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Leading Edge Erosion

Measurement and Modeling Campaigns

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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Overview and Motivation

- Historically, wind turbine capacity factors have been overestimated by 15%.[1]
- This is attributed to annual wind intermittency, wind farm topography, and design performance over predictions.

Heavy blade erosion[2]

- One cause of performance loss is leading-edge surface roughness.
- Over time, blades suffer from erosive and additive roughness.

Contributors

- Sandia National Laboratories
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  - Mark Rumsey
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- Texas A&M
  - Ed White
  - Ben Wilcox
  - Robert Ehrmann
- UC Davis
  - Chris Langel
  - Ray Chow
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Technical Approach

Mechanisms
What causes it?

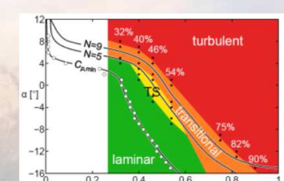
Standards

Technology Improvement

Erosion

Treatment
How to deal with it?

Aerodynamics
How is performance affected?



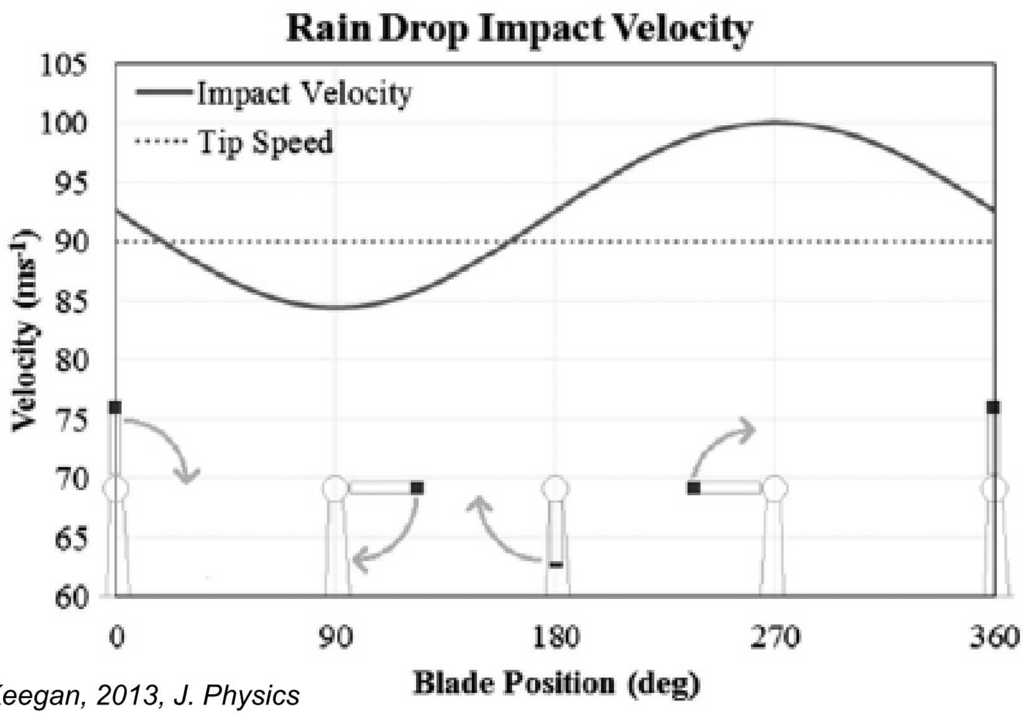
Leading Edge Erosion Project

- Goal: Quantify Effects of Surface Contamination and Erosion on Wind Turbine Performance

- Tasks:
  - Field measurements of surface roughness and erosion
  - Wind tunnel testing of effect of surface roughness and erosion on airfoil performance
  - Development of computational roughness model to account for effect on aerodynamic performance of airfoils, blades, rotors
  - Correlate wind tunnel and CFD results

Types of Leading Edge Erosion and Surface Roughness

- 2D Step, Paint Chip or Repair
- Contamination Roughness (Bugs)
- Light to Moderate Erosion, Random Pits
- Heavy Erosion



Keegan, 2013, J. Physics

- **Mechanisms of LEE**
  - Manufacturing or transportation issues
  - Dust and Sand
  - Rain induced fatigue
  - Ice

2D Step, Paint Chip or Repair

Contamination Roughness (Bugs)

Insect roughness[3]

