Improved Wind Turbine Blade Reliability

Dr. Doug Cairns

Lysle Wood Distinguished Professor

Nathan Palmer, Jon Ehresman, MSME Candidates

Mechanical and Industrial Engineering

MONTANA STATE UNIVERSITY

BOZEMAN

Mountains & Minds

From Gen. George S. Patton

Now I want you to remember that no bastard ever won a war by making PowerPoint viewgraph presentations for his country. He won it by making the other poor dumb bastard make PowerPoint viewgraph presentations for his country.

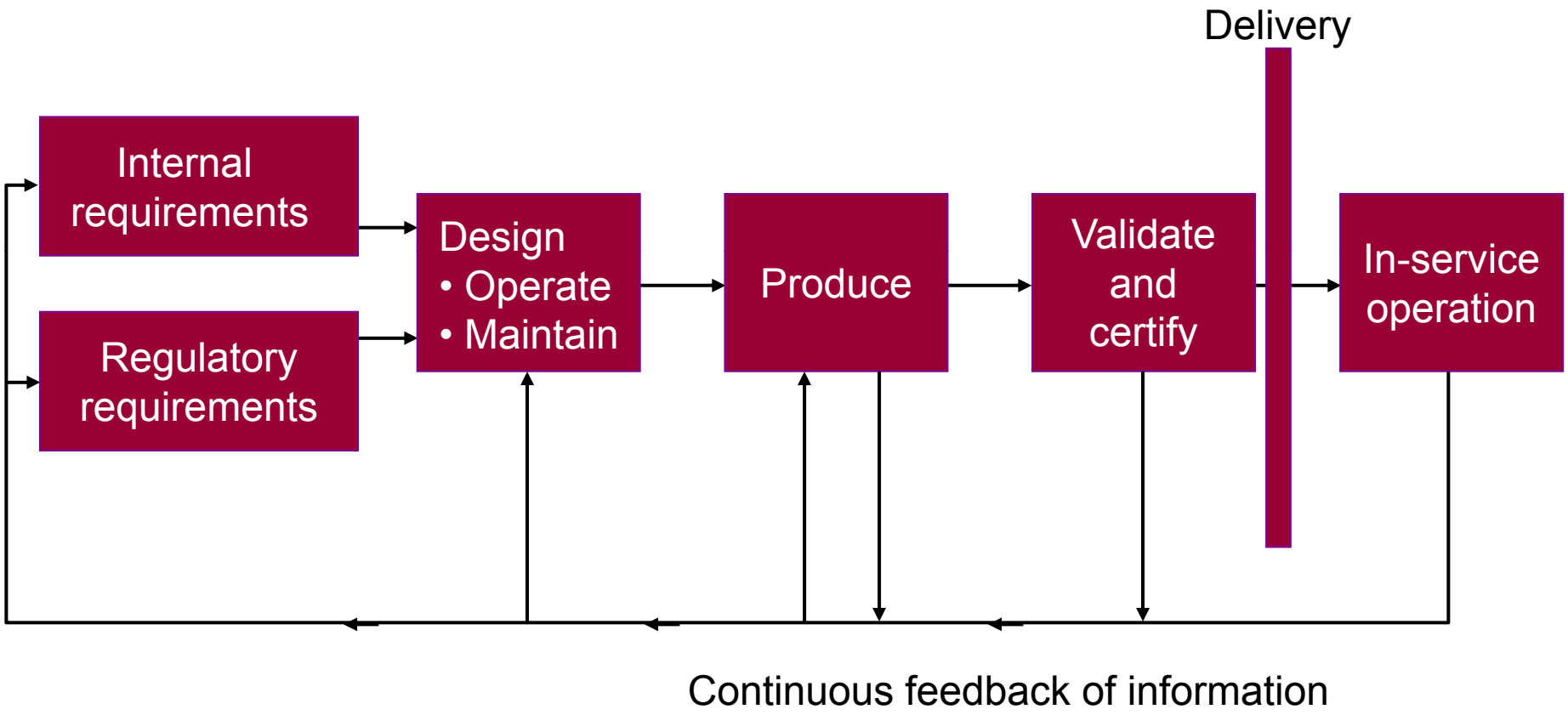
Organization of This Talk

- Basics on Structural Reliability
- Needs for Composite Material Wind Turbine Blades
- Specifics of what Montana State University (Cairns) is doing
- The Next Steps

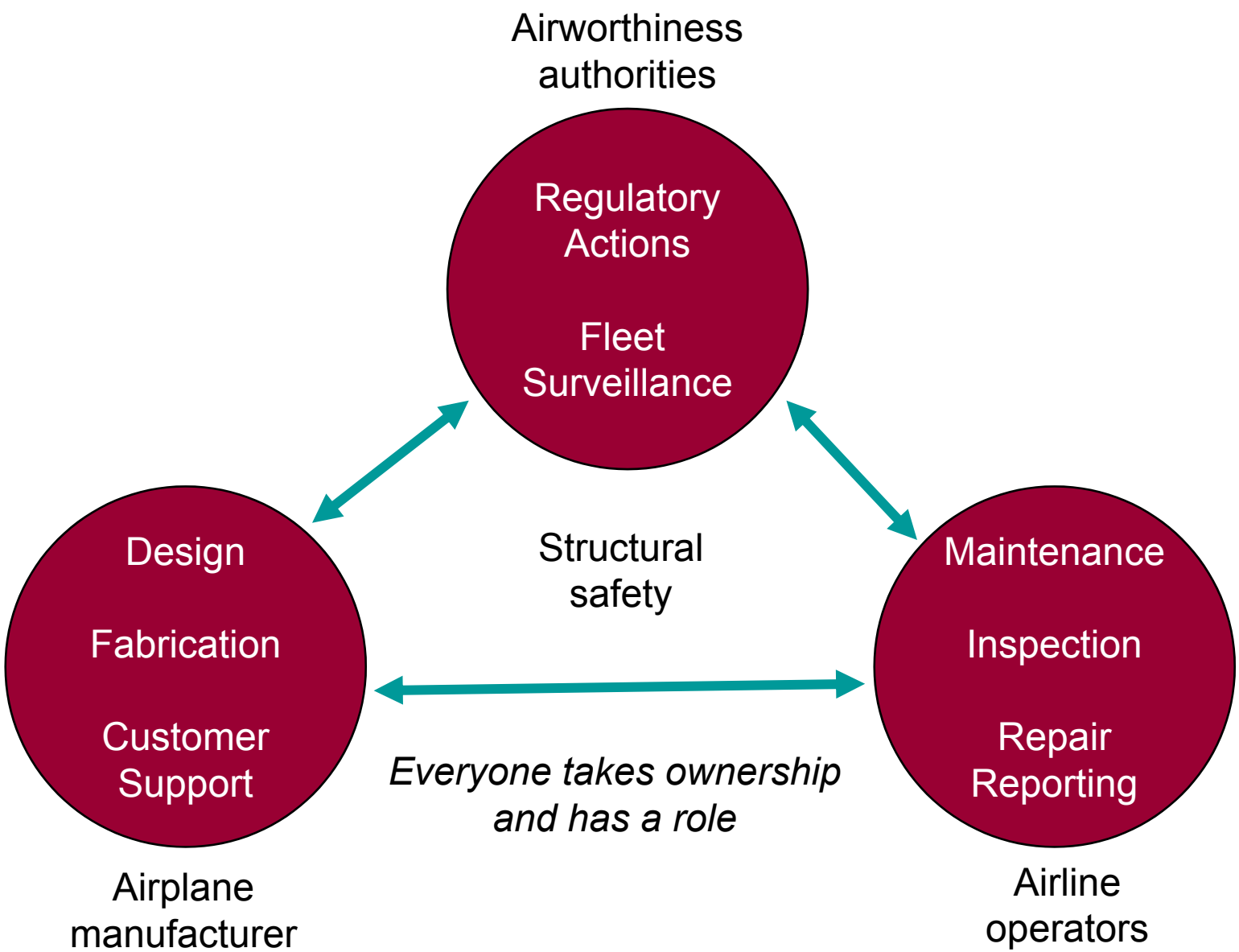
Who Knows About Reliability?

- When an aircraft company designs and sells an airplane, **its primary product is reliability.**
- When you get on an aircraft, you are statistically assured of its reliability.
- Aircraft reliability is a SAFETY issue, wherein almost any price is acceptable; wind turbines are primarily an ECONOMIC issue.
- Nonetheless, the aircraft industry has a well established track record for quantifiable reliability
- The following few slides are from a Montana State University course on Aircraft Structures

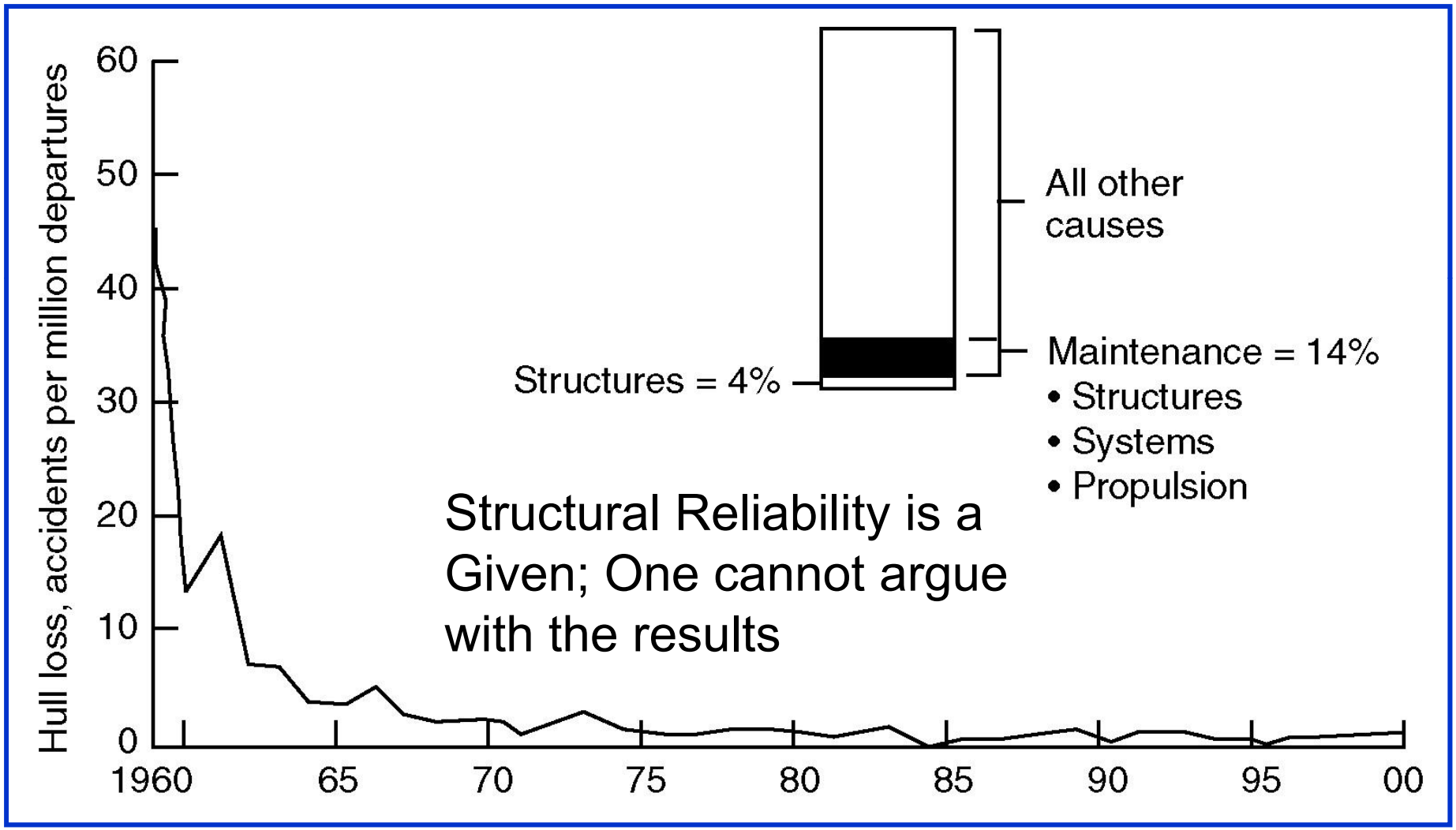
How Does a Commercial Aircraft Manufacturer Do It?



