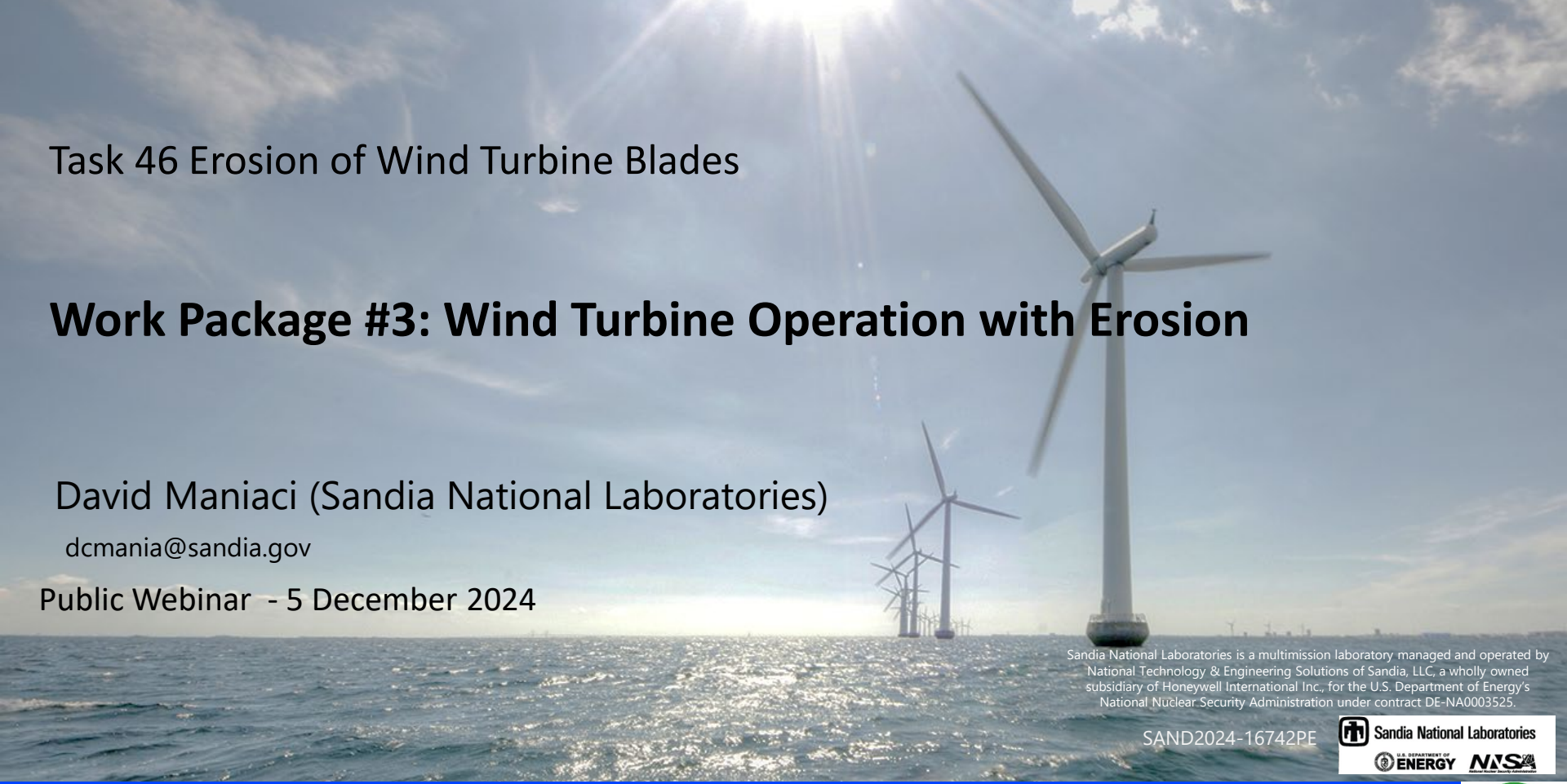

Task 46 Erosion of Wind Turbine Blades

Work Package #3: Wind Turbine Operation with Erosion

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Public Webinar - 5 December 2024

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WP3 - Wind Turbine Operation with Erosion

This work package has three key overarching objectives:

1. Promote collaborative research to mitigate erosion by means of wind turbine control, assessing the viability of erosion safe mode.
2. Improve the understanding of droplet impingement in the context of erosion.
3. Improve the understanding of wind turbine performance in the context of erosion, specifically the effect of LEE surface roughness on aerodynamics.

