Gearbox Reliability Collaborative Update

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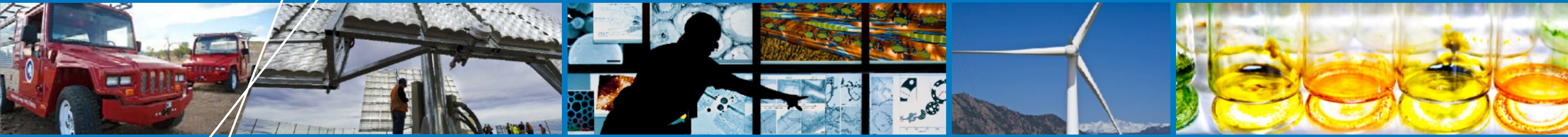
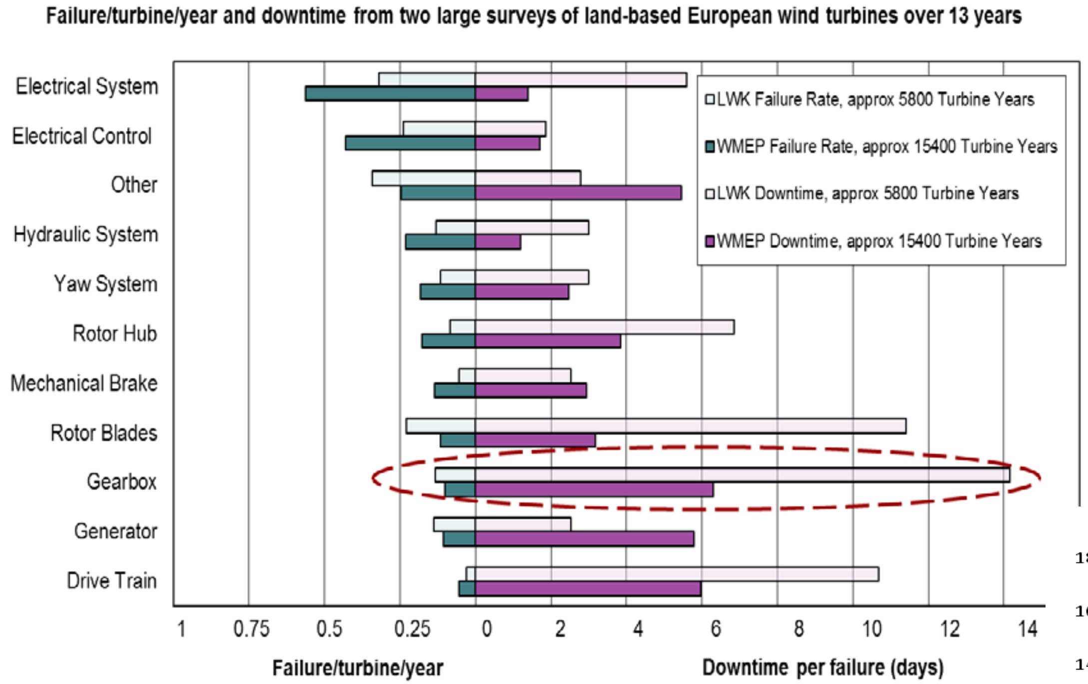
Outline

- **Introduction**
  - “Classic” Statistics
  - New Results
  - Gearbox Reliability Collaborative (GRC)
- **Status Update**
  - Key Failure Modes
  - Lessons Learned
  - Design Changes in Gearbox #3
  - Test Summary
  - Key Findings
  - Schedule
- **Next Steps for the GRC**
- **Several Other Reliability Research and Development (R&D) Activities**