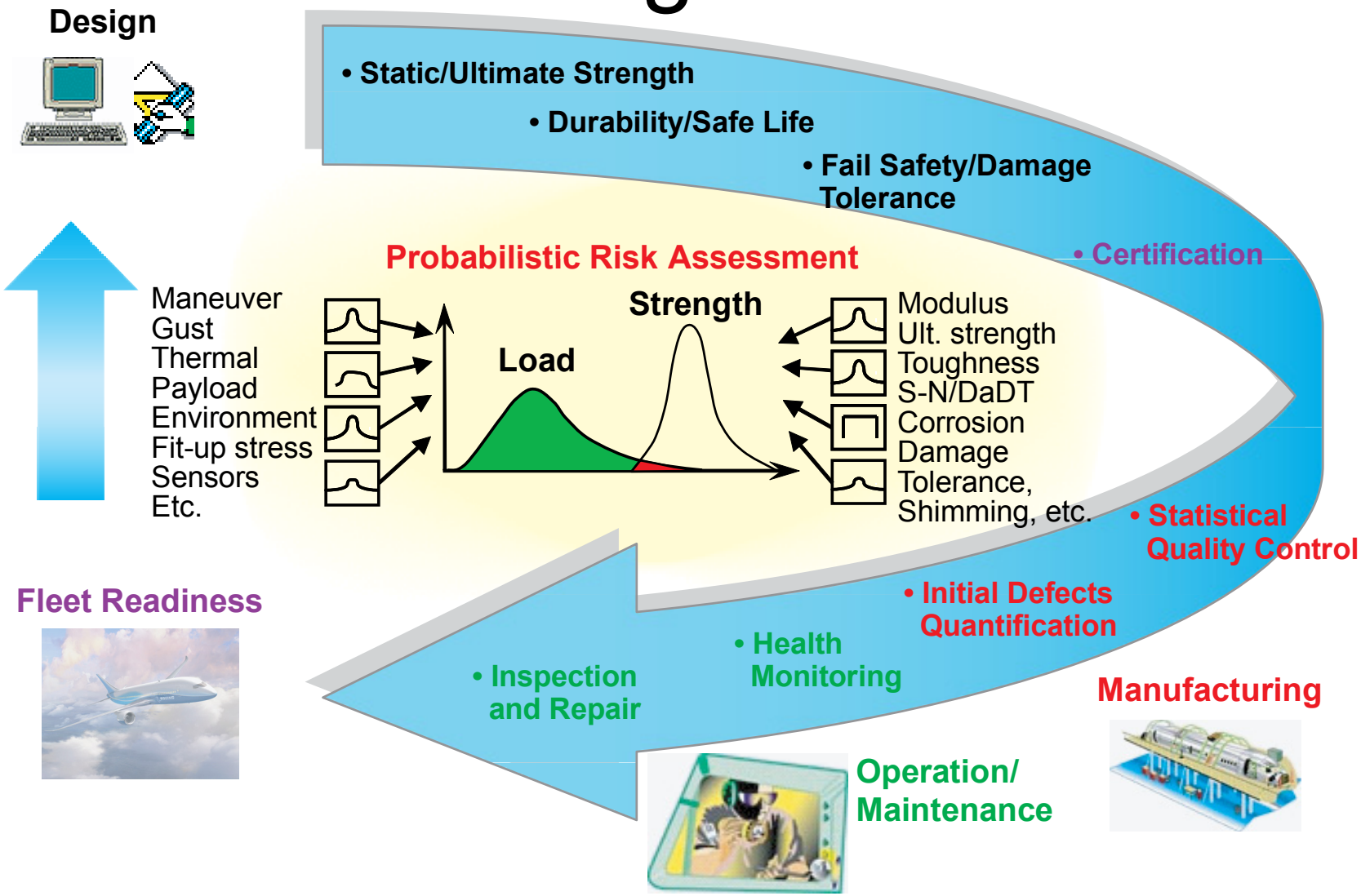
Structural Safety System



Commercial Jet Fleet Safety Record



Probabilistic Life Cycle Management



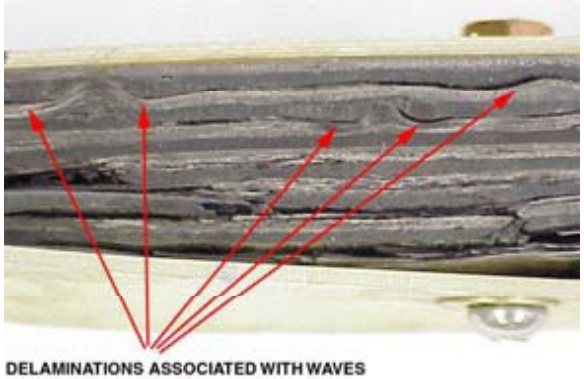
All Elements are Applicable for Probabilistic Reliability of Wind Turbines

- Static Strength
- Safe Life or Damage Tolerant Design
- Certification Process
- Manufacturing
- Statistical Quality Control
- Defects Quantification
- Health Monitoring
- Operation and Maintenance
- Inspection and Repair

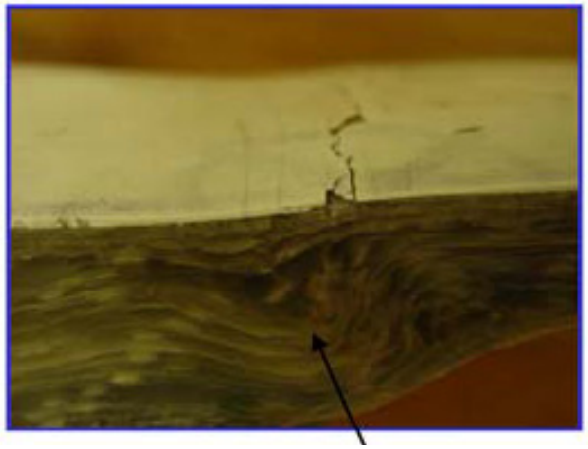
The Probabilistic Life Cycle for Wind Turbine Blades

- Clearly, the aircraft approach is too expensive, but it has elements from which we can learn.
- A notable example is the US Civil Infrastructure issue; we cannot afford to replace all structures, but we can monitor and play triage (e.g. Sandia's blade sensor initiatives).
- Some distributions are available (e.g. loads, materials) which can be convolved (Paul Veers is an expert on this topic) to begin to develop probabilistic reliability distributions.

Wind Turbine Blade Reliability – Not Just an Academic Problem



Delaminations in a Low-Cost Composite Structure



Glass Fiber Reinforced Wind Turbine Blade Local Failure at a Manufacturing Flaw

Field Failure of a Wind Turbine Blade

The Key Question:

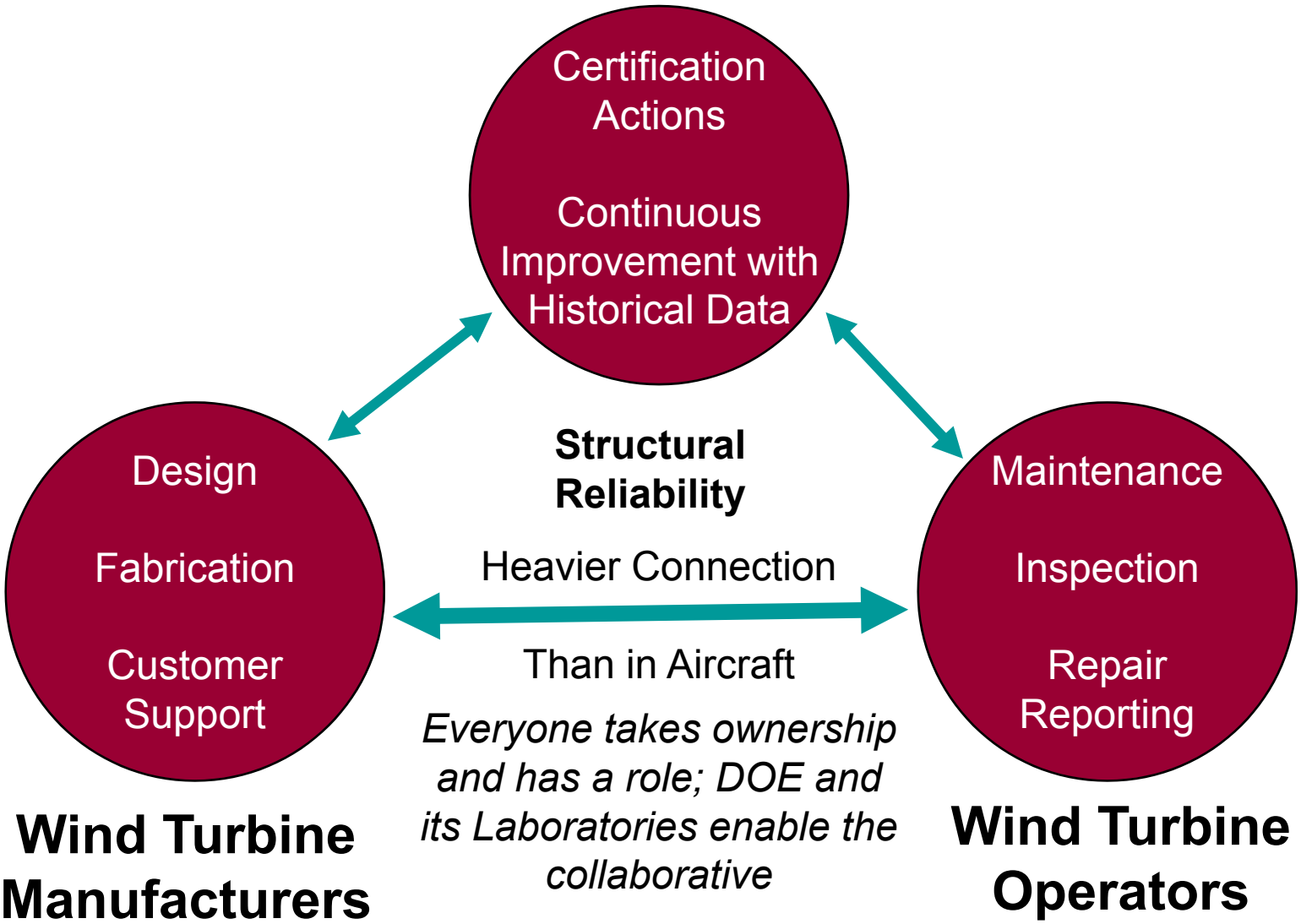
Can an affordable, meaningful approach be developed for wind turbine blade reliability?

What We May Be Able to Do for Wind Turbine Blade Reliability

- Form a collaboration and interaction between wind turbine manufacturers, wind turbine certifying agencies, and wind turbine operators to determine needs and hierarchy (ala Aircraft triad)
- Develop lower cost methodologies for materials qualification, manufacturing details variability, and loads variability
  - Composite civilian aircraft structures cost approximately $500/lb; composite wind turbine blades cost $5-10/lb; rough cost for a wind turbine blade reliability program should be around 10-50 times LESS than an aircraft structures to make economic sense
  - Proof testing (test up to design limit load with subsequent inspections) is a proven, low cost reliability technique; eliminates early, anomalous failures (success story – filament wound rocket motor cases)
- Combine materials variability, manufacturing details variability, loads variability to determine statistical reliability (easier said than done, determine if current data are useful; if not, determine what data are needed)
- Determine which elements Probabilistic Life Cycle Management will yield the highest payoff to provide reliability (assessment and improvement)

Wind Turbine Reliability Collaborative

Potential Role for AWEA or Others?



The Low Hanging Fruit for Improved Reliability

- Manufacturing

  Famous Quote:

  "Your cannot make good structures from poor materials, but we have proven time and again that you can make poor structures from good materials."

  - Wind turbine blades fail at manufacturing defects; a 12 mm flaw in a 50 meter structure is just as deleterious as a 12 mm flaw in a 5 meter structure
  - (Strength of Large Structure/Strength of Small Structure) = $(V_{large}/V_{small})^{1/m}$
    - Where V is the volume and m is the Weibull Statistical Distribution Modulus, i.e., a larger structure has a greater probability of a critical flaw.

The Low Hanging Fruit for Improved Reliability (cont.)

- Manufacturing (cont.)

Manufacturing research does not have the "cachet" of other topics for wind turbine blades

However, improved manufacturing of wind turbine blades still offers the best payoff for improved blade reliability

The Low Hanging Fruit for Improved Reliability (cont.)

- Data Mining
  - With respect to composite material wind turbine blades, composites have been around a long time; there are well-known solutions to problems
  - Many other industries have reliability problems and have addressed them
    - Aerospace
    - Nuclear
    - Automotive
    - Marine
    - Public transportation
    - Civil Infrastructure

From one of the most successful Formula 1 automobile racing teams in history:

"Our success is based on innovation and an unabashed use of technology developed by others and modified to meet our needs."

The Low Hanging Fruit for Improved Reliability (cont.)

- Inspection Database

- From experience and usage, we typically know where a given structure will fail
  - Model after the Airworthiness Directives (AD) database from FAA
  - ADs are specific inspection protocols for a specific aircraft or component
  - For example, “Inspect leading edge outboard 30 inches for cracks every two years.”
  - The AD is signed off in a logbook, and monitored

- This is a simple and low cost way to formalize our inspection and maintenance protocol

The Low Hanging Fruit for Improved Reliability (cont.)

- Probabilistic Design and Analysis Methodologies
  - The current approach to design of wind turbine blades adopts a “safe life” approach
    - Rudimentary statistics are applied for “confidence limits”
    - Circa 1930s mentality for reliability
  - We can do much better with probabilistic design and a damage tolerant approach
  - Well established statistical methodologies

The “catch”: This approach requires statistically significant data and a breadth of field experiential data. However, we may be reaching the point of having those data for improved, statistically-defensible designs

The Low Hanging Fruit for Improved Reliability (cont.)