Activity	WP code
WP3.1: Model to predict annual energy production loss on blade erosion class Common model of performance loss due to leading edge roughness and erosion standardized classes.	WP3.1
WP3.2: Report on standardization of damage reports based on erosion observations Erosion classification report released February 2023 (https://iea-wind.org/task46/t46-results/)	WP3.2
WP3.3: Droplet impingement model for use in fatigue analysis Develop a standard model for droplet impingement, validated with wind tunnel experimental data.	WP3.3
WP3.4: Potential for erosion safe-mode operation Report describing potential for leading edge erosion safe mode operation.	WP3.4
WP3.5: Accuracy of LEE performance loss model based on field observations (validation) Iterative aerodynamic loss benchmarks. Validation of performance loss model using analysis of field observations.	WP3.5

Accomplishments in Work Package 3: Erosion Classification System

- Deliverable 3.2 was completed with the erosion classification report, published on the website for Task 46

Evaluation Criteria	Severity Level 0	1	2	3	4	5
Visual Condition (LEP)	Initial factory condition	Lightly worn external coating/LEP Instances of reduced LEP adhesion	Notable areas of localized damage on external coating/LEP Individual Instances of LEP adhesive failure.	LEP is largely compromised over a large area and no longer providing protection to underlying layers	Delamination of topcoat with immediate layer underneath clearly visible and exposed	Notable damage to substrate
Visual Condition (No LEP)		Erosion barely visible or pinholes	Localized pitting	Widespread or coherent pits, some gouges		
Mass-loss		Coating <10% Laminate 0%	Coating 10-50%, Laminate 0%	Coating 50-100%, Laminate <10%	Coating 100% Laminate 10-100%	Coating 100%, Laminate 100%
Aerodynamic Performance		Normal surface roughness Region 2 Power loss 0 -1%	Region 2 Power loss 1%-2%	Region 2 Power loss 2%-3%	Region 2 Power loss 3-4%	Region 2 Power loss >4%
Blade Integrity		Initial erosion of topcoat	Erosion through topcoat	Initial exposure of immediate laminate layers	Erosion through immediate laminate layers	Exposure of structural laminate layers

Erosion Classification System Example

Observation Category	Erosion Class
Visual data definition	3
Mass-loss or Depth	3
Aerodynamics/Perf.	3
Structural	3

