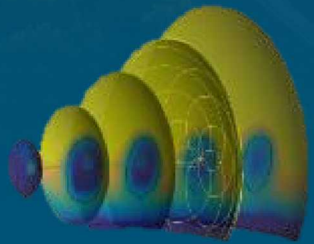
Sandia National Laboratories

SAND2020-1290C

Predicting Leading Edge Erosion Performance Degradation Through Experimental Measurement and CFD Modeling of Wind Turbine Airfoils



PRESENTED BY

David Maniaci
Principal Member of the Technical Staff
Wind Energy Technology Department

International Symposium on Leading Edge Erosion of Wind Turbine Blades

February 4-6, 2020
Roskilde, Denmark

SAND2020- PE

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Leading Edge Erosion Project

When should Erosion be remediated?

What is the performance impact of LEE?

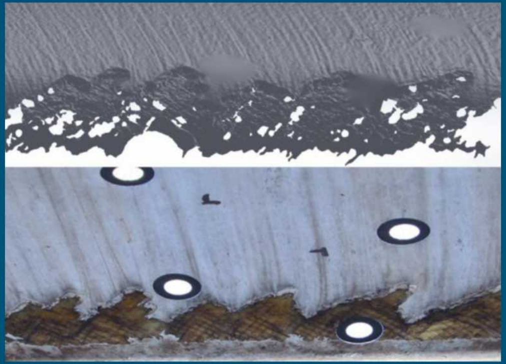
Goal:

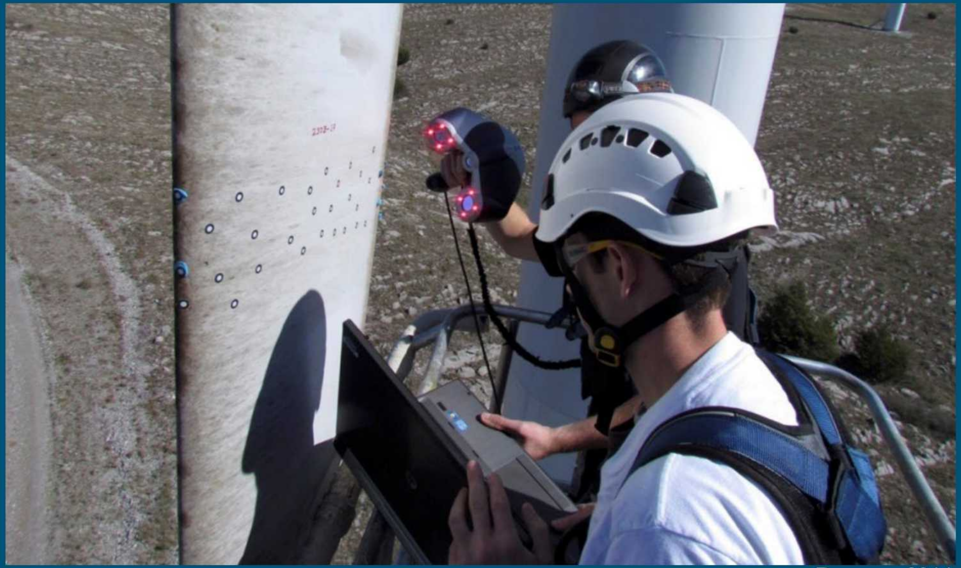
- Quantify effects of surface contamination and erosion on wind turbine performance
- Develop and validate an airfoil roughness model to predict the effects of surface roughness and erosion

- 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
  - Validate: Correlate wind tunnel and CFD results

Field Measurements

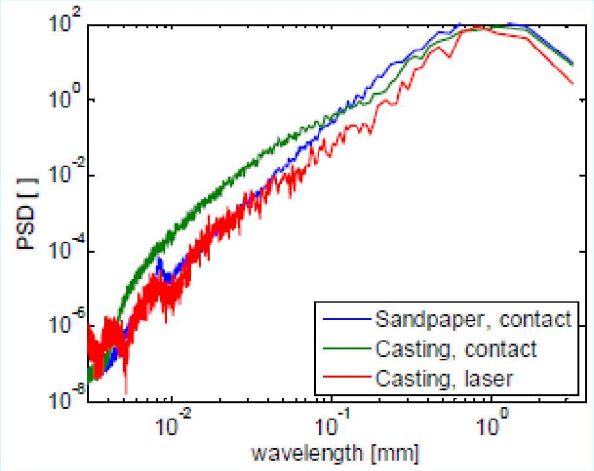
- Creaform EXAscan Laser scanner used to capture roughness >1mm.



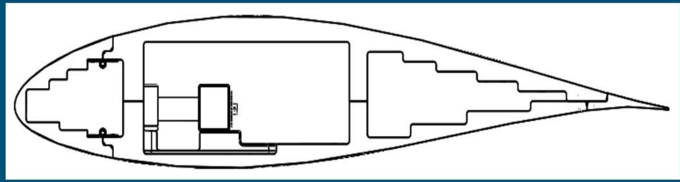


Rumsey, 2014

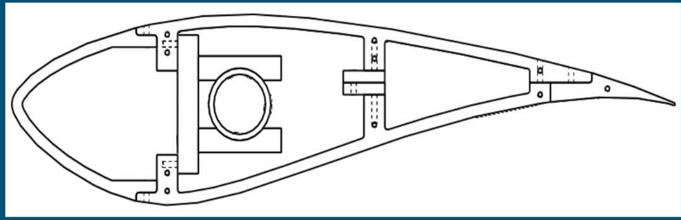
- Casting and profilometer used to capture roughness < 3mm.
- NASA LEWICE code used to simulate bug accretion.



Wind Tunnel

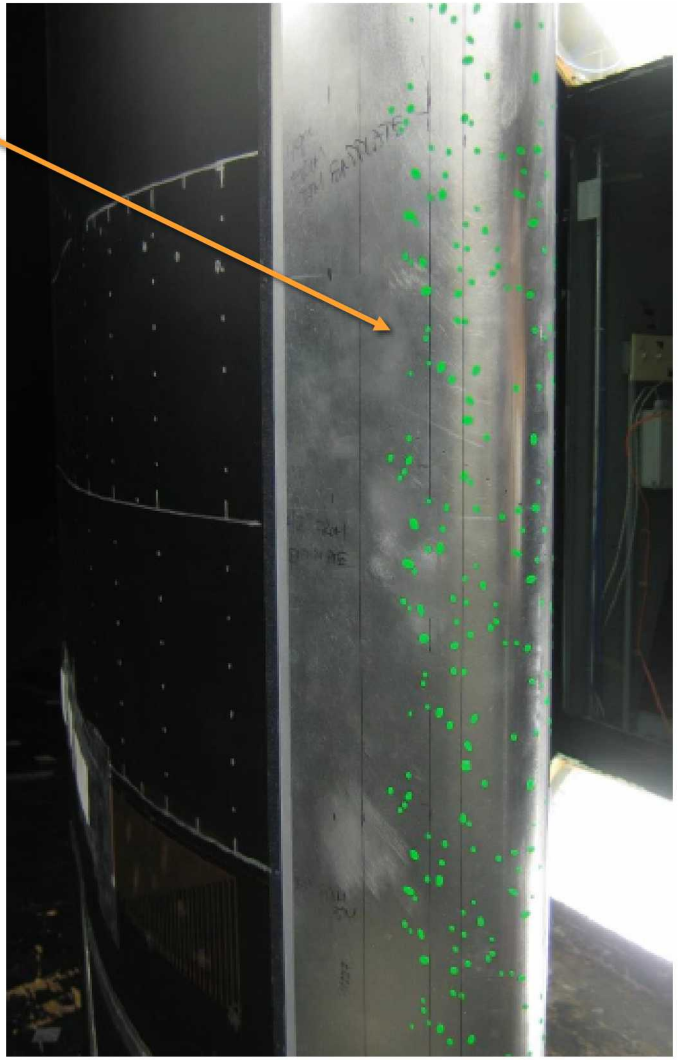


NACA 63_3-418

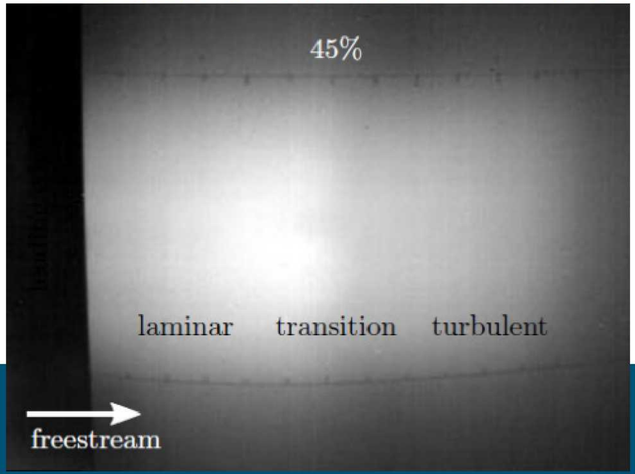


SERI S814

- 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.