- Automated Inspection Technologies, Health Monitoring
  - Wind Turbine Sensors - A recent emphasis within Sandia National Laboratories
  - Recent developments in lower cost sensors, data acquisition and data management make such an approach possible

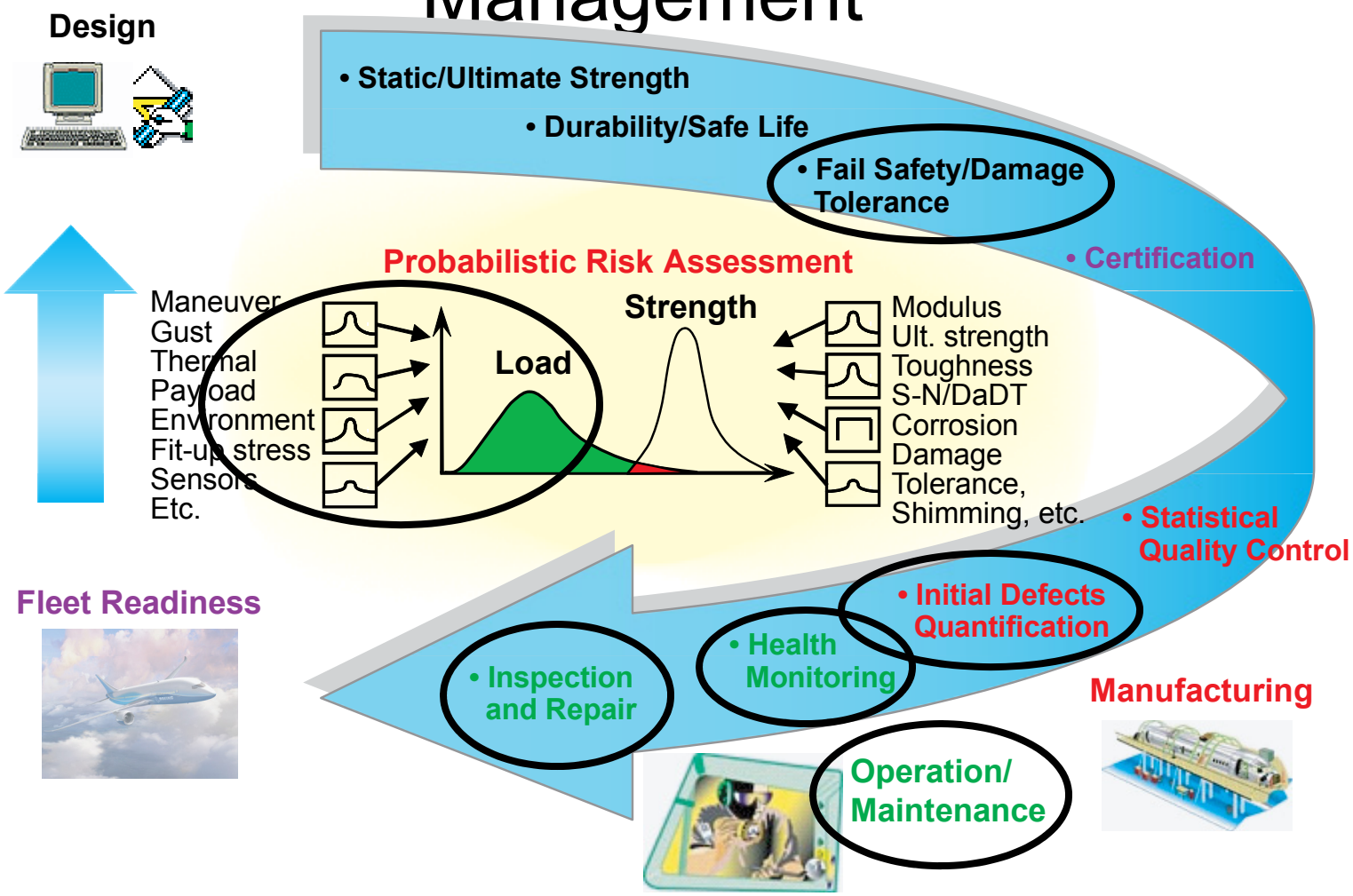
Montana State University (Cairns) and Sandia, Sensor and blade integration development; ***the focus for the remainder of this talk***

Constraints for Blade Inspections

- Achieving 10 – 50x lower inspection costs is a “sporty” goal
  - Low cost, robust sensors
  - Minimal labor (low cost automation)
  - Low cost data reduction and analysis
- Inspection protocol will need to be done in the field (You cannot tow a wind turbine into a hangar for inspections)

Challenge to MSU initiated circa August 2007; two year contract beginning February 2008

Montana State University Automated Sensor Studies for Probabilistic Life Cycle Management



Blade Sensing Needs and Protocol

What to sense	Why to Sense	Comments	How	Where (location)	Rank
Wind Velocity	Extreme wind velocities for monitoring limitations	May already be velocity sensors on turbines, but used to identify possible failure situations.	Wind speed sensor, Anemometer	Top of tower or Nacelle	9
Temperature	Extreme variations to correspond with other data and corrections.	May already be temperature sensors on turbines, but used to identify possible failure situations.	Thermocouple, RTD, digital thermometers	Top of tower or Nacelle	6
Blade Strain	Check for extreme strain along blade length and leading/trailing edges.	Checking for delamination and strain at different positions along the blade	Strain gauge rosette	At various locations along blade: base, middle, tip, leading and trailing edges	1
Moisture/ Humidity	Moisture could effect material properties.	Moisture accumulation along blade.	Impedance moisture sensors	Atmosphere location, Top of tower or Nacelle	5
Angular Position	To correct with other acquired data for efficiency purposes.	Used in conjunction with optimizing efficiency.	In conjunction with other trim adjustment systems.	Base of blades	8
Torque	Possible torsion at base of blades.	Torque could lead to blade failure.	Infrared (IR), FM transmitter	Base of the blade towards Nacelle	10
Loading	Excessive loads will lead to fatigue.	Modeling of design or life purposes.	Associated with Strain	Various locations along blade length	7
Blade Acceleration	Extreme changes in velocity could lead to failure.	To model force excessive changes.	Piezoelectirc Accelerometers, Capacitive Accelerometers, MEMS	Internally at tip where acceleration is greatest	4
Blade Tip Deflection	To avoid tower strikes	Keep overall blade tip deflection in check.	Fiber Optic, Infared (IR)	Attached to base at blade length to sense blade tip position	2
Blade Imperfections	To check for impurities within blade material.	non-destructive ultrasonic testing, cracks, voids	Ultrasonic, vibratory	Ideally along entire blade length	3

Low cost sensing, data acquisition, and data analysis are key technologies to achieve wind turbine reliability goals

Sensor Manufacturing Studies

- Has required the development of a repertoire of surface treatments
  - Surface bonding
  - Embedment
- Different sensors require different surface treatments
  - Mechanical Abrasion
  - Surface Etchants (with chemical functionalization)
  - Solvents and washes

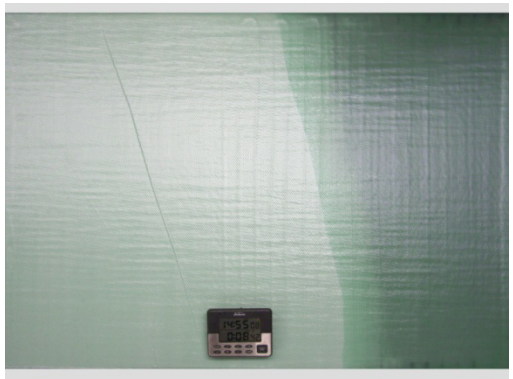
Manufacturing Demonstrations

- Embedded
  - Fiber optics
  - Foil strain gages
  - Thermistors
  - Thermocouples
  - PVDF piezoelectric sensors
- Bonded onto blade
  - Foil strain gages
  - PVDF sensors
  - Fiber optics
  - Humidity
  - Accelerometers
  - Through transmission IR

Implemented and Demonstrated in both vinyl-ester and epoxy matrix composites

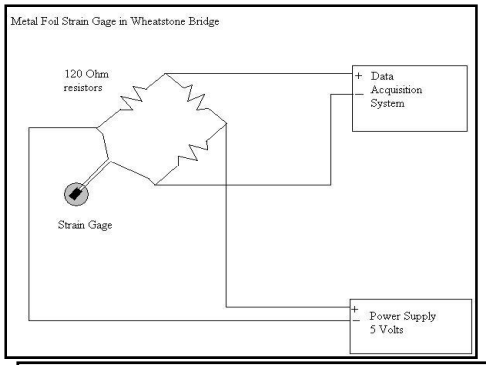
Sensor Laminate Demonstrator Manufacturing and Processing

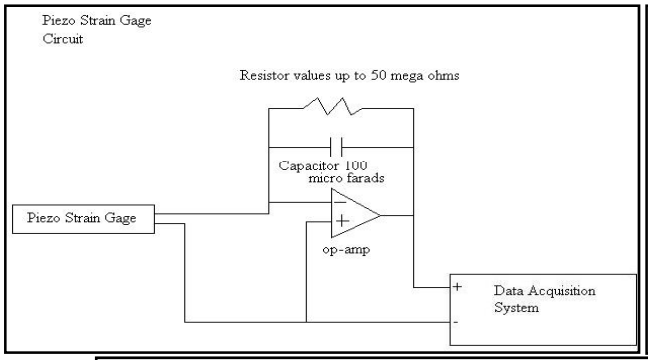
Layup

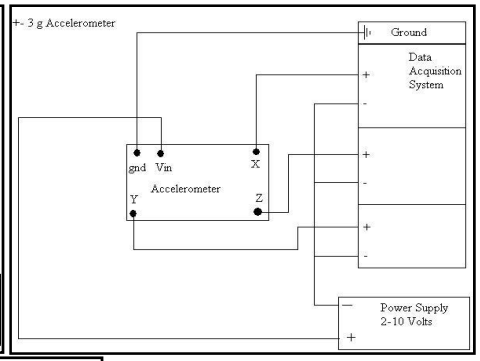


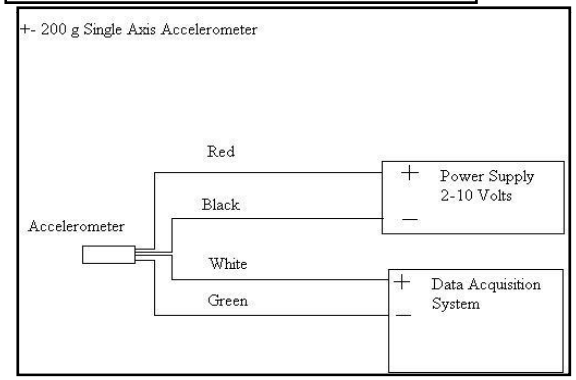
Infusion

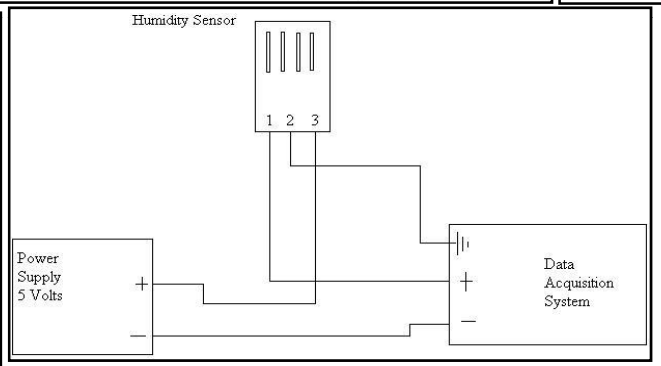
Composite Laminate/Sensor Signal Conditioning Block Diagrams