https://iea-wind.org/task46/

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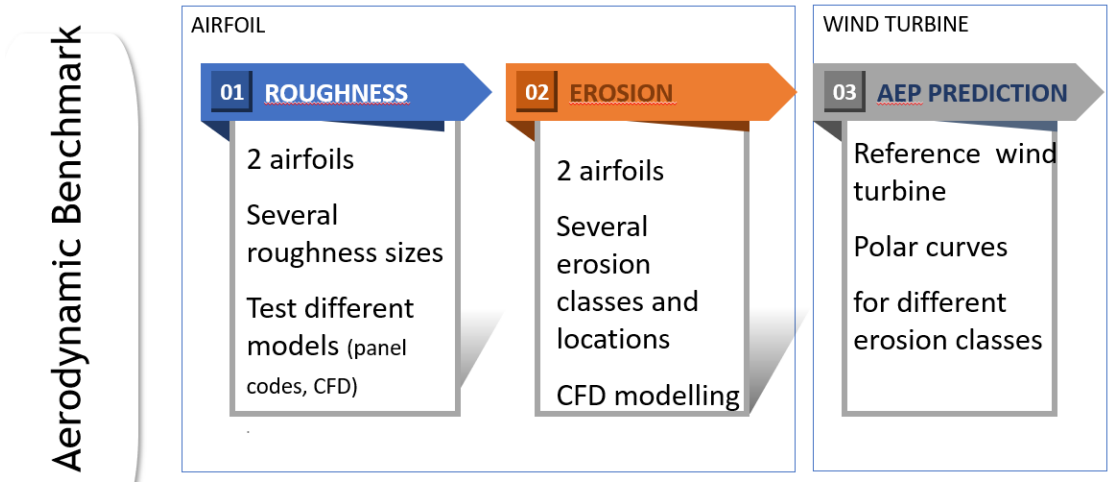
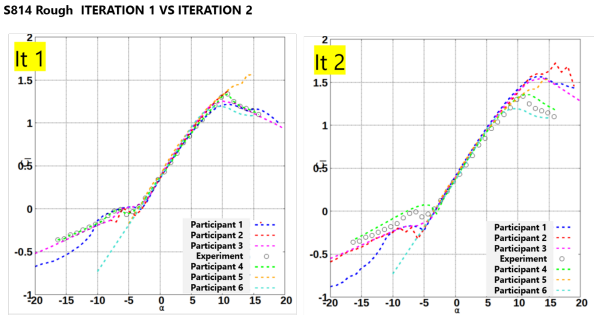
WP3: Aerodynamic Benchmark

- Aerodynamic benchmark kicked off in Fall 2022, coordinated by Beatriz Mendez at CENER.
  - Focused on NACA 63_3-418 and S814 airfoils
- Eight participants; includes national labs, academia, and OEMs.
- Initial results presented at 2024 DTU Erosion Symposium

Next steps:

- AEP loss computation of the NREL 5MW wind turbine
- Journal publication on the results in the next year
- Benchmark will continue in phase 2 with data from the LERCat project





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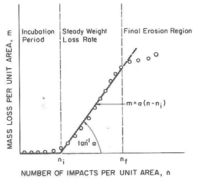
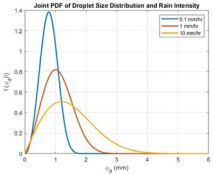
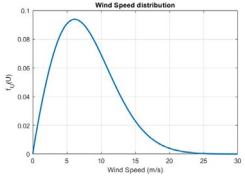
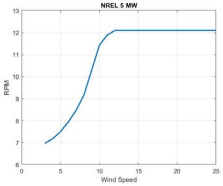
WP3: Erosion Damage Growth Model for O&M Prediction and Optimization









Short-Term Damage Rate/Mass Loss Rate
(Springer Model [1])

Rain Statistics
(Rain Intensity, Droplet Size Distribution)

Wind Statistics
(Wind Speed)

Turbine Model
(Power Curve)

Long-Term Damage Rate [2]
(Weighted sum of short term erosion damage rate together with probability of occurrence of all possible rain and wind conditions)

Incubation Period Prediction

Rate of Mass Loss

Erosion Category
(Severity of erosion at all points in a wind blades lifetime)

[1] GS Springer, CL Yang; PS Larsen, "Analysis of Rain Erosion of Coated Materials," *Journal of Composite Materials*, vol. 8, pp. 229-252, 1974.

[2] A. Shankar Verma *et al.*, "A probabilistic long-term framework for site-specific erosion analysis of wind turbine blades: A case study of 31 Dutch sites," *Wind Energy*, vol. 24, no. 11, pp. 1315-1336, 2021, doi: 10.1002/we.2634.

