INSTITUTE OF ENGINEERING AND TECHNOLOGY

Argonne NATIONAL LABORATORY 75 1946–2021

WIND TURBINE DRIVETRAIN RELIABILITY

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U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

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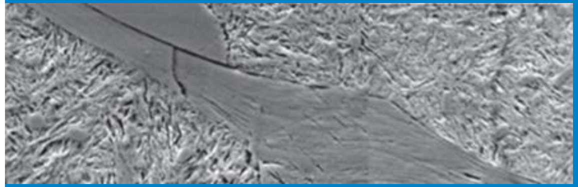
Sept. 14, 2022

OUTLINE

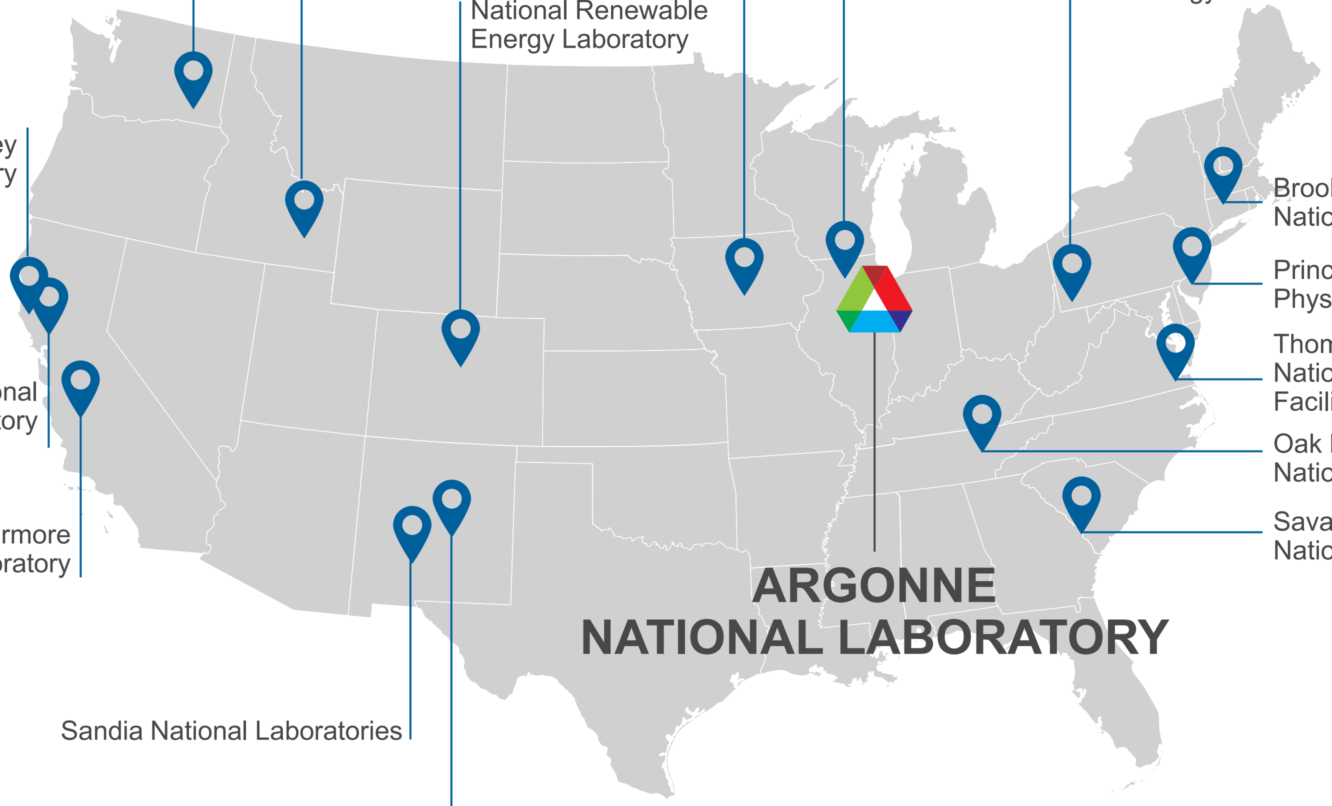
- Introduction to Argonne National Laboratory

- Background of Wind Energy

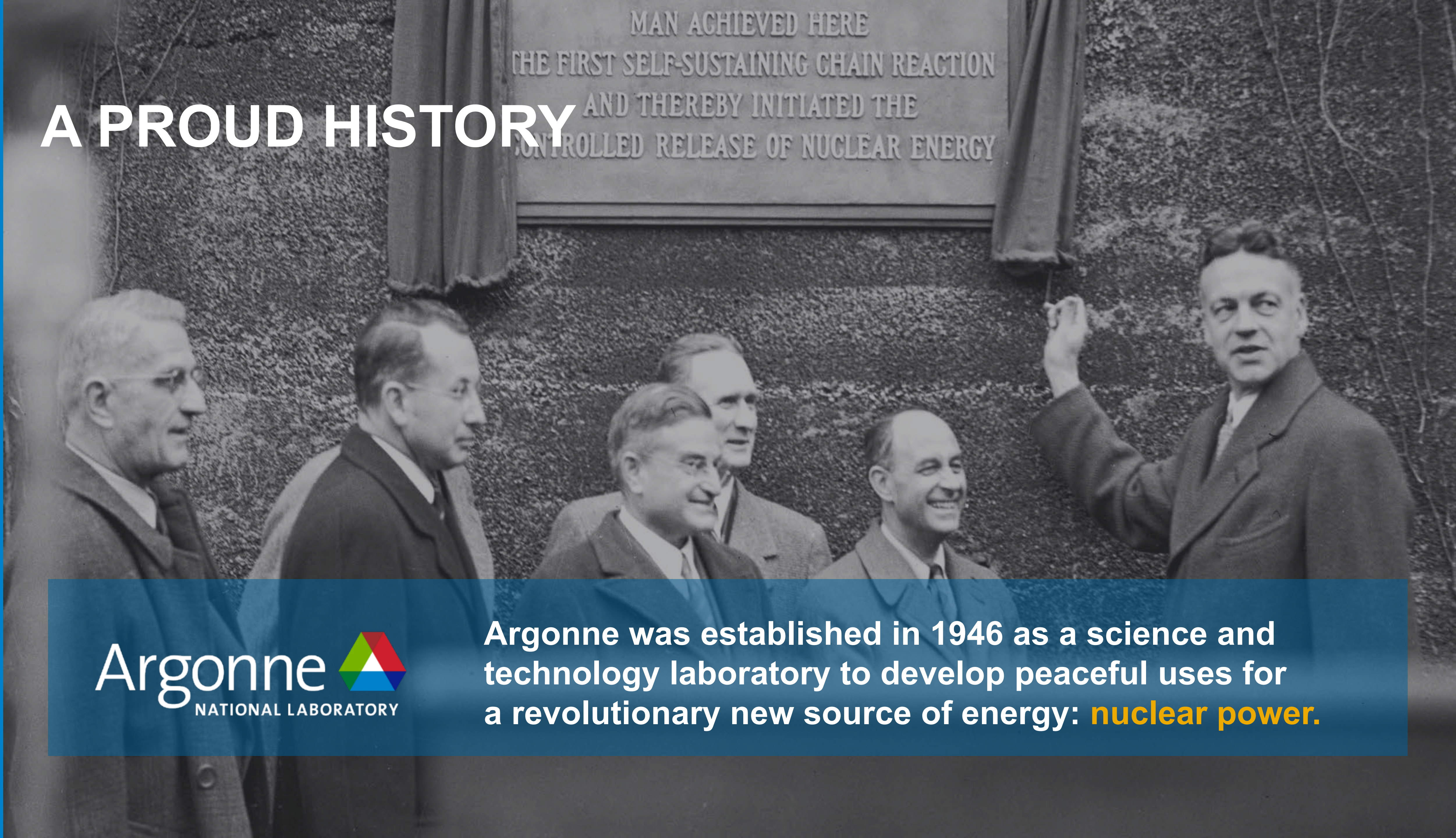


- Premature Bearing Failures (white-etching cracks)

A VITAL PART OF THE U.S. DEPARTMENT OF ENERGY NATIONAL LABORATORY SYSTEM



A PROUD HISTORY

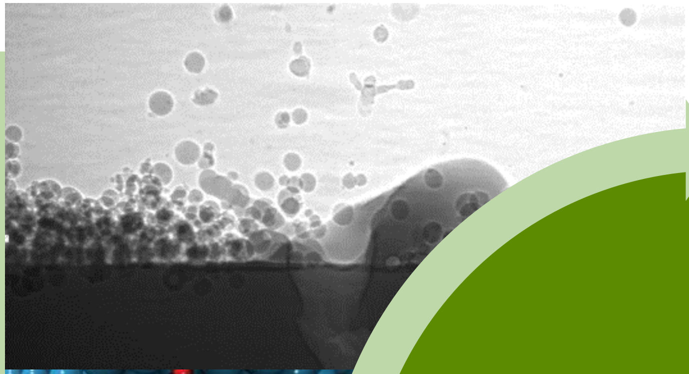


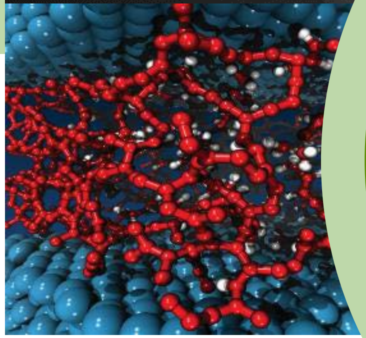
Argonne NATIONAL LABORATORY

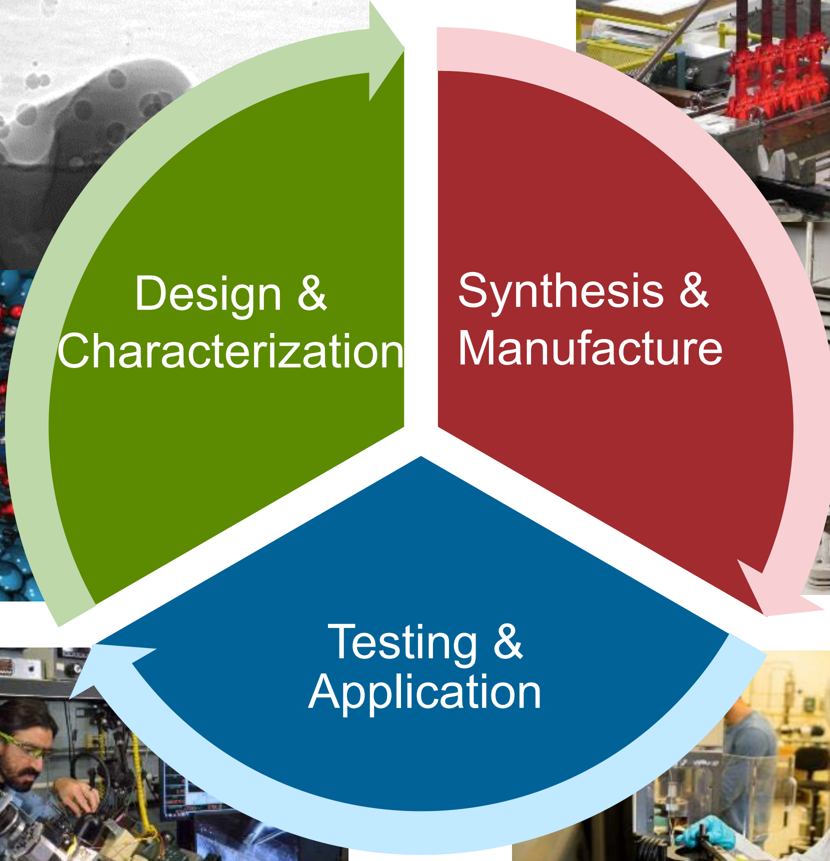
Argonne was established in 1946 as a science and technology laboratory to develop peaceful uses for a revolutionary new source of energy: nuclear power.