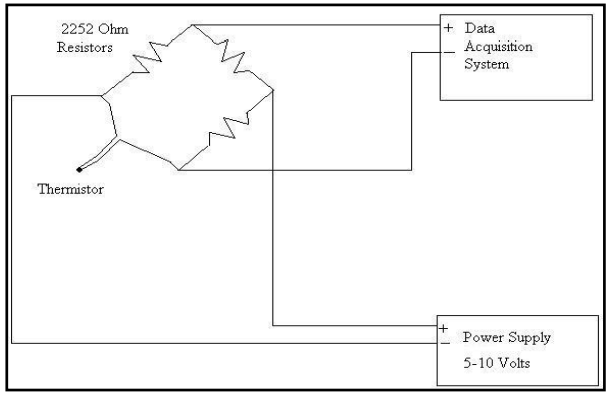


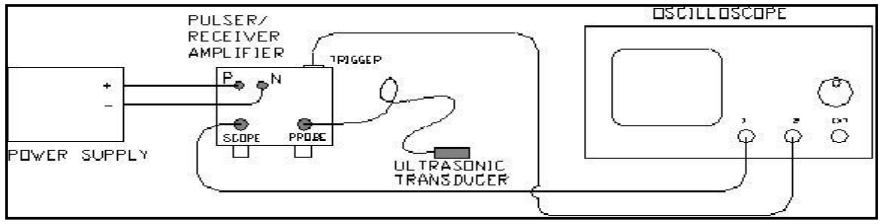


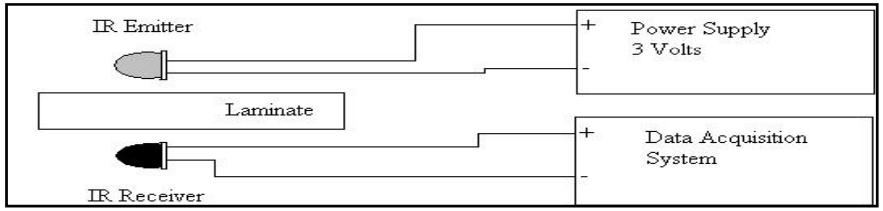




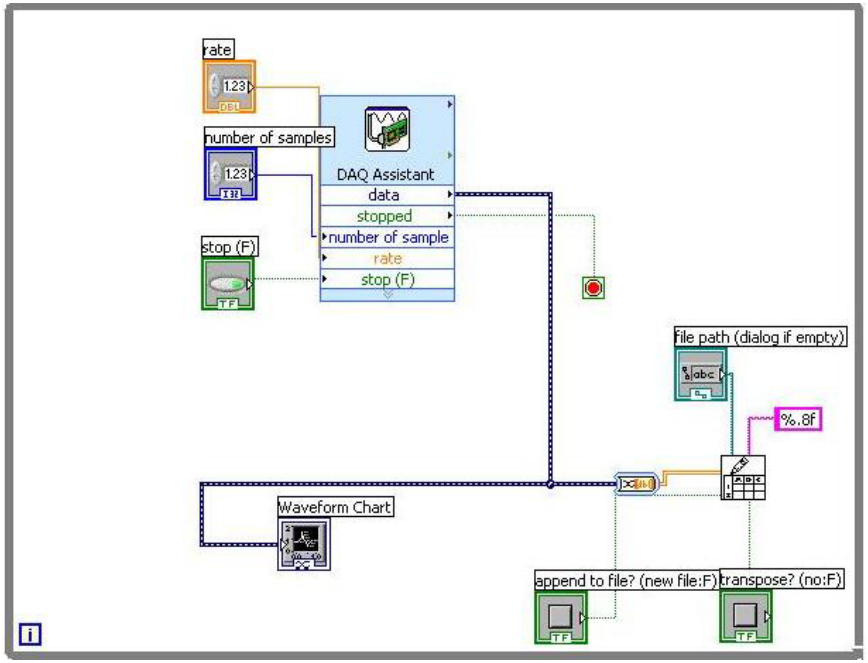




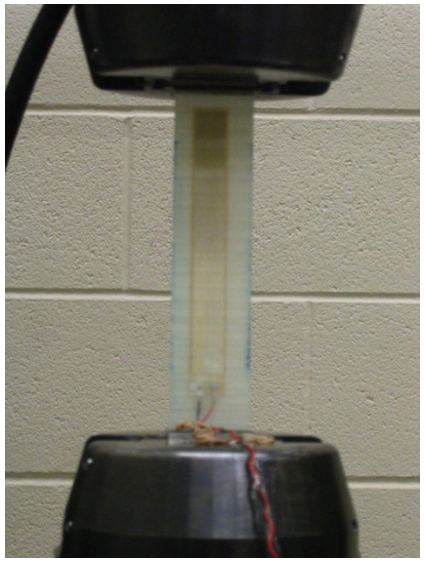


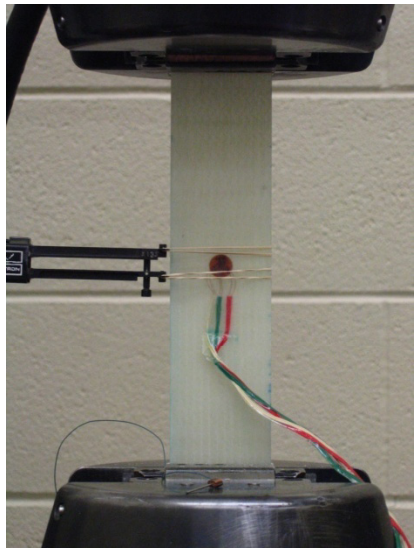


Data Acquisition and Testing



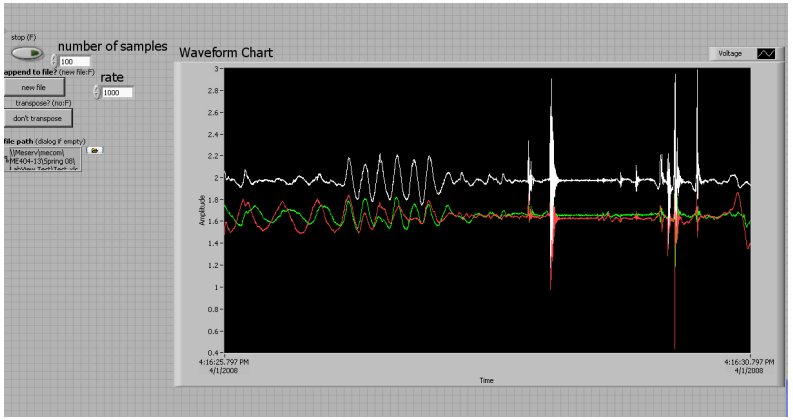
LabView Block Diagram



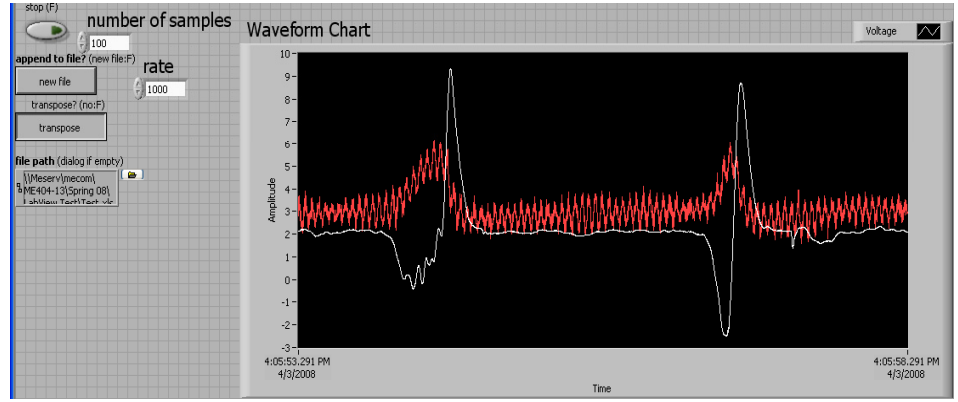


PVDF and Foil Strain Gages being Tested and Calibrated

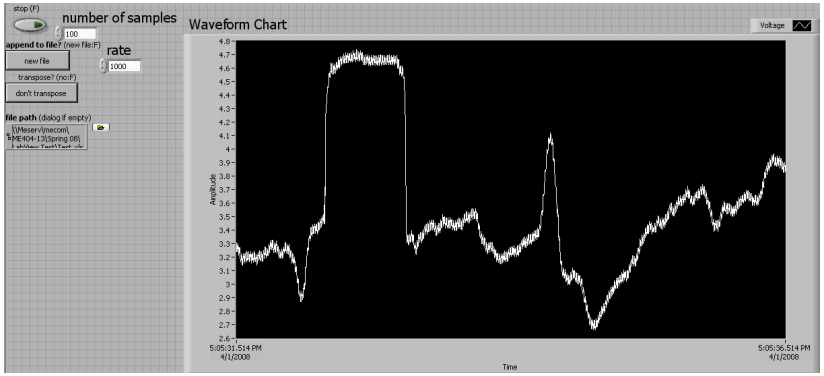
Preliminary Sensor Laminate Demonstrator Sample Results