Leading-edge Erosion Study (LEES) Project
https://a2e.energy.gov/projects/lees

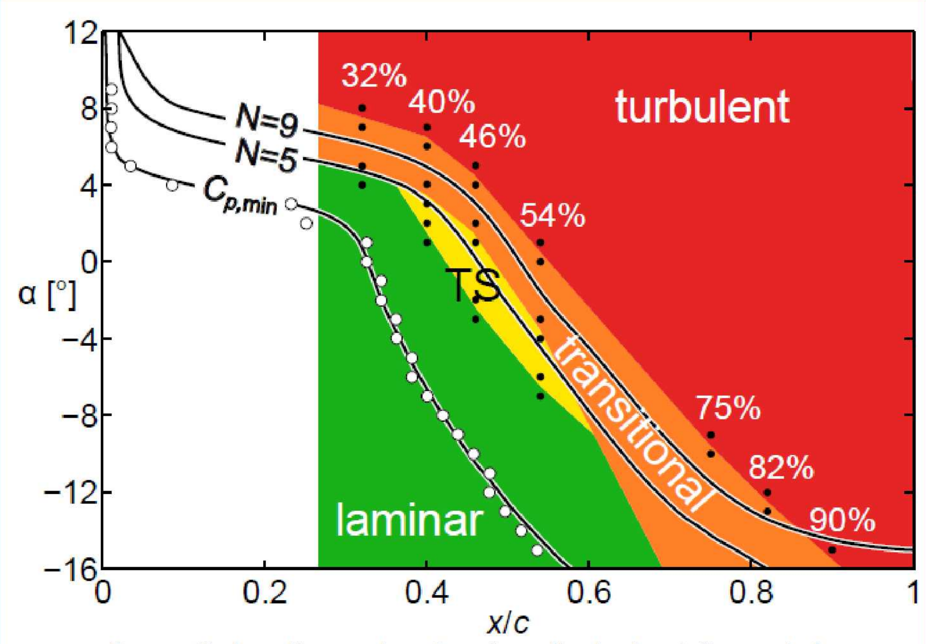
Wind Tunnel

- 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 $Re_c = 3.6\times10^6$ based on $c_{l,\max}$ loading
- Maximum $Re_c = 5.0\times10^6$ to $\alpha = 4°$

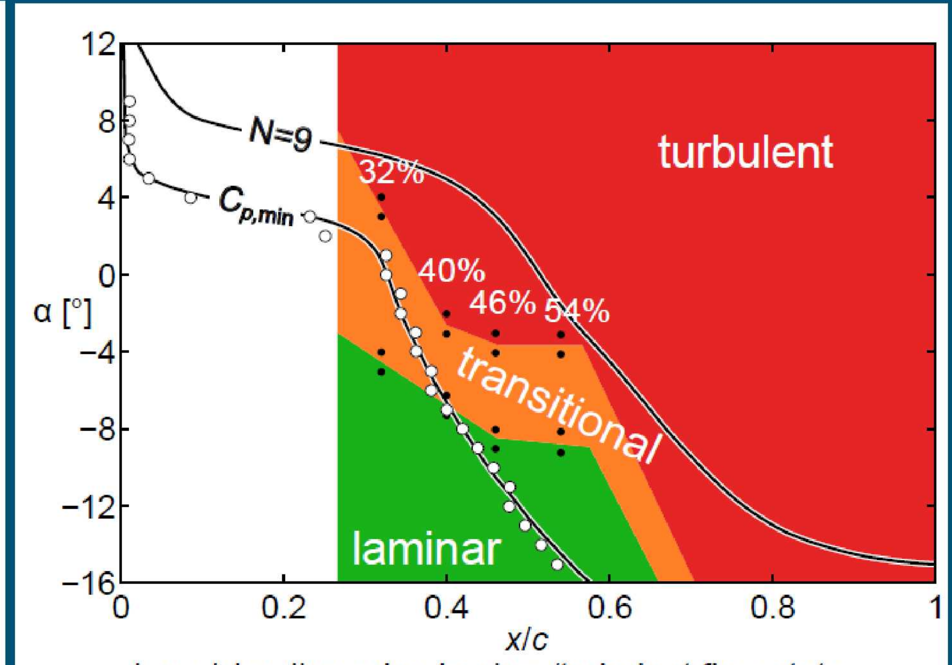
Leading-edge Erosion Study (LEES) Project
https://a2e.energy.gov/projects/lees

Model installed in wind tunnel

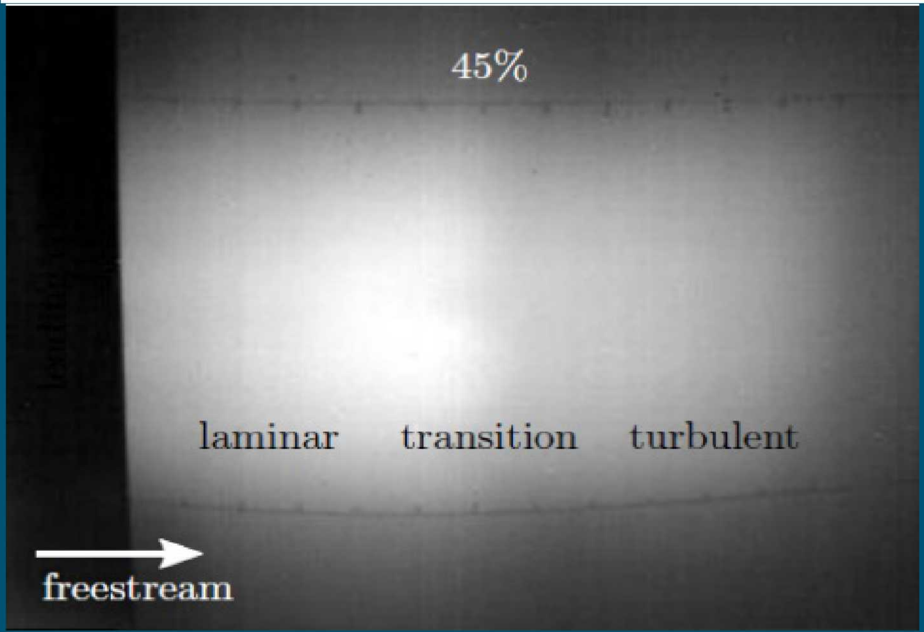
Wind Tunnel Testing: Transition Location (Model Calibration)