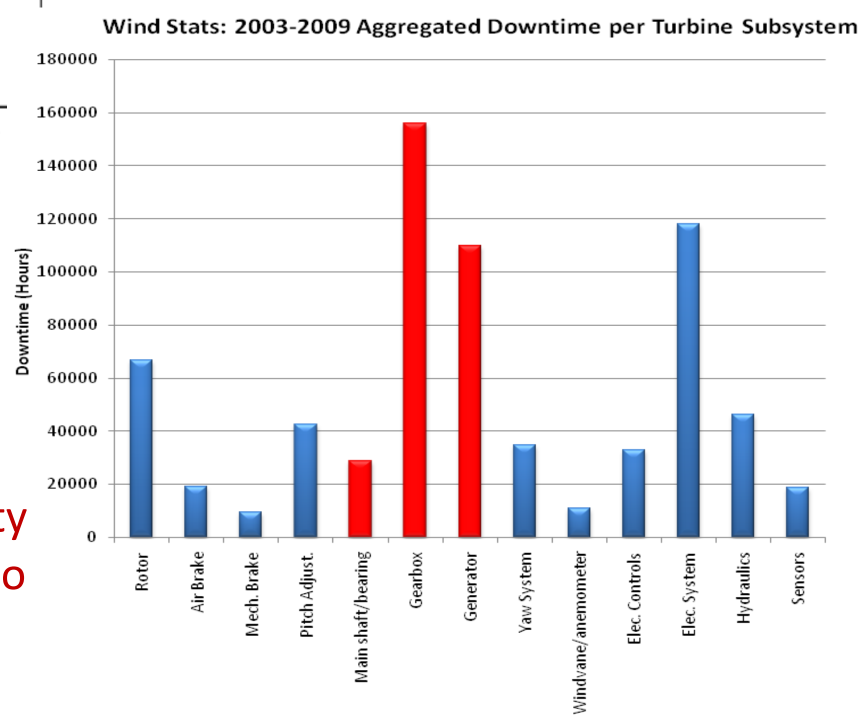


Introduction

"Classic" Statistics

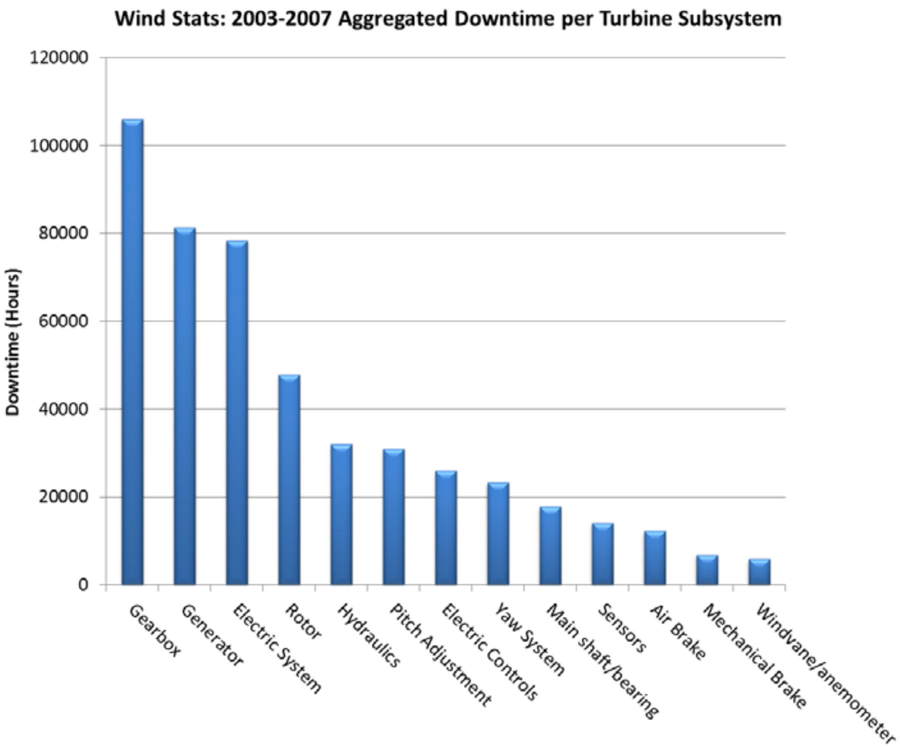


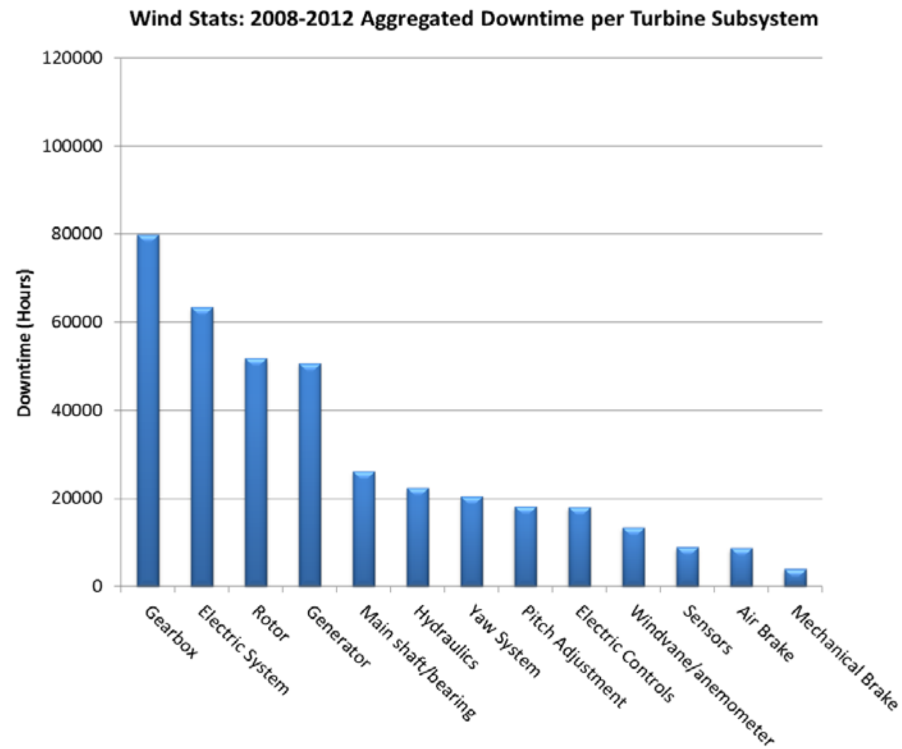
- WMEP and LWK databases represent ~2,150 turbines [1]
- Data ranging from 1993 to 2006, when both databases were closed [1]
- Gearboxes do not fail often but cause the highest downtime [1]



- Wind Stats: aggregated downtime per turbine subsystem from 2003 to 2009 [2]
- Based on the data for the first quarter of 2010, it represents about 27,000 turbines, ranging from 500 kilowatts (kW) to 5 megawatts (MW) [2]
- Highest downtime caused by gearboxes; reliability of generators and main bearings may also need to be considered because of crane costs [2]

New Results: Wind Stats [3]