INTERFACIAL MECHANICS & MATERIALS

- Characterization of surface material structure, chemistry and material degradation
- In situ characterization of material processes
- Characterization of root cause analysis for failures in field components

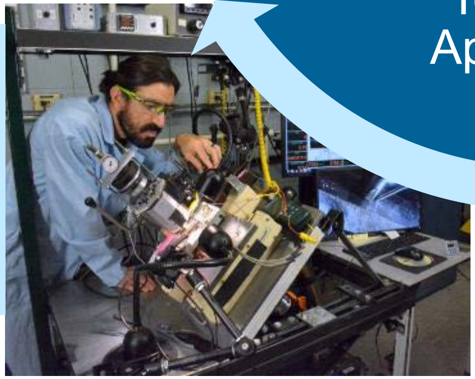






- Discovery, patenting, and licensing of new hard material coatings, surface treatments, and lubricant additives

- Analysis of mechanical, rheological, tribological, and thermal material properties
- Custom design of test rigs to fit application specific issues
- Development of benchtop standardized tests for emerging material failures



WIND ENERGY BACKGROUND

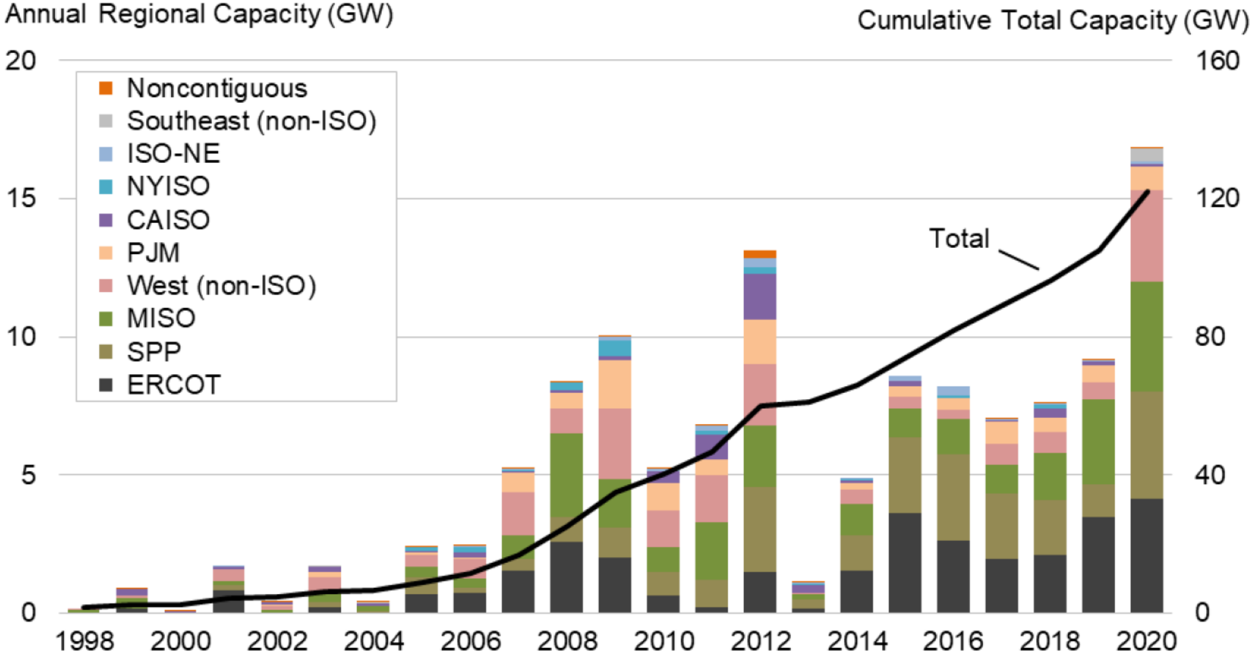
WIND ENERGY- INSTALLED CAPACITY

Annual Capacity (2020, MW)	
China	52,000
United States	16,836
Brazil	2,297
Netherlands	1,979
Germany	1,668
Norway	1,532
Spain	1,400
France	1,318
Turkey	1,224
India	1,119
Rest of World	11,538
TOTAL	**92,910**

Cumulative Capacity (end of 2020, MW)	
China	288,320
United States	121,955
Germany	62,850
India	38,625
Spain	27,250
United Kingdom	23,937
France	17,948
Brazil	17,750
Canada	13,578
Italy	10,543
Rest of World	119,572
TOTAL	**742,327**

Sources: GWEC, ACP

U.S. Land-Based Wind Energy[1]

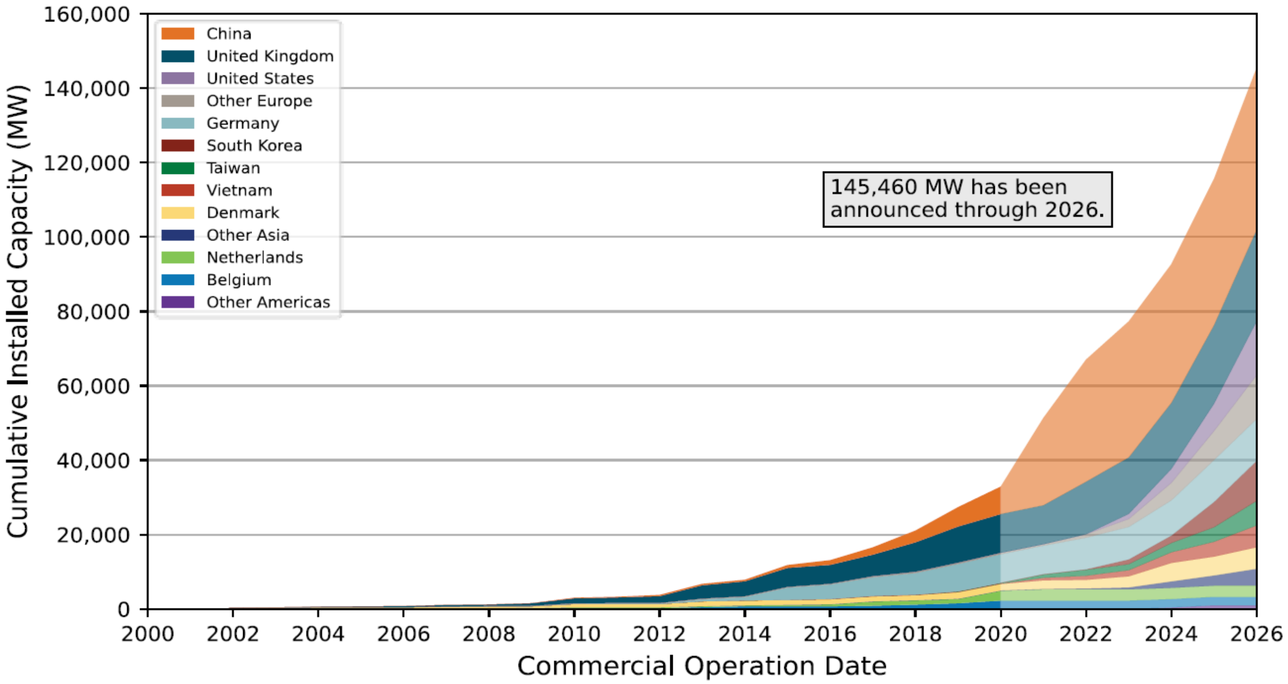


Source: ACP

https://www.energy.gov/eere/wind/articles/land-based-wind-market-report-2021-edition-released

OFFSHORE WIND ENERGY

Actual and Estimated Cumulative Offshore Wind Energy Capacity[1]

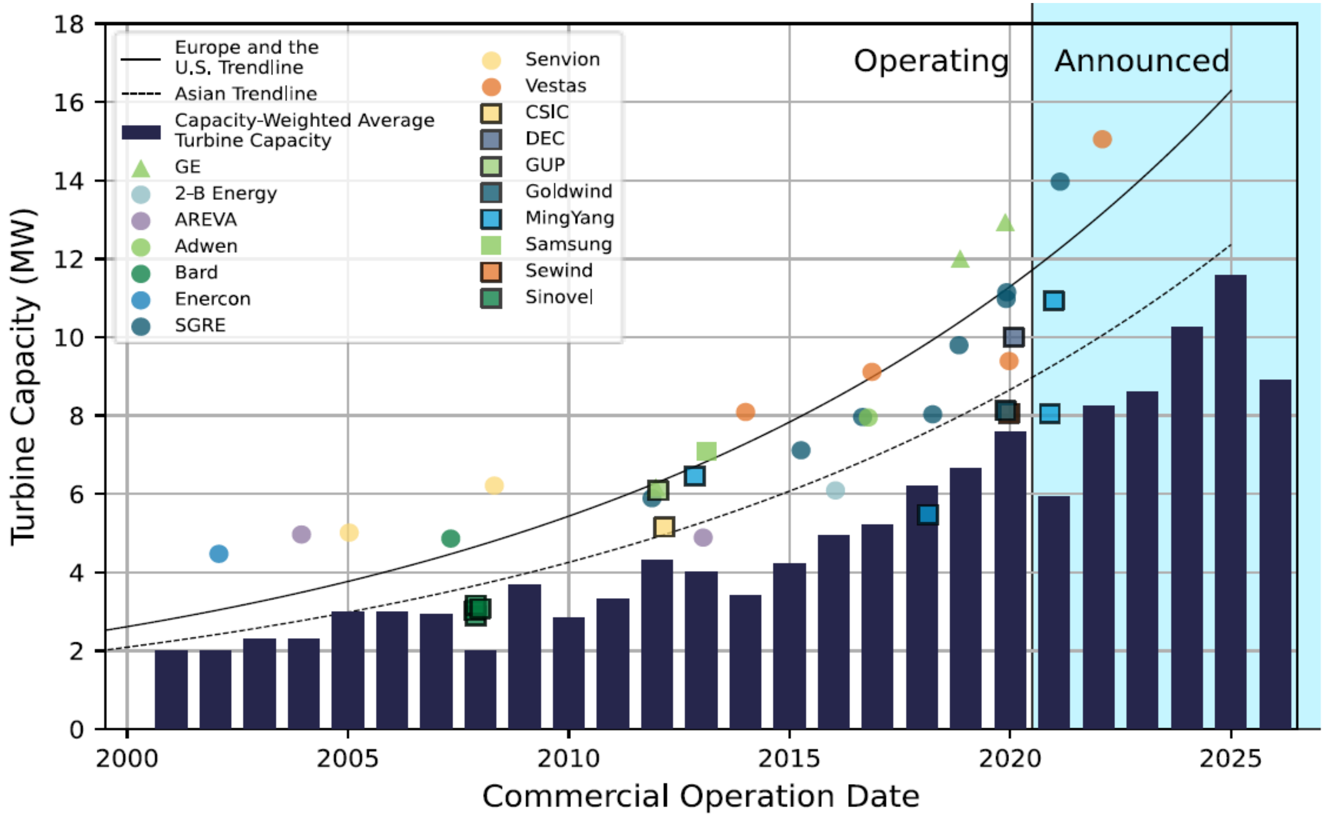


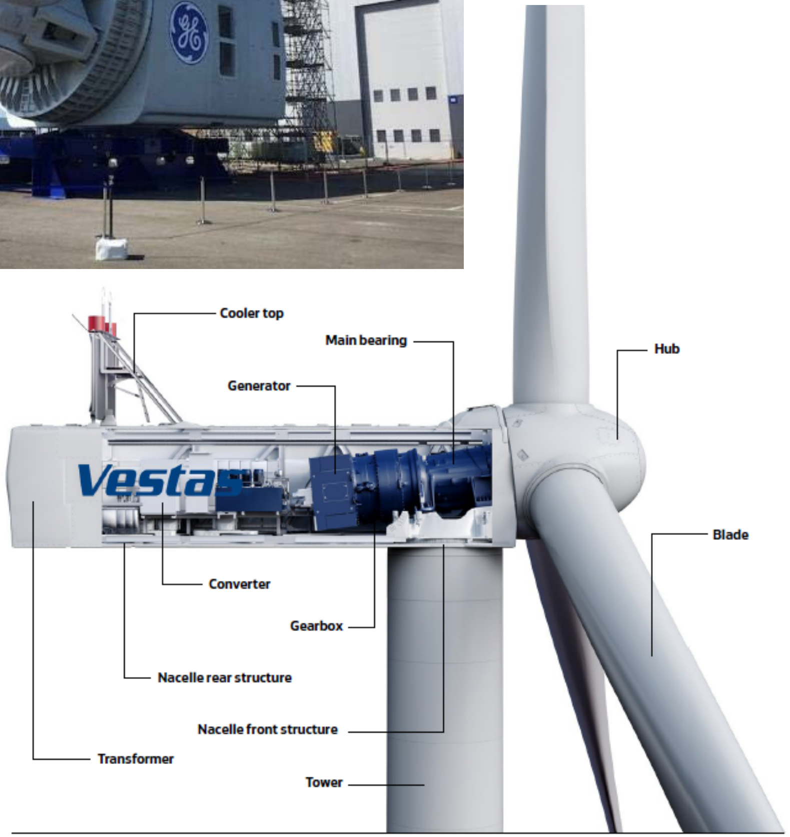
Offshore wind energy targets:

- United States[2]: 30 GW by 2030

1 - https://www.energy.gov/eere/wind/articles/offshore-wind-market-report-2021-edition-released
2 - https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/29/fact-sheet-biden-administration-jumpstarts-offshore-wind-energy-projects-to-create-jobs/

WIND TURBINE SIZE TRENDS





1 - https://www.energy.gov/eere/wind/articles/offshore-wind-market-report-2021-edition-released

TURBINE COMPONENT RELIABILITY

- **Operations and maintenance (O&M) costs are an important part of cost of energy!**
  - Account for 25% to 35% of levelized cost of energy (LCOE), representing $5 billion annual market in the United States
  - O&M costs are higher than expected; estimated opportunity for reduction in LCOE can account for 10% (land-based) to 50% (fixed offshore)

Photo by Dennis Schroeder, NREL

R. Errichello, S. Sheng, J. Keller, A. Greco. Wind Turbine Tribology Seminar- A Recap. 2012. U.S. Dept of Energy Wind and Water Power Program (image provided by Jurgen Gegner of SKF)