Smooth leading edge laminar/turbulent flow state



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

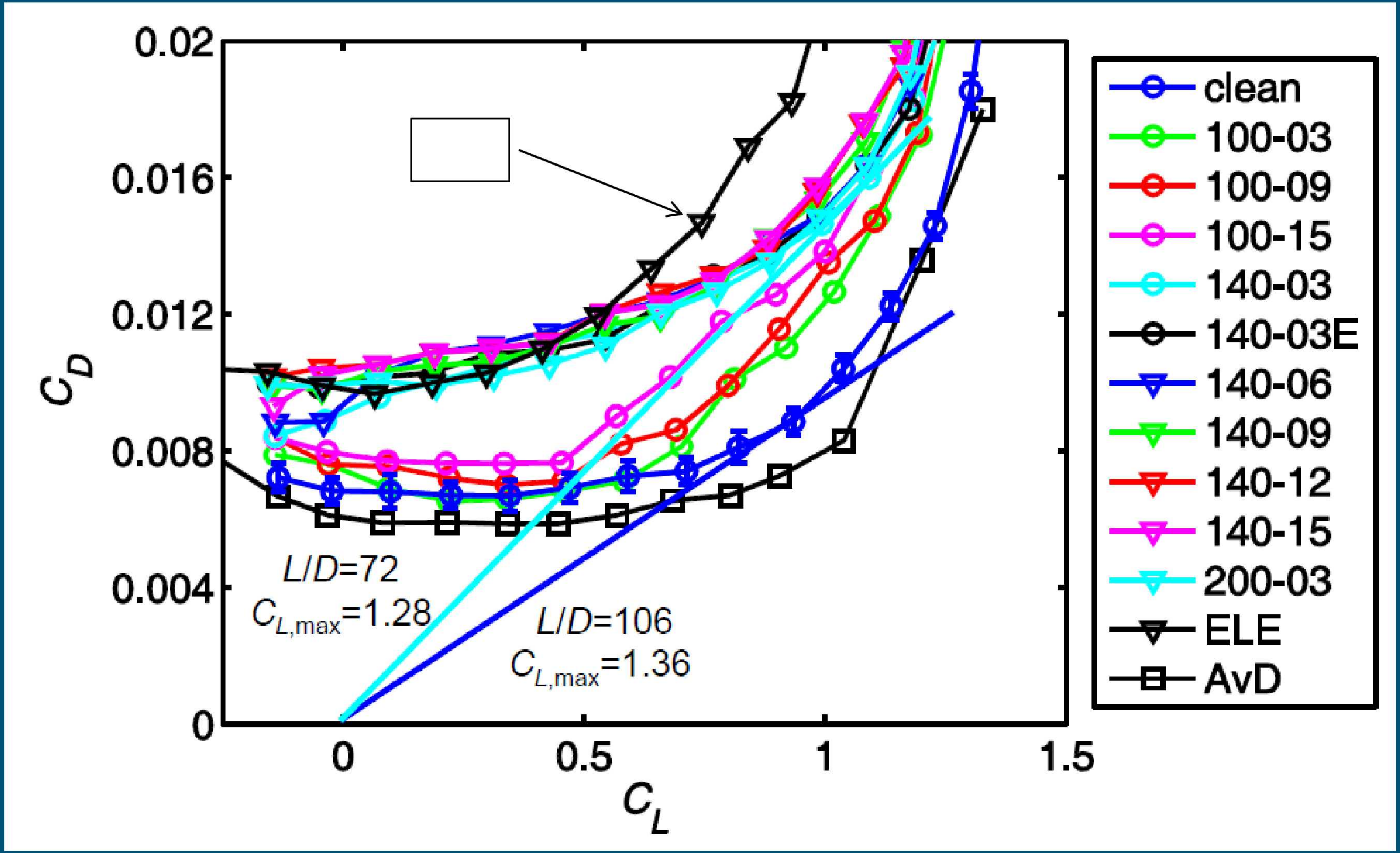


a2e.energy.gov/projects/lees

energy.sandia.gov

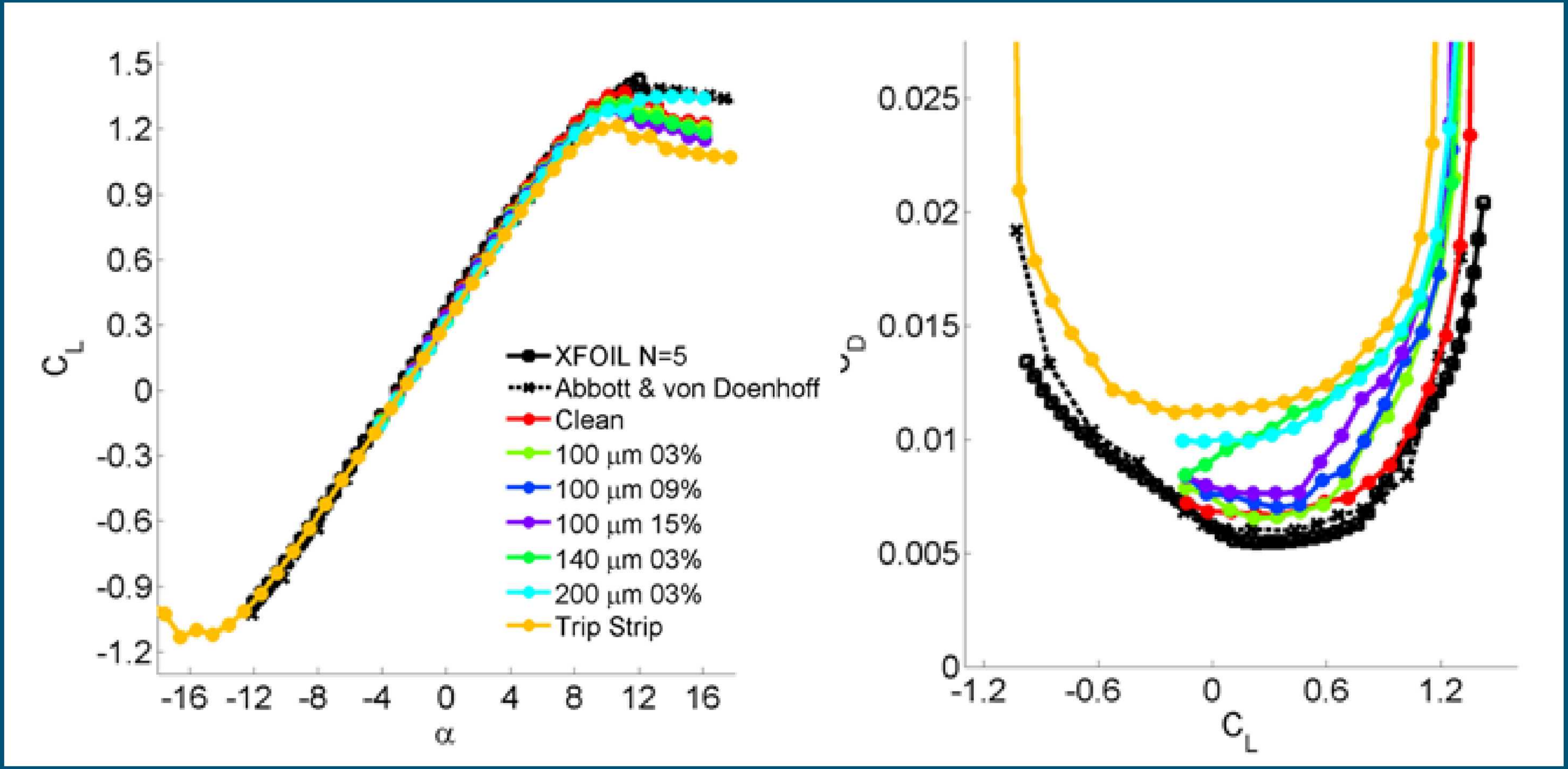
Wind Tunnel Testing: Lift and Drag (Model Validation)

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



Wind Tunnel Testing: Lift and Drag (Model Validation)

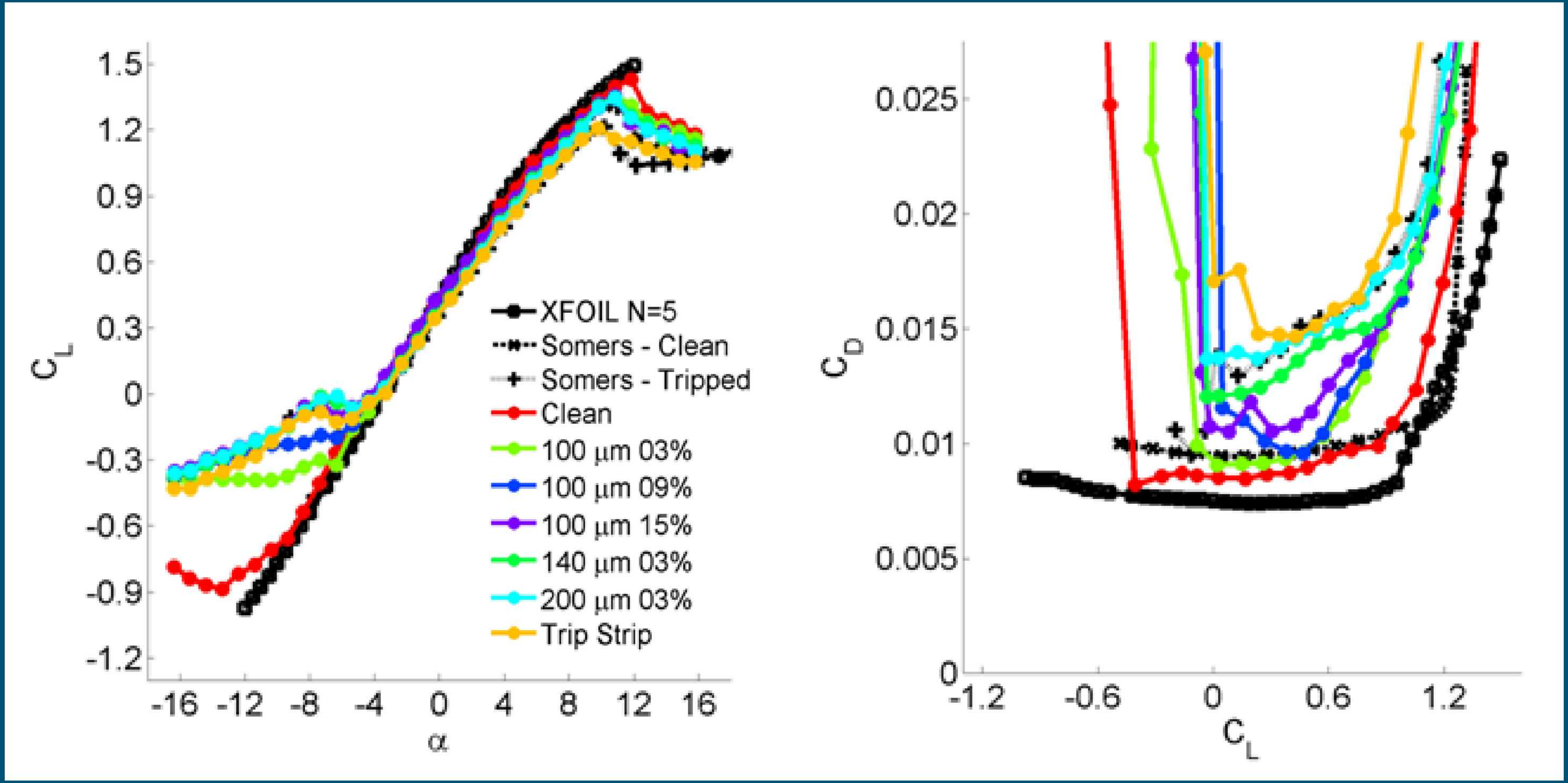
NACA 63_3-418



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

Wind Tunnel Testing: Lift and Drag (Model Validation)

SERI S814



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

Reynolds Number Effects

ReynoldsNumber:	S814 Clean dCL/dalfa (1/rad)	S814 Clean cL_{max}	S814 Clean $(cL/cD)_{max}$	S814 Rough, 140um_03% dCL/dalfa (1/rad)	S814 Rough, 140um_03% cL_{max}	S814 Rough, 140um_03% $(cL/cD)_{max}$
Re1.6e6	6.1	1.33	99.33	5.85	1.26	76.21
Re2.4e6	1.6%	3.8%	-10.3%	-6.6%	3.6%	-22.3%
Re3.2e6	2.6%	8.1%	-12.7%	0.8%	6.7%	-23.0%

