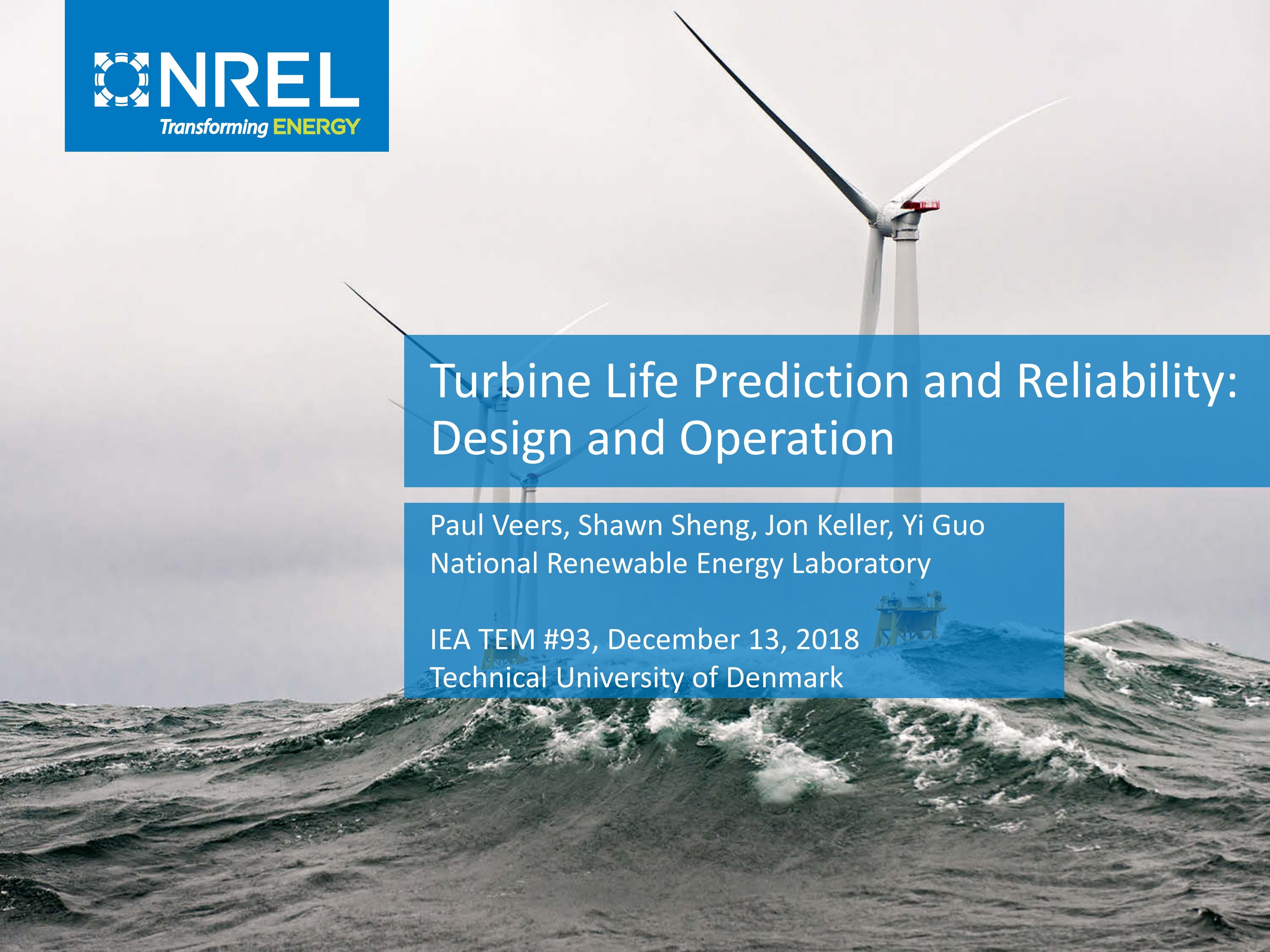


Turbine Life Prediction and Reliability: Design and Operation

Paul Veers, Shawn Sheng, Jon Keller, Yi Guo
National Renewable Energy Laboratory

IEA TEM #93, December 13, 2018
Technical University of Denmark

Design and Operation

Life Extension

- In design: Move to greater economic life (30–40 years?)
- In operation: Extend economic life beyond design estimates
- Components to consider: Structural, mechanical and electrical