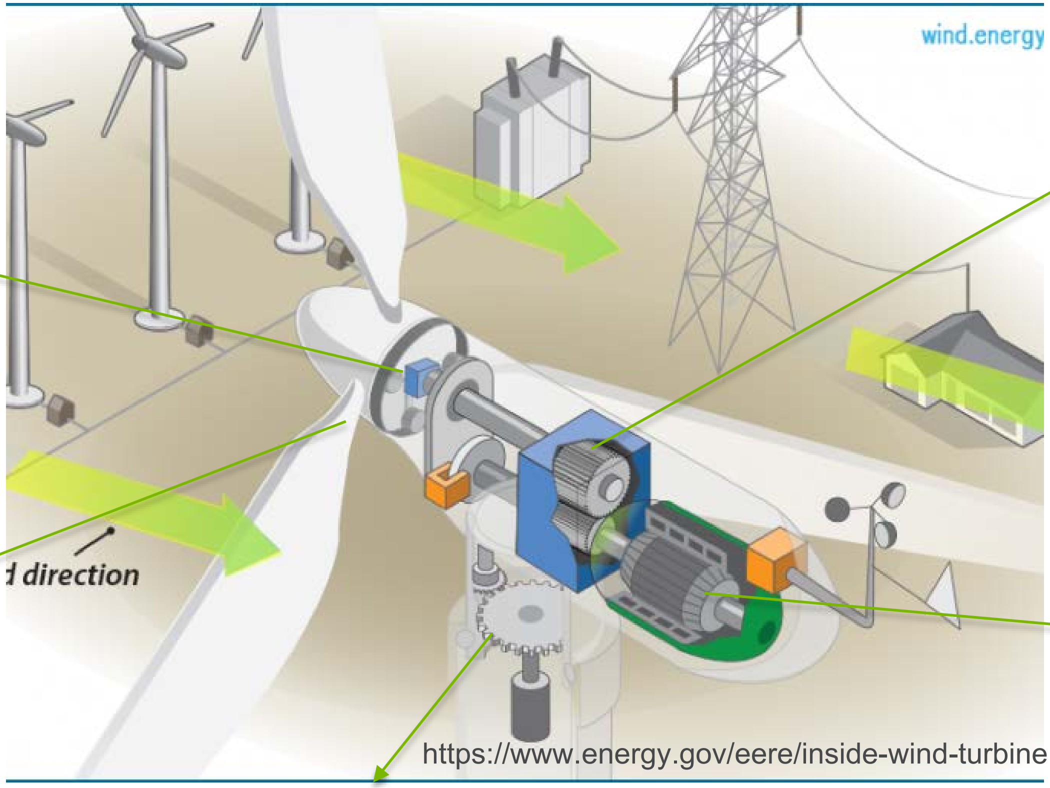
TRIBOLOGICAL COMPONENTS

Main Shaft Bearing

NREL/TP-5000-71529

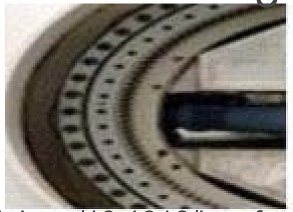
Blade Pitch

https://en.wikipedia.org/wiki/Pitch_bearing



https://www.energy.gov/eere/inside-wind-turbine

Yaw Bearing



https://doi.org/10.1016/j.surfcoat.2022.128545

Gearbox

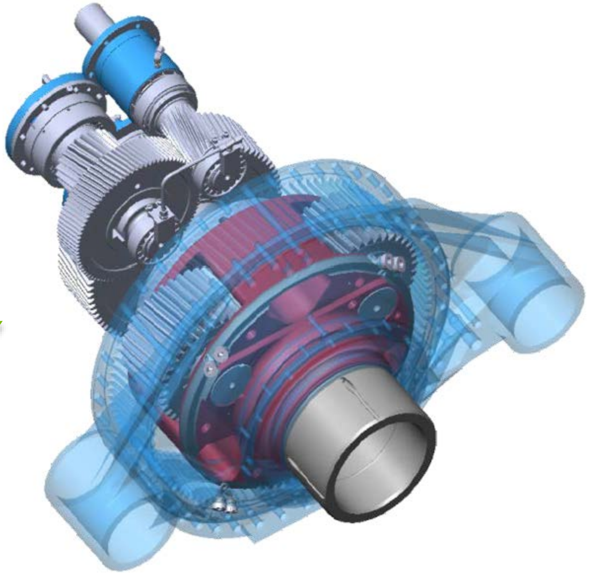


Illustration by NREL

Generator

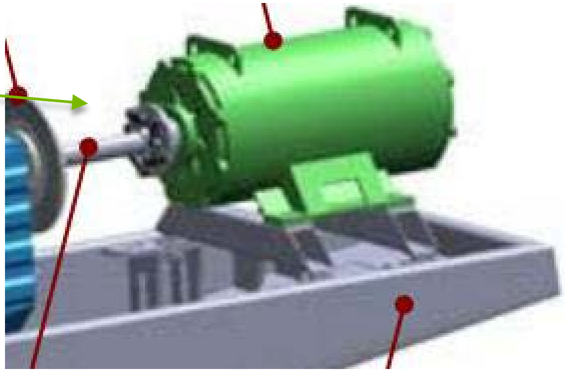


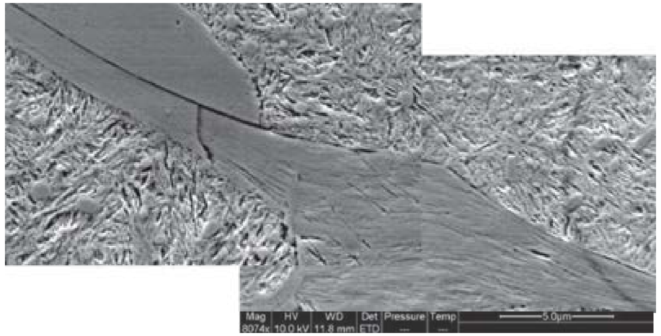
Illustration by NREL

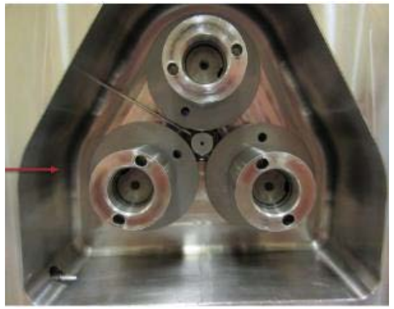
WIND TURBINE DRIVETRAIN RELIABILITY R&D FOCUS @ ARGONNE & NREL

- White-etching crack/axial crack (gearbox bearing, main bearing)
- Main bearing wear (micropitting)
- Pitch bearing fretting wear
- Journal/plain bearing wear
- Advanced lubricant technology

Main Bearing Wear

D. Brake. WTG SRB Main Bearing Failures. Presented at the 2013 UVIG Wind Turbine/Plant Operations & Maintenance Users Group Meeting.



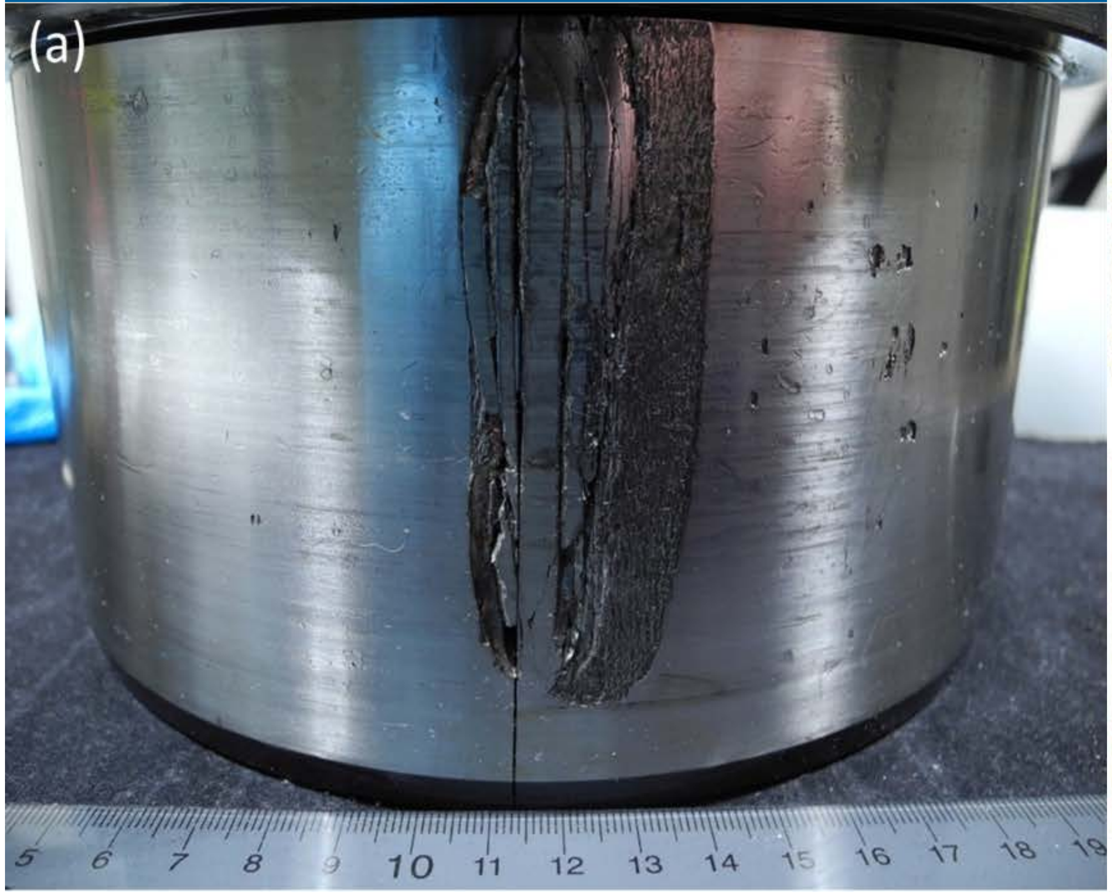


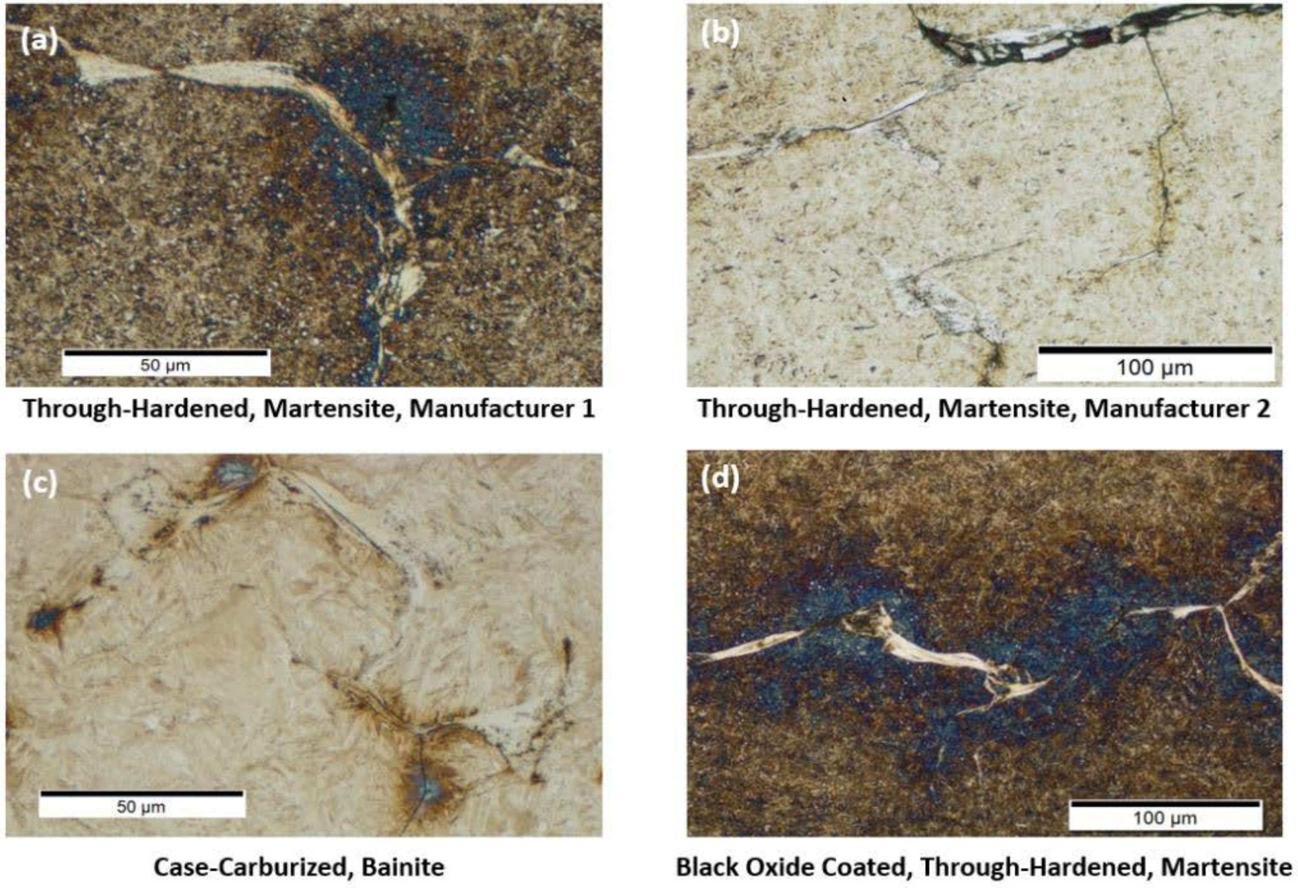
WHITE ETCHING CRACK BEARING FAILURE

AXIAL CRACKS / WHITE-ETCHING CRACKS

White-etching cracks (WECs) cause premature bearing failure through spalls or cracks and are characterized by **irregular microstructural alteration** in the subsurface material.