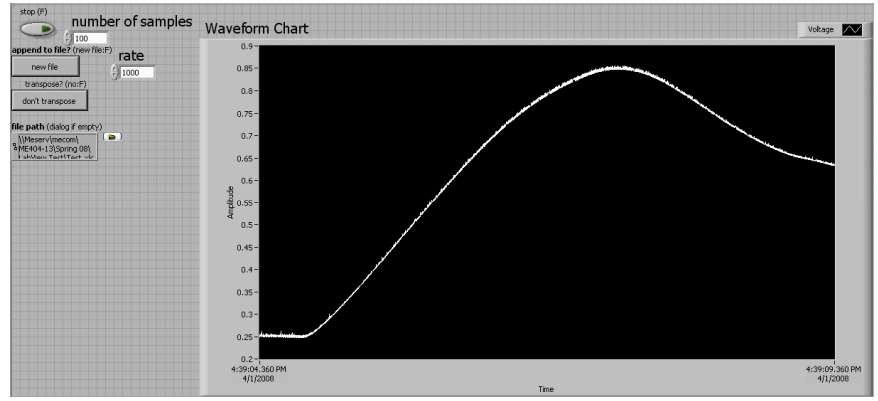
3 Axis Accelerometer



Foil and Piezo Strain Gages

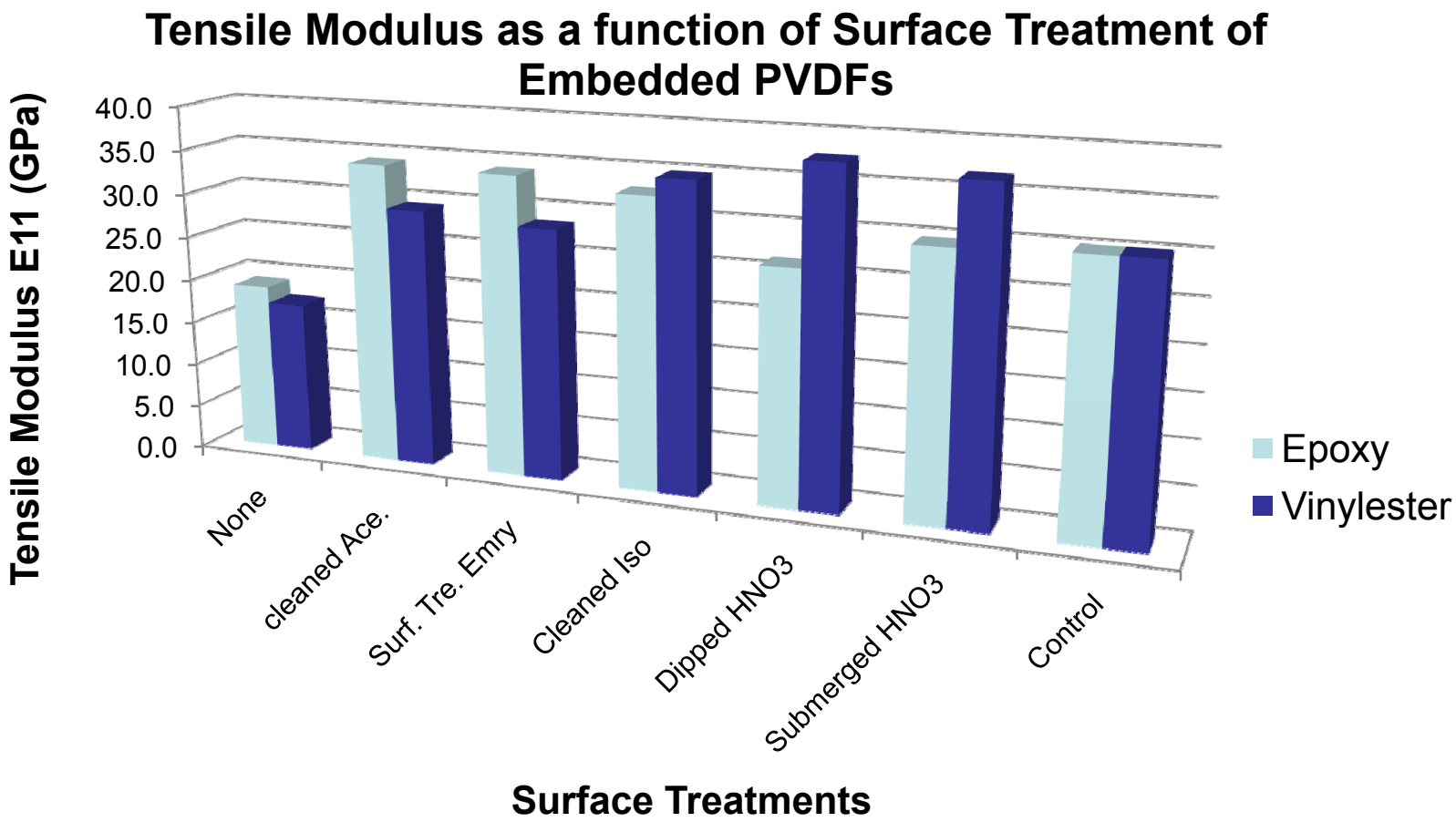


IR Emitter and Photo Transistor



Humidity Sensor

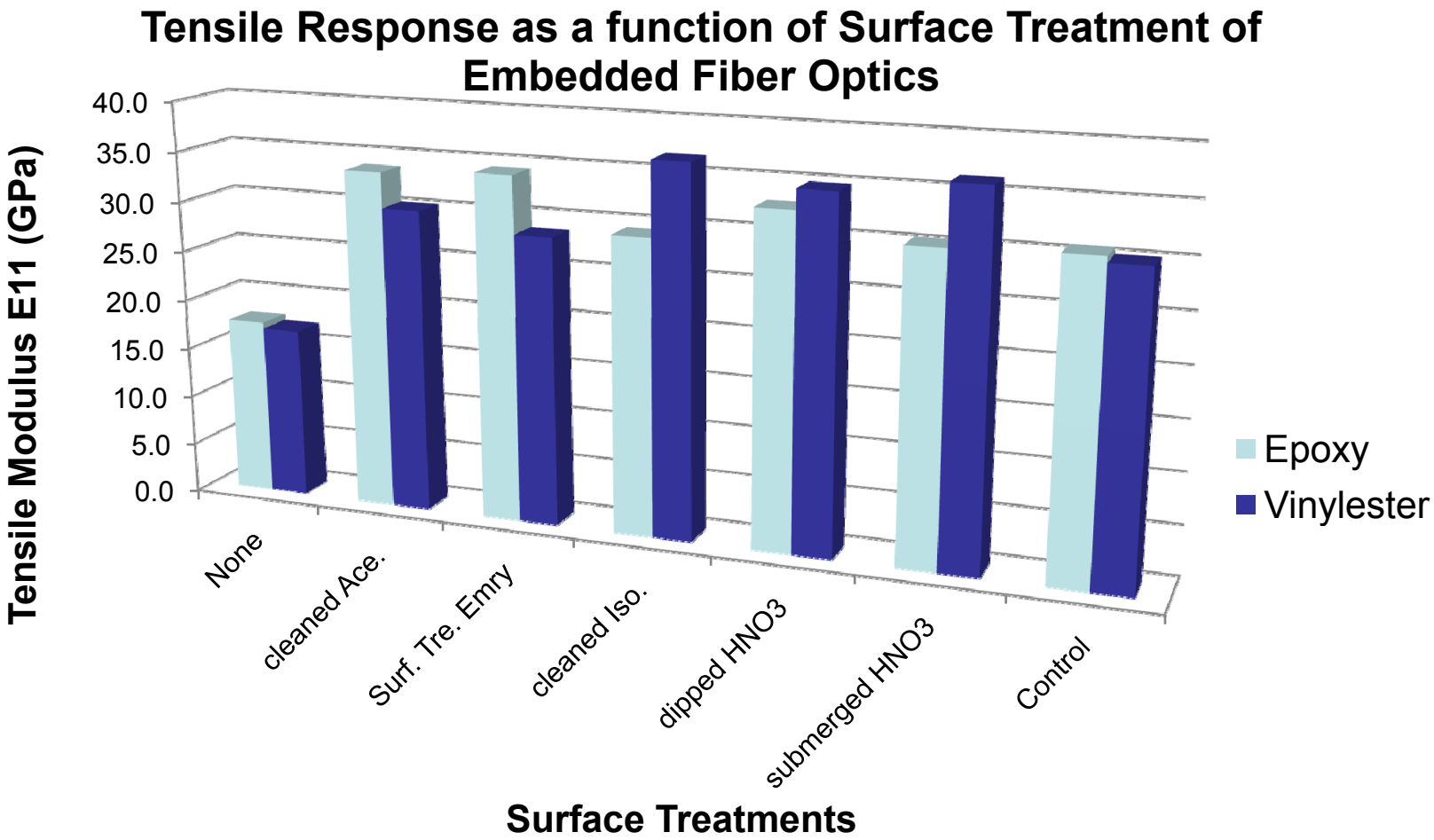
Results of Embedded PVDF Piezo-electric Films



Percent Difference between Dipped Sensors and Controls
Epoxy ~ 12.6 Vinylester ~ 24.6

Percent Difference between Submerged Sensors and Controls
Epoxy ~ 1.3 Vinylester ~ 21.7

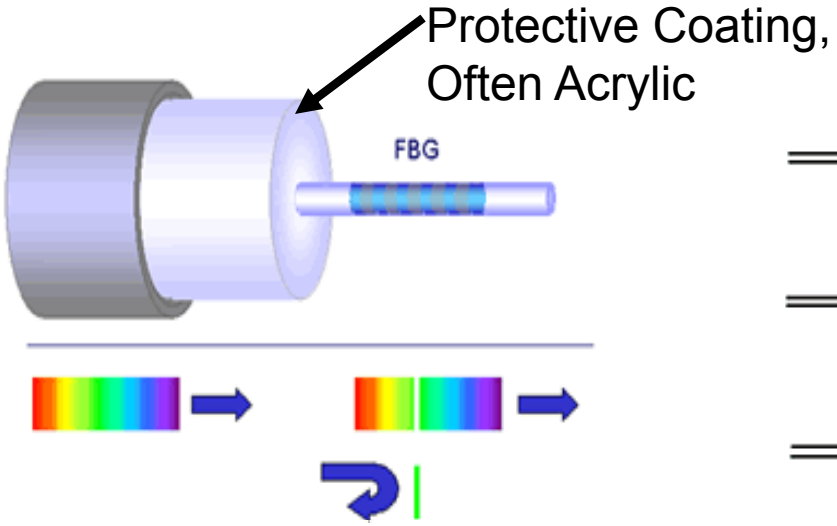
Results of Embedded Fiber Optics



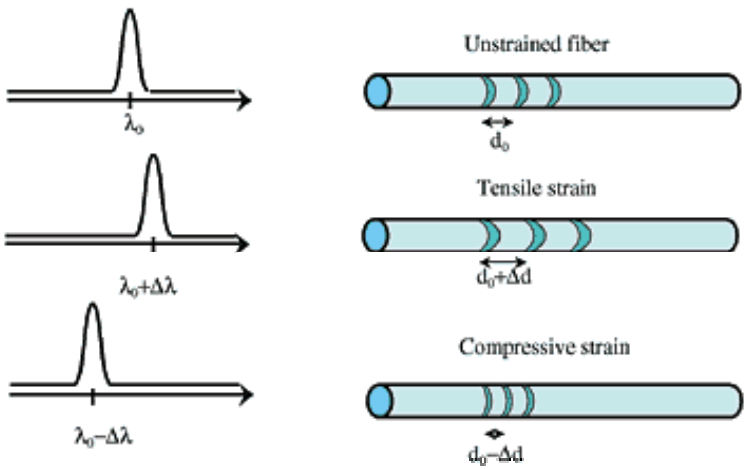
Percent Difference between dipped Sensors and Controls
Epoxy ~ 6.9 Vinylester ~ 15.5

Percent Difference between submerged Sensor and Controls
Epoxy ~ 1.1 Vinylester ~ 20.3

Fiber Bragg Grating Principles



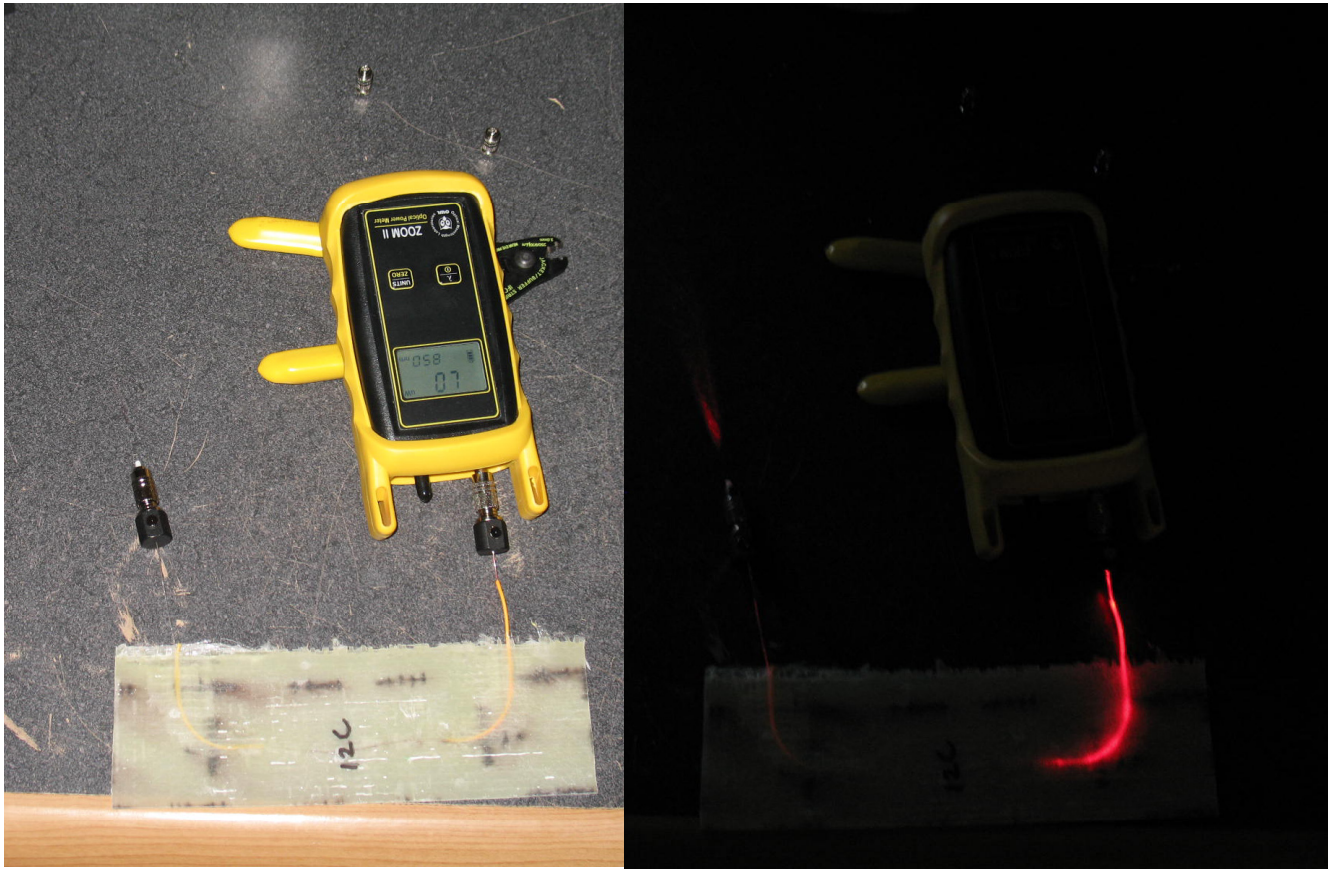
http://www.bayertechnology.com/img_basis/de_Faser-Bragg-Gitter.gif



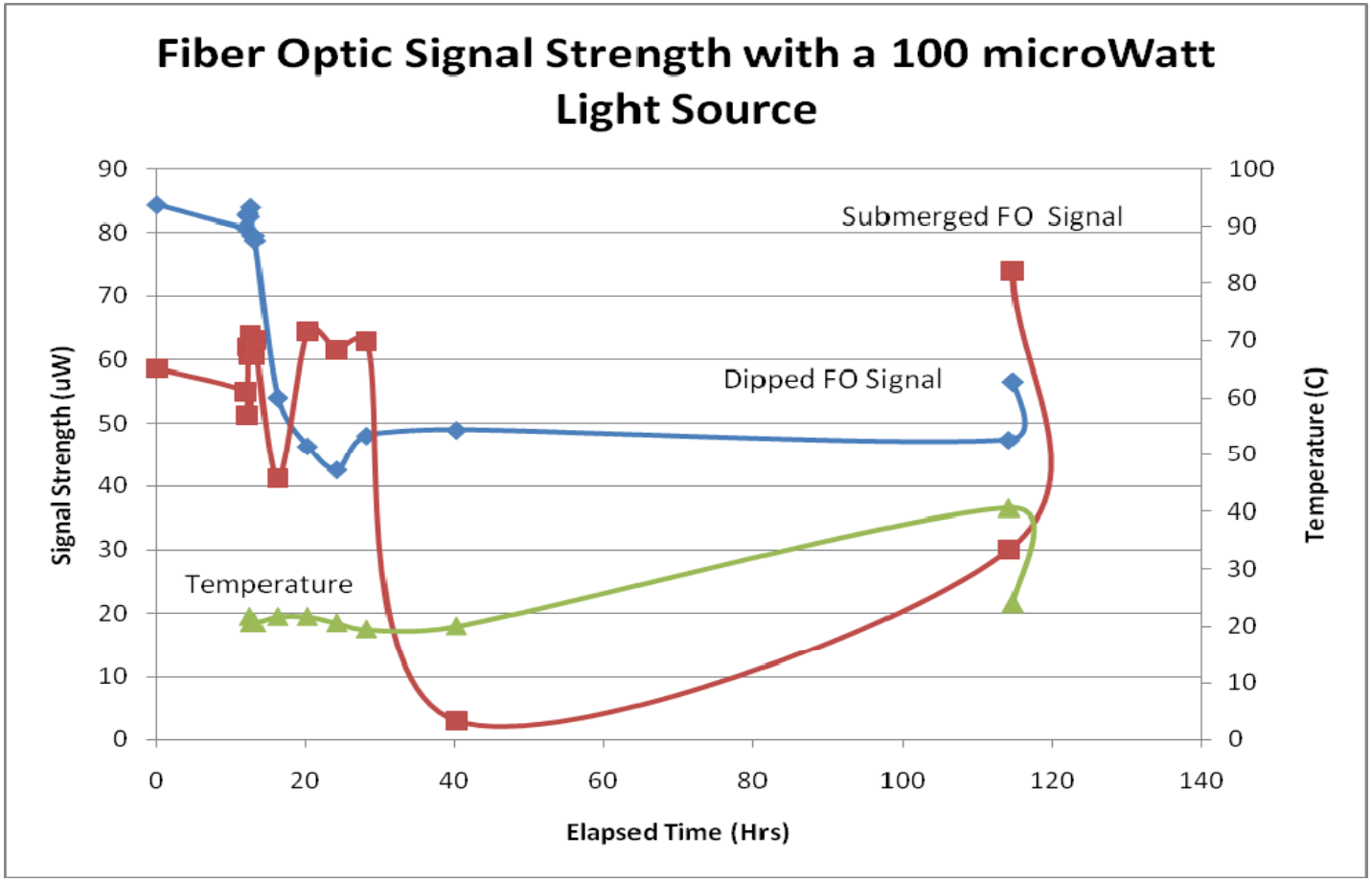
http://www.sensorsmag.com/sensors/data/articlestandard/sensors/162006/321349/fig1b.gif