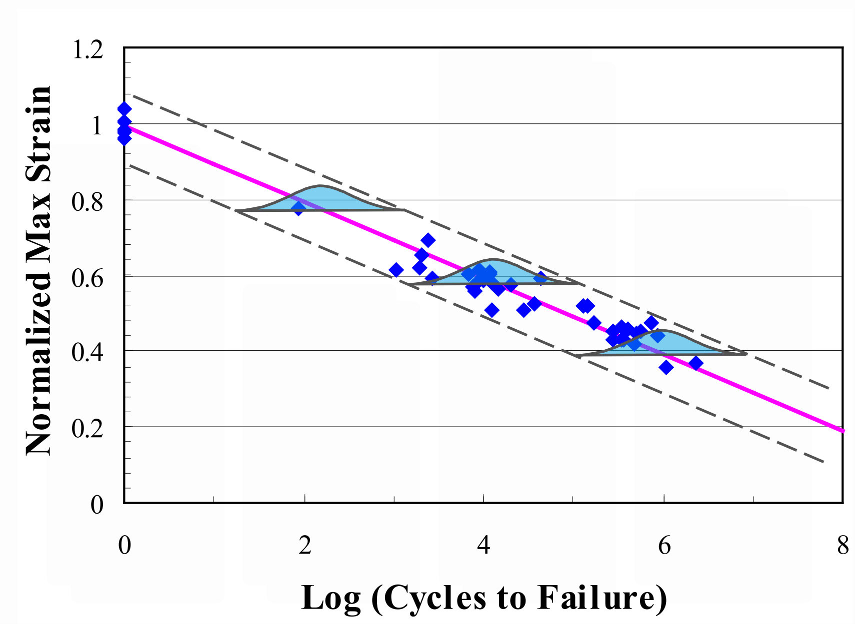
Reliability Assessment

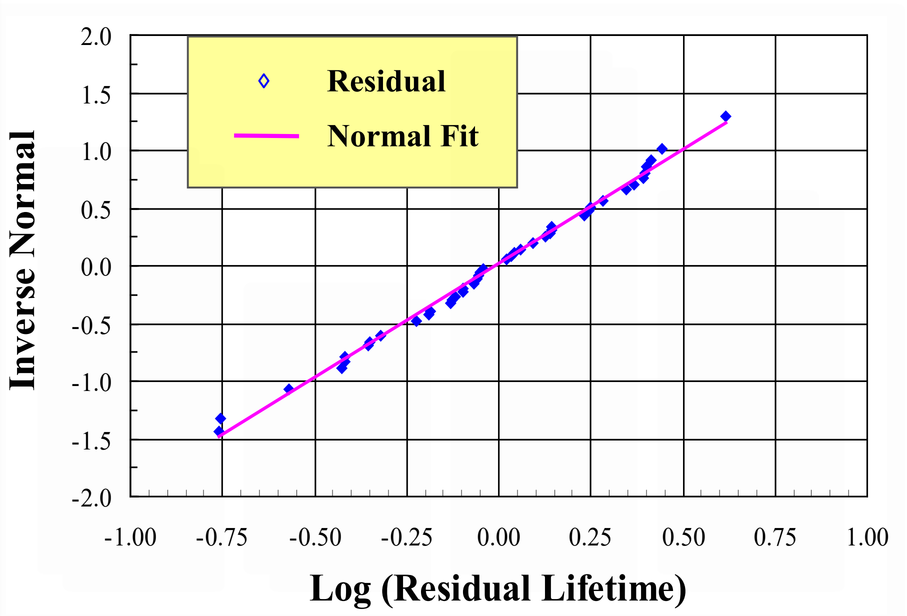
- In design (inherent): Material properties, assumed loading spectrum, idealized operational conditions, damage models, etc.
  - Mostly physics based: Data supported
- In operation: Impacted by load deviated from design, maintenance practices, environmental conditions, etc.
  - Data-based analysis: Physics supported

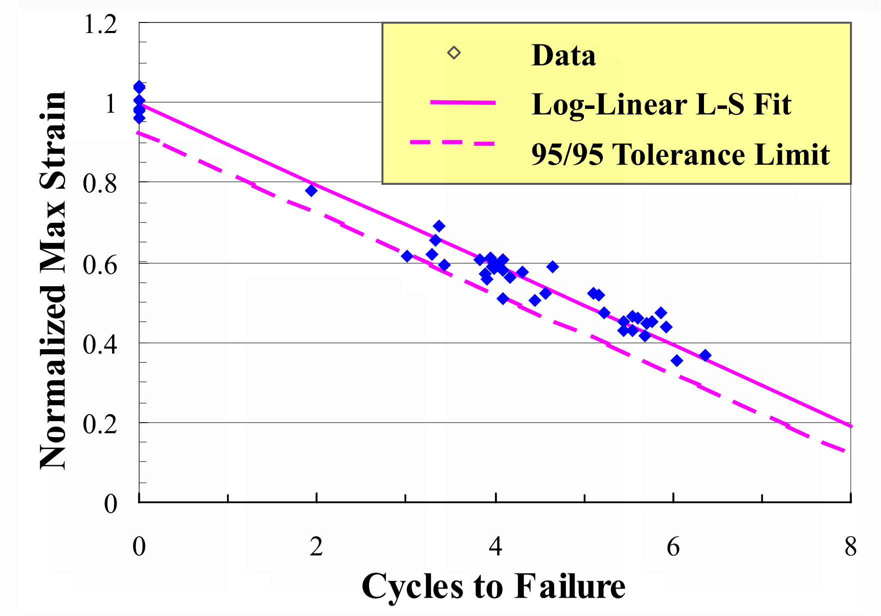
Design Criteria vs. Experience

- Example: NREL’s Drivetrain Reliability Collaborative
- Mechanical: Gearboxes and bearings