ReynoldsNumber:	NACA 63_3-418 Clean dCL/dalfa (1/rad)	NACA 63_3-418 Clean cL_{max}	NACA 63_3-418 Clean $(cL/cD)_{max}$	NACA 63_3-418 Rough, 140um_03% dCL/dalfa (1/rad)	NACA 63_3-418 Rough, 140um_03% cL_{max}	NACA 63_3-418 Rough, 140um_03% $(cL/cD)_{max}$
Re1.6e6	6.73	1.31	146.53	6.58	1.24	104.18
Re2.4e6	-0.2%	1.9%	-26.6%	-4.0%	3.4%	-30.9%
Re3.2e6	-0.6%	5.1%	-27.9%	-0.6%	6.1%	-34.1%

Model Development

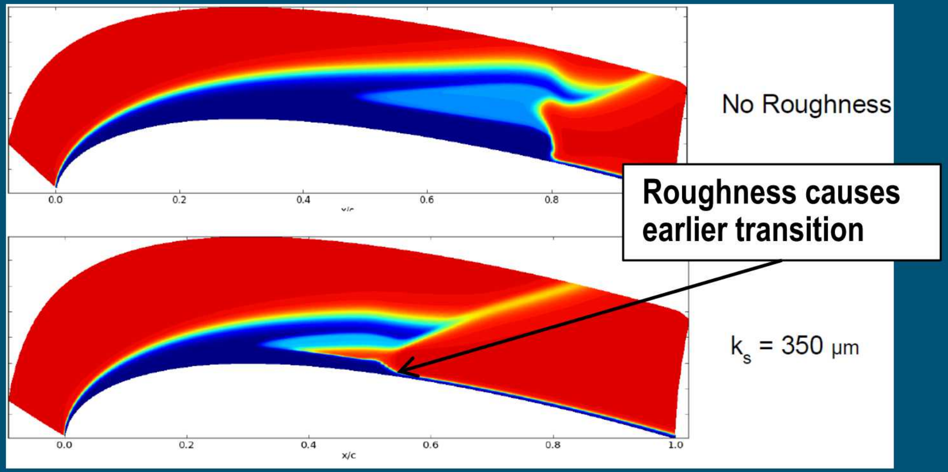
Created CFD model of leading edge erosion

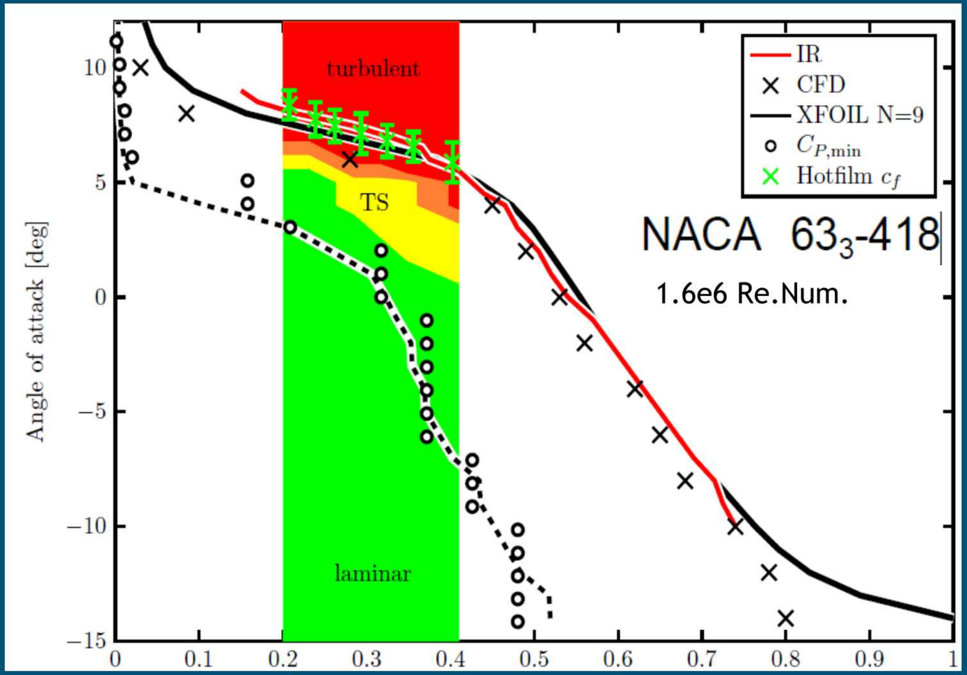
Tight interaction between modelers and experimentalists

Detailed calibration and validation of model

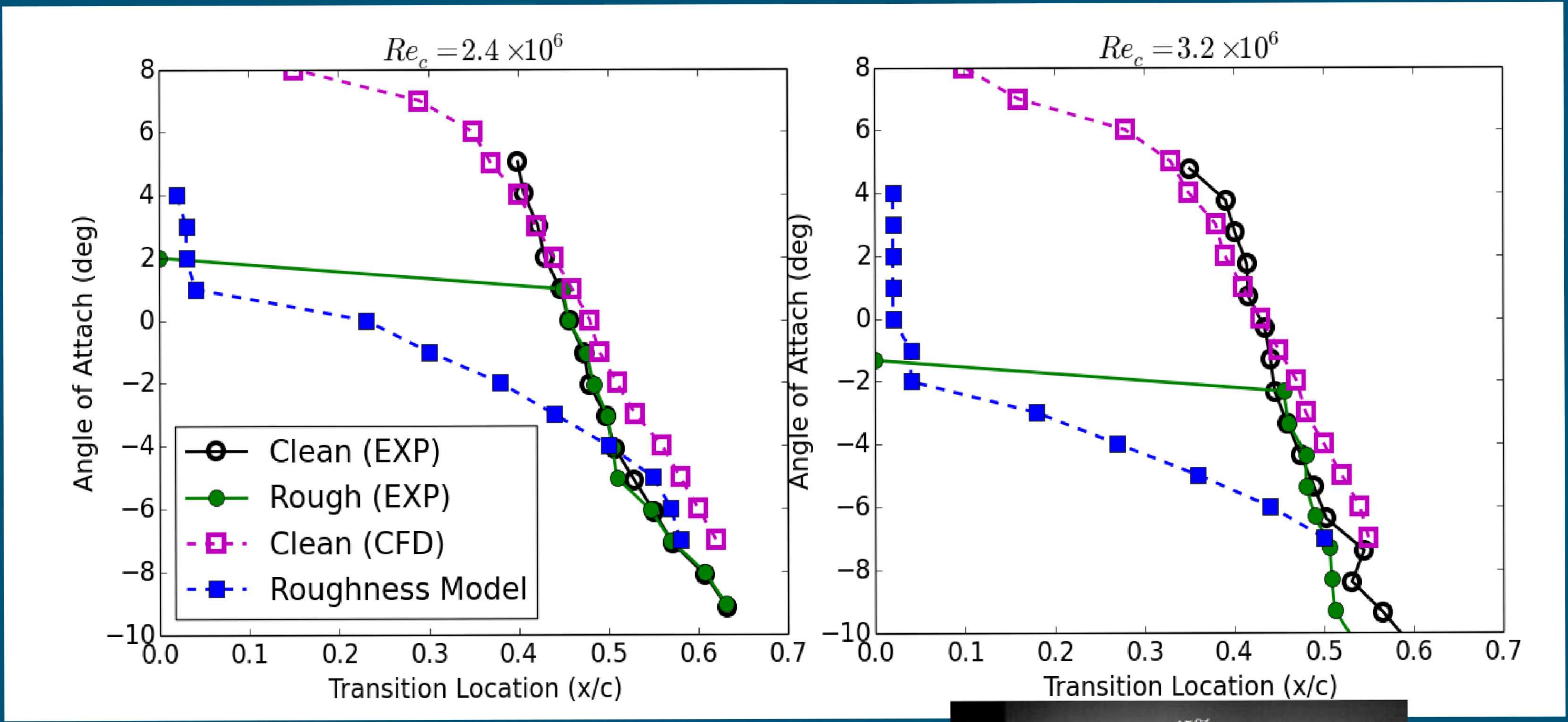
Two equation turbulence model w/ transition model and roughness model

- Langtry-Menter paired with "Roughness Amplification" model increases system to five equations