- Failure at 1%–10% of rolling contact fatigue L_{10} design life
- Exact cause is unknown

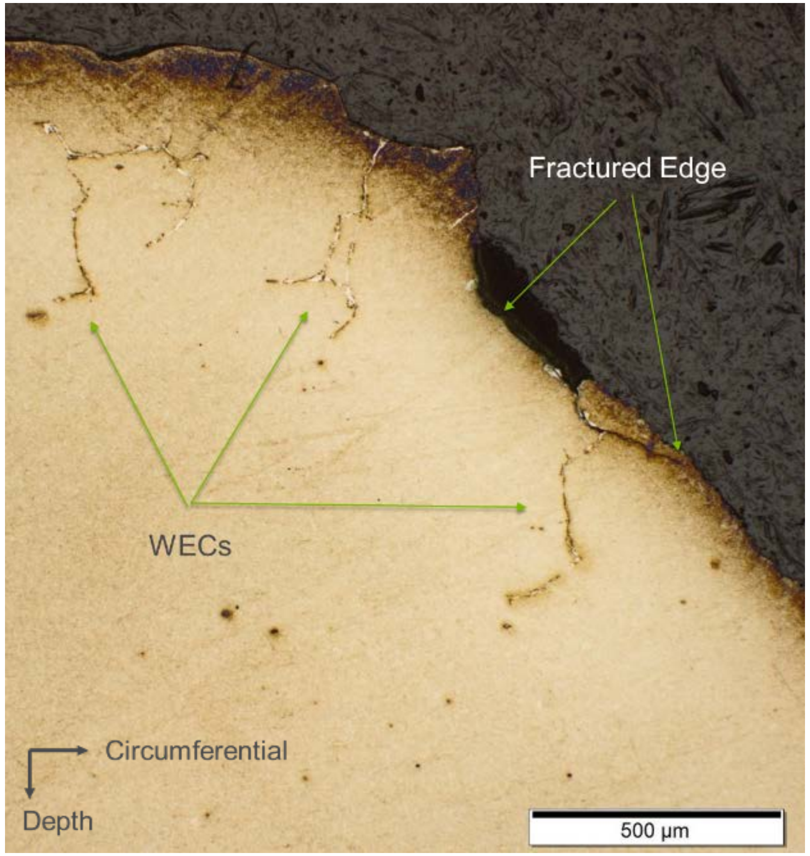




Gould, Benjamin, and Aaron Greco. "The Influence of Sliding and Contact Severity on the Generation of White Etching Cracks." doi:10.1007/s11249-015-0602-6.

MAIN BEARING WEC FAILURES

- White Etching Cracks (WECs) observed in subsurface analysis of main bearings, with similar characteristics to WECs observed in high-speed shaft gearbox bearings.
- Evidence of WECs initiating at inclusion in the steel, indicating that steel cleanliness could be a factor
- Electrical current was also measured up-tower across main bearing contact for this example bearing



POSSIBLE PATHWAYS TO PREMATURE WEC BEARING FAILURE

System

Idling

Emergency stop

Grid loading

Wind transient

Misalignment

Torque reversals

Incomplete grounding

Lightening strike

Component

Slip

Vibration

Bending load

Impact load

Stray current

Water contamination

Tribo-chemistry

Contact

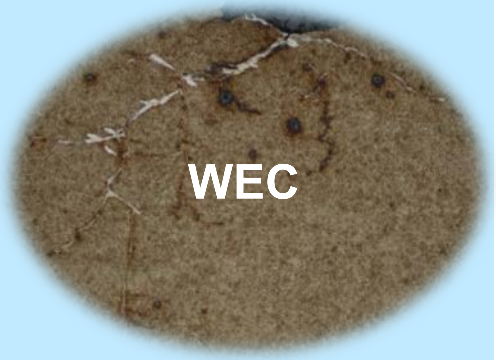
Lubricant Chemistry

Mechanical stress
- Surface shear (slip)
- Load

Electrical current

Sub-Surface

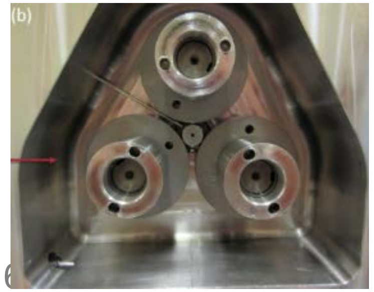
Material Compromise
- Embrittlement
- Heat effect

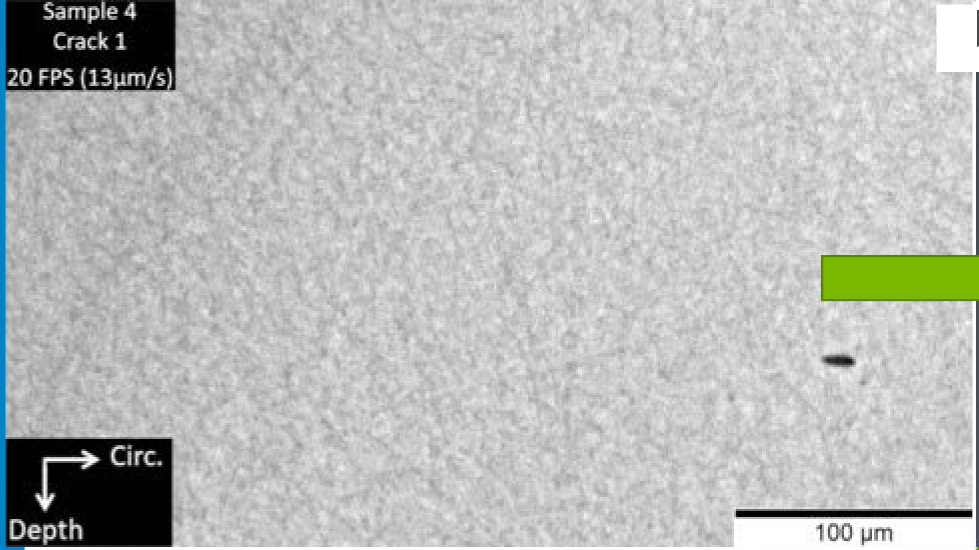


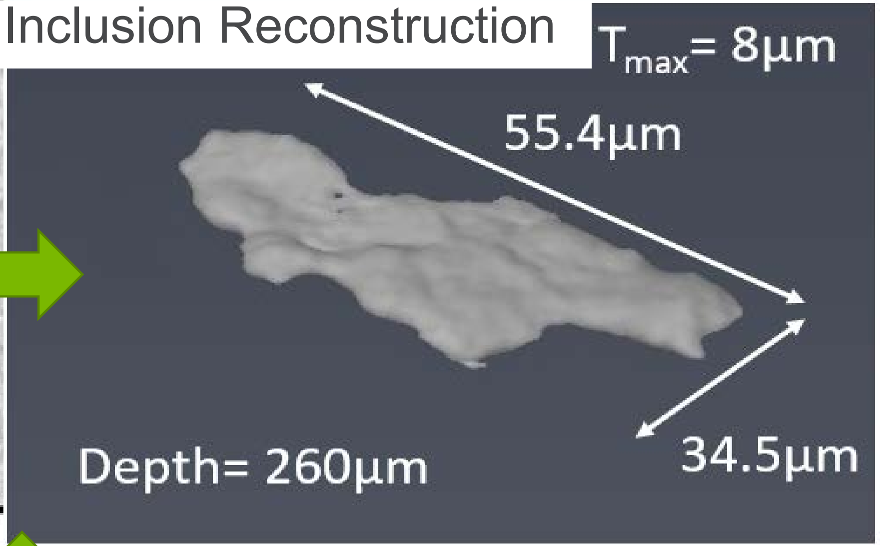
Localized over strain
- Plasticity

Photo from NREL

Photo from NREL

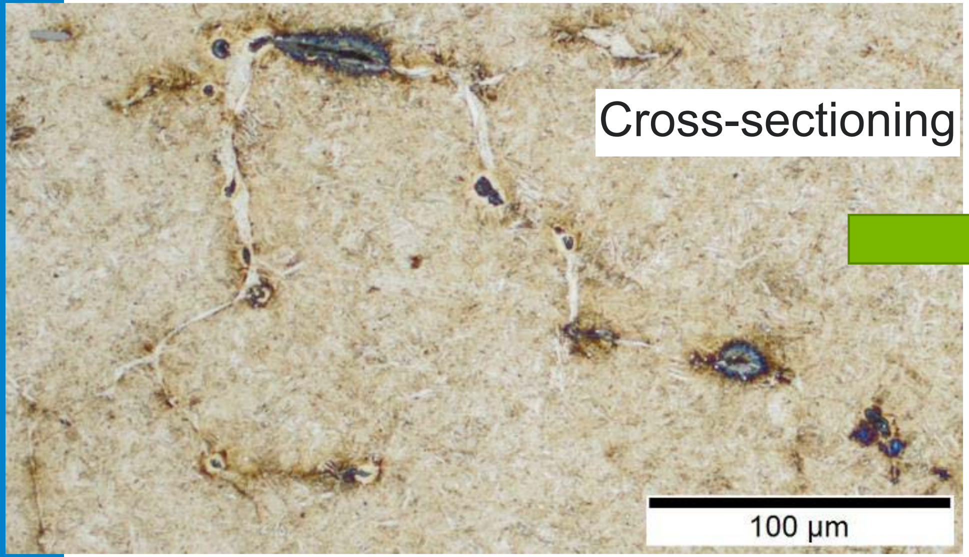


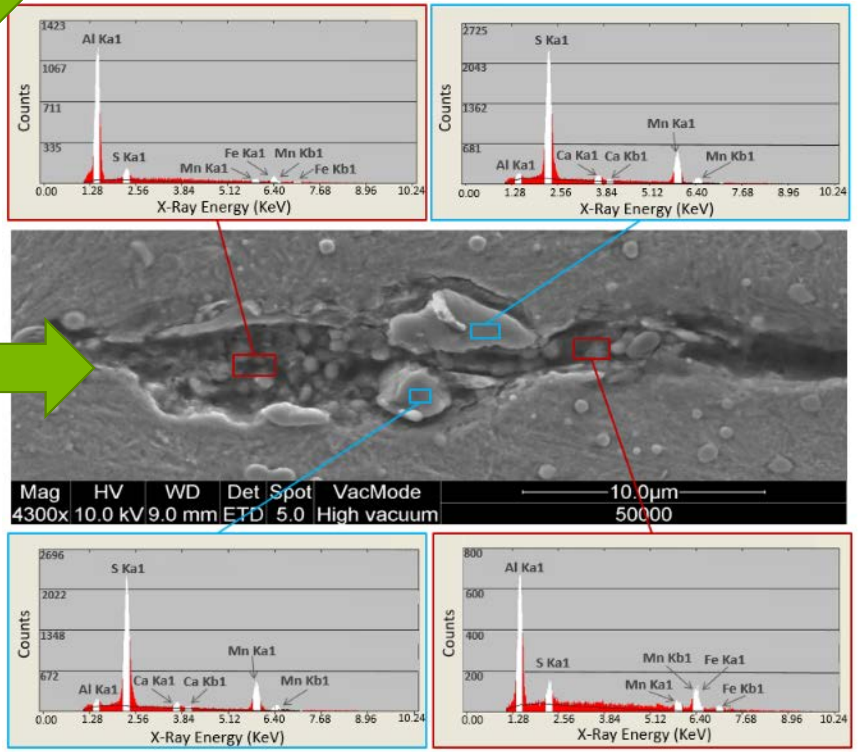


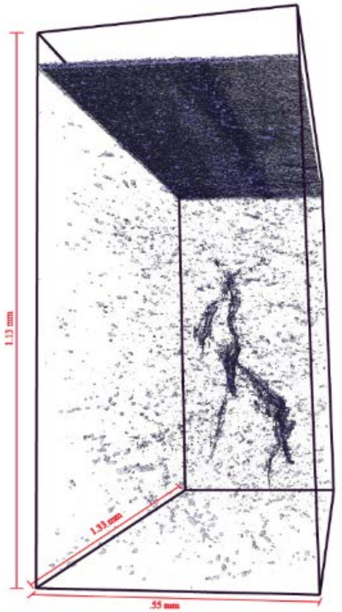


X-ray Tomography

EDX Identification







Gould, Benjamin, et al. "An analysis of premature cracking associated with microstructural alteration in an AISI 52100 failed wind turbine bearing using X-ray tomography" *Materials & Design,* 117 (Mar. 2017) 417-429 doi:10.1016/j.matdes.2016.12.089