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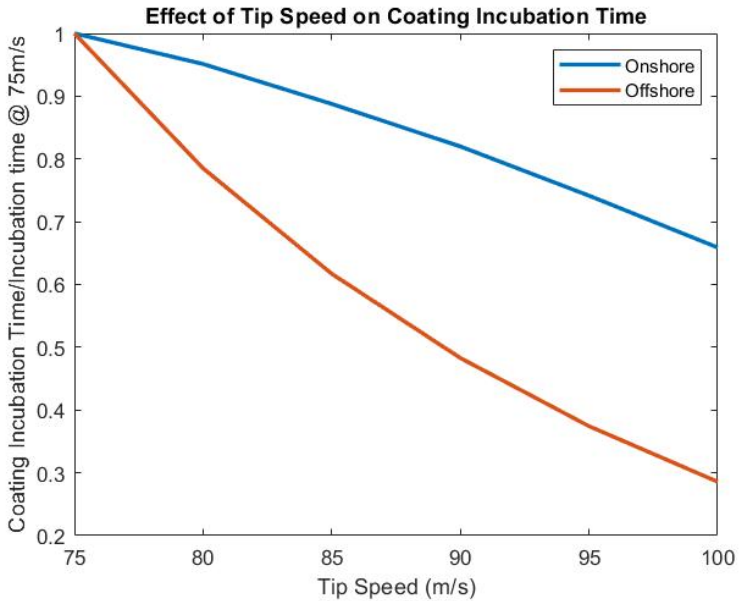
Case Study – How does rated tip speed affect coating lifetime



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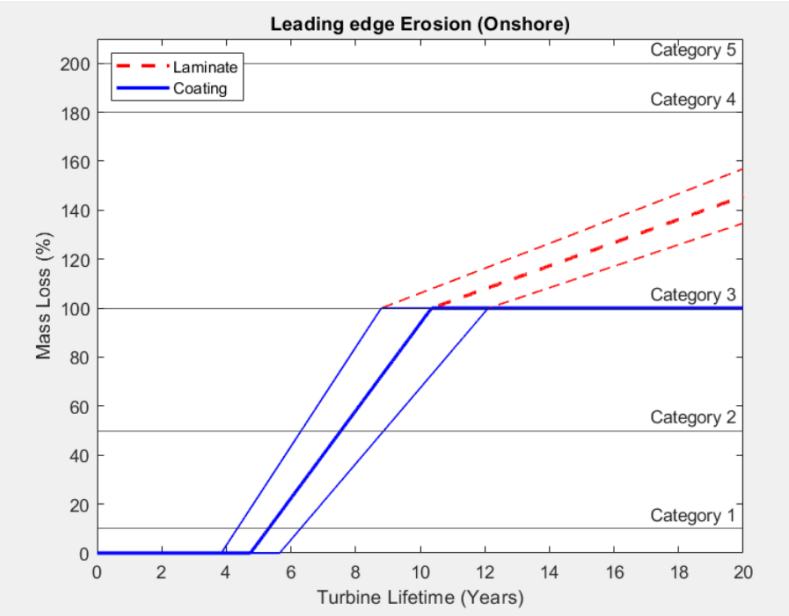
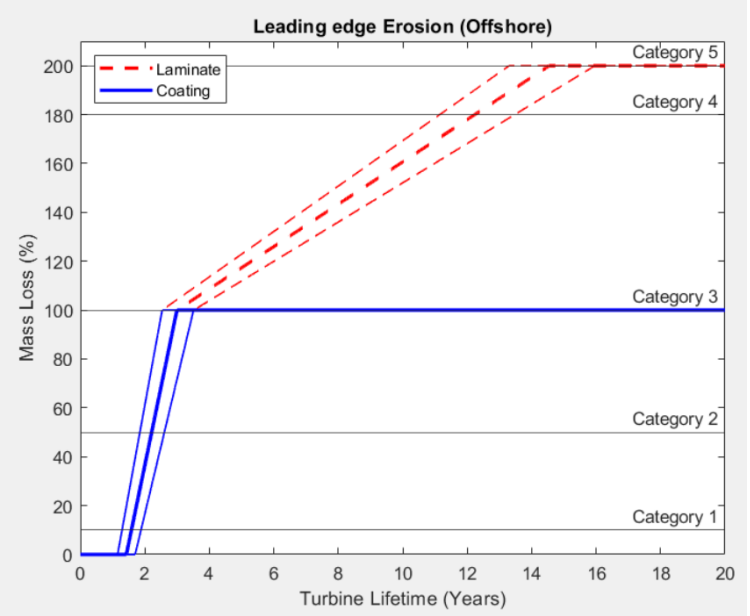
Example output of model