Leading Edge Protection or Repair

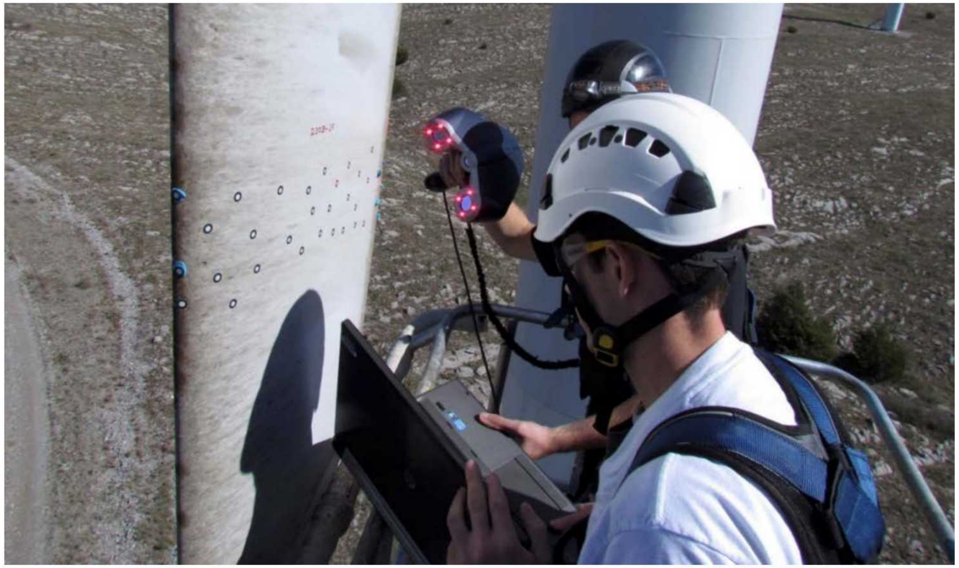
Light to Moderate Erosion, Random Pits

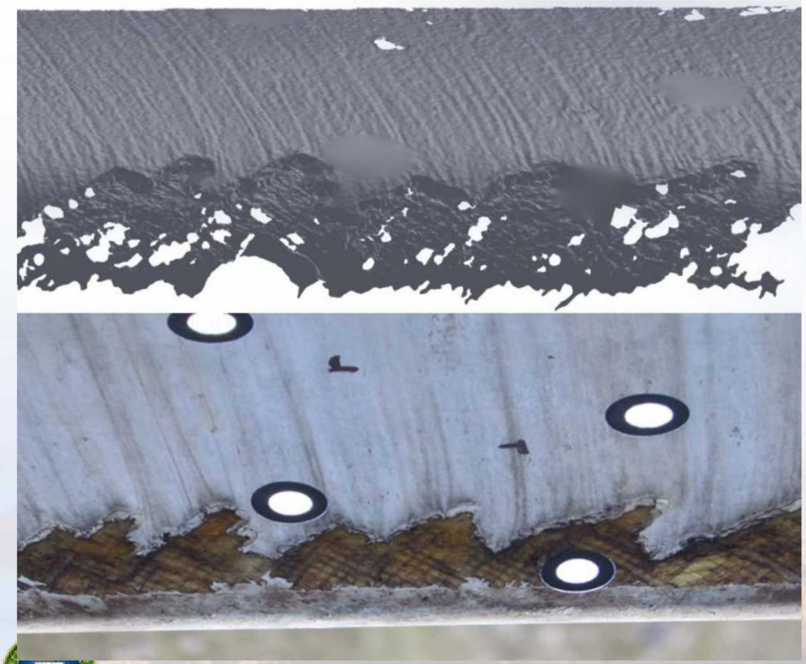
Heavy Erosion

Field Measurements

Creaform EXAscan measuring the wind turbine blade.

Laser scanner used to capture roughness >1mm.





Roughness Measurements

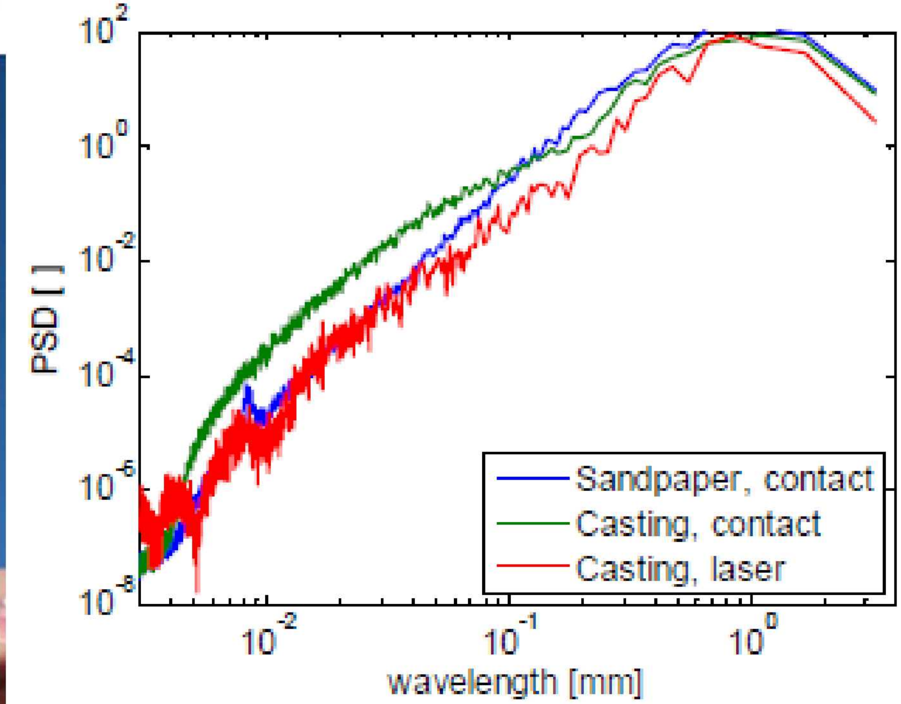
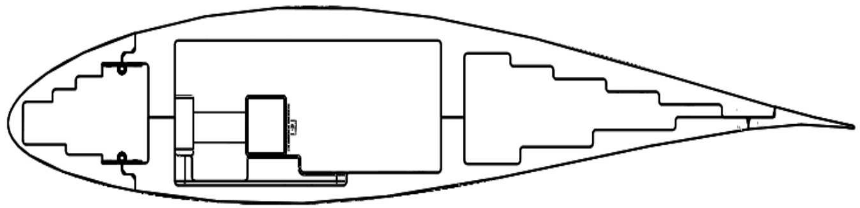