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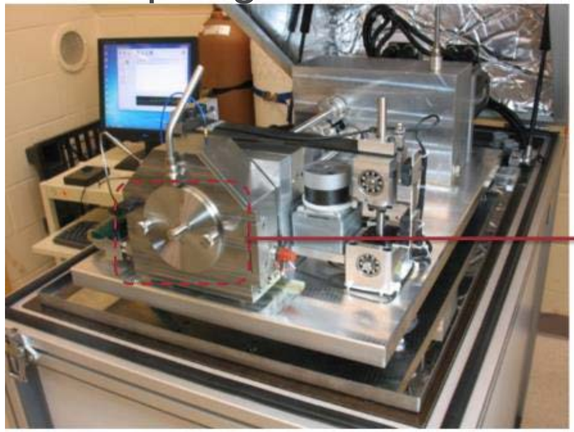
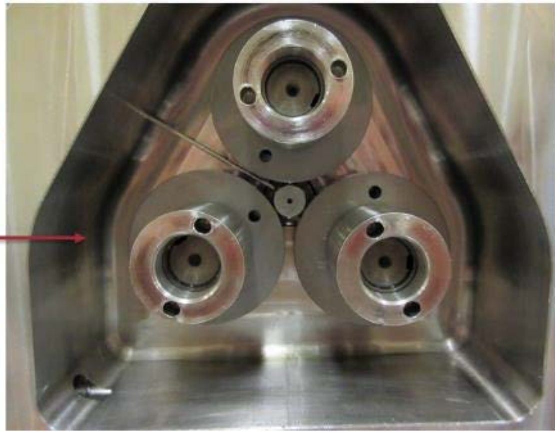
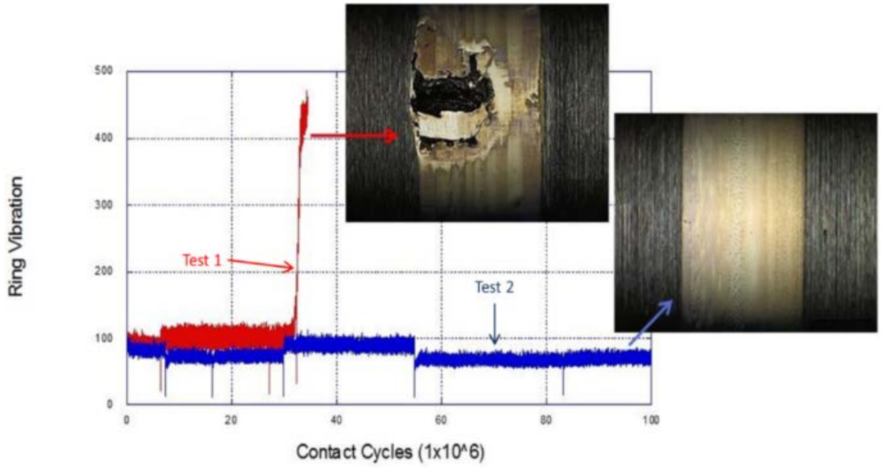
ACCELERATED BENCHTOP TESTING

- Enables the study of WEC drivers independently *(load, slip, lubricant chemistry, stray electrical currents, etc.)*
- Accelerated, low-cost method for testing mitigation technologies *(lubricants, coatings, advanced materials)*

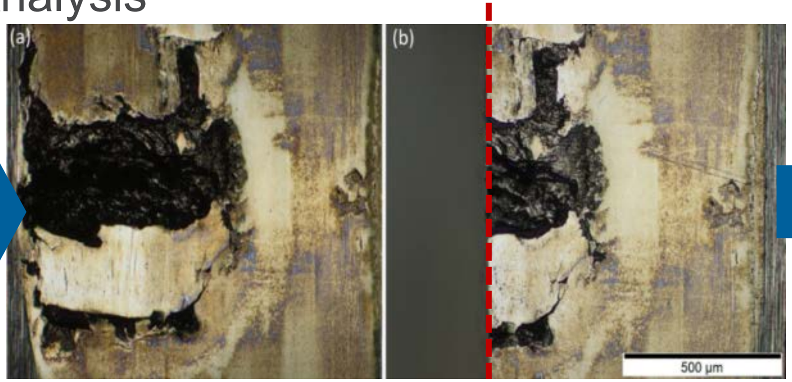
Bench-Top Rig

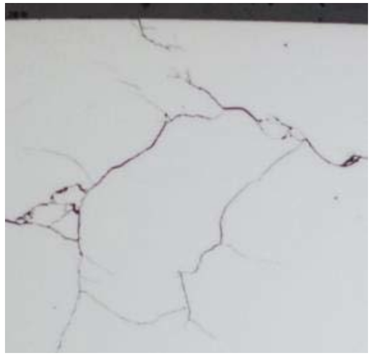






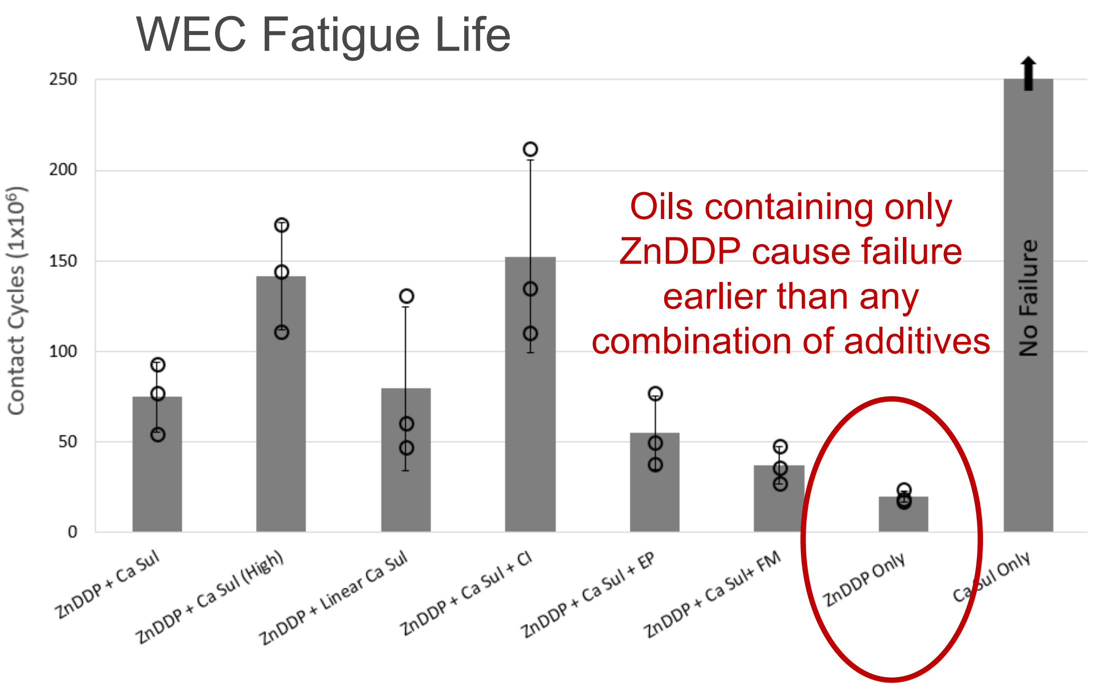
Post-Test Sample Analysis

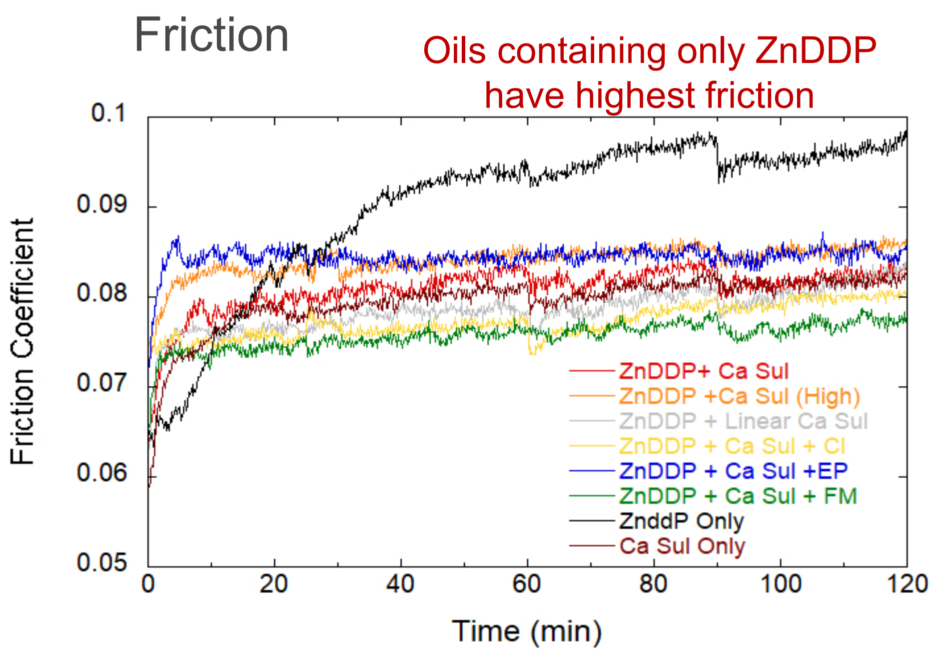




LUBRICANT ADDITIVE CHEMISTRY

- Reverse-engineered the "bad reference oil"
- Identified that a common anti-wear additive, zinc dialkyldithiophosphate (ZnDDP), accelerated WEC failures
- Oils containing only ZnDDP also have the highest friction, resulting in higher frictional heating

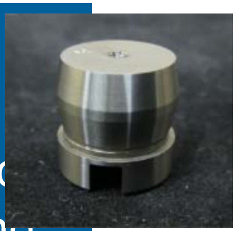


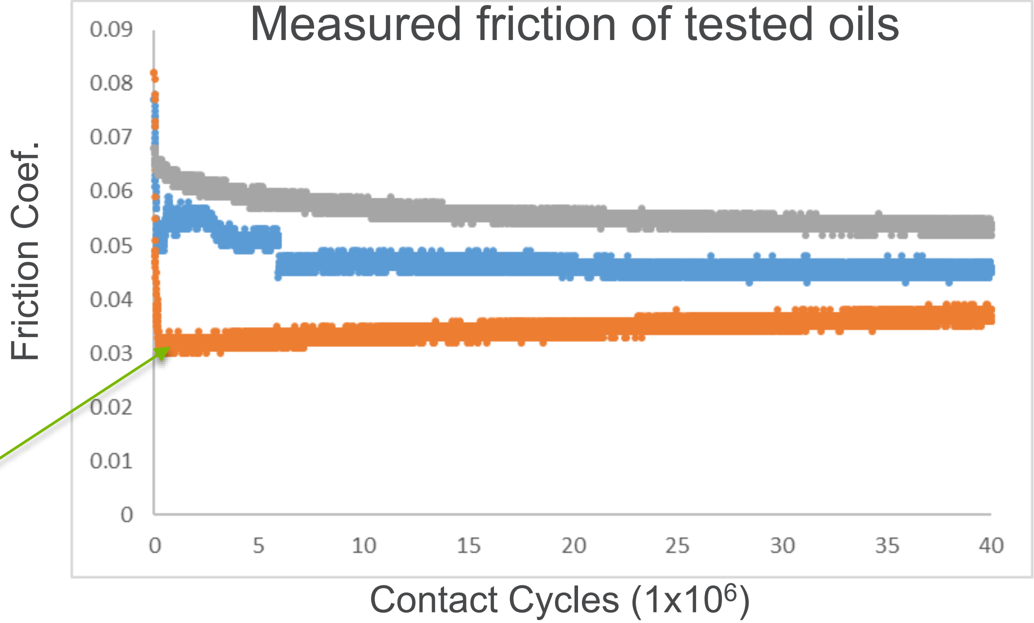


Gould, Benjamin, Nicholaos G. Demas, Grant Pollard, Jakub Jelita Rydel, Marc Ingram, and Aaron C. Greco. "The Effect of Lubricant Composition on White Etching Crack Failures." *Tribology Letters* 67, no. 1 (November 29, 2018): 7. https://doi.org/10.1007/s11249-018-1106-y.

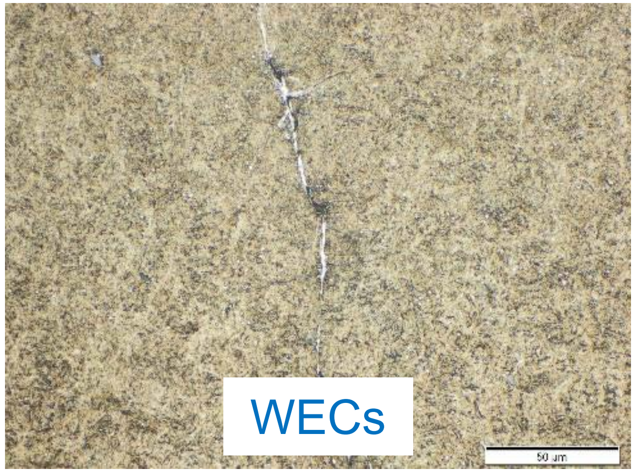
WIND TURBINE GEAR OILS WITH WIND TURBINE BEARING STEEL

- WEC tests were performed using test samples extracted from wind turbine bearings
- Several commercial wind turbine gear oils showed WECs, which under the same test conditions using clean steel would not show WECs
- A correlation was observed between friction and WEC formation:
  - Higher friction oils => higher probability of WEC formation