Uncertainty in ultimate strength of material

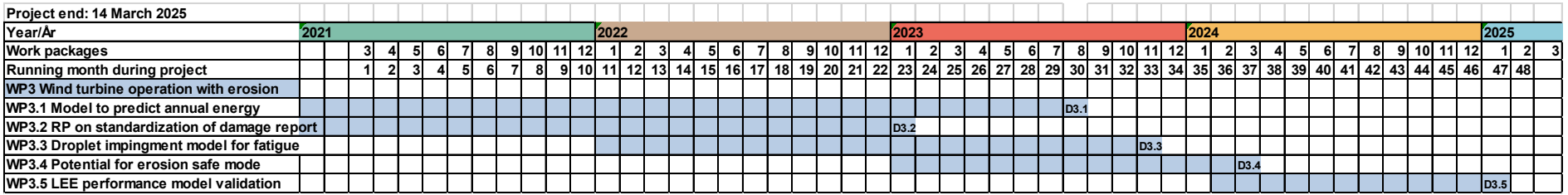




- Substrate is considered fatiguing even while it is covered by coating.
- Currently only two material combinations can be considered.
- Both coating and substrate are modeled as homogeneous materials.

Next Steps in Work Package 3, Phase 1 Final Year

- **Aerodynamic benchmarks**, publication of phase 1 results and phase 2 to commence in spring 2024
- 3.1 **AEP loss model**. Work will progress through the aero. benchmarking group for detailed modeling.
  - Will also pursue simpler model, likely based on DTU or SNL simple performance models
  - Turbine reference models will be developed
- 3.3 **Impingement model**: via aerodynamic benchmark group
  - WP3: Model the aero. impact of the geom. Change (lwift/drag curves, then used for power and AEP change). WP5: Damage progression modeling of the eroded shape, quantify damage evolution
- 3.4 **Erosion Safe Mode**: demonstrated by able participants on the reference turbine model(s)
- 3.5 **Validation with field data**: retargeted to aerodynamic benchmarks and summary of recent field test studies.



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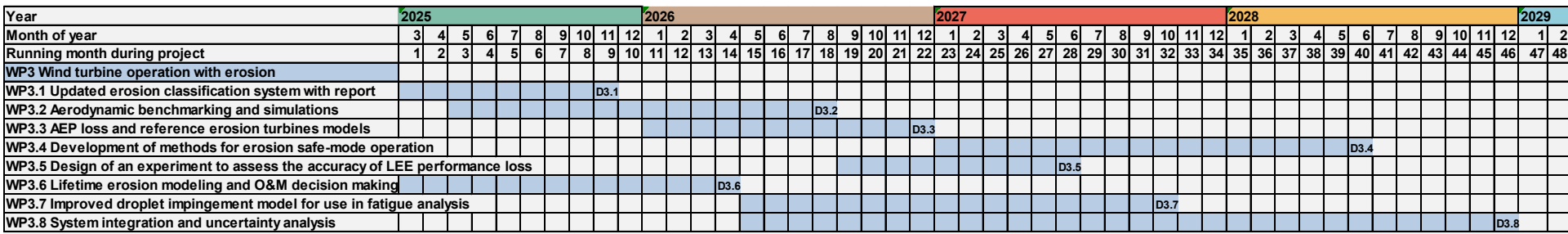
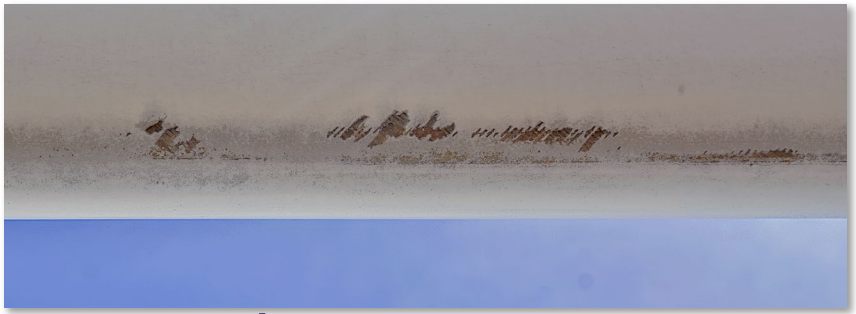
Phase 2 Proposal: WP3 Activities and Deliverables