- Each grating reflects only a small wavelength
- Non-reflected waves allowed to continue on
- Shift in reflected wavelength can be read

Visual Fault Indicator to Determine Signal Loss Locations

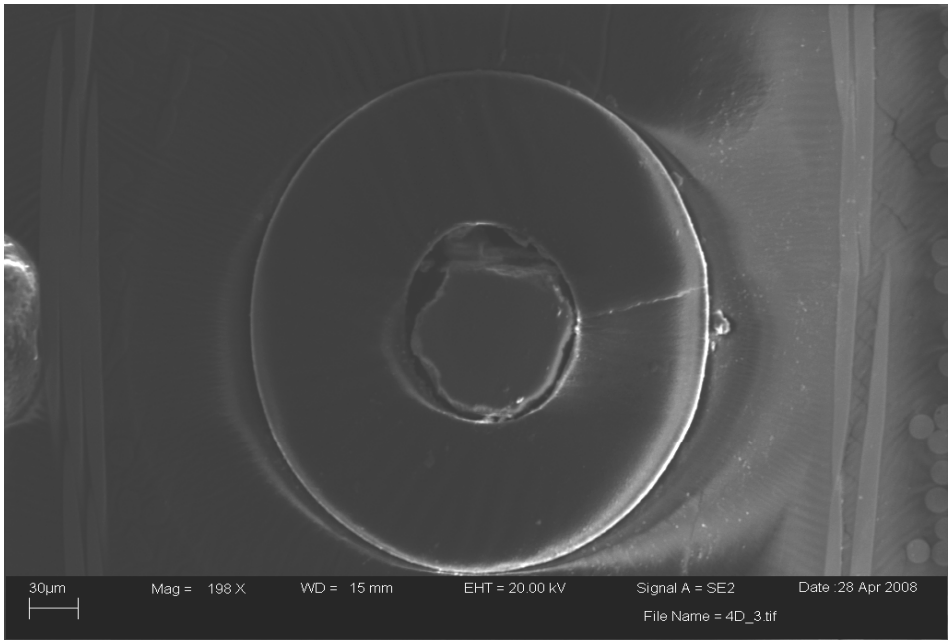


Fiber Optic Signal During Composite Laminate Processing

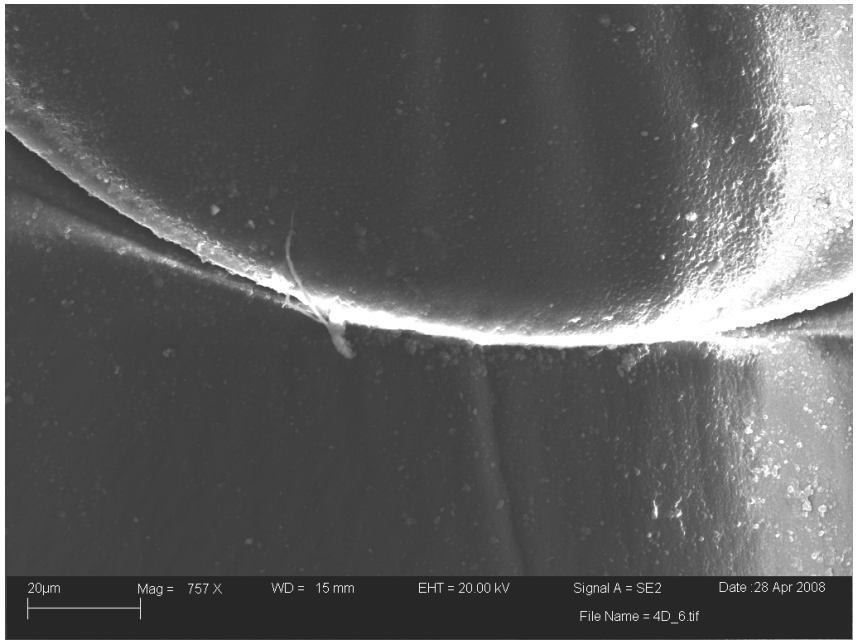


Signal losses due to handling and manufacturing - observed by others

Embedded Fiber Optics (composite/fiber interface)



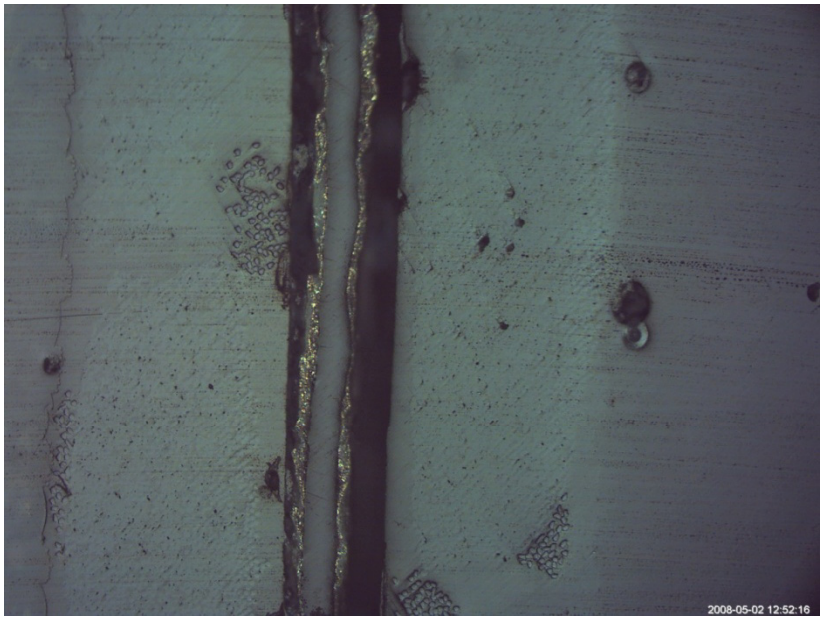
Fiber Optic (fiber plus cladding)
FEM 198x



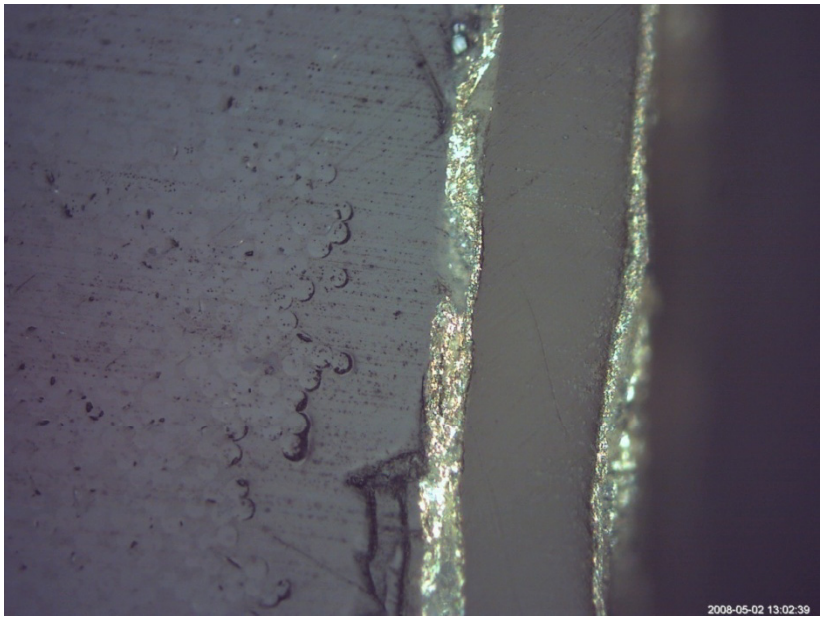
Cladding/Composite Interface
FEM 757x

Consistent application to composite wind turbine blades will probably require surface treatment of fiber (similar issues with all embedded sensors studied)

PVDF Film Sensors

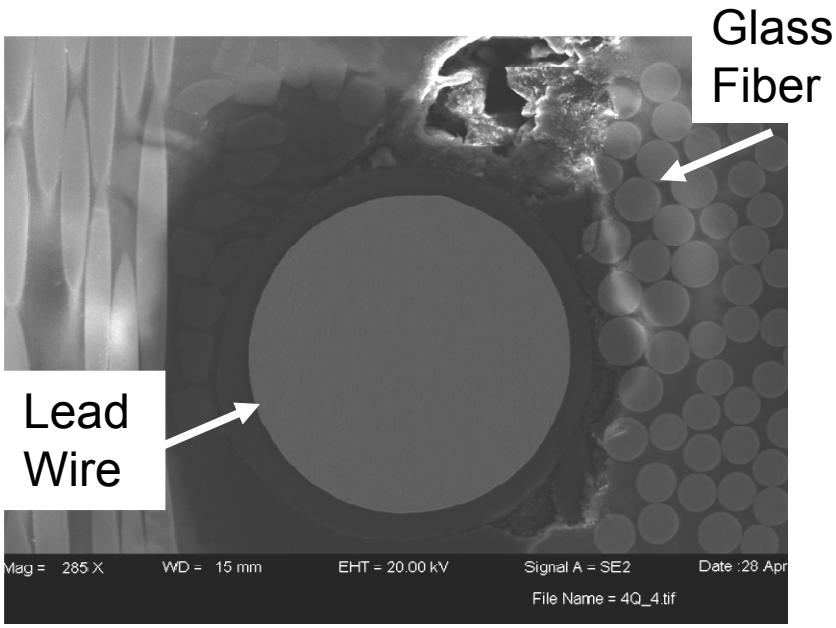


Poorly Bonded (50x)

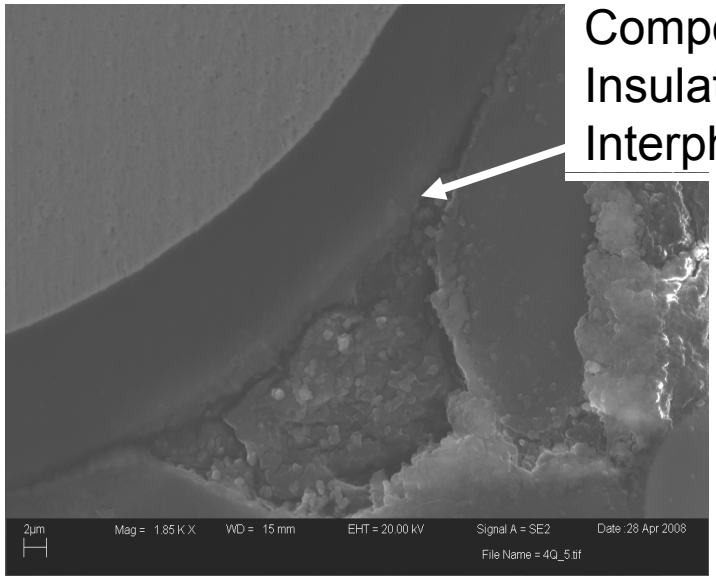


Well Bonded (200x)