Image of alginate castings curing on a wind turbine blade.

Casting and profilometer used to capture roughness < 3mm.

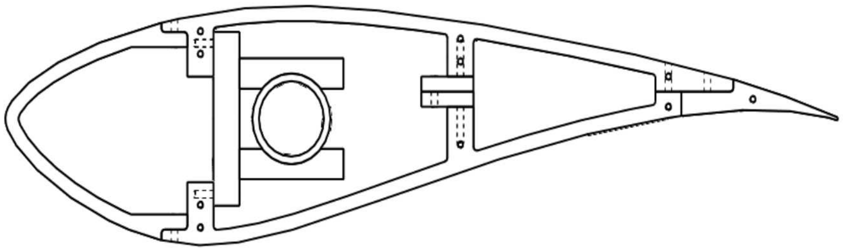
NASA LEWICE code used to simulate bug accretion.

Airfoil Wind Tunnel Models



NACA 63_3-418

Representative tip airfoil
18% thickness to chord ratio
Designed for high Lift/Drag ratio



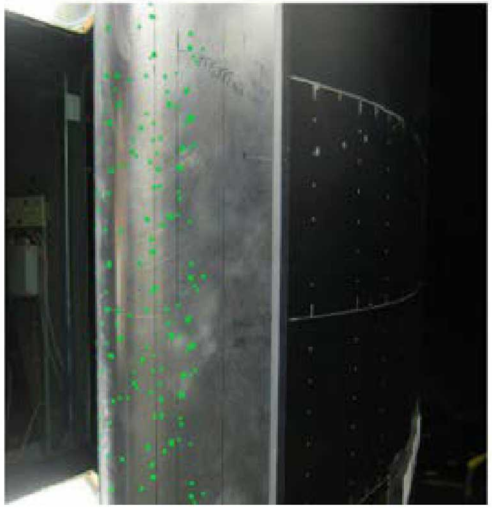
SERI S814

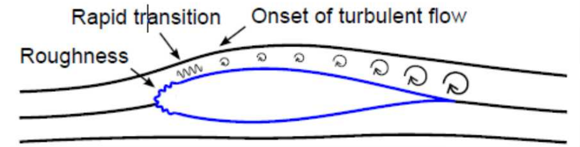
Representative mid-span airfoil
24% thickness to chord ratio
Designed for wind turbines
Designed for high Lift/Drag ratio
Including decreased roughness sensitivity

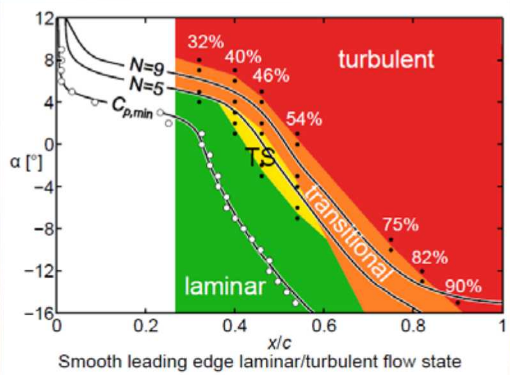
- Airfoils were tested using clean, trip-strip, and distributed roughness configurations at Reynolds numbers of 1.6×10^6, 2.4×10^6, 3.2×10^6, and 4.0×10^6; Maximum $Re_c = 5.0 \times 10^6$ to $\alpha = 4°$
- The NACA 63_3-418 was also tested with a forward facing step to simulate paint chipping, and a simulated eroded leading edge

Wind Tunnel Testing

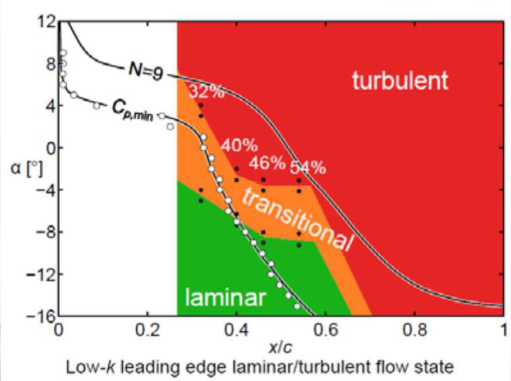
- Measurements from the field used to parameterize roughness
- LE erosion wind tunnel models based on parameterized roughness elements
- Large database of airfoil boundary layer characteristics