#	Activity
3.1	Updated erosion classification system with report
3.2	Aerodynamic benchmarking and simulations
3.3	AEP Loss and Reference Erosion Turbines Models
3.4	Development of methods for erosion safe-mode operation
3.5	Design of field experiment to assess accuracy of LEE performance loss models
3.6	Lifetime Erosion Modeling and O&M Decision Making
3.7	Improved droplet impingement model for use in fatigue analysis
3.8	System integration and uncertainty analysis

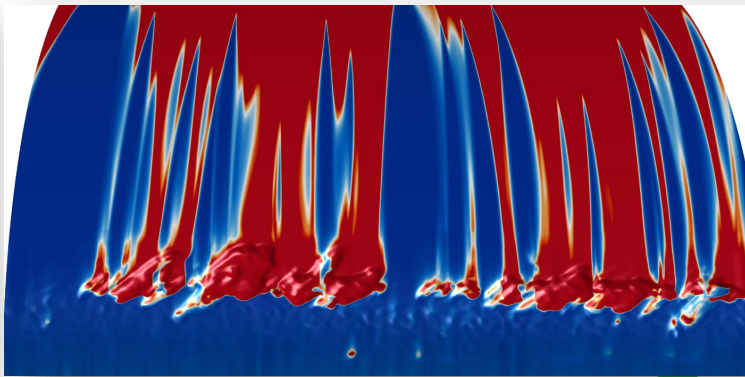


LERCat Aerodynamic Benchmark

- **General**
- Blind benchmark against wind tunnel measurements of LEs with roughness/erosion from the LERCat project
- 9 model submission for clean, tripped and sandpaper cases => good agreement
- 2D slices of high-resolution LER topography are going to be simulated next (description is online)