Embedded Sensor Lead Wires



Sensor Lead Wire
FEM 285x



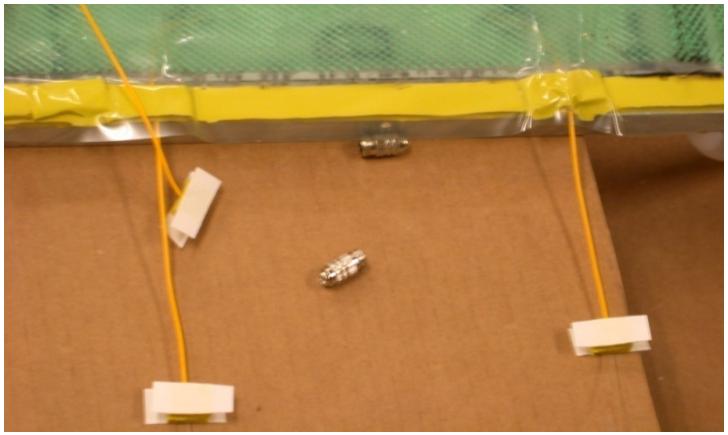
Sensor Lead Wire
FEM 1,850x

Thin, polymeric insulation with questionable composite interface

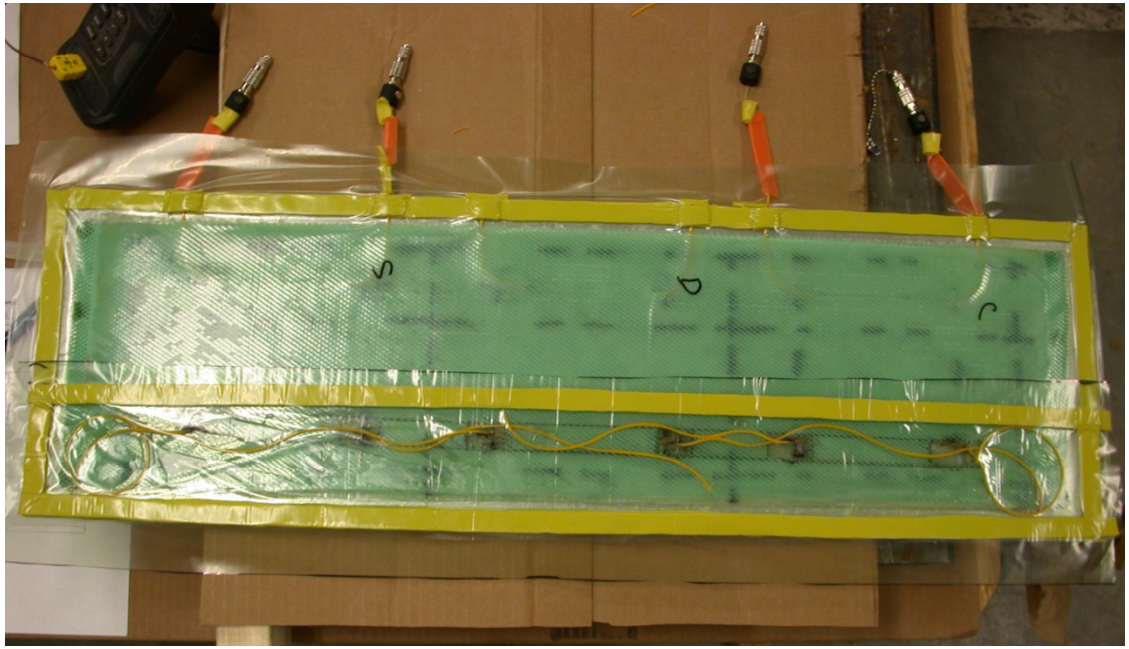
Present Scheme for Fiber Optic Transition Through Layup

Covering Fiber Optics with wire sheathing material

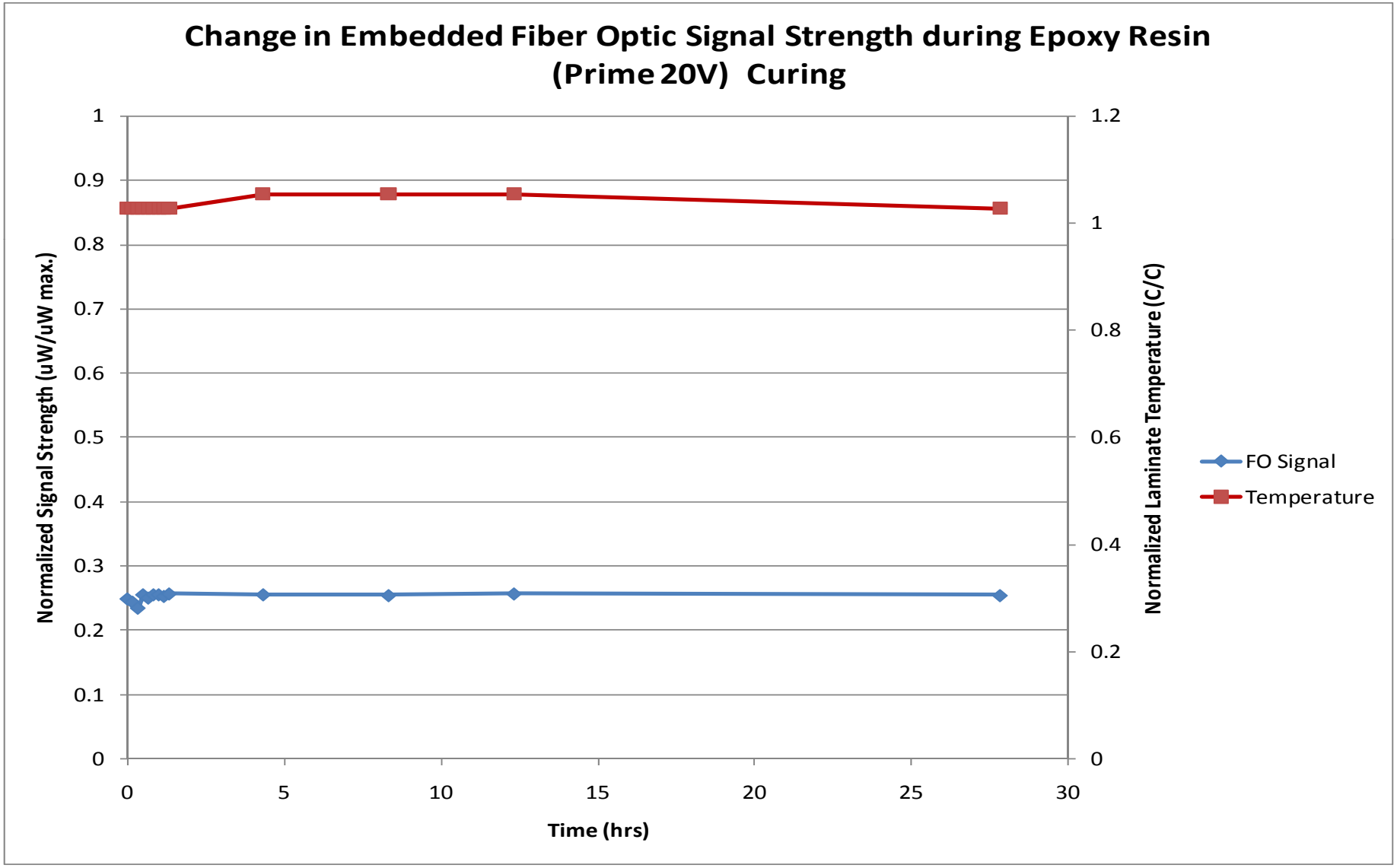
This provided reliable signal input and output



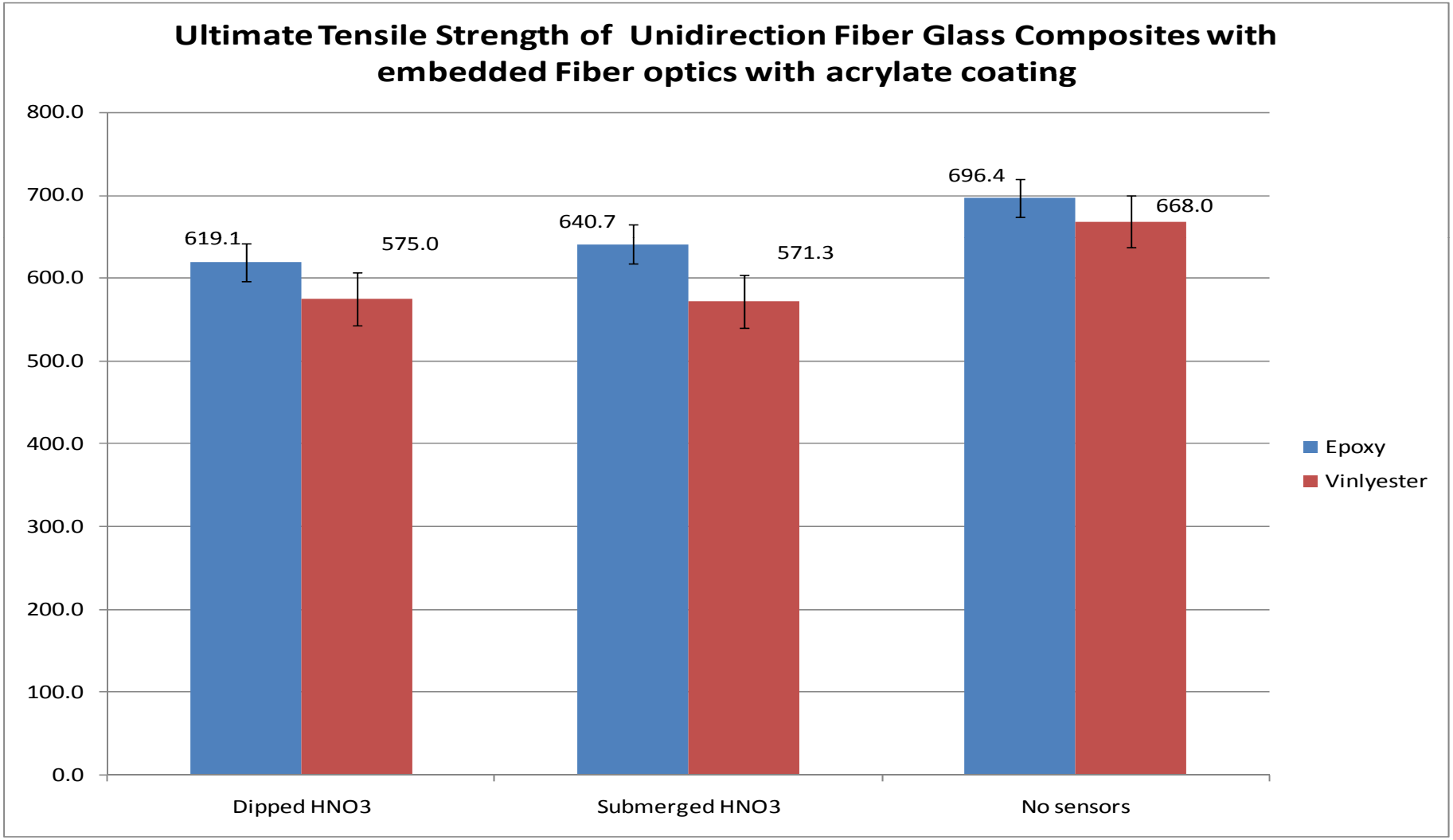
Small sections were cutout of the peel ply and flow media to accommodate the Fiber Optics



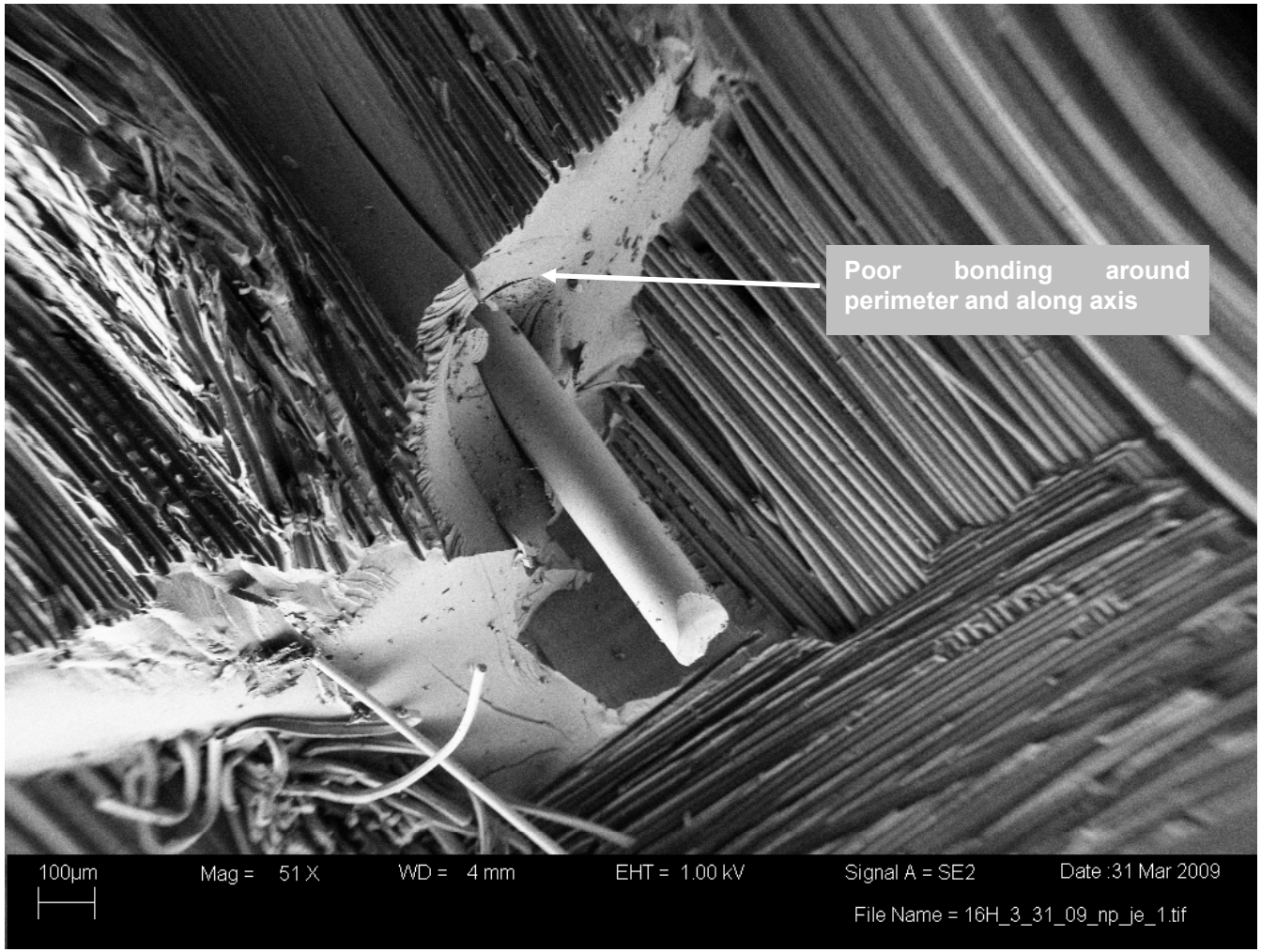
Improved Manufacturing and Handling Has Virtually Eliminated Signal Losses