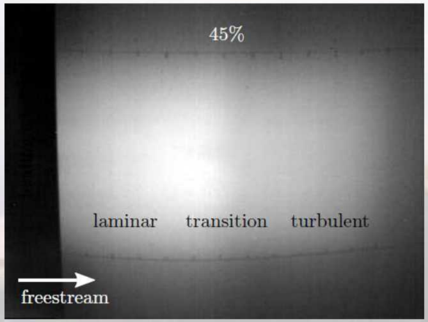




Smooth leading edge laminar/turbulent flow state



Low-*k* leading edge laminar/turbulent flow state



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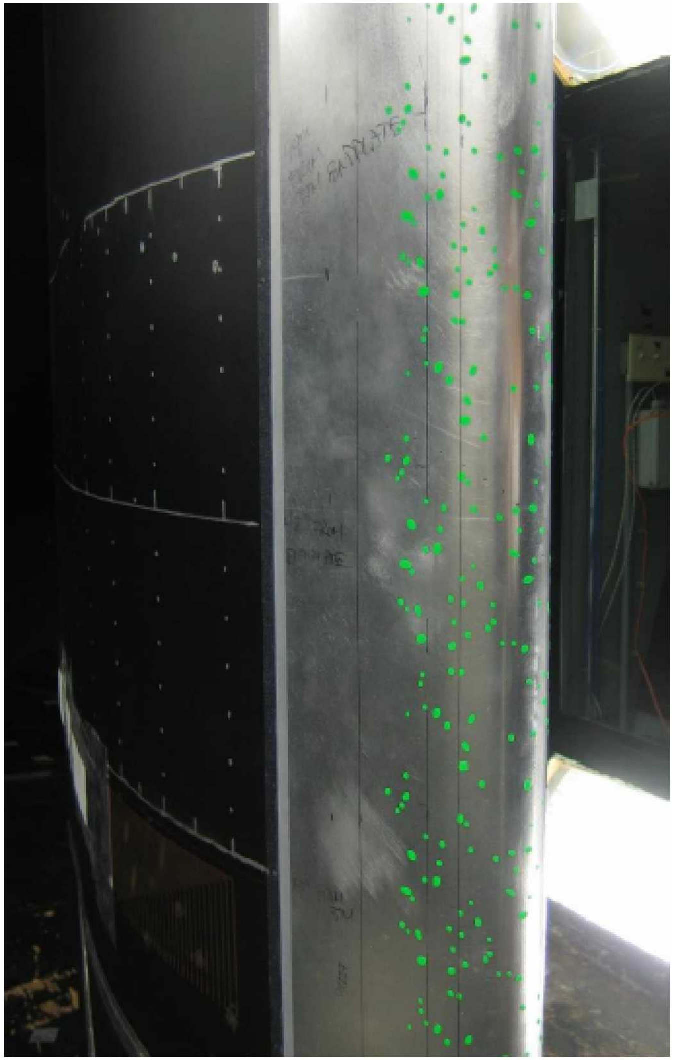
Wind Tunnel

- Oran W. Nicks Low Speed Wind Tunnel at Texas A&M
- Closed return tunnel
- Test section 7 ft × 10 ft
- Maximum velocity of 90 m/s
- Blockage of 4.8%
- Turbulence intensity of 0.25%
- Maximum Re_c = 3.6×10^6 based on $c_{l,\max}$ loading
- Maximum Re_c = 5.0×10^6 to α = 4°