Wind tunnel CFD



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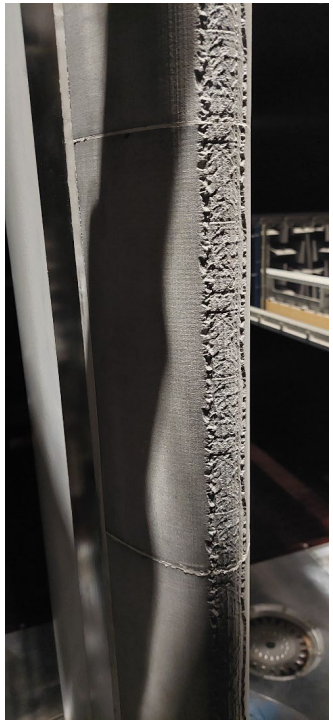
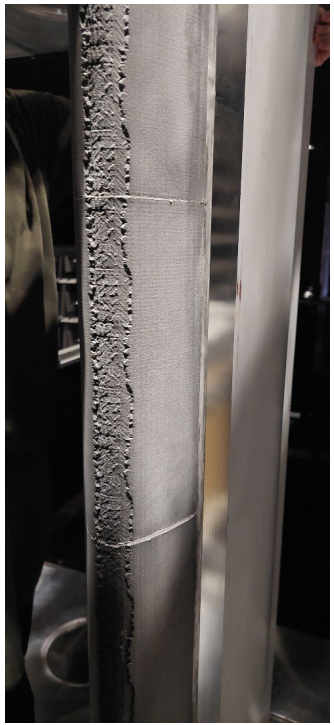
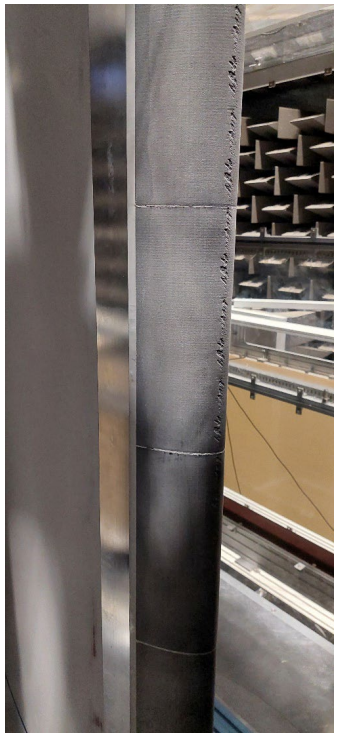
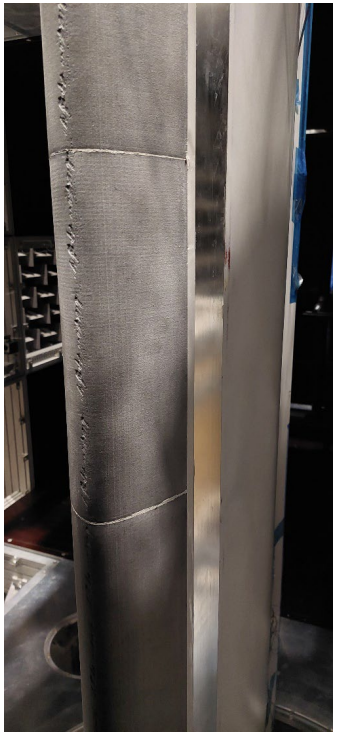
LERCat Aerodynamic Benchmark: XLE LER samples



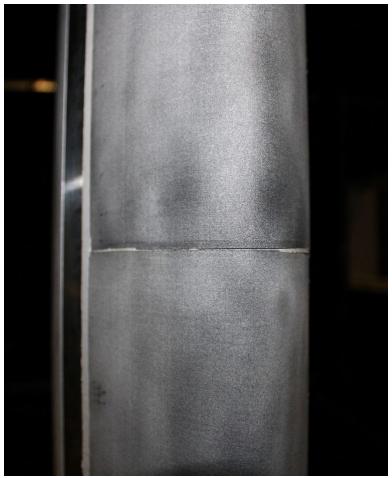


XLE LER-2





XLE LER-1



XLE LER-0

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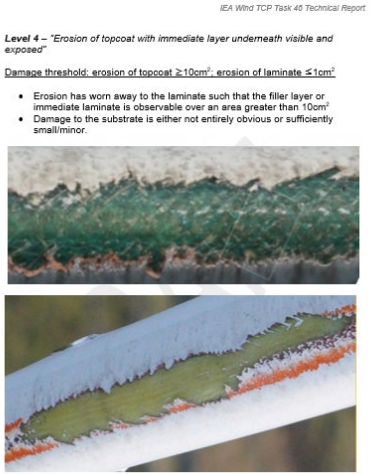
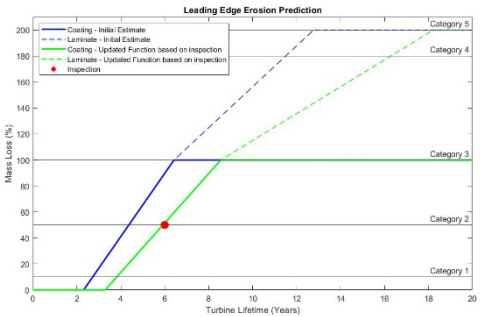
WP3: Erosion Classification System - Update