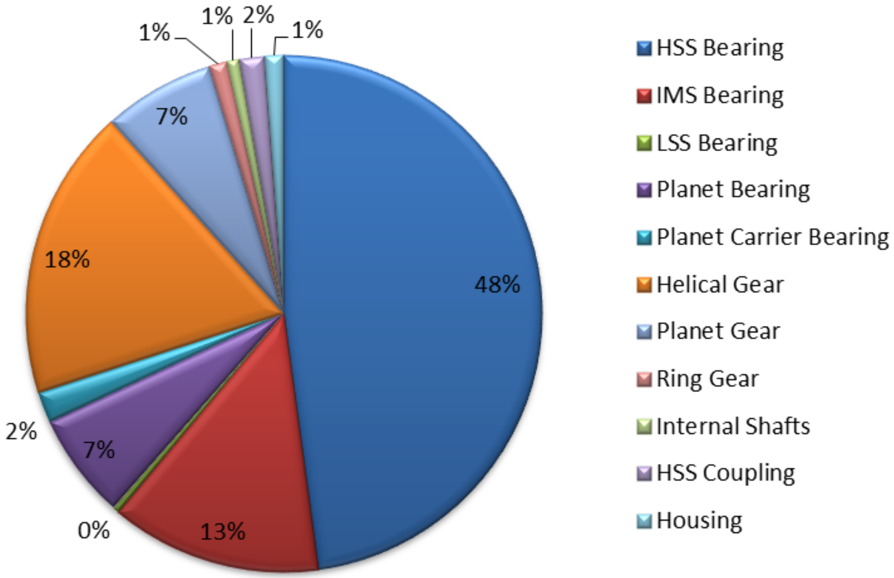


- Aggregated downtime per turbine subsystems from 2003 to 2007 (left) and from 2008 to 2012 (right):
  - Both periods indicate the gearbox as the highest downtime driver
  - The 2008–2012 period shows less downtime than the 2003–2007 period for most subsystems
  - The top four drivers stay the same with a little variation in sequence: gearbox (1 = >1), generator (2 = >4), electric systems (3 = >2), and rotor (4 = >3)

New Results: Gearbox Failure/Reliability Database [3]

- Gearbox failure event data highlighting damaged components, failure modes, and possible root causes
- About 20 partners involved, including turbine/gearbox manufacturers, owners/operators, gearbox rebuild shops, and operation and maintenance (O&M) service providers
- Assets owned by owner/operator partners represent ~31% of the United State's end of 2012 capacity
- The database contains 289 gearbox failure incidents with 257 confirmable damage records (Note: one incident may have multiple damage records and inconsistent data reporting)

- Observations:
  - Gearboxes fail in different ways
  - Bearings: ~ 70%; Gears: ~ 26%; and Others: ~ 4%
  - Both bearing and gear faults are concentrated in the parallel section
  - Top gearbox failure mode is high-speed shaft (HSS) or intermediate-speed shaft (IMS) bearing axial cracks



Gearbox Reliability Collaborative (GRC)

- Gearboxes do not always achieve their 20-year design life
- Premature failure of gearboxes increases the cost of energy through:
  - Extended turbine downtime
  - Unplanned maintenance
  - Gearbox replacement and rebuild
  - Increased warranty reserves
- The problem:
  - Is widespread
  - Affects most original equipment manufacturers (OEMs)
  - Is not driven by manufacturing defects

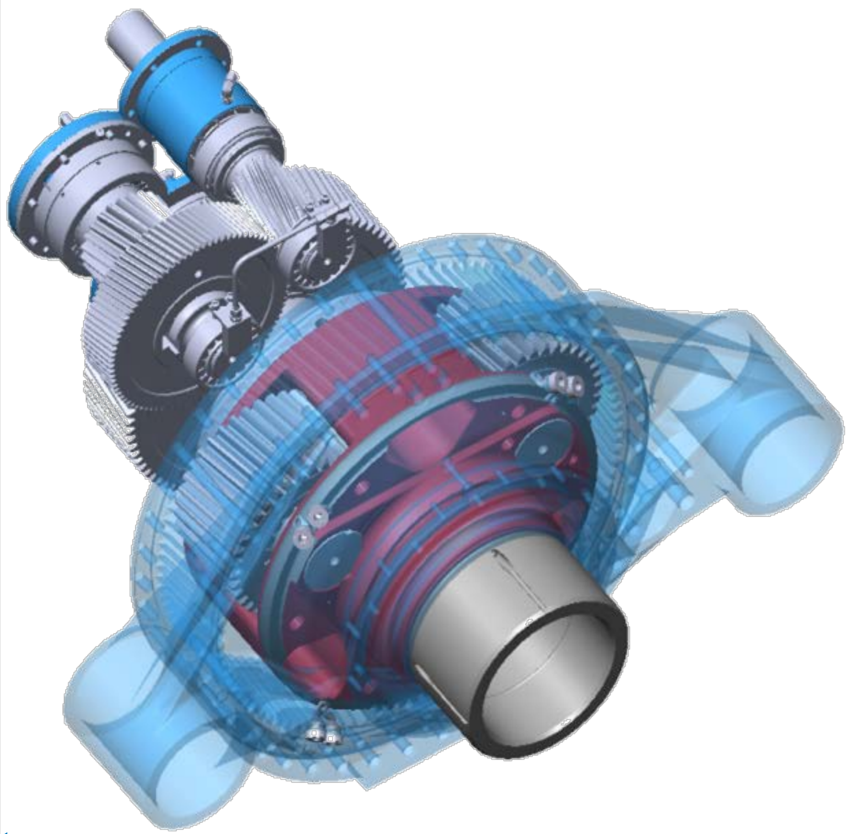


Illustration by NREL

Industry-wide collaboration is needed, but…

GRC (*Continued*)