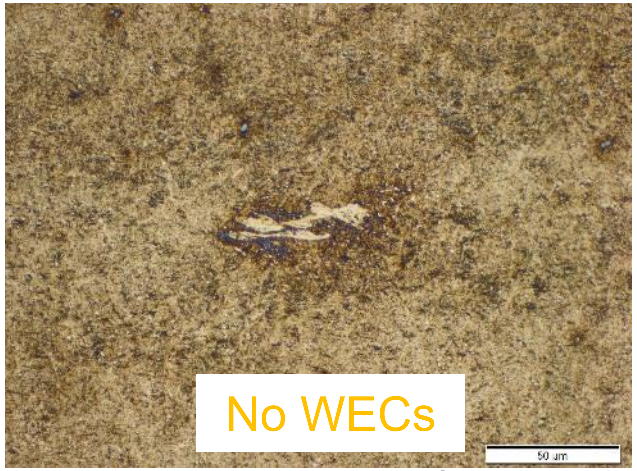




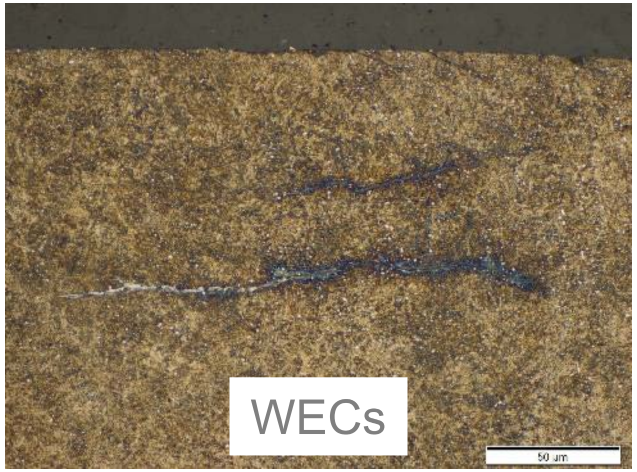
Commercial Oil 1



Commercial Oil 2



Commercial Oil 3

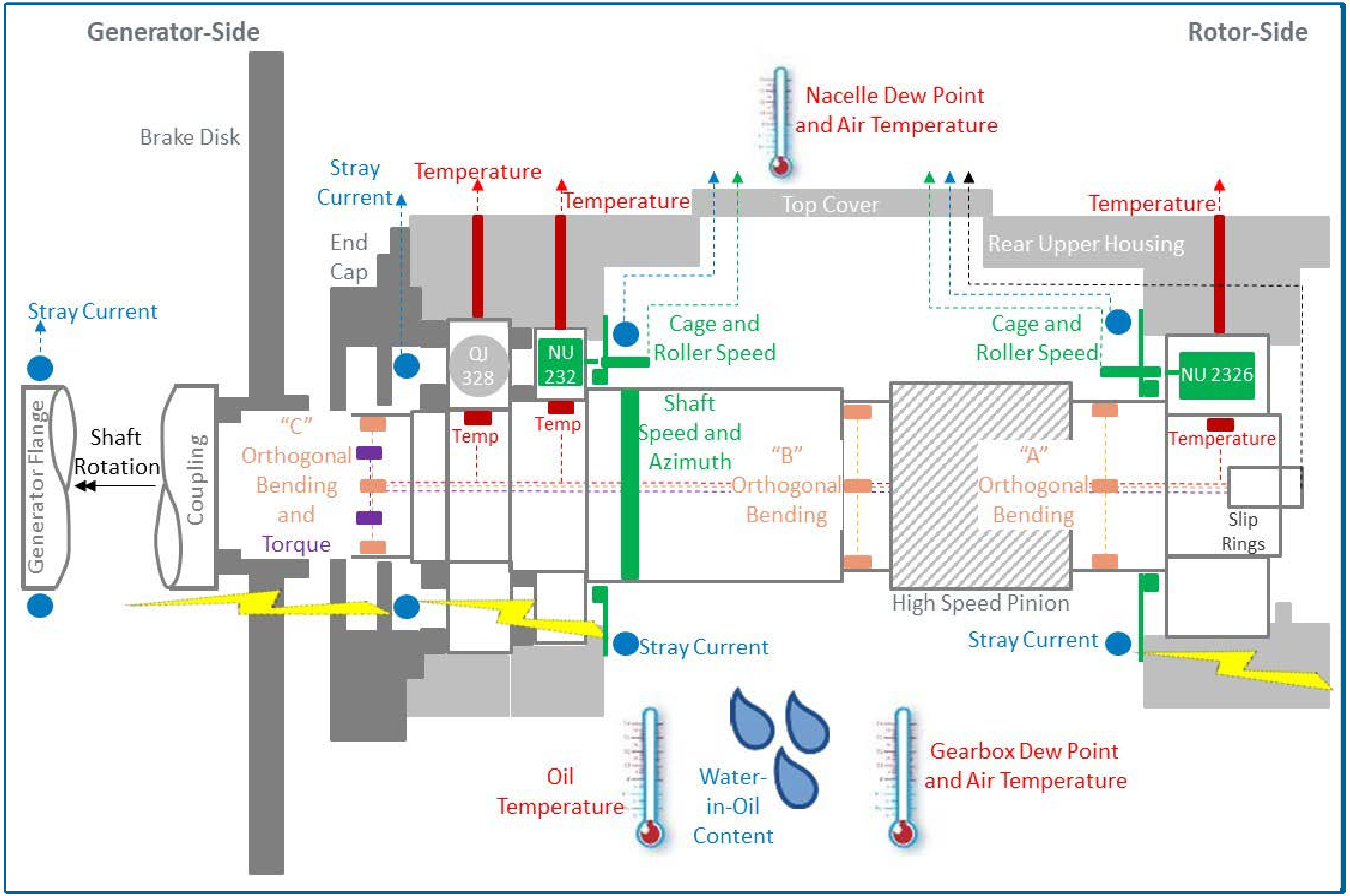


Gould, B., et al. *Materials Science and Engineering: A* 751 (March 28, 2019): 237–45. https://doi.org/10.1016/j.msea.2019.02.084.

MOTIVATION FOR TESTING ELECTRICAL CURRENT

- The National Renewable Energy Laboratory, in collaboration with SKF, fully instrumented the main bearing and the high-speed shaft of the gearbox within a wind turbine.

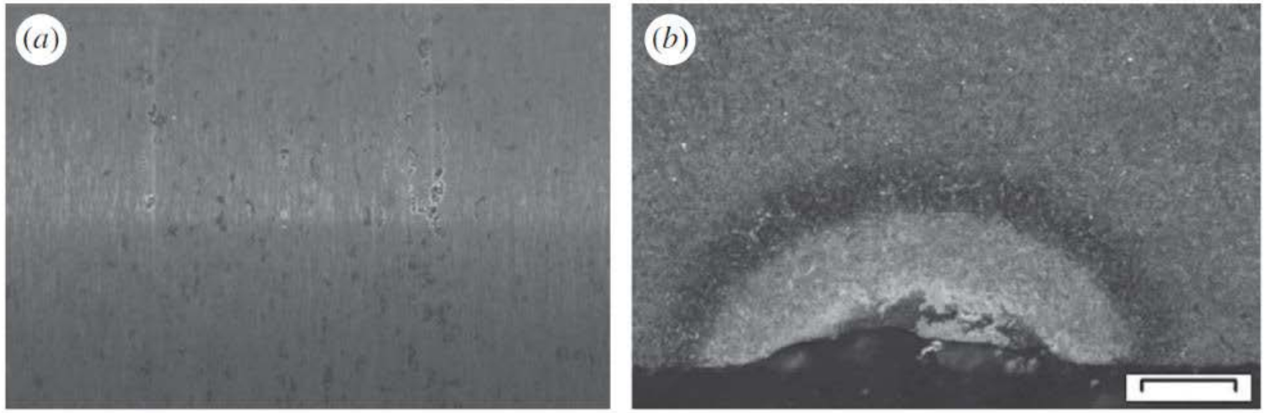
- High levels of slip as well as shaft current were documented
  - The main bearing showed current levels as high as 800 mA stemming from the rotor
  - The HSS bearings showed currents over 1 A stemming from the generator.



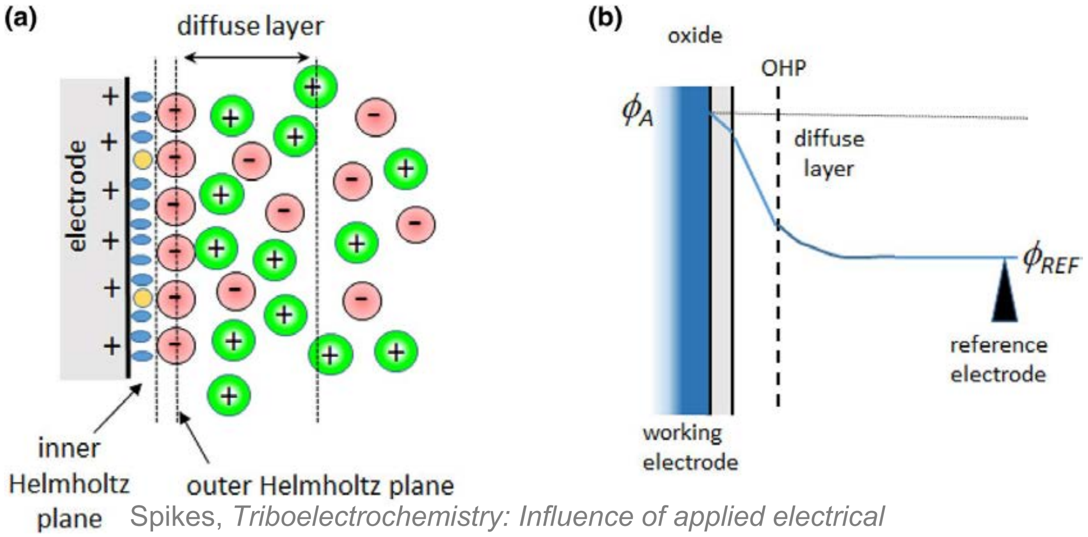
Keller, Guo, and Sethuraman, Uptower Investigations of High-Speed-Shaft Bearing Reliability (2019)

ELECTRICALLY INDUCED DAMAGE MECHANISMS

- Fluting
  - Material vaporization and microstructural alterations caused by high-voltage differentials, and fully lubricated/separated surfaces



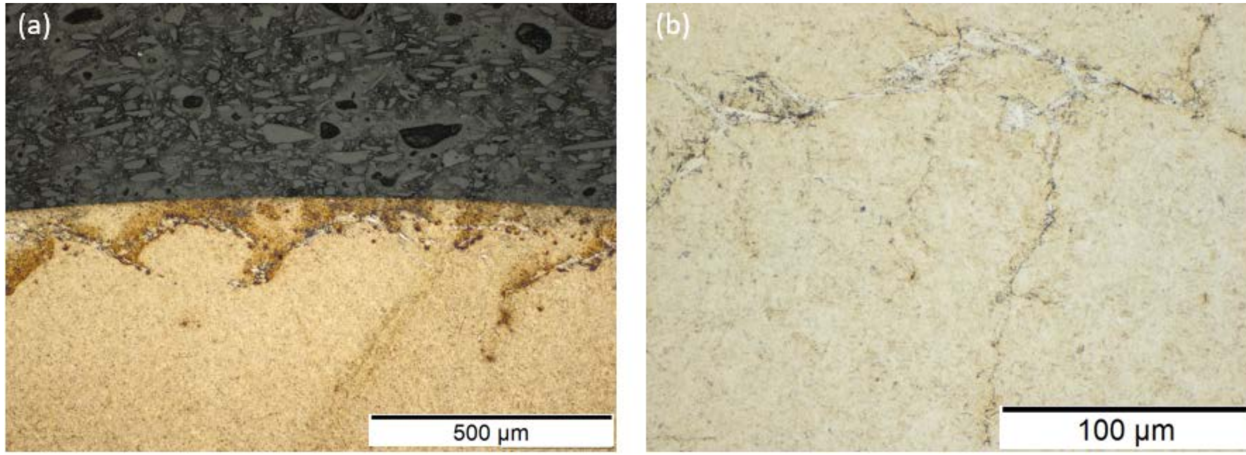
Kotzalas and Doll, *Tribological Advancement for reliable wind turbine performance* (2014)



Spikes, *Triboelectrochemistry: Influence of applied electrical potentials on friction and wear of lubricated contacts* (2020)

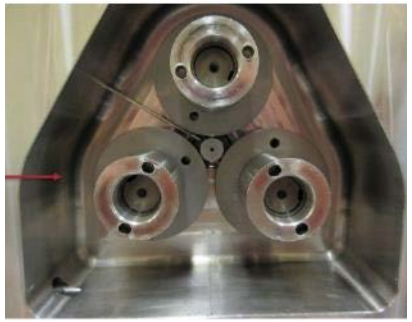
- Triboelectrochemistry
  - Effects on polar additives
  - Effects on redox reactions (oxidation/reduction)
    - Including water within lubricant
  - Effect on accelerated lubricant degradation

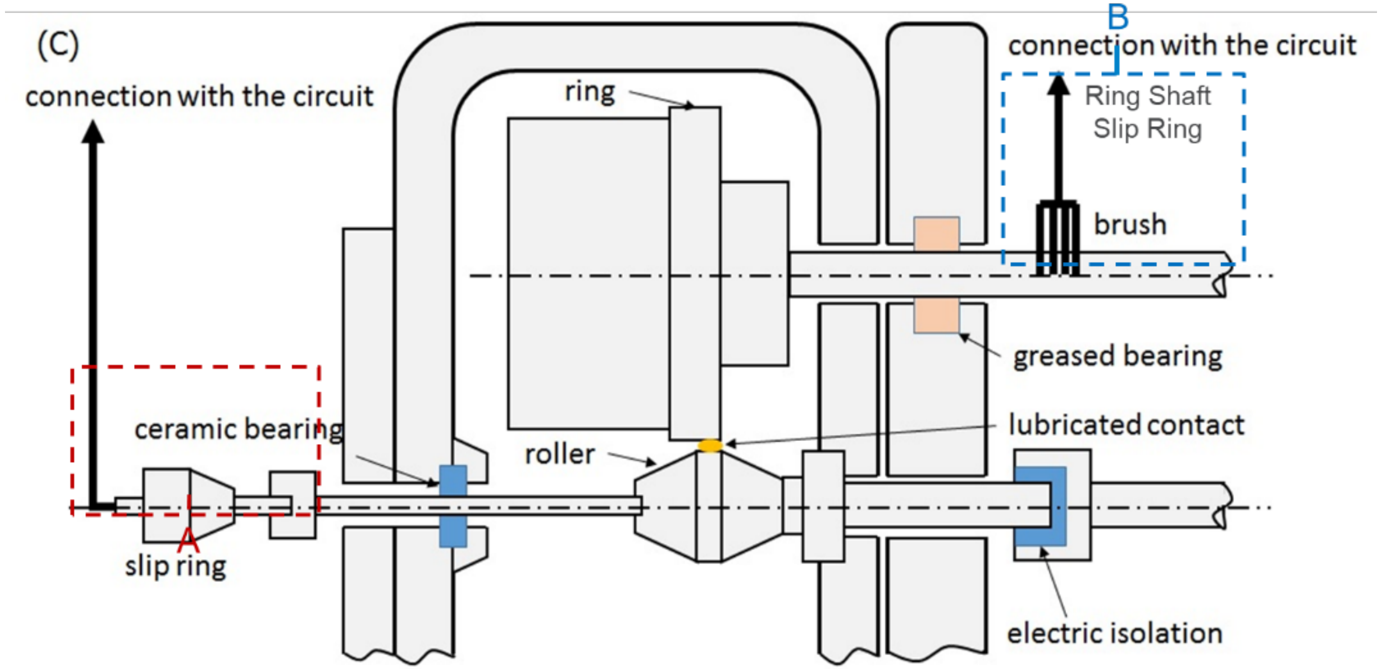
- White-Etching Cracks
  - Hydrogen embrittlement
  - Joule Heating
  - Electrically accelerated local plasticity