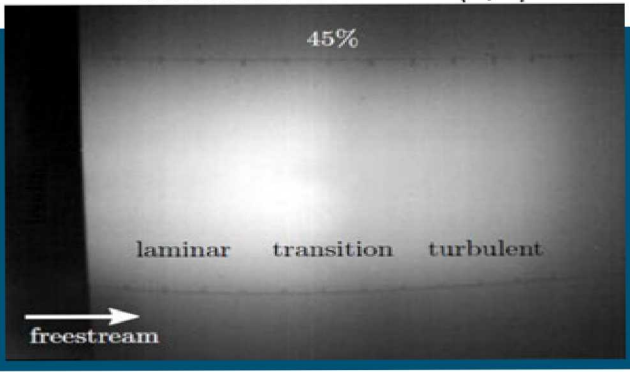




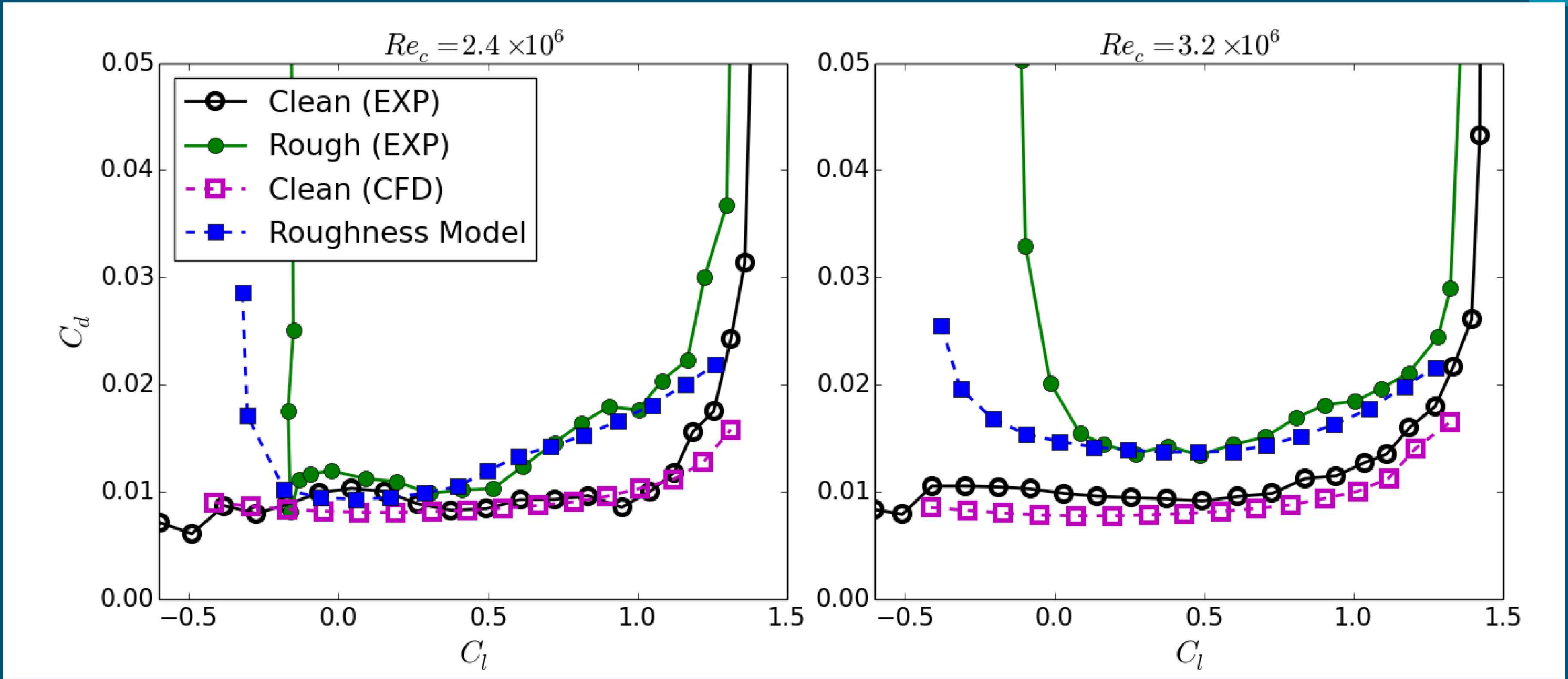
Model Application: Tuning



- Transition locations for upper surface of the SERI S814 airfoil for clean and rough configurations, roughness height 140 μm (k/c = 172 $\times$ 10^{-6}) at 03% density roughness applied



Model Application: Validation



- Drag polars for the SERI S814 airfoil for clean and rough configurations, roughness height 140 μm (k/c = 172 $\times$ 10^{-6}) at 03% density roughness applied

Model Application: 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

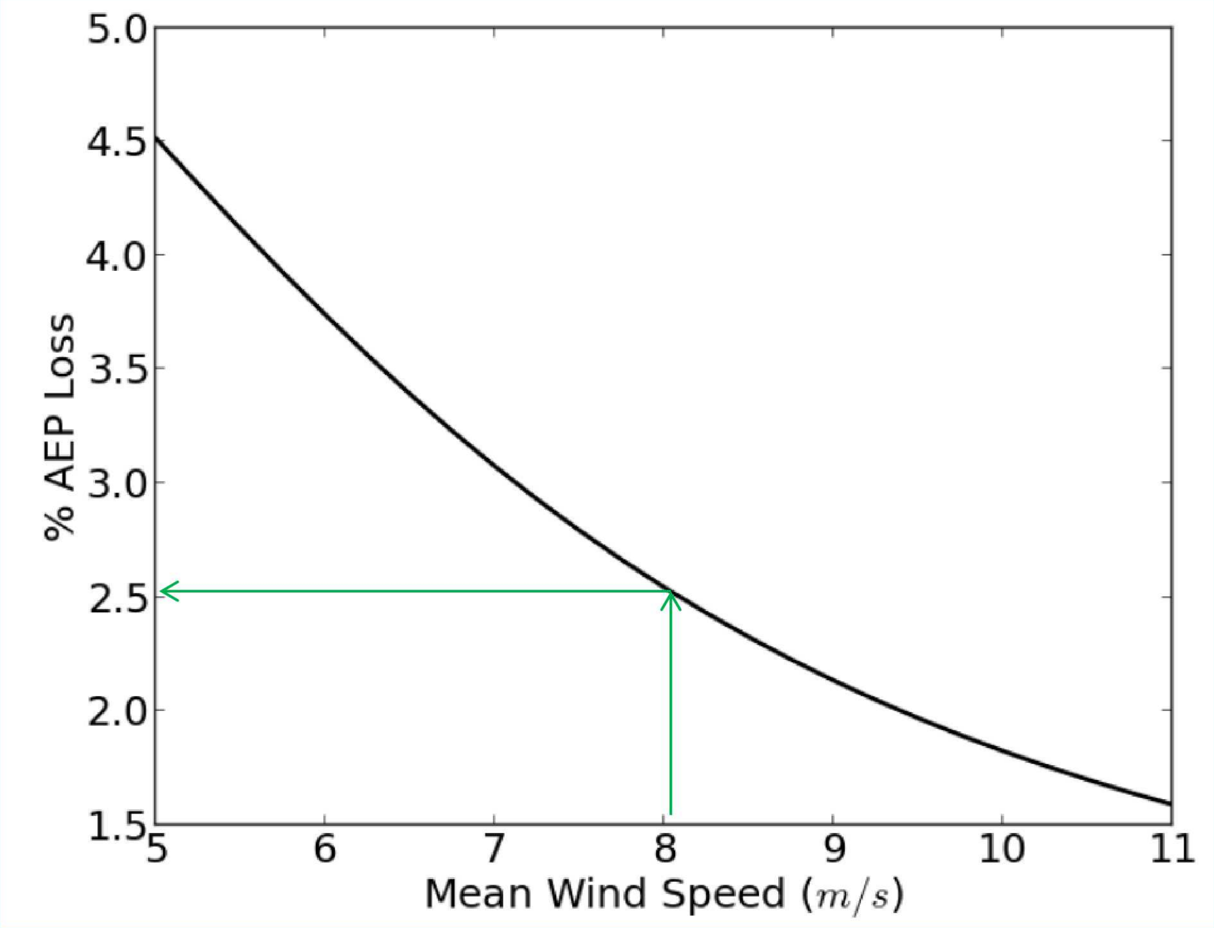
Roughness applied from 5% chord on lower to 5% chord on upper surface

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%

Model Application: AEP Loss Prediction, 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

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

https://a2e.energy.gov/projects/lees
https://energy.sandia.gov/energy/renewable-energy/wind-power/blade-reliability/leading-edge-erosion/