- Technical approach:
  - Modeling and analysis
  - Field test
  - Dynamometer test
  - Failure database
  - Condition monitoring
- Goal:
  - To improve gearbox reliability and decrease O&M costs, which will reduce the cost of energy

Field Test

- Test plan
- Test turbine
- Test setup and execution

Test Turbine at NREL/*Photo by Dennis Schroeder, NREL 19022*

Dynamometer Test

- Test plan
- Test article
- Test setup and execution

NREL Dynamometer/*Photo by Lee Jay Fingersh, NREL 16913*

Analysis

- Load cases
- System loads
- Internal loads

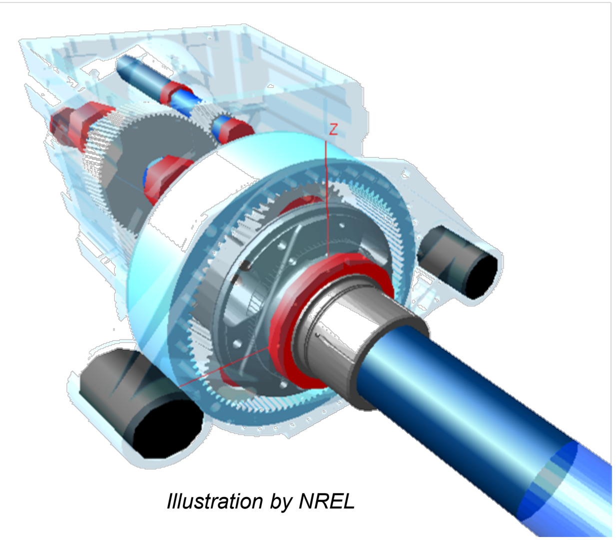


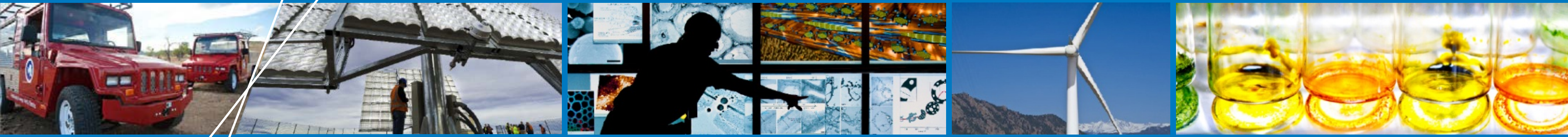
Illustration by NREL

http://www.nrel.gov/wind/grc/

GRC (*Continued*)

- Use smaller gearbox to control costs: 750 kW
- Lack of public models → redesign/rebuild gearbox
  - First iteration brings to state-of-the-art circa 2007: gearbox 1 and 2
  - Second iteration brings to state-of-the-art circa 2012: gearbox 3
- Significant internal and external instrumentation
  - Main shaft, gearbox, coupling, and generator displacements
  - Planetary section loads
  - High-speed shaft, pinion, and bearing loads recently added