Fatigue Analysis – Probability of Failure

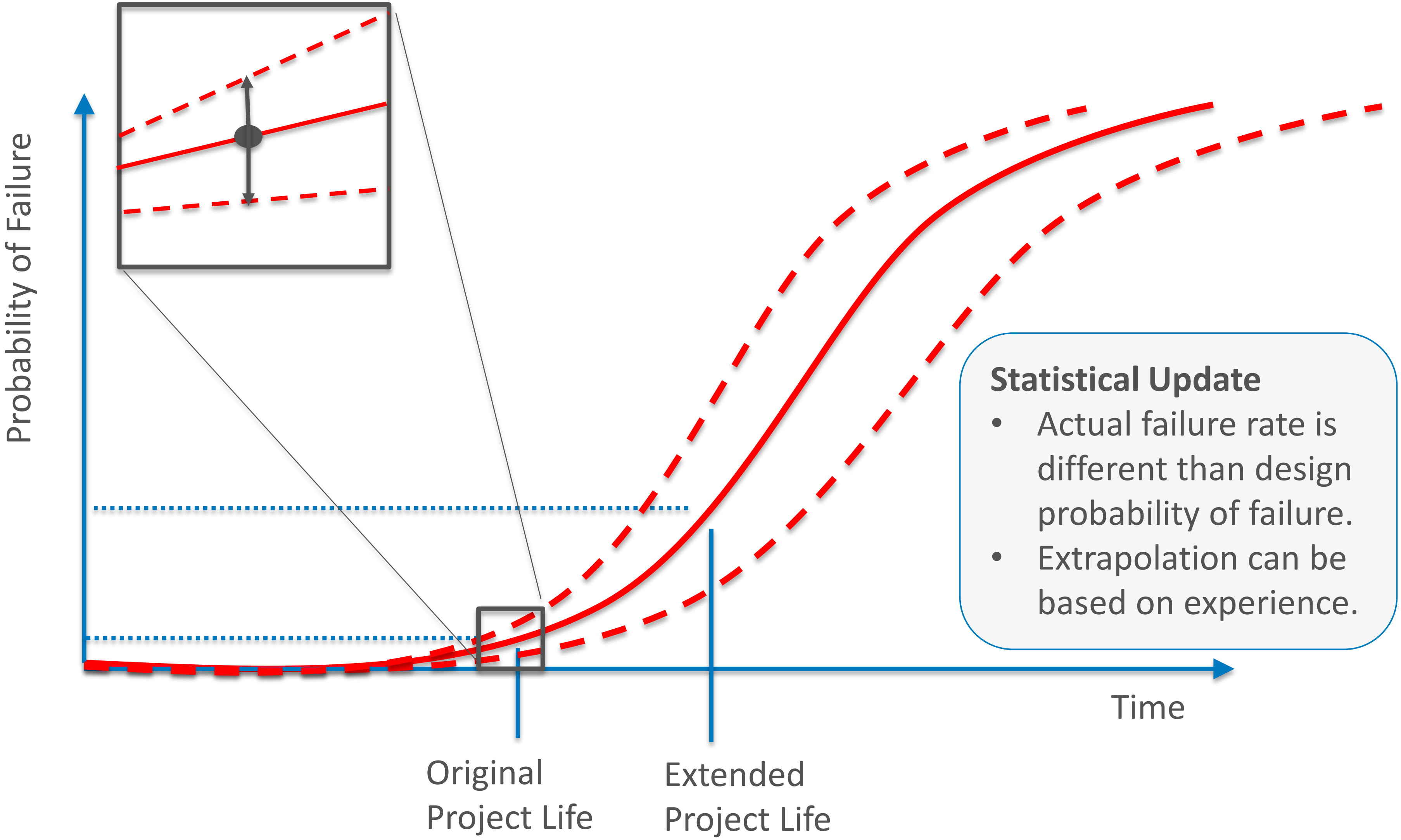






- Material variability is estimated with constant-amplitude tests.
- Variation in cycles to failure is fit to a known distribution.
- Standards require designing to an acceptable failure probability within a specified lifetime (e.g., 95/95).

“Weibull” Curve: Component Probability of Failure over Time

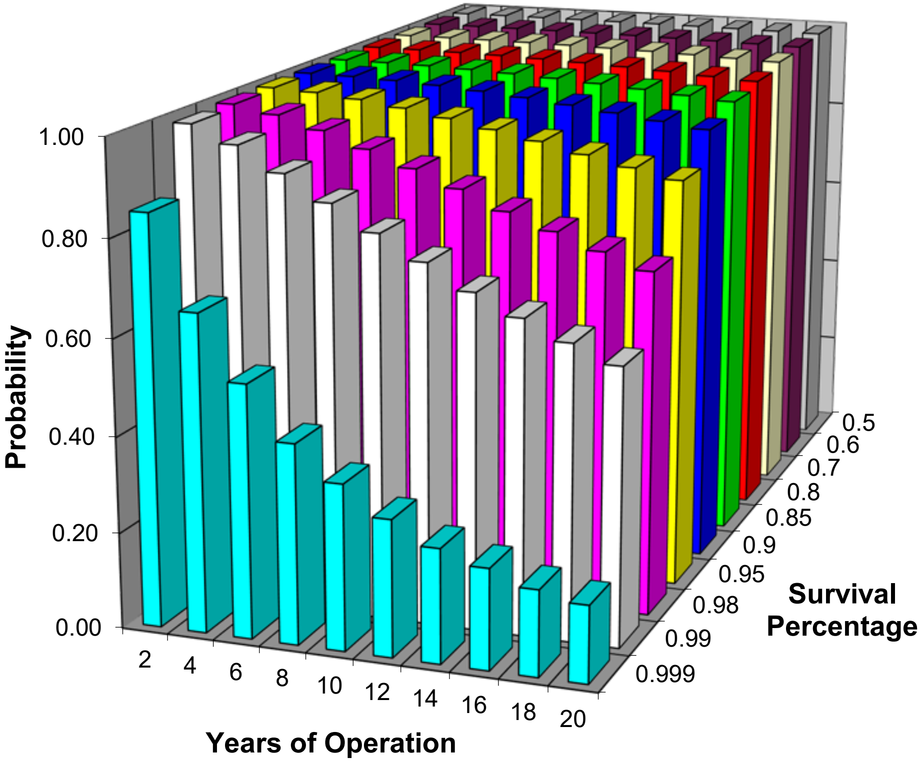


Statistical Update

- Actual failure rate is different than design probability of failure.
- Extrapolation can be based on experience.