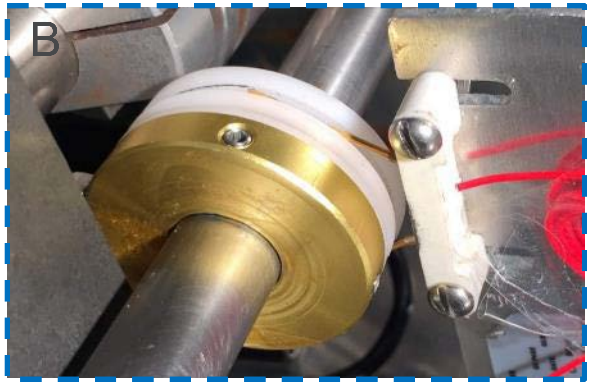


TEST RIG MODIFICATIONS TO APPLY ELECTRICAL CURRENT

- Benchtop rig was modified to enable application of controlled electric current across contact
- Accommodates testing in both oil and grease



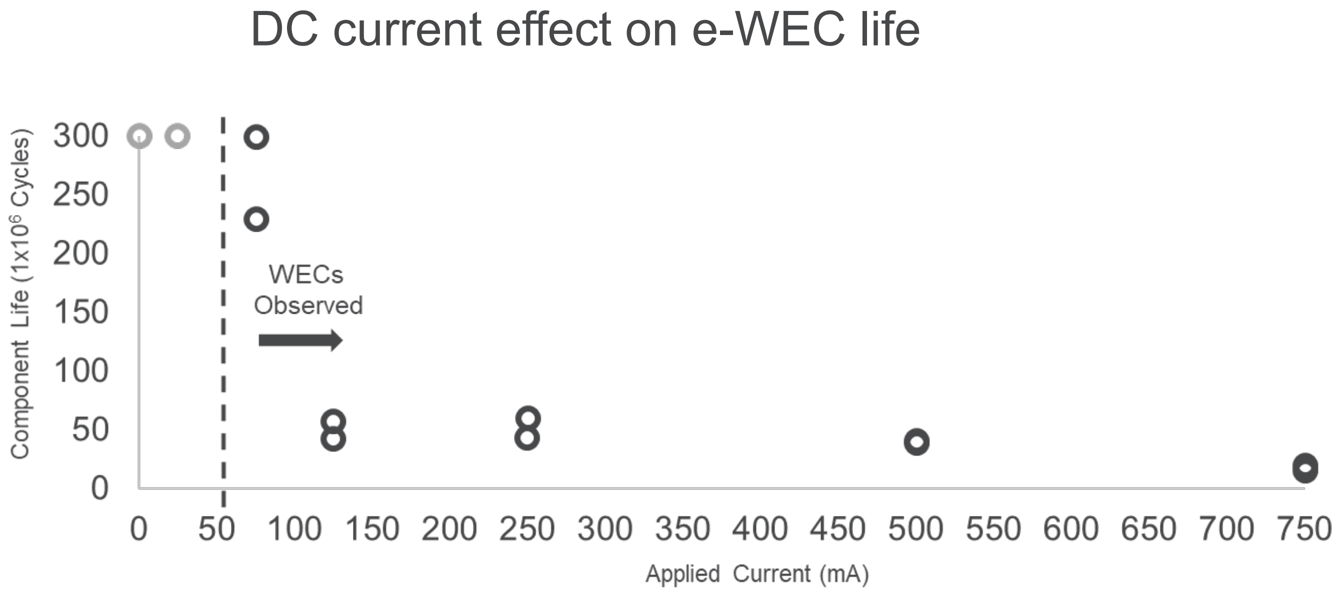


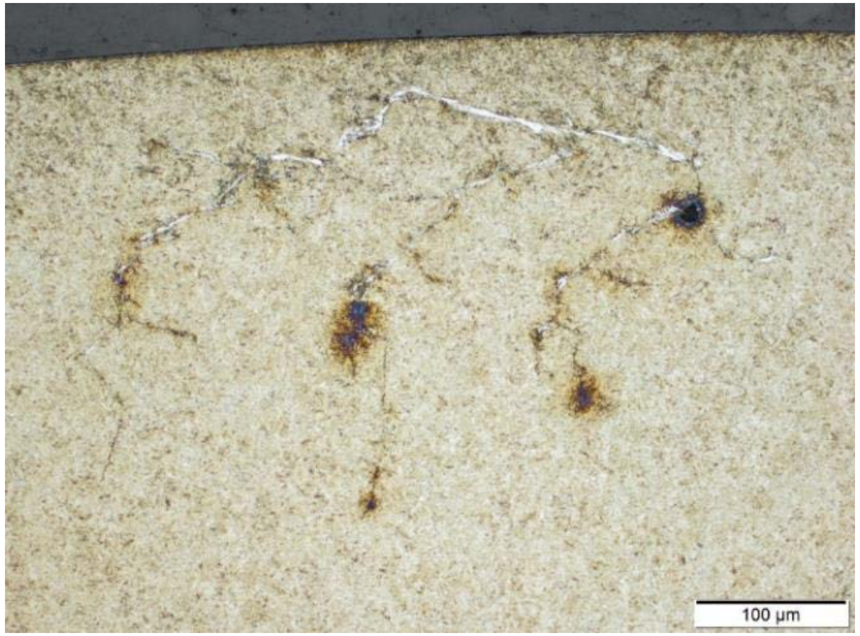


Gould, Benjamin, Nicholas Demas, Robert Erck, Maria Cinta Lorenzo-Martin, Oyelayo Ajayi, and Aaron Greco. "The Effect of Electrical Current on Premature Failures and Microstructural Degradation in Bearing Steel." *International Journal of Fatigue* 145 (April 1, 2021): 106078. https://doi.org/10.1016/j.ijfatigue.2020.106078.

WEC FORMATION IN DC ELECTRICAL CURRENT
e-WEC

- WECs are significantly accelerated for wind turbine gear oils when electrical current is applied
- Observe a strong dependence of e-WEC on current level in wind turbine gear oils, >75mA

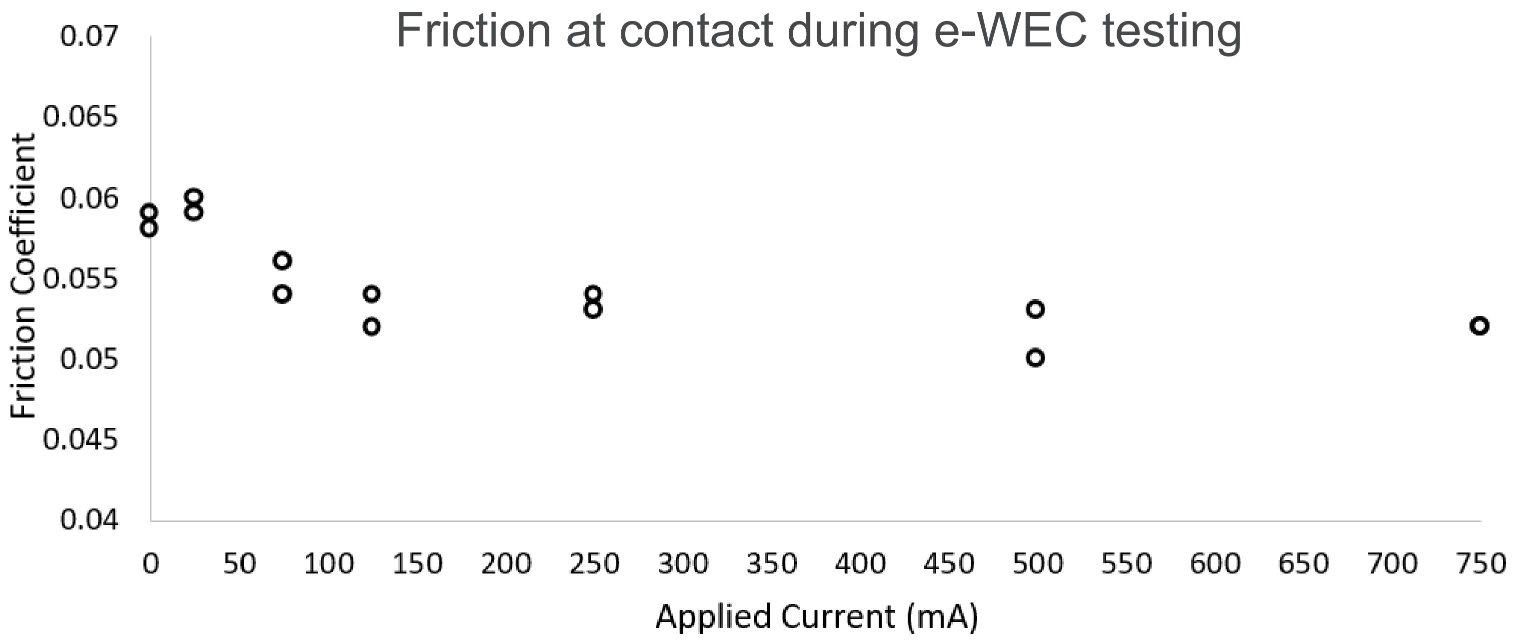




Gould, B., et al, *International Journal of Fatigue* 145 (April 1, 2021): 106078. https://doi.org/10.1016/j.ijfatigue.2020.106078.

ELECTRICAL CURRENT EFFECT ON LUBRICANT

- Applying electrical current changes how wind turbine gear oils behave/perform
  - Observed to impede tribofilm formation on surface, other oil chemistries show increased activation with applied electrical current
  - Measured friction reduction with increased current, likely due to tribofilm
  - Applying electrical current adds additional energy input, contributing to total energy



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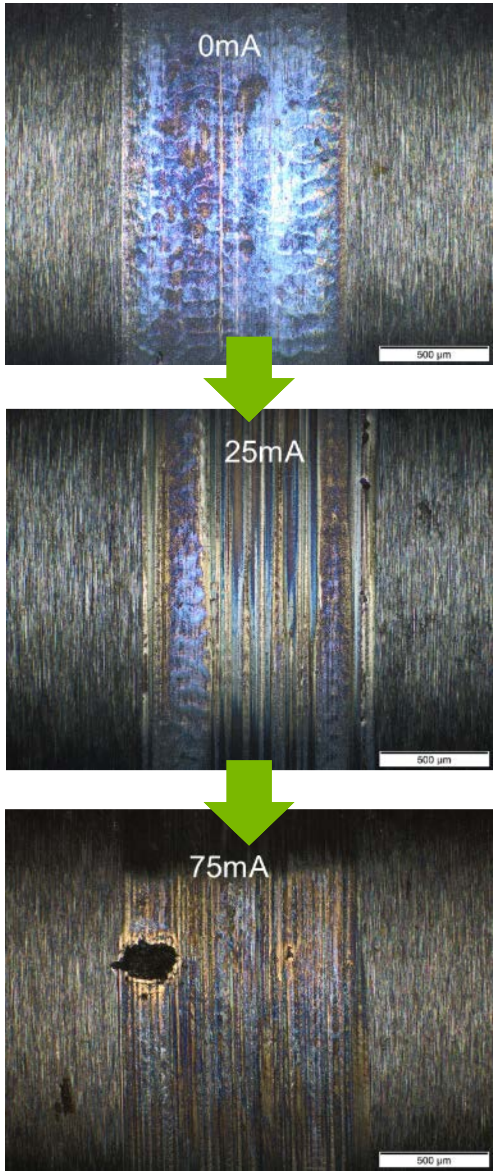
Tribofilm formation