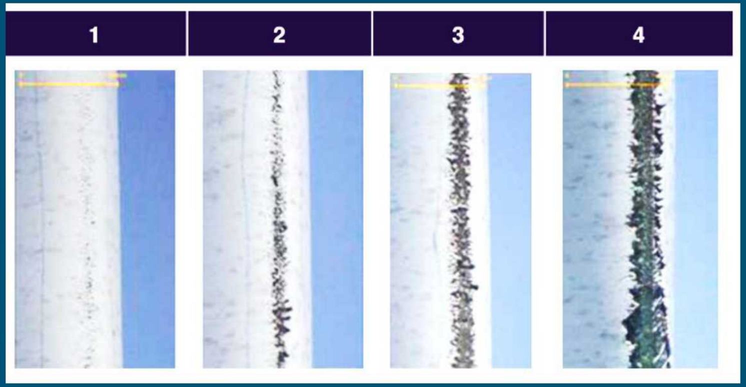
Conclusions

- 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

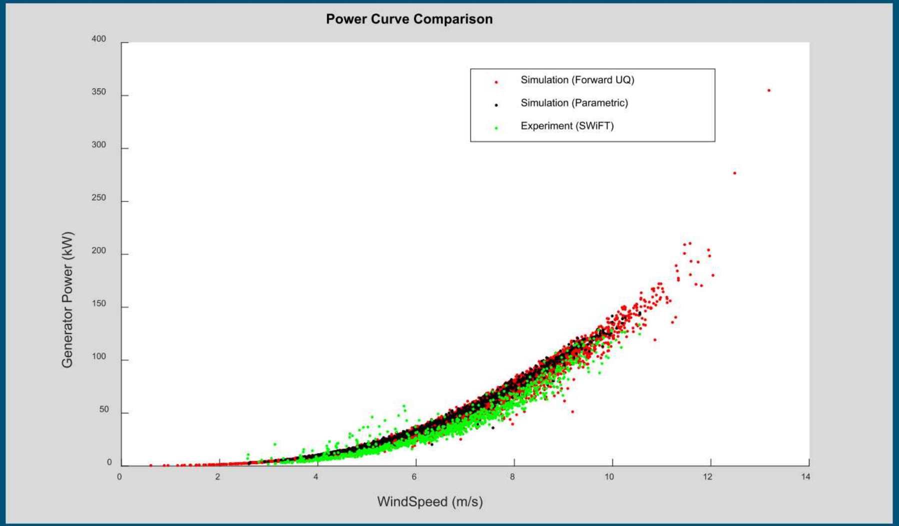
- Experimental data publicly available through the DOE Atmosphere to electron (A2e) Data Archive and Portal: **https://a2e.energy.gov/projects/lees**
- Reports are available at energy.sandia.gov: **https://energy.sandia.gov/energy/renewable-energy/wind-power/blade-reliability/leading-edge-erosion/**

On the Leading Edge of Leading Edge Erosion: Future Work

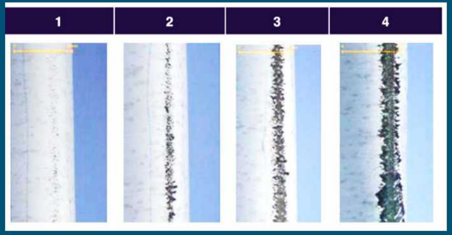
- Standards for erosion classification
- Impact of Turbulence Intensity and Turbulence Spectra on roughness effects
- Reynolds number, airfoil thickness, and airfoil design impacts
- Probabilistic models of AEP and O&M:
  - Rain, Hail, bugs, dirt, etc.
  - Mechanical erosion material variability
  - Operational Variability (RPM, yaw, pitch)
  - Performance uncertainty (airfoils, surface, repairs, etc.)
- Design of add-ons and airfoils to mitigate performance impact
- Control of turbines to balance AEP and O&M: Value of power now vs. later



Source: Vestas and Siemens commercial brochures
Thanks to Carsten Westergaard



Thank You



Source: Vestas and Siemens commercial brochures

Standards

Mechanisms
What causes it?

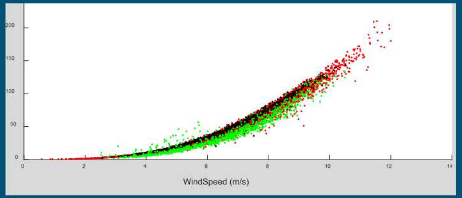
Technology Improvement

Erosion

Treatment
How to deal with it?

Aerodynamics
How is performance affected?

When should Erosion be remediated?



Contributors:

Sandia National Laboratories
- David Maniaci
- Josh Paquette
- Mark Rumsey
- Matt Barone

Texas A&M
- Ed White
- Ben Wilcox
- Robert Ehrmann

UC Davis
- Case van Dam
- Chris Langel
- Ray Chow
- Owen Hurley

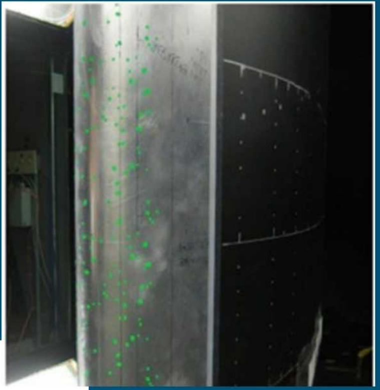
Contributors

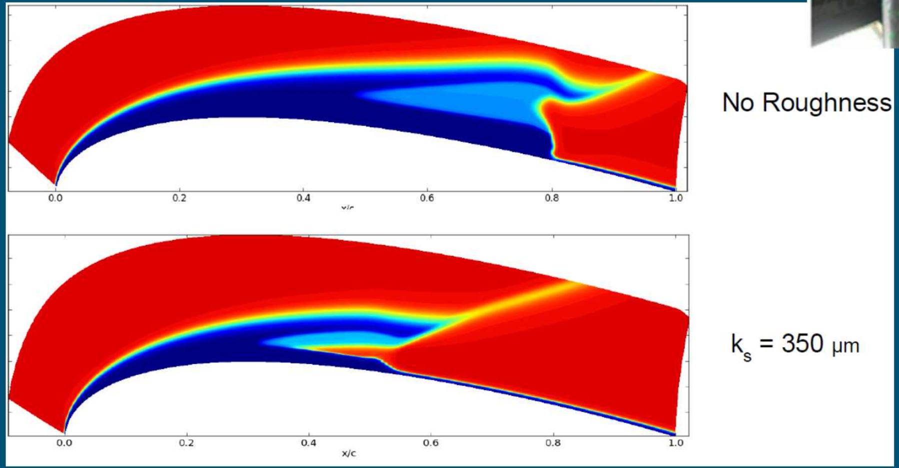
Sandia National Laboratories
- David Maniaci
- Josh Paquette
- Mark Rumsey
- Matt Barone