Photo by Lee Jay Fingersh, NREL 16913



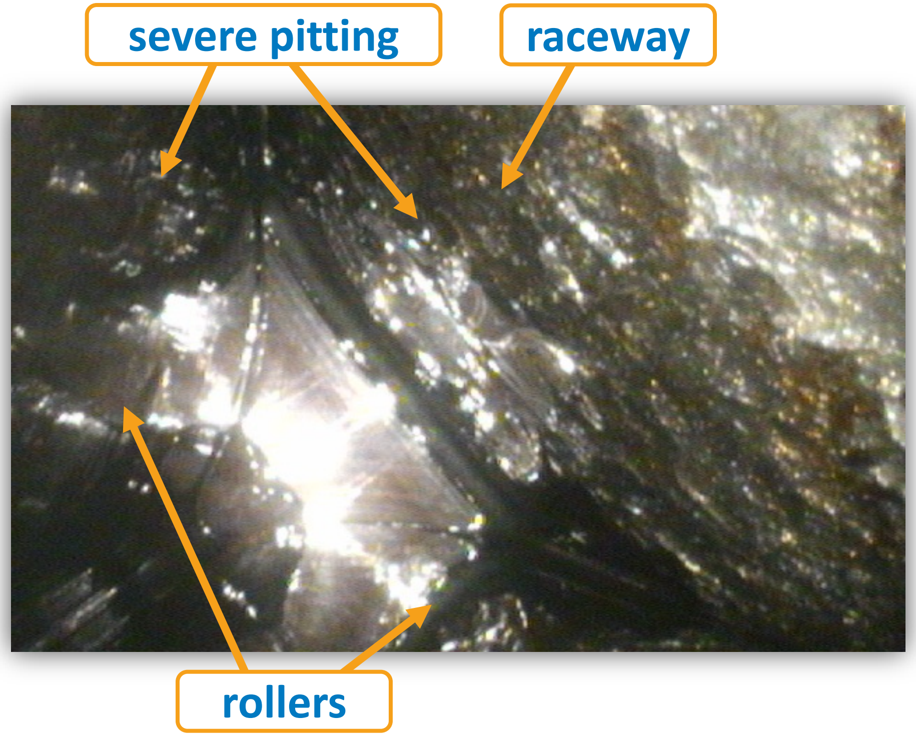
Status Update

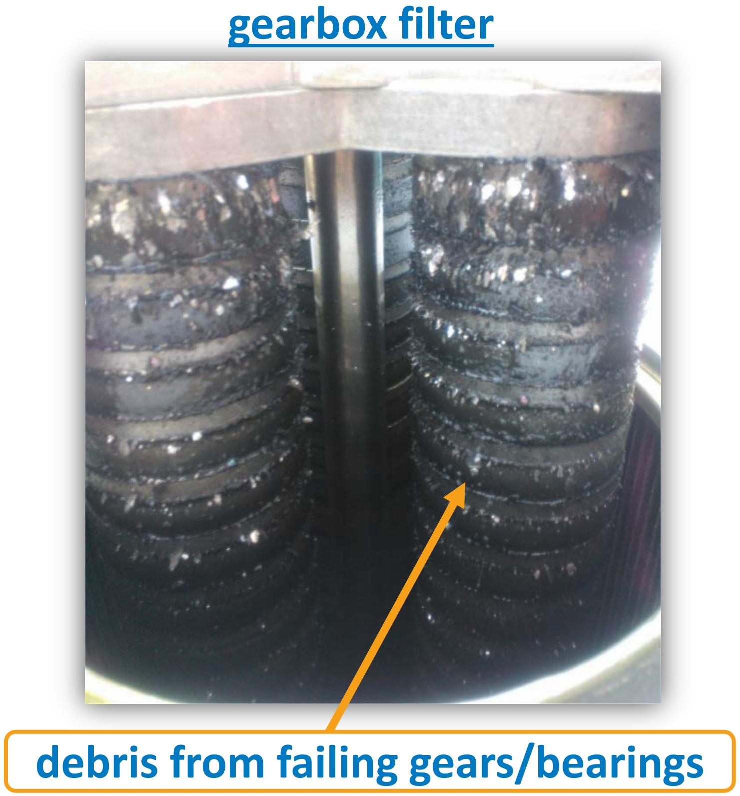
Segue Into GRC Updates

- **Industry Experience – Key Failures and Observations**
  - Planetary bearings
  - Manufacturing defects
  - Gear teeth
  - Bearing axial cracks
  - Sun splines
- **GRC Gearbox History**
  - Gearboxes 1 and 2 lessons learned
- **GRC Gearbox 3**
  - Key design improvements

Key Failure Modes – Planetary Bearings

- Most costly repair
- Commonly due to rolling contact fatigue
- Bearings are designed close to the margins (safety factor close to 1)
- Excellent filtration can save the rest of the gearbox