Model installed in wind tunnel

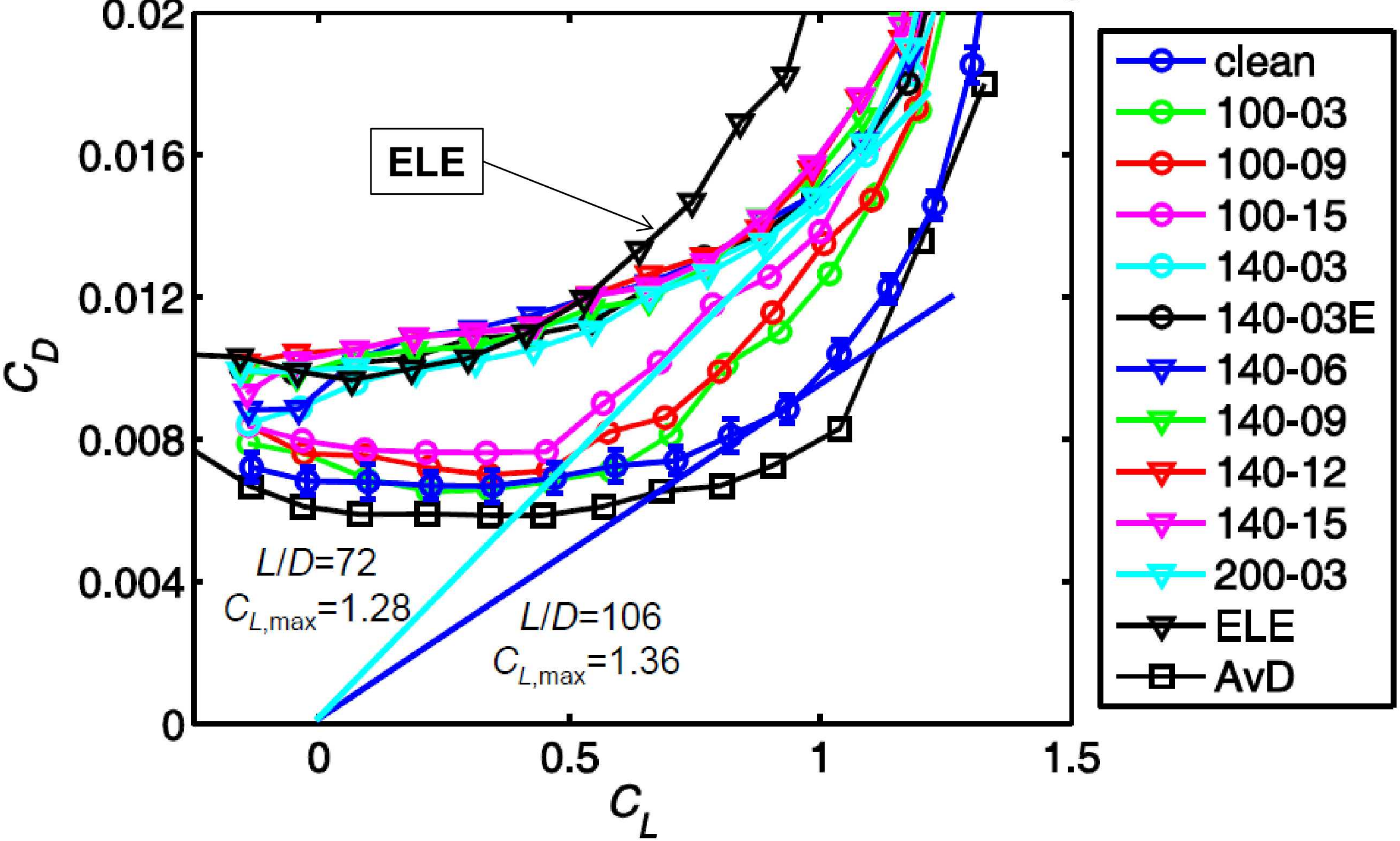
Configurations

- Clean
- Tripped
- Forward Facing Steps
  - Chipped paint 157µm
  - Straight step 157µm
- Distributed Roughness
  - 100 µm, 3, 9, 15% coverage
  - 140µm, 3, 6, 9, 12, 15% cov.
  - 200µm, 3% cov.
  - Distributed and 2D roughness