Present Value of Future Failures

Component Probability of Failure Over Time



Present Value of Failure Cost

- Probabilistic fatigue analysis has had little traction before now.
- It is difficult and often contains more simplification than many are willing to accept.

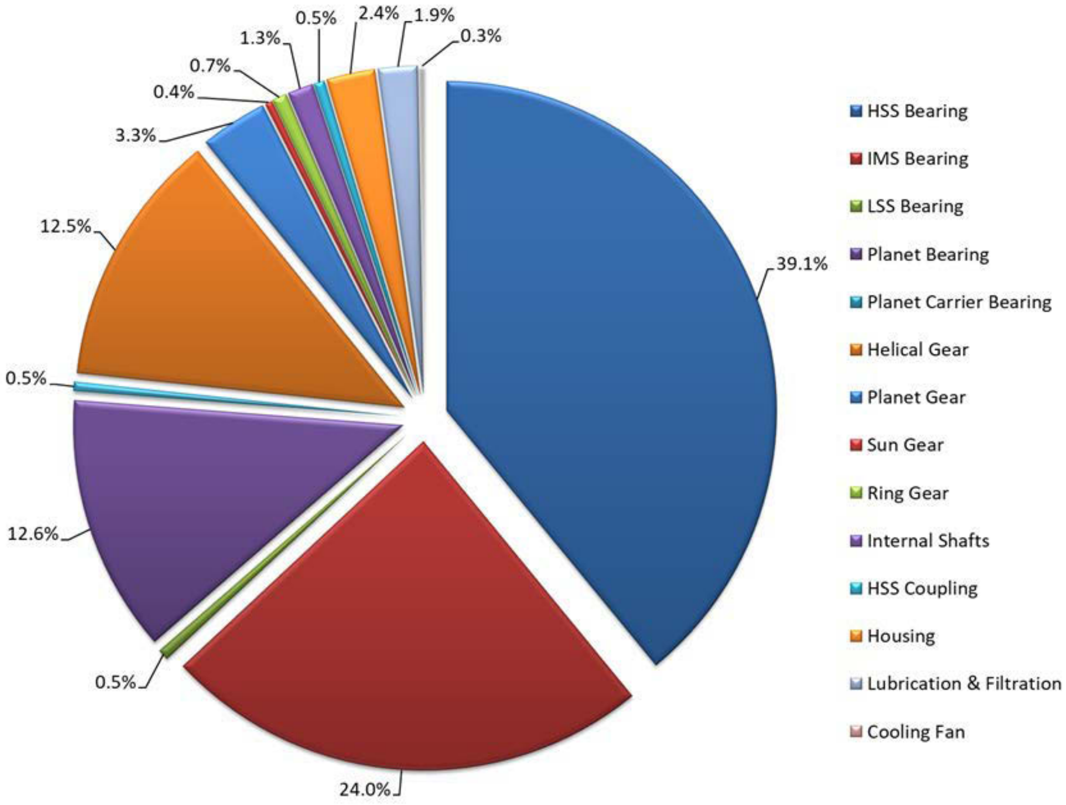
Source: Veers, P. S., .1996. “Fatigue Reliability of Wind Turbine Fleets: The Effect of Uncertainty on Projected Costs,” *Journal of Solar Energy Engineering*, Trans. of the ASME, Vol. 118, No. 4 (November). https://doi.org/10.1115/1.2871782.

Assumptions

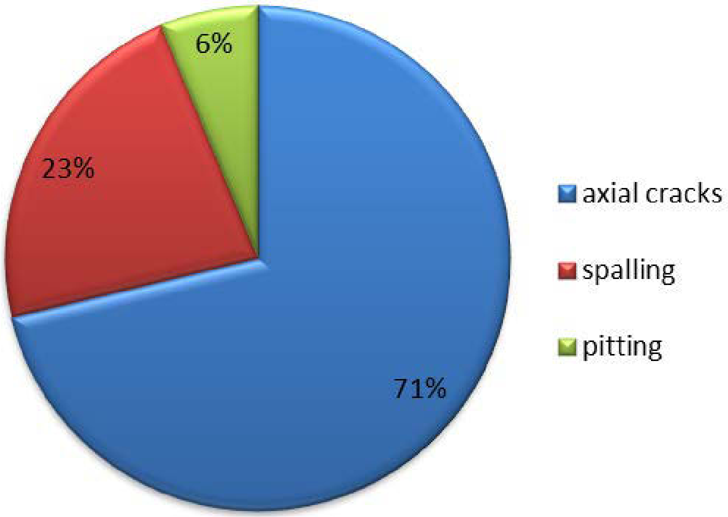
- The failures experienced in the operating plants are related to the failure modes addressed by the design requirements.
- As-manufactured material properties are well characterized.
- Loadings are consistent with the design criteria.
- Damage models are known and appropriate.
- Governed by a single damage mechanism.
- These are not always satisfied.