Texas A&M
- Ed White
- Ben Wilcox
- Robert Ehrmann

UC Davis
- Case van Dam
- Chris Langel
- Ray Chow
- Owen Hurley

Rumsey, 2014



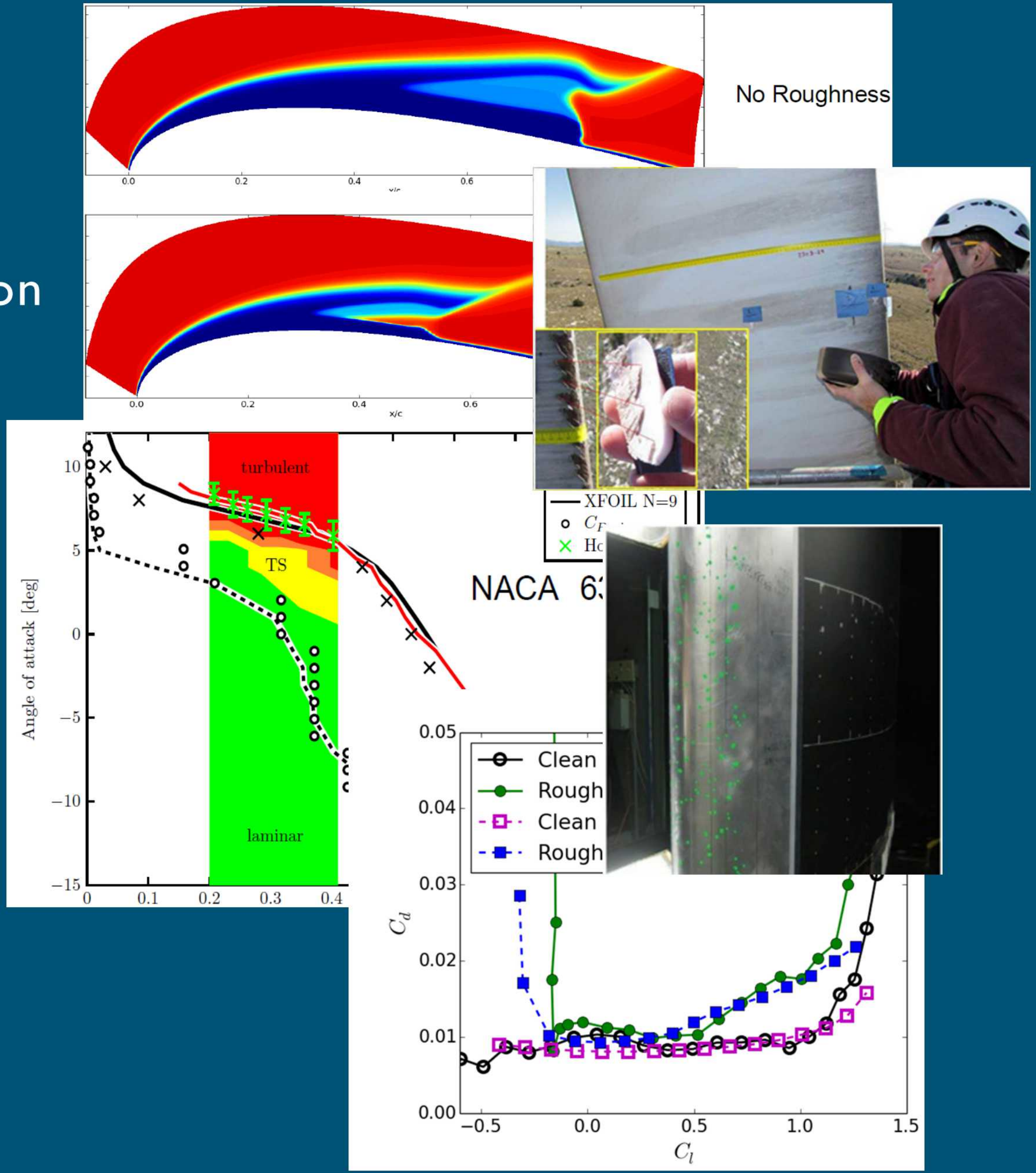


Validation Process

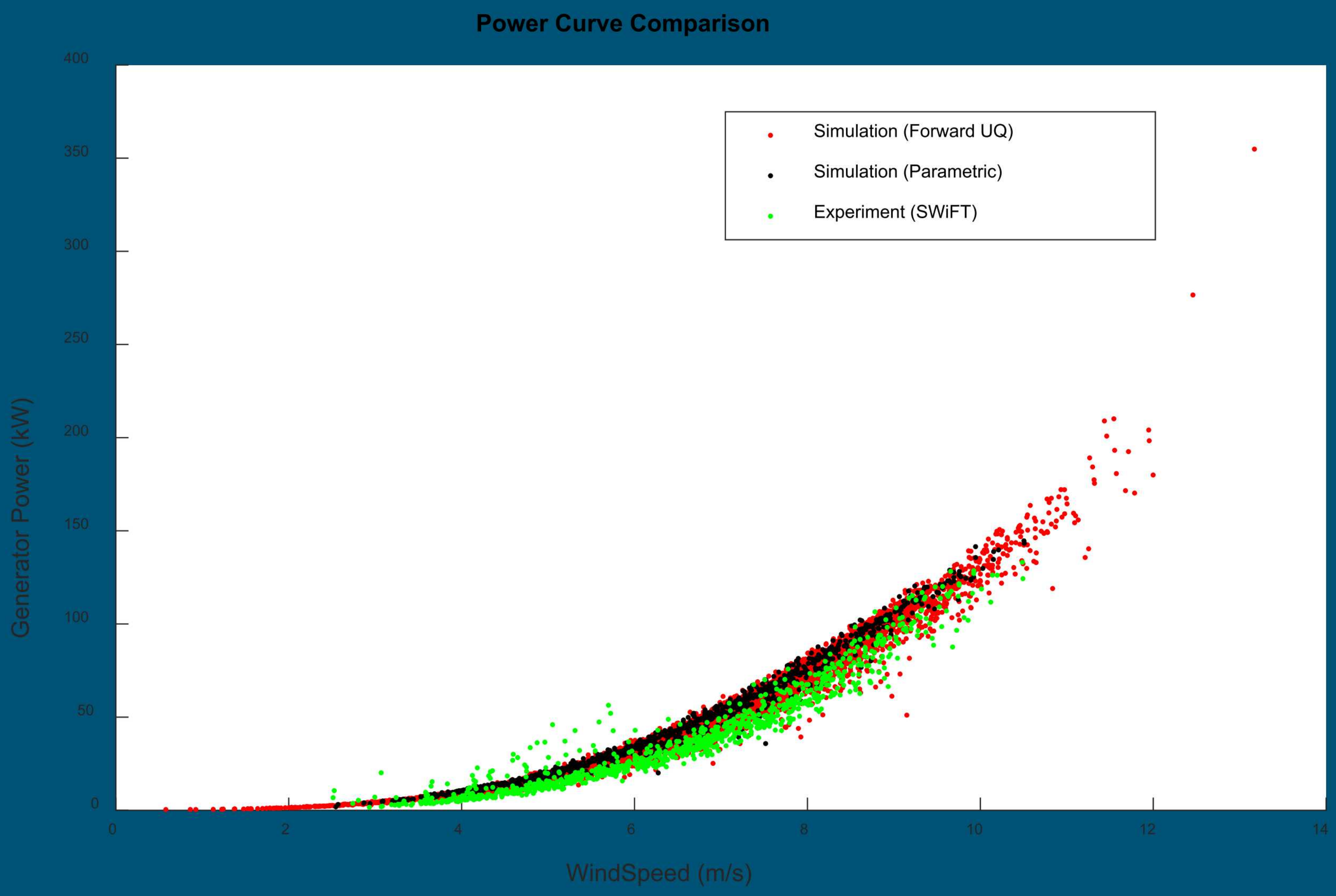
Model Development
- Concept
- Equation derivation
- Numerical implementation
- Verification

Calibration
- Experimentation
- Data Assimilation
- Uncertainty Analysis

Validation
- Experimentation
- Data Assimilation
- Comparison
- Uncertainty Quantification
- Credibility Assessment



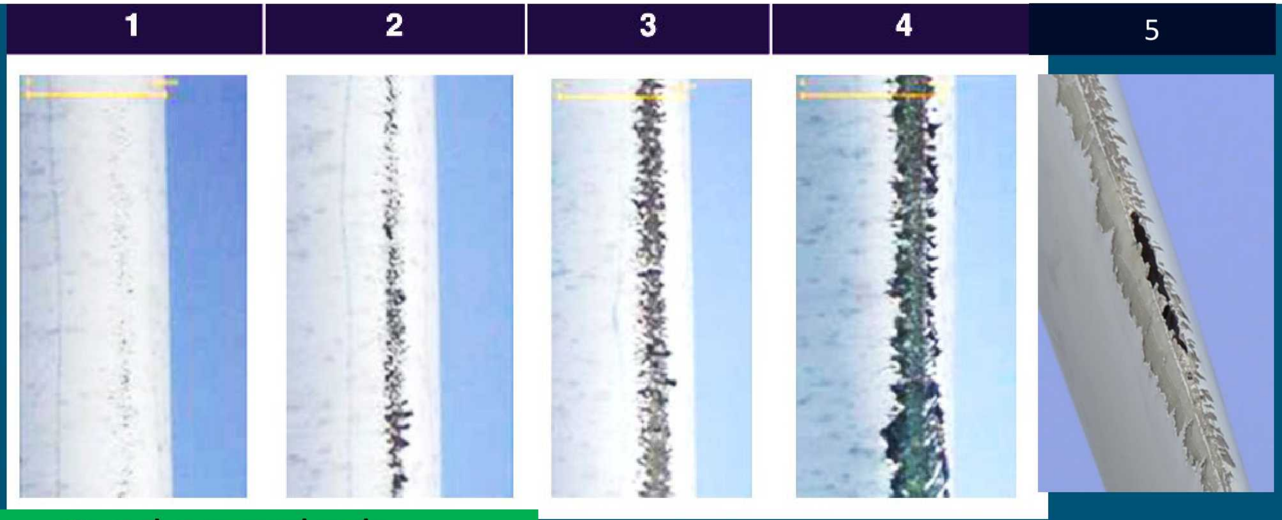
How to estimate erosion effects on power curve uncertainty?



Classification (generic, not just LEE)

Figure 2
Vestas' blade damage categorisation

Category 1	Category 2	Category 3	Category 4	Category 5
Cosmetic	Similar to cosmetic	Damage not serious	Serious damage	Very serious damage
No intervention needed	Intervention only done if there are other damages on the blade	Intervention done during planned WTG inspection within 6 months. Damage monitored at 3-months intervals. Repair time frame may be modified by blade specialist.	Intervention within 3 months. Damage monitored at monthly intervals. Repair time frame may be modified by blade specialist.	Immediate intervention required to prevent damage to the turbine, the surrounding area, or further damage to the blade.



Sand paper look

Someone took a "bite"

Exposed glass/resin

Exposed internals

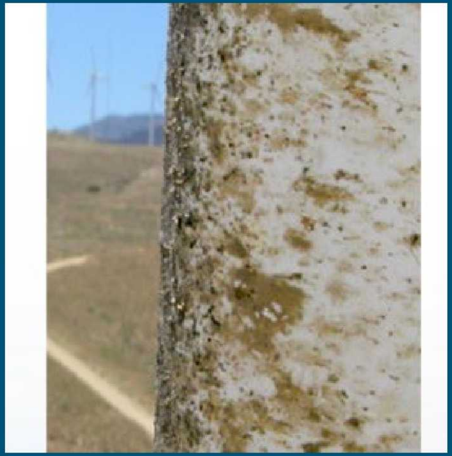
Source: Vestas and Siemens commercial brochures
Thanks to Carsten Westergaard

Types of Leading Edge Erosion and Surface Roughness

2D Step, Paint Chip or Repair

Rumsey 2014

Contamination Roughness (Bugs)



