aerodynamic Tools
  - Investigating new developments in CFD
  - Developed new tool to ease investigation of airfoil shape changes
- Aeroacoustics
  - Obtained flatback noise data from Virginia Tech tests
  - Developing analysis tools

Industry Impact:
- Enable more accurate predictions of performance & loads
- Gain ability to accurately predict noise generation
  - Increase tip speed/decrease torque & cost

Average Noise Spectra

Airfoil Noise Spectra
Active Aerodynamic

Goal:
- Develop small, light-weight control devices & systems to attenuate fatigue loads on turbine blades and enable increased energy capture

Current Status:
- Devices
  - Investigating micro tabs, morphing trailing edge, and micro flaps
  - Building wind-tunnel model with integrated devices and actuators
- Actuators
  - Researching durable/low-power, simple designs
- Controls
  - Developing appropriate control algorithms

Industry Impact:
- Weight reductions
- Lower cost of energy

![Graph showing Blade 1 Root Flap Bending Moment (kNm) for Tabs and No Tabs over time (sec) with Region 3 Turbulent Wind.](image_url)
Sandia Strategy for Enabling Advanced Blades

Future Design Needs

- Advanced Control Strategies
- Advanced Embedded Sensors
- Structural Health Monitoring

Also Need:
- Novel Concepts
- Aeroacoustics
- Structural analysis
- Active aero device
- Manufacturing (integration)

Enabling New Technology
To develop small, lightweight control devices & systems to attenuate fatigue loads on turbine blades and increase turbine efficiency

Controls

Sensors

Aerodynamics

Sandia National Laboratories
SNL initiated a blade research program in 2002 to investigate the use of carbon in blades along with other advanced structural concepts.

Objective: Longer, stronger, and lighter blades for higher energy capture and reduced COE.

Three 9-meter blade designs were built:
- CX-100 (Carbon Experimental 100 kW)
- TX-100 (Twist-Bend Coupled Experimental 100 kW)
- BSDS (Blade System Design Study)

Laboratory and field tests conducted to evaluate the designs and to validate modeling tools.
Blade Advancements
Under Technology Program

Prototype Sub-scale Blades Manufactured (9 meters)

- CX-100
  - Carbon spar cap
  - Glass skin and shear web

- TX-100
  - Carbon triax in skin for passive bend-twist coupling
  - Constant spar cap thickness

- BSDS (Blade System Design Study)
  - Flatback airfoils
  - Carbon spar cap
  - Slenderized planform
  - Large scale architecture
  - Highly efficient structural design

First Blade Designs with Carbon Fiber

TX-100 skin w/ off-axis carbon fiber
• Modal Testing
• Static and Fatigue Testing
• Acoustic Emissions NDT
• Sensor Evaluation
Static Test Results

<table>
<thead>
<tr>
<th>Property</th>
<th>CX-100</th>
<th>TX-100</th>
<th>BSDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (lb)</td>
<td>383</td>
<td>361</td>
<td>289</td>
</tr>
<tr>
<td>% of Design Load at Failure</td>
<td>115%</td>
<td>197%</td>
<td>310%</td>
</tr>
<tr>
<td>Root Failure Moment (kN-m)</td>
<td>128.6</td>
<td>121.4</td>
<td>203.9</td>
</tr>
<tr>
<td>Max. Carbon Tensile Strain at Failure (%)</td>
<td>0.31%</td>
<td>0.59%</td>
<td>0.81%</td>
</tr>
<tr>
<td>Max. Carbon Compressive Strain at Failure (%)</td>
<td>0.30%</td>
<td>0.73%</td>
<td>0.87%</td>
</tr>
<tr>
<td>Maximum Tip Displacement (m)</td>
<td>1.05</td>
<td>1.8</td>
<td>2.79</td>
</tr>
</tbody>
</table>
Fatigue Test Results

CX-100 Crack Growth

TX-100 Crack Growth
**Blade Test Site** *(near Amarillo, TX)*

- **3ea Micon 65/13 (modified)**
  - 115 kW generator
  - Stall regulated
  - 55 RPM
  - Heavily Instrumented
    - 15 rotor strain gauges
    - Rotor speed and position
    - Nacelle acceleration
    - Tower instrumentation

- **Inflow Array**
ATLAS II DAS System
(Accurate Time-Linked data Acquisition System)