Reduced Load Carrying Capability with Embedded Sensors

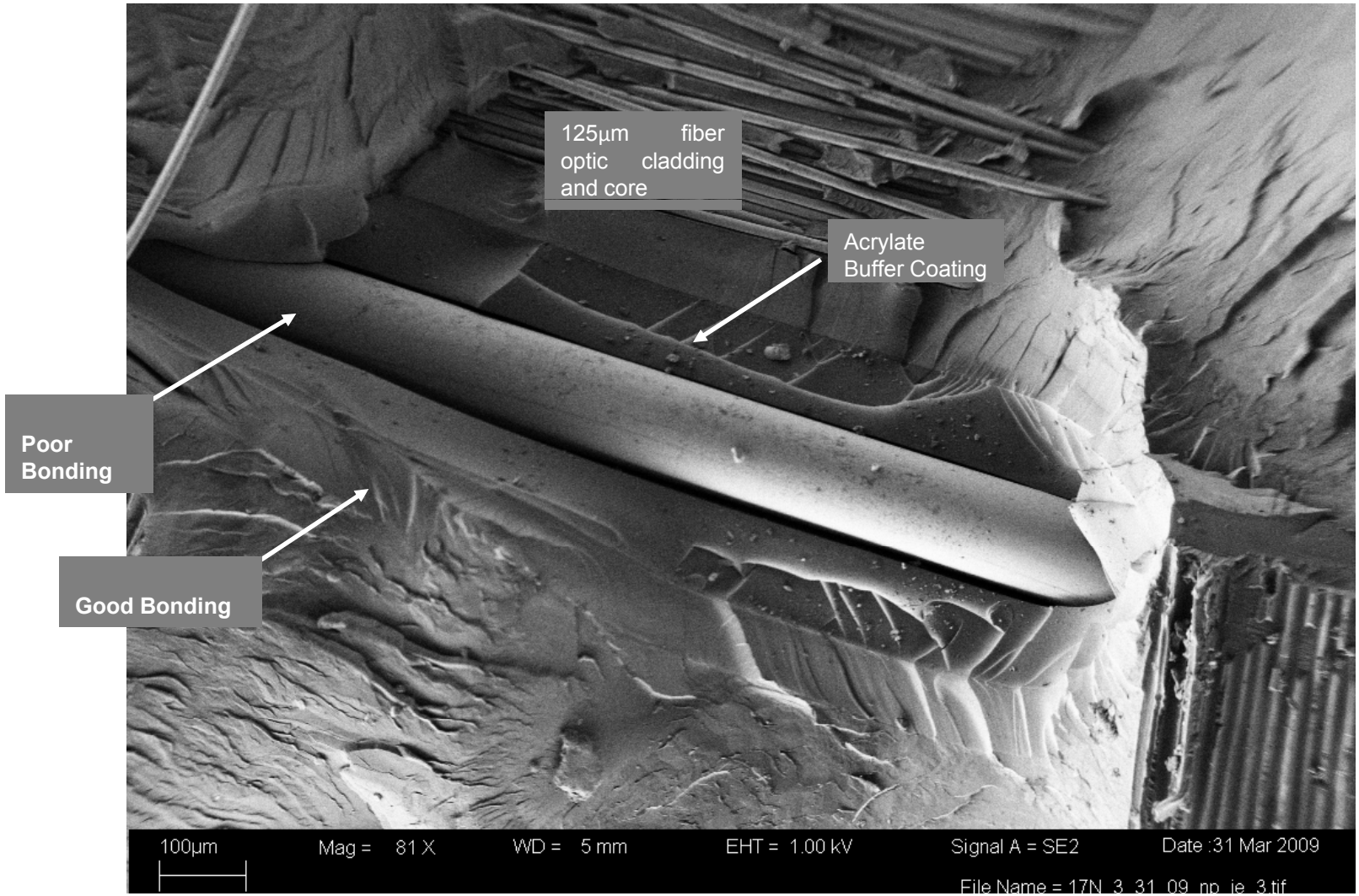


Field Emission Microscopy of Fractured samples with Embedded Fiber Optics



Embedded Fiber Optics (cont.)

Improvements will require help from FO manufacturers



The Bottom Line for Bonded/Embedded Sensors

Each sensor/instrumentation package will require some manufacturing studies to ensure that there is adequate bonding and that its presence does not degrade the structure

Progress

- Low cost sensors have been implemented and demonstrated in composite wind turbine blade laminates
- Sensors data acquisition has been developed in a robust, commercially-available platform
- Embedding sensors will not be trivial
  - Interface issues, preliminary results on unidirectional laminates with embedded sensors have static strength decreases
  - Durability and Longevity issues
    - Sensor
    - Laminate

Ongoing Work

- Calibration of sensors
- Manufacturing and testing of more laminates
  - Glass and Carbon Fiber Reinforcements
  - Vinyl ester, Epoxy, and DCPD Matrices
  - Surface treatment for composite/sensor compatibility
    - Mechanical
    - Chemical
    - Plasma interphases for optimization
- Implementation for composite wind turbine blades
  - New manufacturing
  - Retrofit
- Provide input for applications to manufacturing composite wind turbine blades with integrated sensors
  - Sandia/Industry Blade Development Programs
  - Montana Wind Applications Center (testbed for sensor research)
- Continue to develop a reasonable cost approach to statistically defensible reliability

Montana Wind Applications Center

The Wind Applications Center at Montana State University joins WACs at universities in 5 other western states. Funded by a National Renewable Energy Laboratory grant, the long-term goal of this national program is to promote wind as a clean, viable, and sustainable energy source for today and tomorrow.

MSU WAC GOALS

1.Develop a curriculum in wind education at the University level, to address growing demand for technical employees in the wind industry.

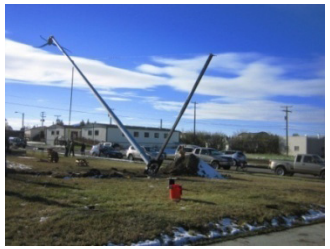
2.Support outreach and assistance efforts to disseminate wind energy knowledge.

3.Support the DOE NREL Wind for Schools initiative to place wind turbines at participating K-12 Schools throughout the state of Montana.

Contact:
Robb Larson, P.E.
Director, Montana Wind Applications Center
Assistant Professor, Dept. of Mechanical and Industrial Engineering
220 Roberts Hall, Montana State University
Bozeman, MT 59717
phone: 406-994-6420
fax: 406-994-6292
rlarson@me.montana.edu

PRESENT AND FUTURE WAC EFFORTS

- *MET "Capstone Design" Student teams worked on Wind Energy issues each of 2 past academic years.*
- *Skystream 3.7 turbine installation completed on MSU campus in October 2008.*
- *Senior-level Alternative Energy Applications course taught Fall 2008, on-tap again Fall 2009.*
- *Site selection and support for Wind for Schools program*
- *Modeling, Design, Analysis and Prototyping of turbine tower infrastructure.*
- *Wind Internship Program Underway.*
- *WAC Website on-line at www.coe.montana.edu/wind includes Wind Energy Monitoring Data & Results.*



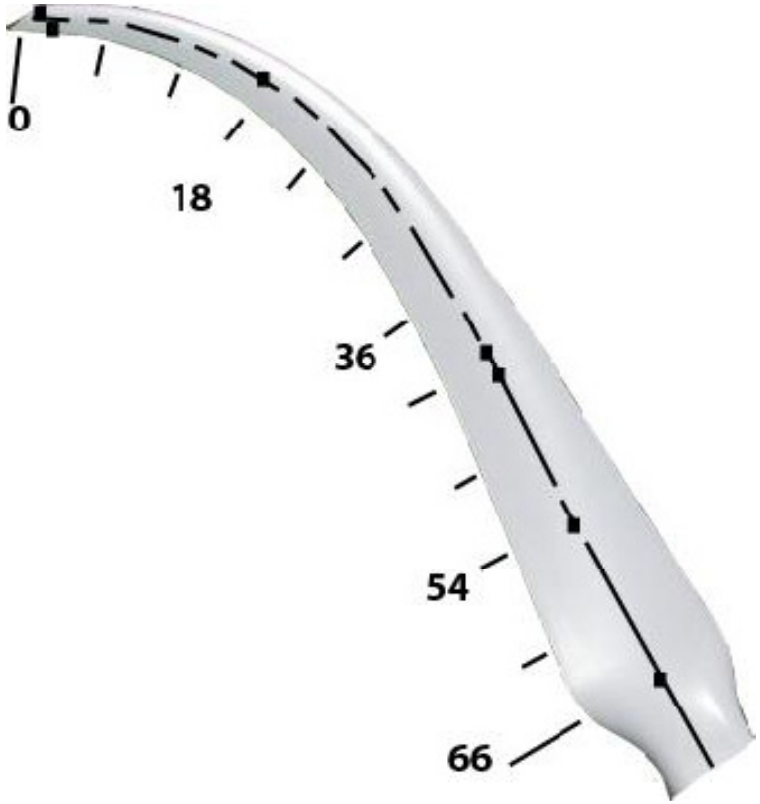
Field Trials With Sensors

Goal-To obtain preliminary feasibility and durability of candidate sensors in a field environment

- System completely under Montana State University control
- Retrofit feasibility
- Initial response data (sensor output)
- Response after field exposure
- Destructive testing to determine long term effects on blade and sensors

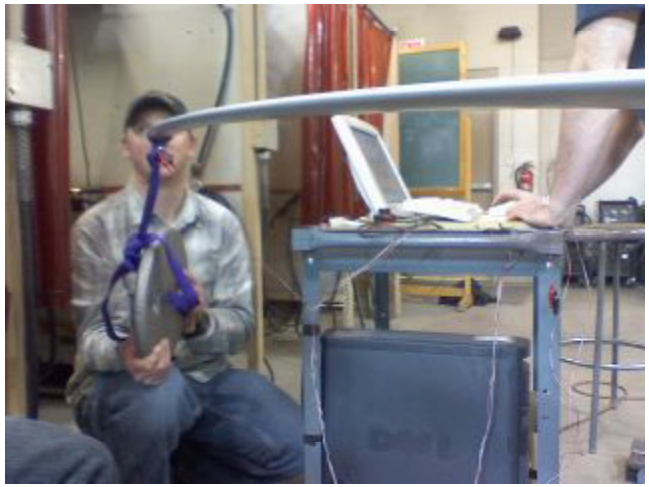
Field Trials With Sensors

MSU Skystream 3.7



Sensors placed at locations on blade

Sensor Mounting and Static Testing before Field Deployment



The Next Steps for Sensor Implementation

- Purchase more hardware
  - Sensors
  - Data Acquisition (especially fiber optic interrogators)
- Develop benchmark demonstrations
  - Retrofit
  - New Blades
- Implement onto/into blades – fly them

The Players

Player	Sandia	MSU	Industry
Role	Set priorities and goals, coordinate efforts, develop parallel efforts within Sandia (manufacturing, data acquisition, data interpretation)	Manufacturing protocol (new blades, retrofit) Sensor hardware and software development Implement into blades	Sensor hardware and software (specialty small companies, larger companies, e.g. National Instruments), Blade manufacturers (TPI, K&C, others?)

Acknowledgements

This works has been done with sponsorship from Sandia National Laboratories – Wind Technology, with specific involvement from Mr. Tom Ashwill and Mr. Mark Rumsey

Thank You!