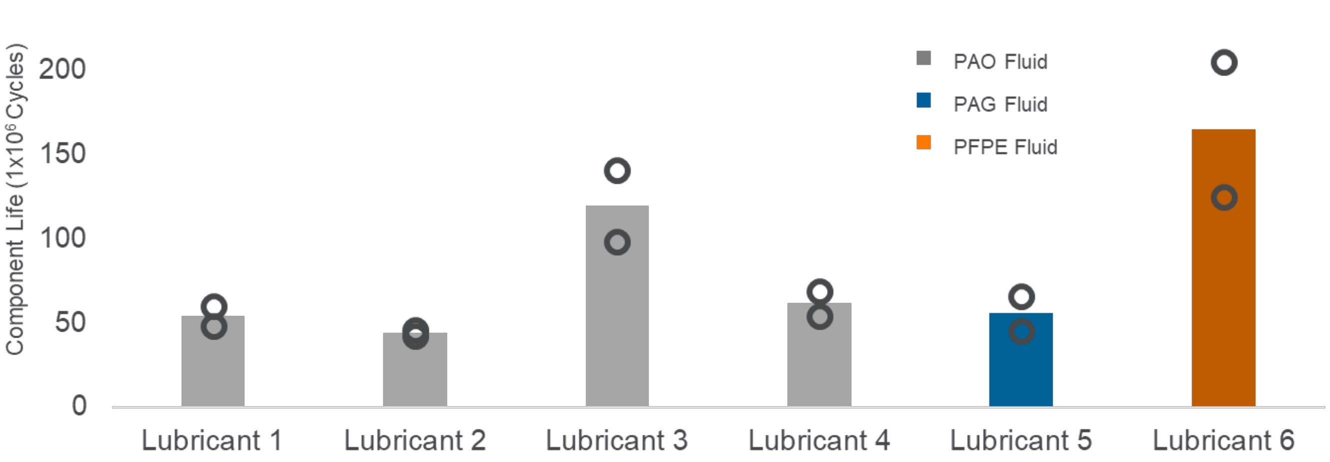


E-WEC PERFORMANCE OF WIND TURBINE GEAR OILS

- Six tested gear oils all showed e-WECs within run-out limit
- Propensity of e-WECs are higher than other WEC drivers
- Oils 1–5 are commercial wind turbine gear oils, 6 is a PFPE oil that does not contain hydrogen (hydrogen is not required to form WECs)
- Oils 1–4 have the same base oil but different additive chemistry
- Initial results show coatings are effective but not preventative

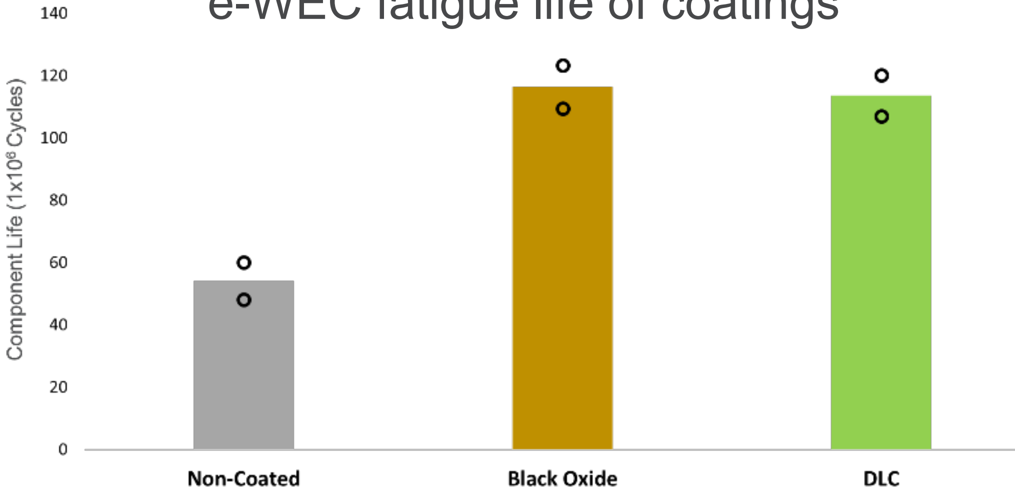
e-WEC density under test track

e-WEC fatigue life of commercial lubricants



Gould, B., et al, *International Journal of Fatigue* 145 (April 1, 2021): 106078. https://doi.org/10.1016/j.ijfatigue.2020.106078.

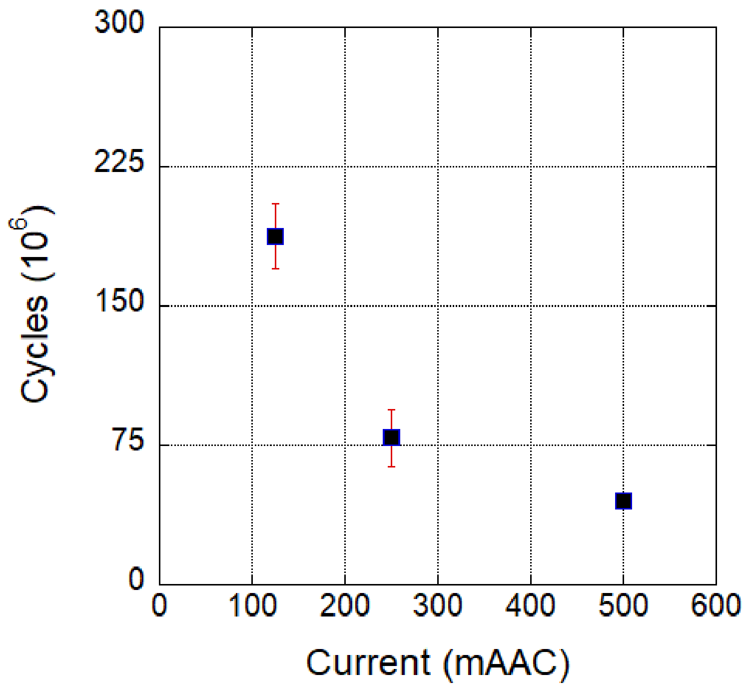
e-WEC fatigue life of coatings



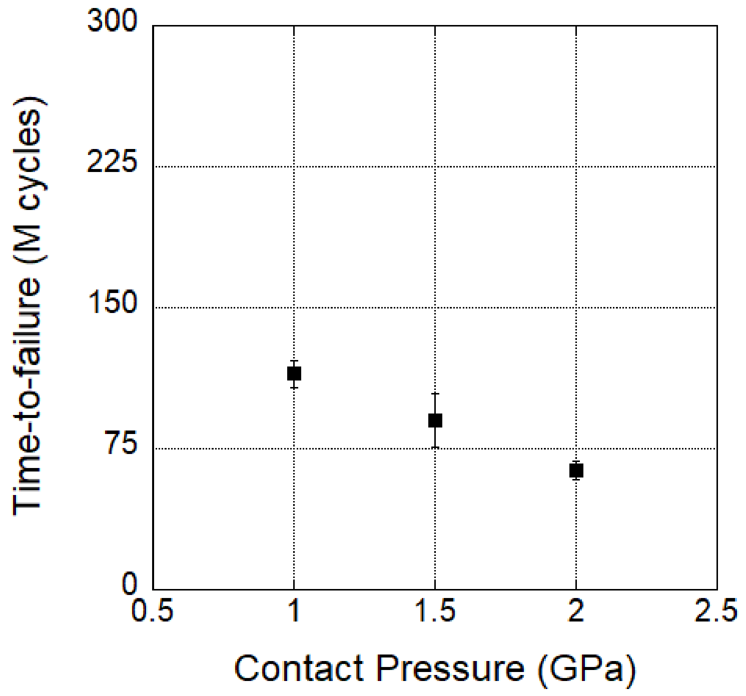
PARAMETRIC STUDY OF E-WEC FAILURES

Commercial ashless wind turbine gear oil, 0.5 lambda, 100C

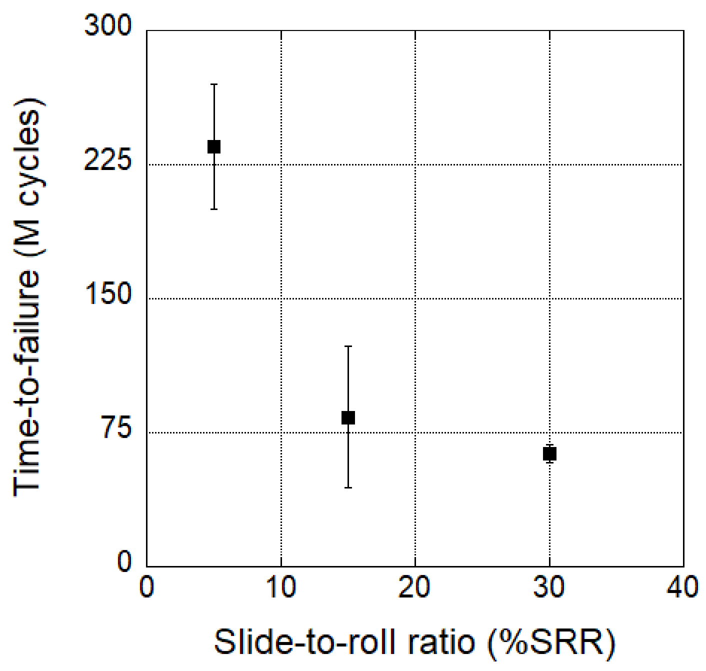
Current



Contact Pressure



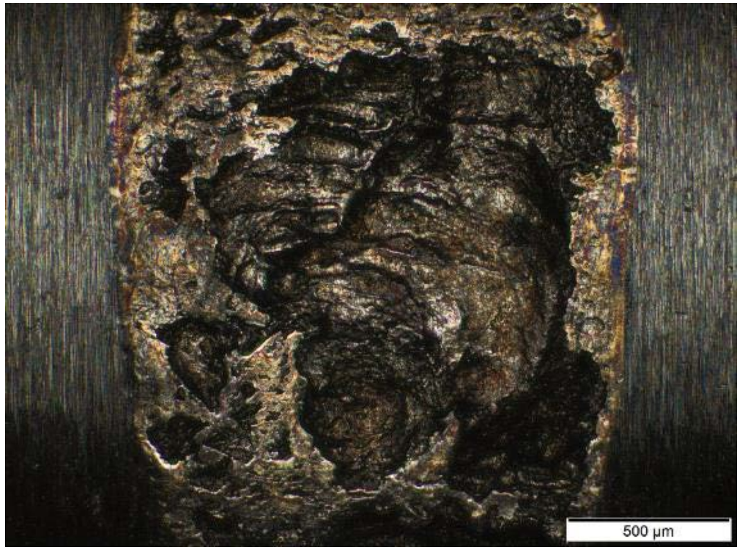
Slide-to-roll ratio

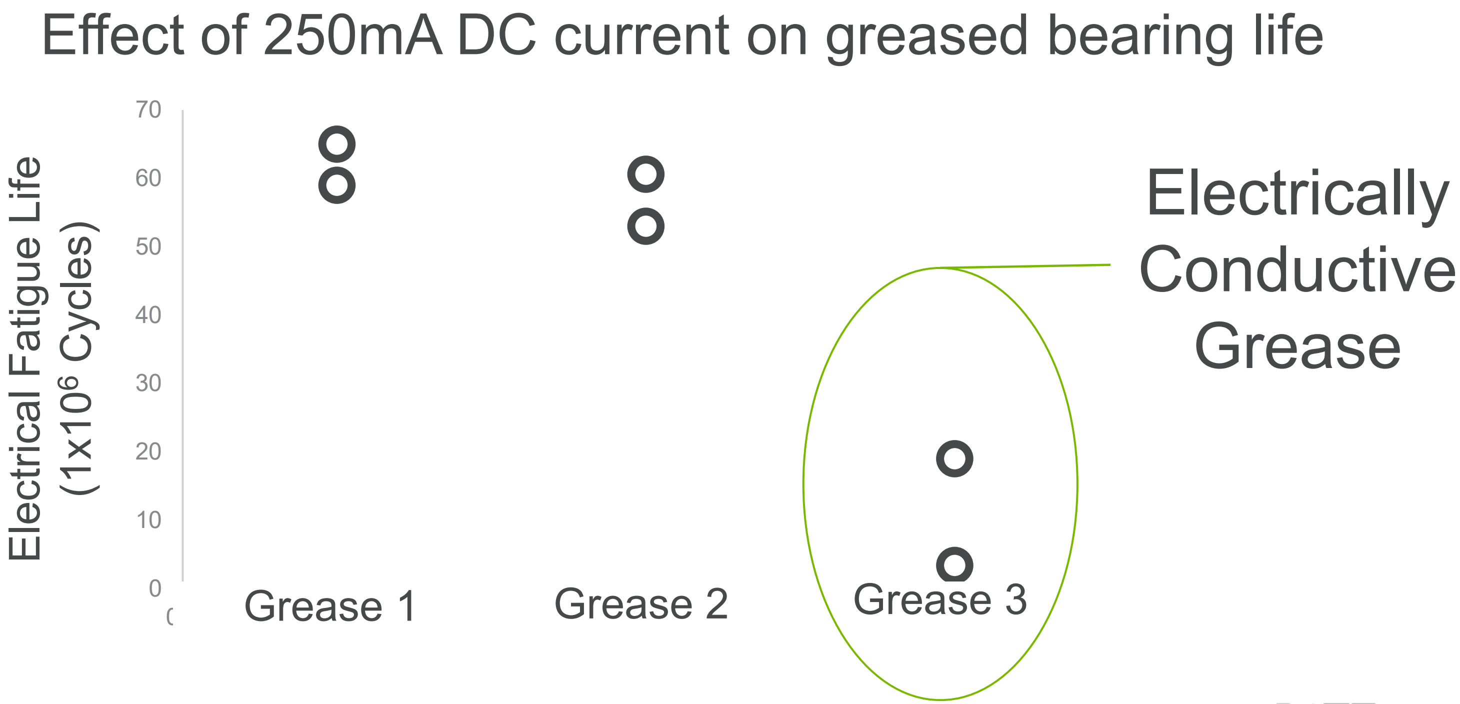


Presented at STLE Annual Meeting 2022, journal article in preparation

GREASE E-WEC TESTING

- Similar to oils, greases also show a strong dependence in time-to-failure rates on formulation.
- Lubricants that are designed to mitigate fluting may show no improvements for electrically accelerated fatigue.





Thank You

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GE Renewable Energy

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