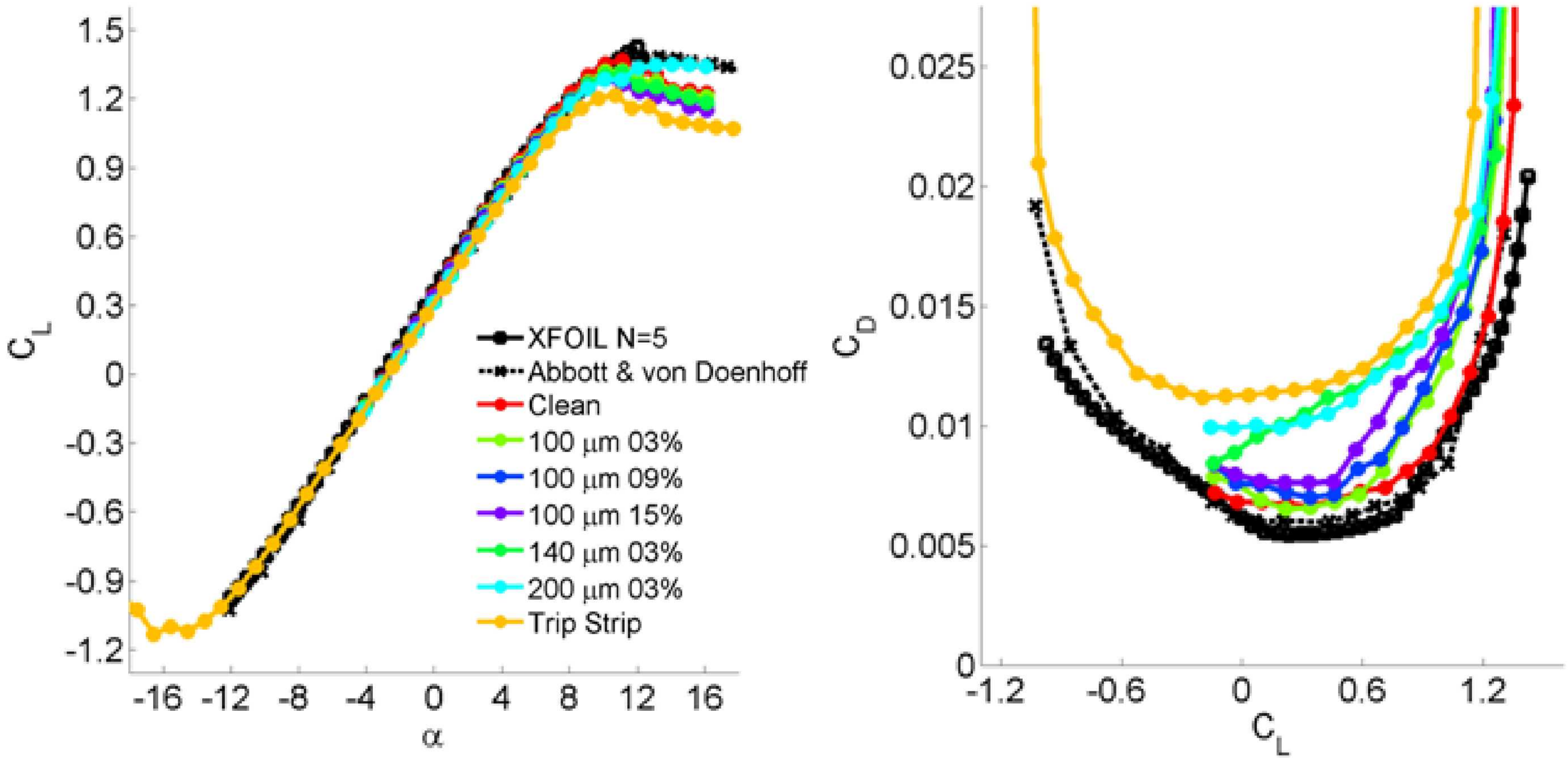


Simulated insect roughness (140 µm, 3% coverage) on NACA 63_3-418.

NACA 63_3-418 Drag Polar
$Re_c = 3.2 \times 10^6$

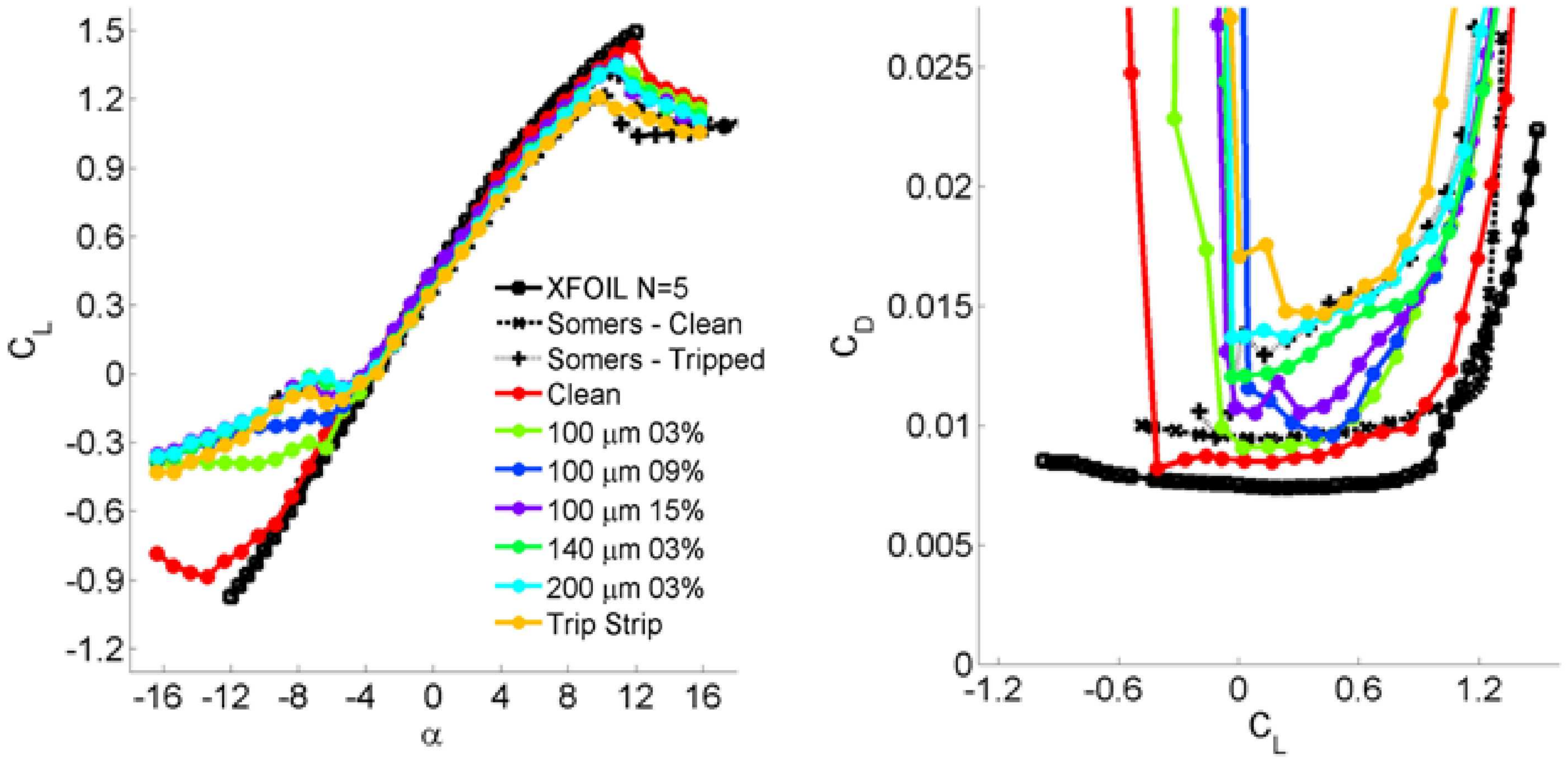


NACA 63_3-418



Lift and drag data for NACA 63_3-418 airfoil for various roughness conditions at $Re = 3.2\times10^6$