Damage of Wind Turbine Gearboxes: Dominant Failure Mode Not Accounted for During Design

Gearbox Failures by Subcomponent



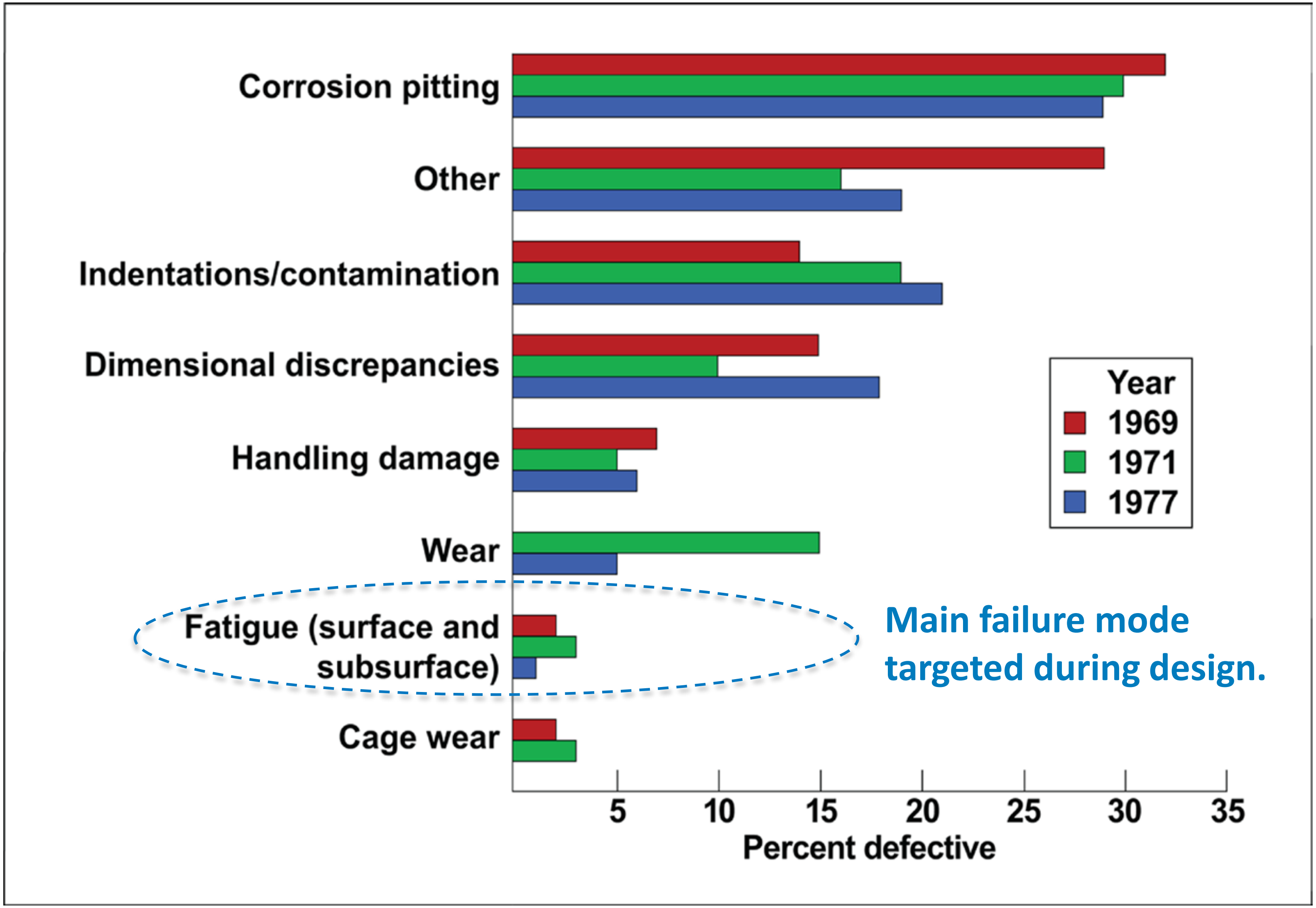
Bearing Failure Causes



- Samples: ~1,100 records
  - Bearings: 77%
  - Gears: 17%
  - Others: 6%

- Samples: ~80 records
  - Axial cracks: 71%
  - Spalling: 23%
  - Pitting: 6%

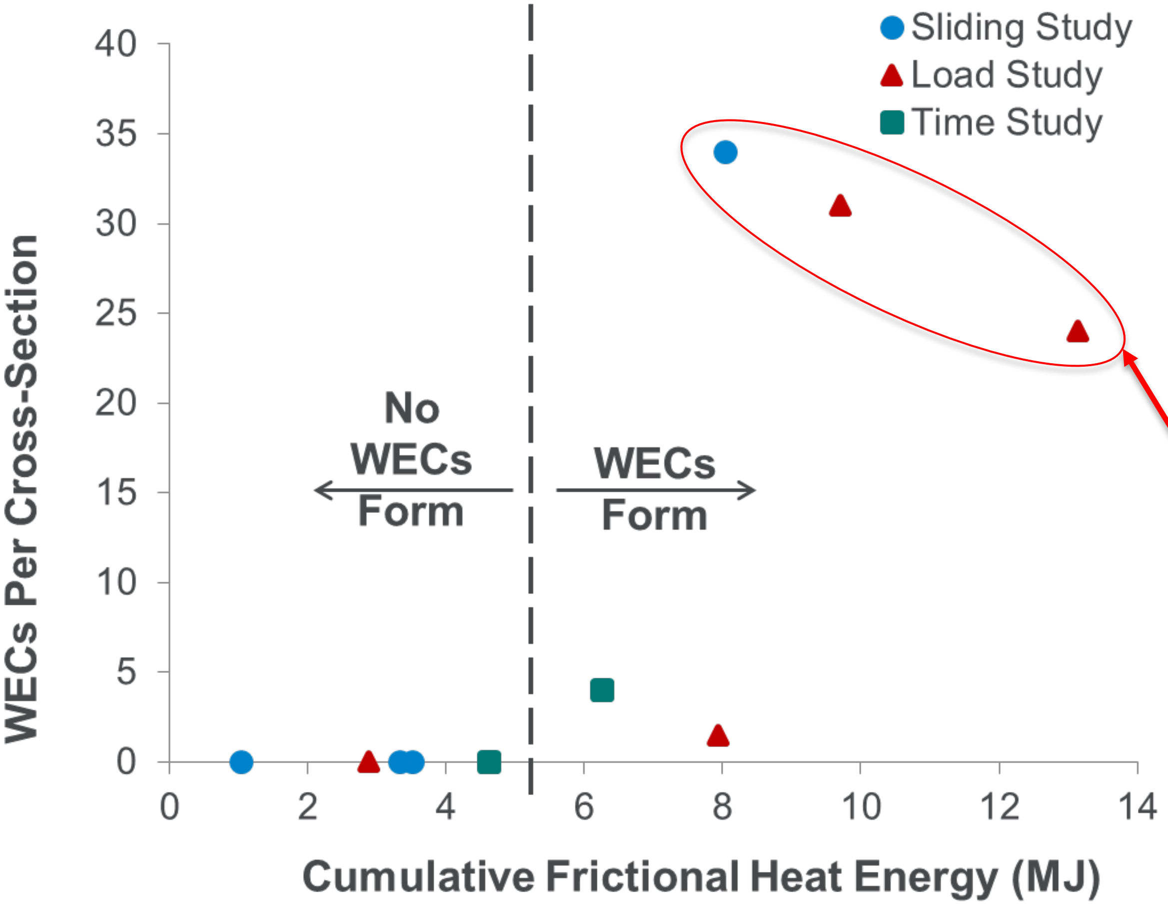
The Challenge Is Not the Wind Industry Alone: Rolling Bearing Causes for Removal

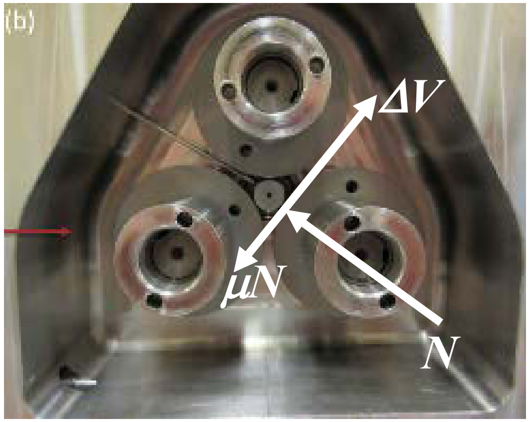