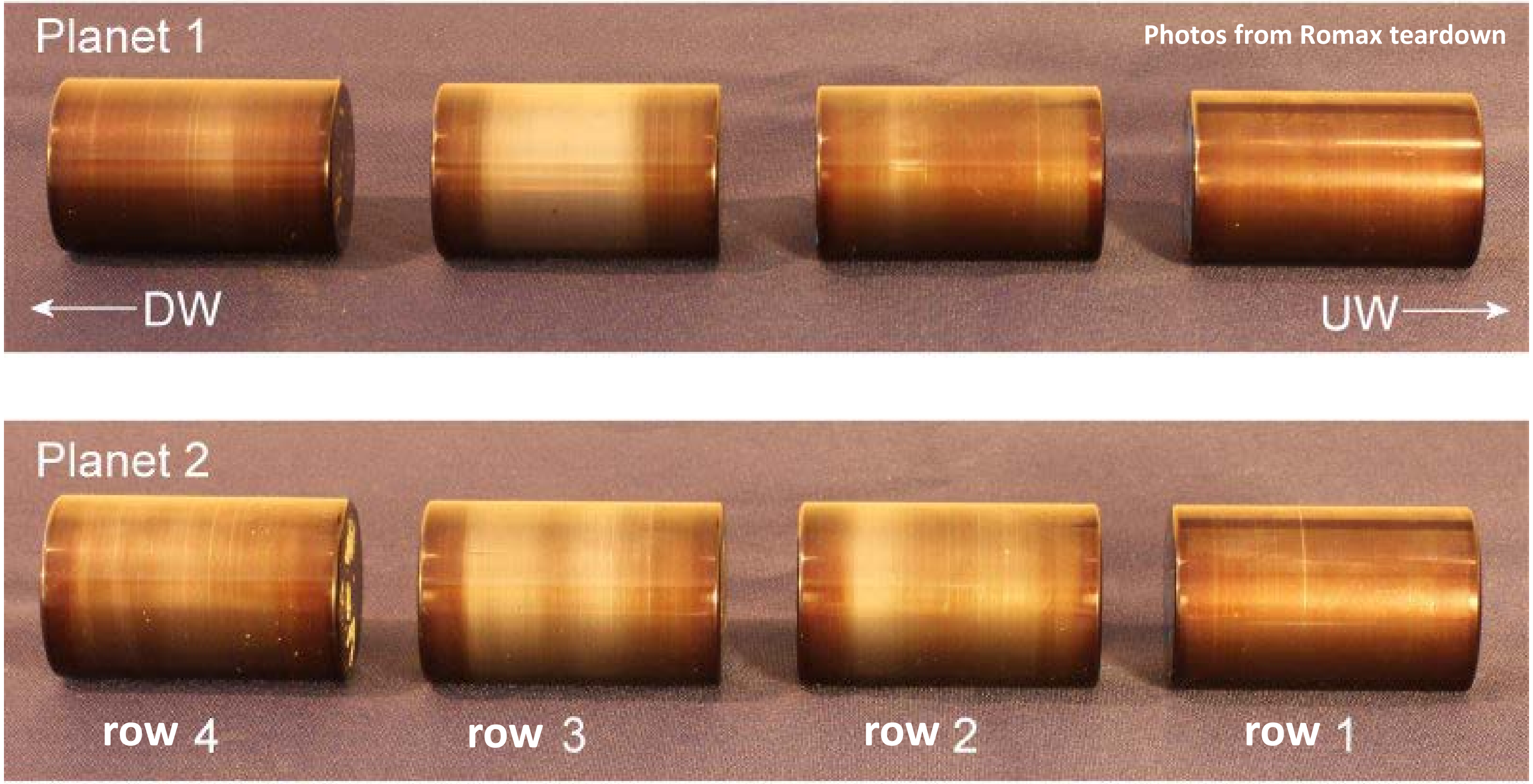


Photos by Romax Technology

Key Failure Modes – Planetary Bearings

- Poor load sharing reduces bearing life
  - Clearances, tolerances, deflections, and bearing selection affect load sharing
- GRC redesign to preloaded taper roller bearings (TRB) to improve load sharing