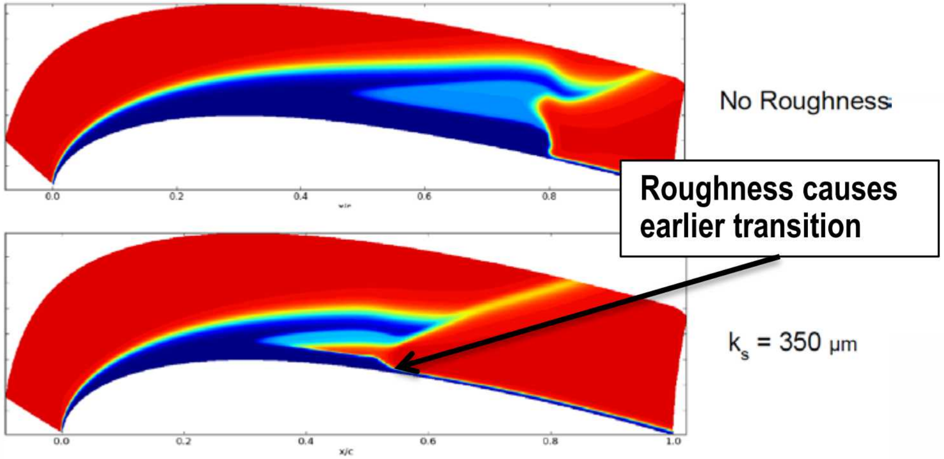
SERI S814

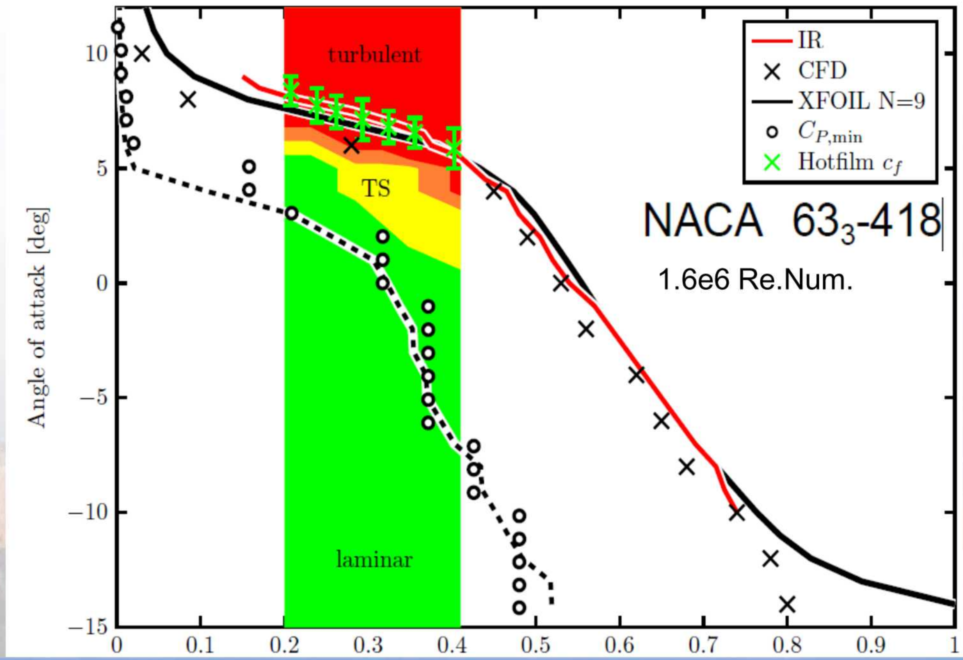


Lift and drag data for SERI S814 airfoil for various roughness conditions at Re = 3.2×10^6

Model Development

- Created CFD model of leading edge erosion
- Tight interaction between modelers and experimentalists
- Detailed calibration and validation of model
- Two equation Turbulence Model w/ Transition Model and Roughness Model
  - Langtry-Menter paired with "Roughness Amplification" model increases system to five equations