Main failure mode targeted during design.

Source: J. S. Cunningham, Jr. and M. A. Morgan, STLE Lubr. Engr., 1979

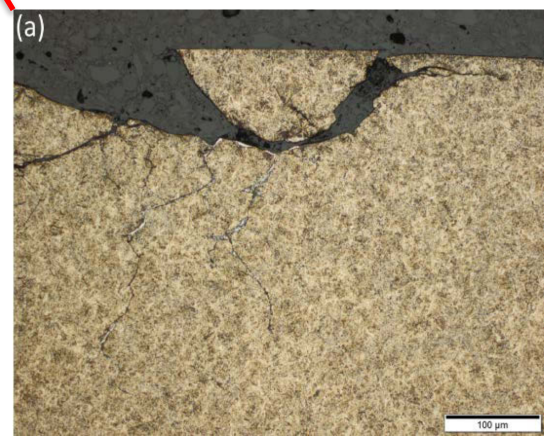
Bearing Axial Cracking: Benchtop Tests





$$E = \frac{3}{2}\Delta V\ \mu\, N\, t$$

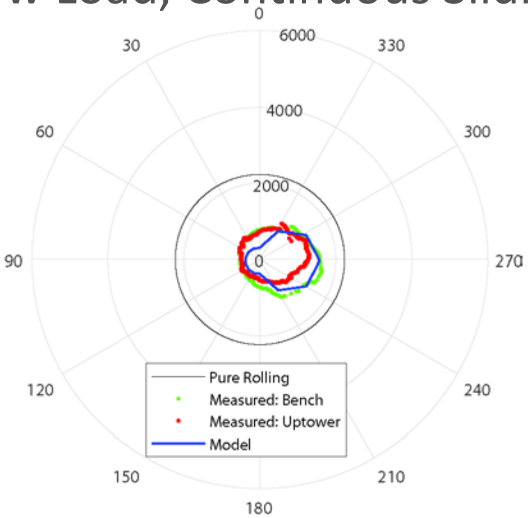
Cumulative Frictional Heat Energy



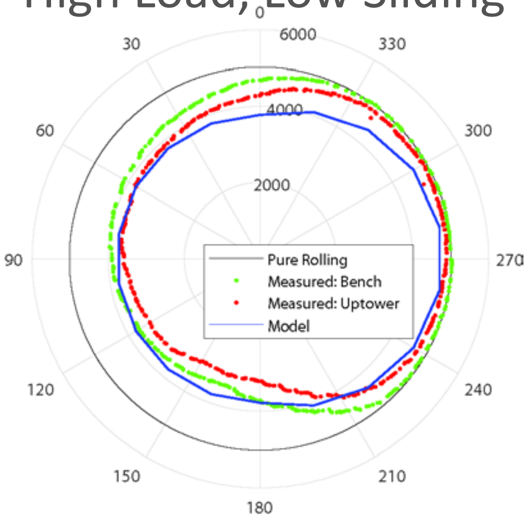
Source: Gould, B., and A. Greco. 2015. "The Influence of Sliding and Contact Severity on the Generation of White Etching Cracks." doi.org/10.1007/s11249-015-0602-6.