- Based Built for Wind Turbine Applications
- Small Size
- Continuous Operation (24/7)
- High Reliability
- Automated Acquisition and Archiving
- Lightning Protection on all Channels
- Field Tested
- Easy Installation

Sandia National Laboratories
Twist-coupled blade:

- power performance comparable to the standard blade
- reduced dynamic fatigue loads over the entire spectrum
- lower extreme operating loads

**Aerodynamic Performance**

**Structural Performance**
Conclusion from Carbon Experimental Blade Tests

- Testing Validates Carbon Blade Design Objectives
  - CX – Demonstrates manufacture of hybrid carbon/glass structure
  - TX – Reduced fatigue loads without energy loss (~10%)
  - BSDS – Reduced weight (30%) with increased strength (~80%)
  - Design tools are capable of predicting capabilities

- Impact on 20% vision
  - Blades can be longer and lighter, sweeping greater area without increased system loads
  - ~10-25% increase in Capacity Factor possible, depending on how an integrated design uses the enhancements
Reliability Program
Goals and Objectives

Working through industry partnerships to:

- Develop National reliability baseline statistics for the US wind energy industry
  - Turbine component failure rates are higher than expected by some
  - This is the first long-term, data based, national effort to quantify and track these failures
- Guide efforts to address important component reliability problems
- Provide feedback for improving design and manufacturing practices
- Help wind plants:
  - Optimize O&M practices
    - Preventive maintenance
    - Parts inventory optimization
    - Condition-Based Maintenance (CBM)
    - Prognostic & Health Management (PHM)
SNL’s Role in the Reliability Program

- **Systems Reliability Analysis**
- **Data Warehouse**
- **Reliability Analysis**
- **Blade Reliability**

**SNL Activities**
- Testing for Partner Problem Resolution
- Gearbox Collaborative

**Product Life Cycle**
- Inception
- Design
- Prototype
- Manufacture
- O&M
- Replacement

Reliability starts here!

Technology Maturity Level (TML) is reflected in product reliability
Science and Technology is Still Needed

- Improved blade designs – Design for manufacturability
- Utilize High Performance Computing (HPC)
  - Predict aerodynamic performance
  - Predict aeroacoustic emission
  - Design optimization
- Testing and evaluation of innovative aerodynamic concepts
- Development and incorporation of reliable sensor technologies
- Development and implementation of advanced control strategies

Industry Impact:
- Enable more accurate predictions of performance
- Accurate aeroacoustic predictions may lead to increase tip speed/decrease torque & cost
- Weight reductions
- Lower cost of energy
Sandia Customers & Partnerships

Current Customers
- Texas Tech (DAS & Field Testing)
- 3TEX (Materials & Field testing)
- Aither (Sensors)
- NASA (Sensors)
- Acellent (Sensors)
- Owens Corning (Materials)
- Knight & Carver (Blades)
- TPI Composites (Blades)
- Clipper Wind (Manufacturer)
- Vestas Wind (Manufacturer)

Past Partnership Success: Example of TPI Composites
- Historic supplier of 100kW blades
- Was out of the wind business
- Now:
  - TPI and Mitsubishi have a joint venture – Vienteck in Juarez, Mexico
  - Manufacturing blades for 1-2 MW Mitsubishi machines
  - 40m long blade now being tested
  - TPI patented SCRIMP® technology
  - Now a leader in AWEA support for the program
20% Wind Energy by 2030

- Sandia-supported DOE Action Plan
- Addresses Scalability
- Approved May 2008
- Provides new program focus

www.doe.gov
SNL Primary Research Focus is on Blades and System Reliability

Efforts Underway to:
- Reduce Blade Weight Growth for Larger Blades
  - Hybrid composite subscale blades have been modeled, manufactured and tested
  - Development of structurally efficient airfoils
  - Advanced research has enabled weight reductions of 66% - 750lb -> 250lb
- Implement active Aero control techniques
  - Strategically embedded sensors and active actuations devices
  - Reduce loads
  - Increase fatigue life

Engaged in Increased Reliability Efforts
- Developing strategic partnerships with industry
- Improvements in Operation and Maintenance

Developing a Manufacturing Initiative Focused on Increasing U.S. Based Manufacturing

Sandia supported the effort of the “20% Wind Energy by 2030” Action Plan
- Approved May 2008 - DOE
- Provides new program focus
Wind Power
Benton County Wind Farm, Fowler, Indiana

Thank you!