Visual Condition



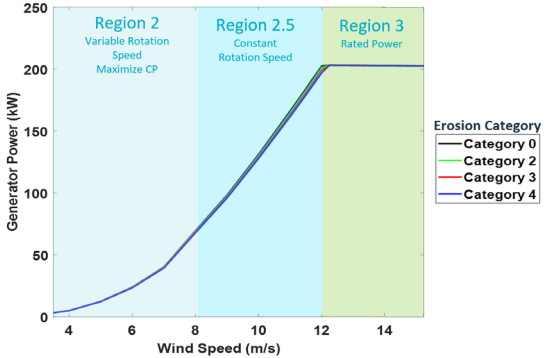
Visual examples of categories of blade and LEP damage.

Mass Loss



Mass loss model has the potential to improve its prediction of future erosion level progression through its incorporation of inspection data.

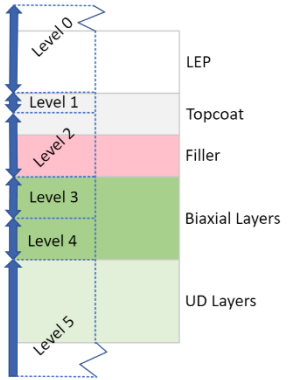
Aerodynamic Performance Categorization



Power loss is defined in Region 2 of the power curve.

Erosion Category	Mean Wind Speed (m/s)				
	4	6	7.5	8.5	10
0	0.0%	0.0%	0.0%	0.0%	0.0%
2	-1.0%	-0.9%	-0.7%	-0.6%	-0.4%
3	-1.9%	-1.6%	-1.3%	-1.1%	-0.8%
4	-3.0%	-2.6%	-2.2%	-1.9%	-1.6%

Structural Integrity



Detailed description of severity level definitions and thresholds.

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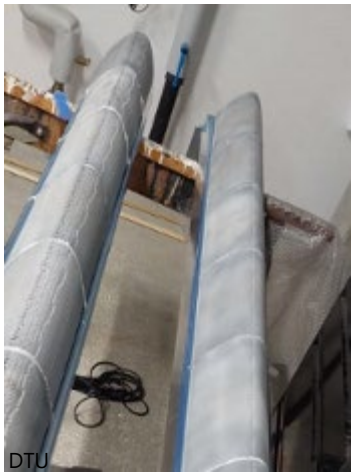
Aerodynamic Benchmarking and Simulations, and Reference models

- Aerodynamic benchmark on LERCat data;
- Relate erosion categories to sandgrain roughness or other roughness parameterization. Application to canonical erosion progression (Springer model) along with actual observations of erosion;
- Predict how higher Reynolds numbers (2-3 times wind tunnel tests) will impact aerodynamics of roughness and erosion, design experiment to address data gaps; and
- Modelling and benchmark on aerodynamic effects and loss due to several representative LEP solutions.



Eroded leading edge models from DTU LERCat project.

WP3: Reference Turbine Models for LEE

- Reference turbine models for a range of modern turbine types for the prediction of AEP
  - Based on blade erosion class or actual observations of erosion;
- Model uncertainty in AEP loss predictions based on ideal erosion classification and realistic uncertainty in classification;
- Include a range of roughness, erosion, and LEP in the results; and
- Development and publication of simple AEP loss models for the reference turbines, applied to a range of wind sites.

- Development of a reference turbine model with a nominal erosion safe mode controller for demonstration of erosion safe mode potential implementation;

Proposed reference turbine models:

- Offshore older: NREL 5MW
- Onshore older: Wind Pact 1.5 (or 2000's era 1.5MW turbine)
- Onshore newer: IEA 3.4MW
- Offshore newer: 15-22MW Reference

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IEA TEM on LEE