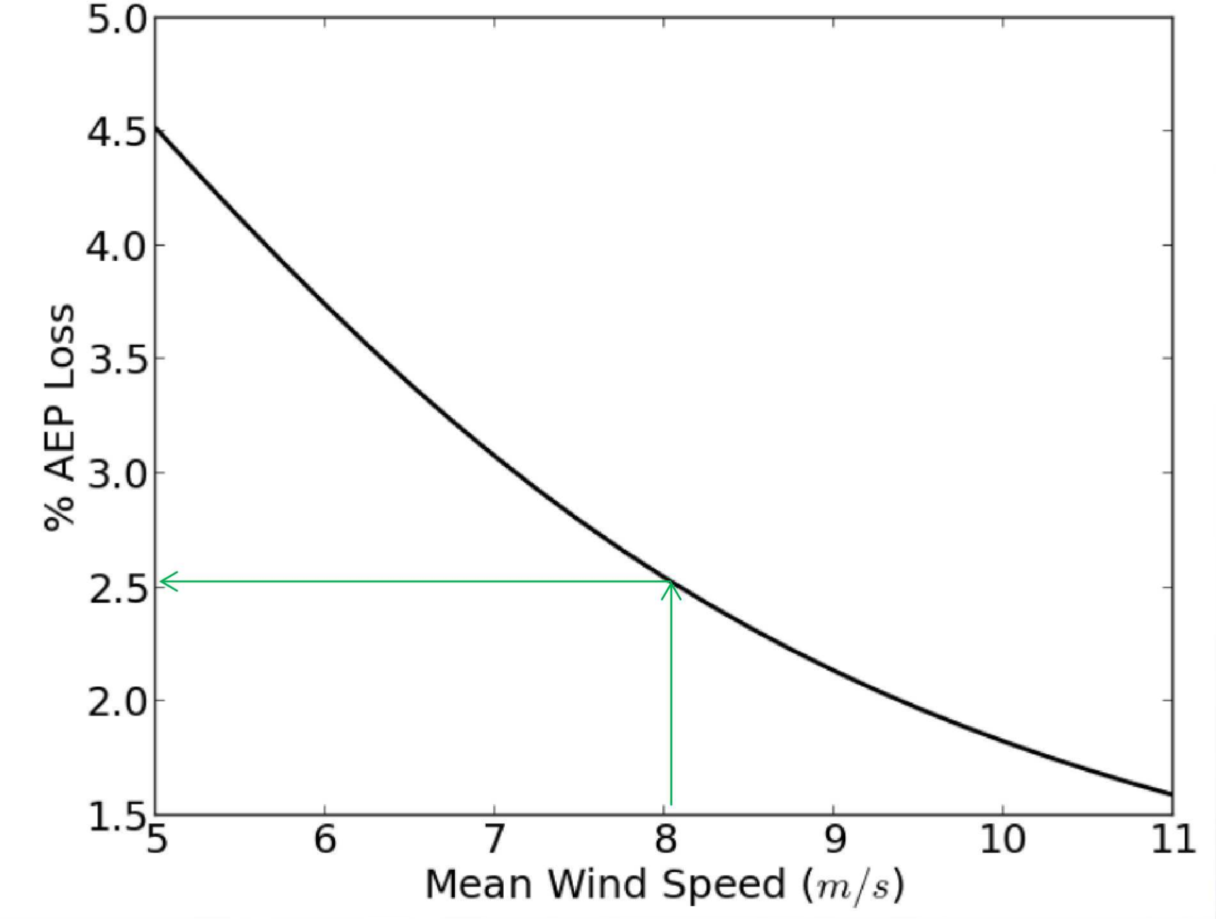


AEP Loss Prediction, NREL 5MW

- **Performance Prediction Using Computational Roughness Model**
- Analyzed NREL 5MW offshore turbine design
- Airfoils analyzed using OVERFLOW-2 in both “clean” and a “rough” configuration corresponding to heavy soiling
- Roughness applied from 5% chord on lower to 5% chord on upper surface
- Height of roughness set at $k/c = 240 \times 10^{-6}$
  - k = 0.24 mm or 0.001 in. for a chord of 1 m

Case	Reduction in max C_l	Reduction in max L/D
140 μm at 15% (exp)	-7%	-42.0%
DU-97-W-300 (CFD)	-9.8%	-20.2%
DU-91-W2-250 (CFD)	-7.9%	-23.7%
DU-93-W-210 (CFD)	-15.2%	-24.8%
NACA 64-618 (CFD)	-8.3%	-34.0%

AEP Loss Prediction, NREL 5MW



- Predicted AEP loss for NREL 5-MW due to leading edge roughness
- Power loss in Region II is ~ 5%

AEP Loss, NREL 5MW

Configuration	IEC II [%]	Annual Earning* [thousands $]
Clean	20.9 GW-hr	1,046
100-03	-0.6	-6
100-09	-0.8	-8
100-15	-1.3	-14
140-03	-1.9	-20
140-03ext	-2.2	-23
140-06	-2.0	-21
140-09	-2.2	-23
140-12	-2.3	-24
140-15	-2.3	-24
200-03	-1.4	-14
ELE full	-3.2	-33
ELE real	-0.1	-1

*Assuming $0.05 kWh

Conclusions

- Erosion and surface roughness from an operating wind farm were measured and reproduced in two wind tunnel test campaigns
- The effects of field roughness fall between clean airfoil performance and the effects of transition tape
- Roughness can decrease AEP by ~2.5% at a moderate average wind speed site, ~5% for a low wind speed site

Future Work:

- Release two final reports on the experimental results and model development, calibration, and validation
- Publicly releasing the experimental data through the DOE Atmosphere to electron (A2e) Data Archive and Portal

Thank You.