High-Speed Bearing Analysis

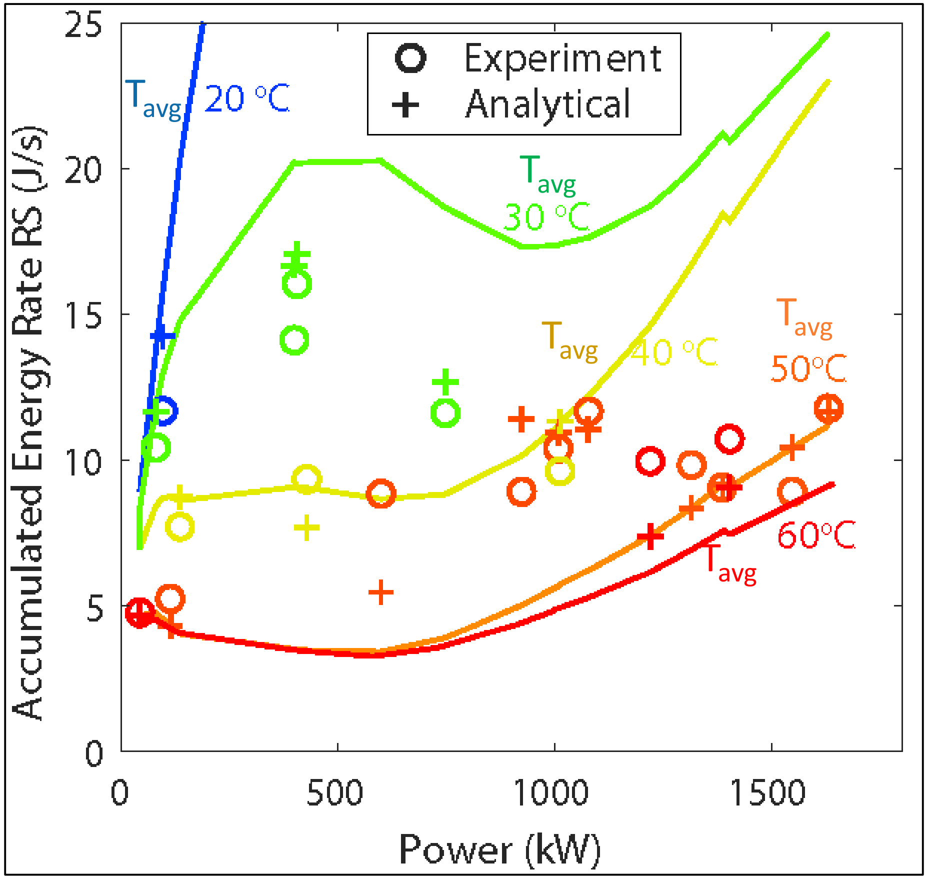
250 kW Power
Low Load, Continuous Sliding



Rated 1,500 kW Power
High Load, Low Sliding



T_{oil} =



Cold operations at low power generate more frictional energy than warm operations at high power.

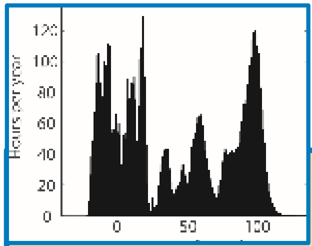
Source: Keller, J. and Y. Guo. 2018. *High-Speed Shaft Bearing Roller Sliding Analysis.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-72415.

Frictional Energy Loss-Based Reliability Assessment Using Probability of Failure as the Metric

- Target dominant failure mode: high-speed-stage-bearing axial cracking
- Frictional energy loss under both normal and transient operations:

$$E = E_{np} + E_{tt}$$

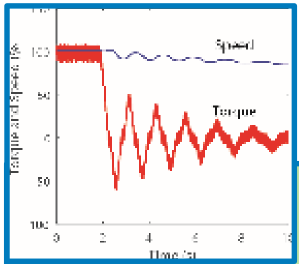
Operation



$$E_{np} = f(\mu, N, F, \Delta v)$$

- μ: Friction coefficient
- N: Number of cycles (roller)
- F: Load
- Δv: Sliding velocity between roller/raceway

Transient



$$E_{tt} = f(\mu, t, F, \Delta v)$$

- μ: Friction coefficient
- t: Time
- F: Load
- Δv: Sliding velocity between roller/raceway

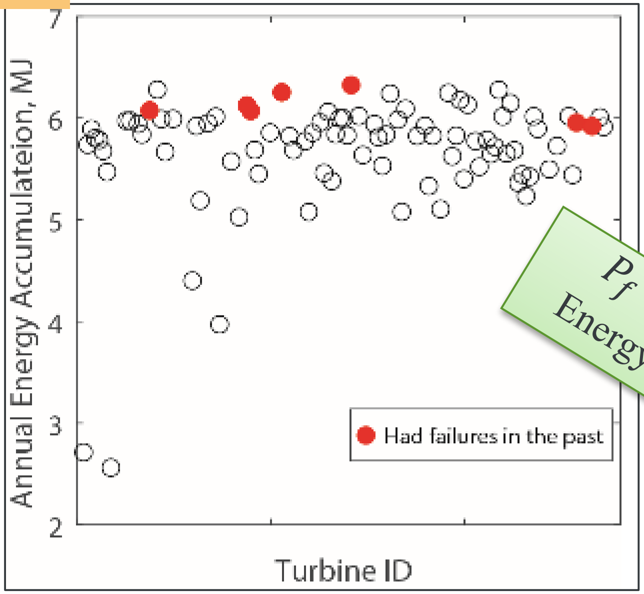
- First- and second-order reliability methods:

$$G = e^* - (E_{np} + E_{tt}) \qquad P_f = P\{G(U) < 0\}$$

Source: Guo, Yi and Shawn Sheng. 2018. *Probability of Failure for Gearbox High-Speed-Stage Bearings in Wind Turbines*. Golden CO: National Renewable Energy Laboratory. NREL/PR-5000-70972. https://www.nrel.gov/docs/fy18osti/70972.pdf.