Spruce, 2006

Light to Moderate Erosion, Random Pits

Rumsey 2014

Heavy Erosion

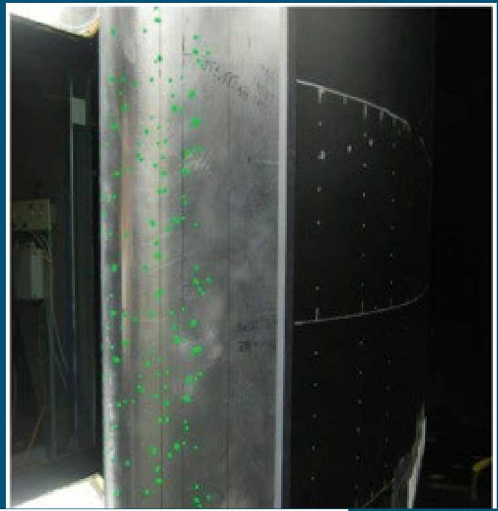
Rumsey, 2014

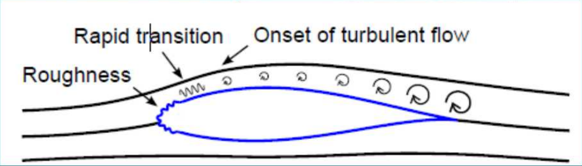
Wind Tunnel Testing

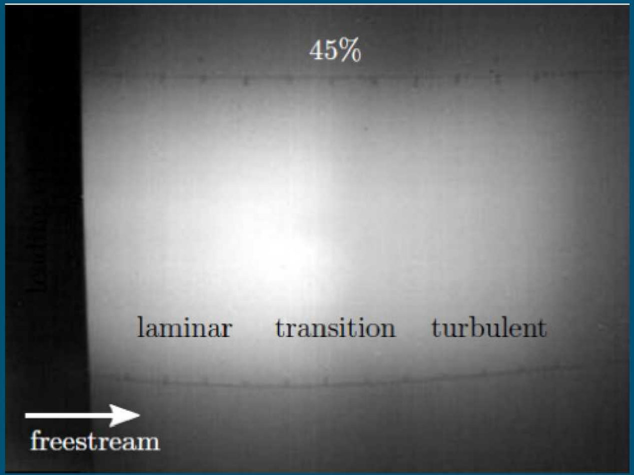
Measurements from the field used to parameterize roughness

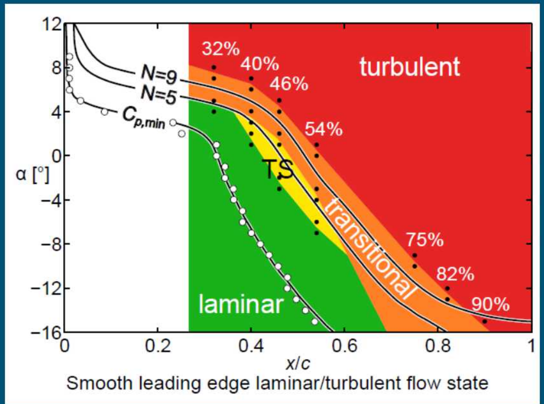
LE erosion wind tunnel models based on parameterized roughness elements

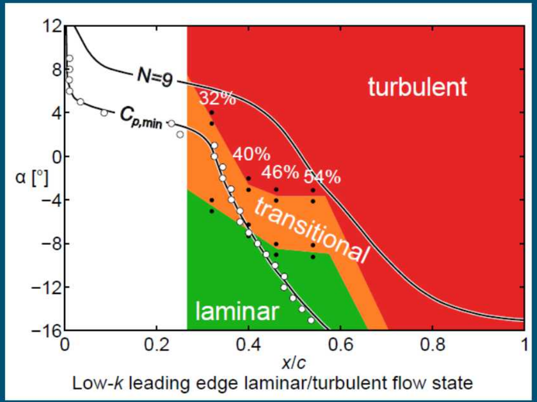
Large database of airfoil boundary layer characteristics



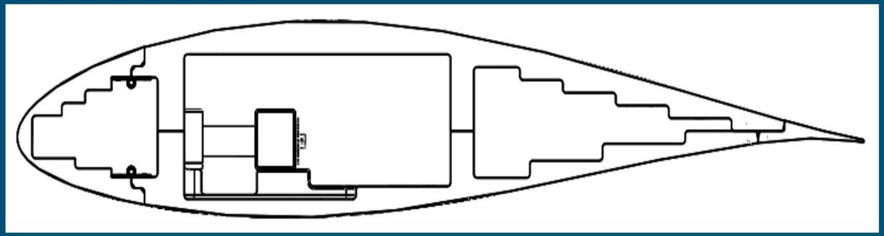






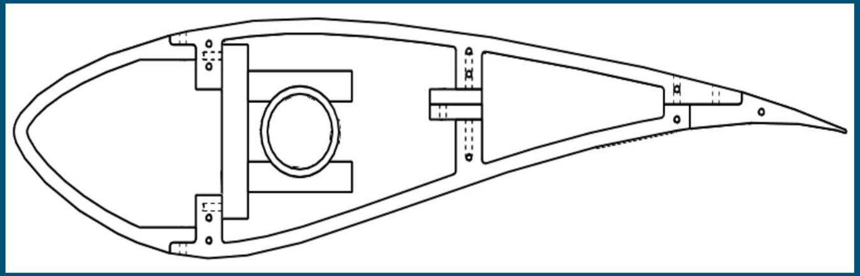


Airfoil Wind Tunnel Models



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

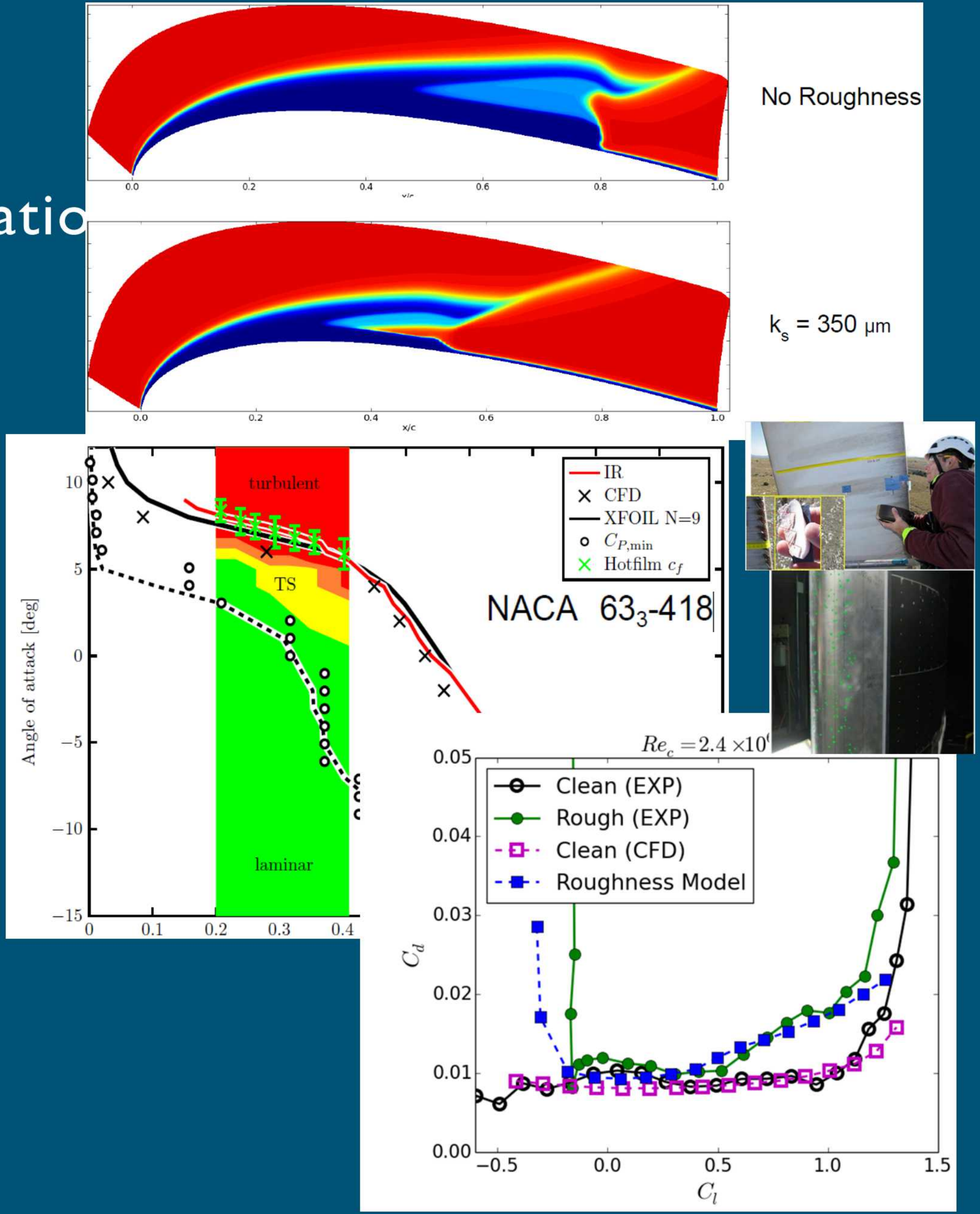
- Airfoils were tested using clean, trip-strip, and distributed roughness configurations at Reynolds numbers of 1.6×10^6, 2.4×10^6, 3.2×10^6, and 4.0×10^6; Maximum $Re_c = 5.0 \times 10^6$ to $\alpha = 4^\circ$
- The NACA 63_3-418 was also tested with a forward facing step to simulate paint chipping,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

V&V: Integrated Model Planning and Execution

Model Development
- Concept
- Equation derivation
- Numerical implementatio
- Verification

Calibration
- Experimentation
- Data Assimilation
- Uncertainty Analysis

Validation
- Experimentation
- Data Assimilation
- Comparison
- Uncertainty Quantification
- Credibility Assessment



Wind Turbine Validation Hierarchy