Reliability Assessment Probability of Failure, P_f, of Axial Cracking: Preliminary Results

Verification

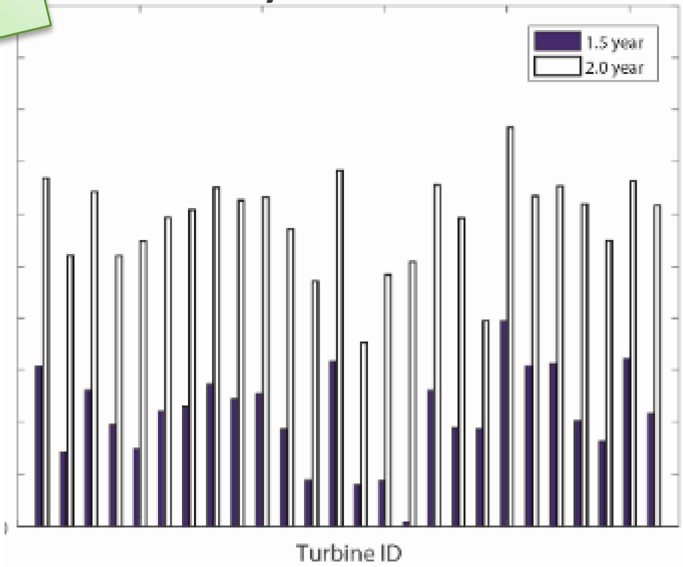

Annual Energy Accumulation

- Some correlation between high energy with previous failures present.
- Turbine failures occurred two years earlier than the evaluation period that was available for analysis:
  - Failure records yet to be updated.

P_f Calculated from Energy Accumulation

Prediction

- P_f quantifies failure risk for each turbine.
- P_f is a function of age, wind loads, turbine design, and operations.


Probability of Failure in A Plant

Turbine or Plant Perspective

Reliability Assessment and Prediction: Single Component

- Component failure mechanism
- Measurements
- Damage analysis
- Uncertainty quantification

Methodology Applied to Other Major Components

- Structural or electrical
- Dominant failure mode
- Damage model and failure criterion
- Probability of failure metric

Risk Analysis and Decision Making

- Risk is probability times consequence
- Economic analysis

Photo from Gary Doll, University of Akron

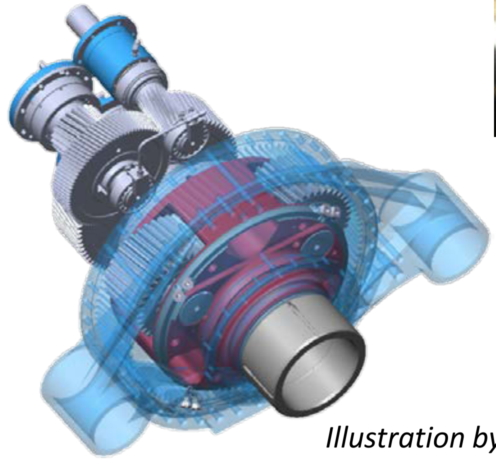
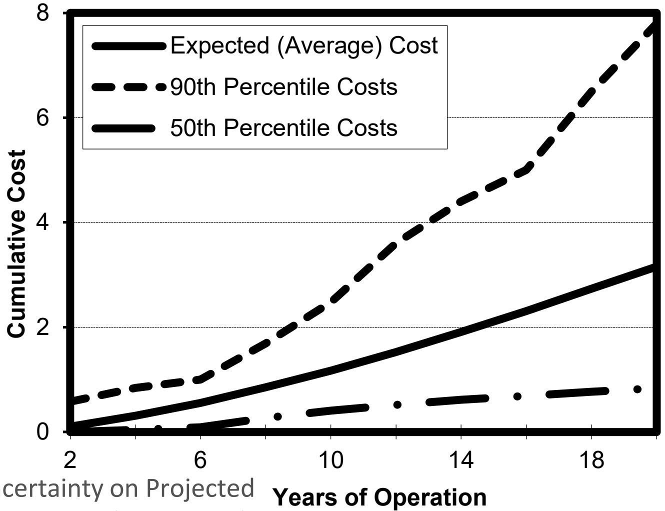


Illustration by NREL

Plant-Wide Cost Estimates



Source: Veers, P. S., .1996. "Fatigue Reliability of Wind Turbine Fleets: The Effect of Uncertainty on Projected Costs," *Journal of Solar Energy Engineering*, Trans. of the ASME, Vol. 118, No. 4 (November). https://doi.org/10.1115/1.2871782.

Special thanks go to the U.S. Department of Energy drivetrain reliability collaborative research partners!

The Block Island Wind Farm—the first offshore wind farm in the United States. *Photo by Dennis Schroeder, NREL 40389*

Thank You

www.nrel.gov

NREL/PR-5000-73023

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL
Transforming ENERGY