Downwind (DW)



Upwind (UW)

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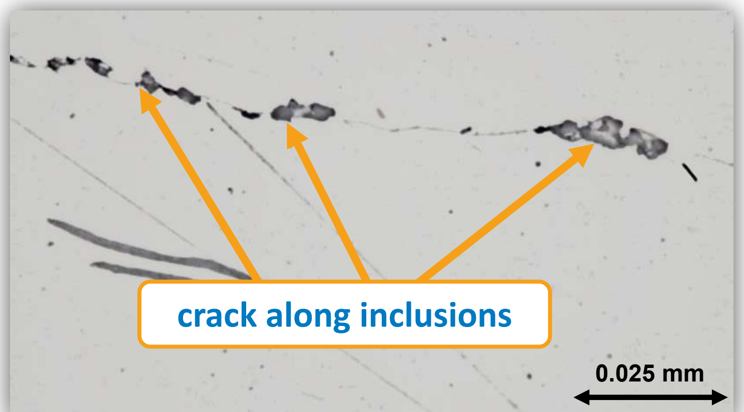
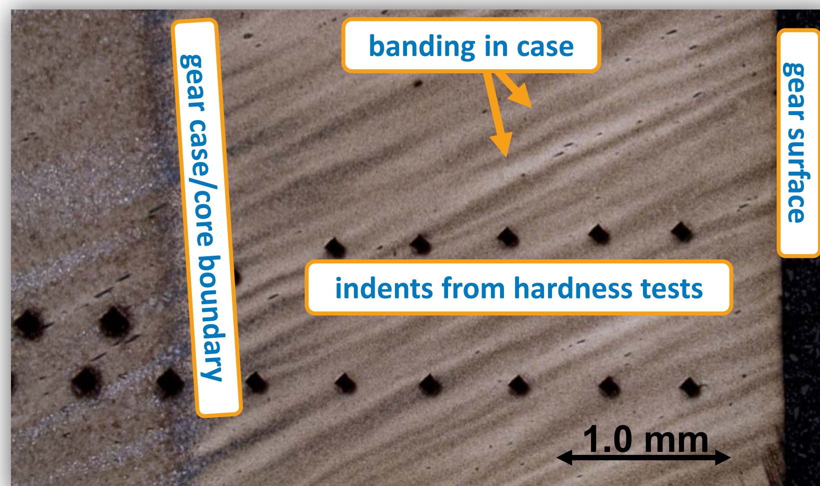
Key Failure Modes – Manufacturing Defects

- **Manufacturing defects**
  - Nonmetallic inclusions
  - Microstructural banding
  - Inconsistent induction hardening depth
  - Gear-grinding temper
- **Defects alone are not a *failure mode*, but serve as the *initiation of failure***
- **More common in gears than bearings**

poor de-oxidation process → nonmetallic (oxide) inclusions → nucleation point of failure

poor heat treat → banding in case-hardened layer → reduced local hardness





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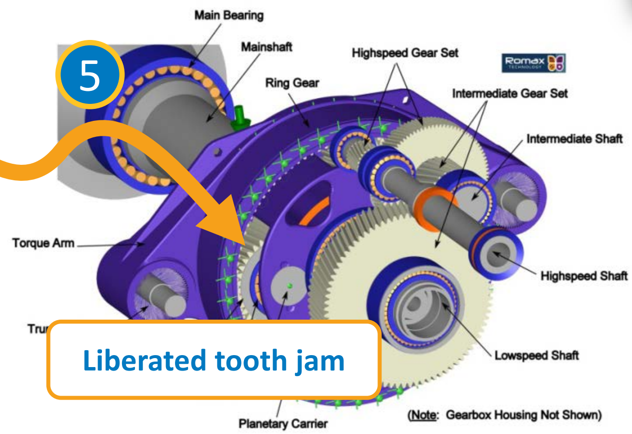
Key Failure Modes – Gear Teeth



- Gear rating standards assume that the designer has good quality steel and a well-controlled heat treat process

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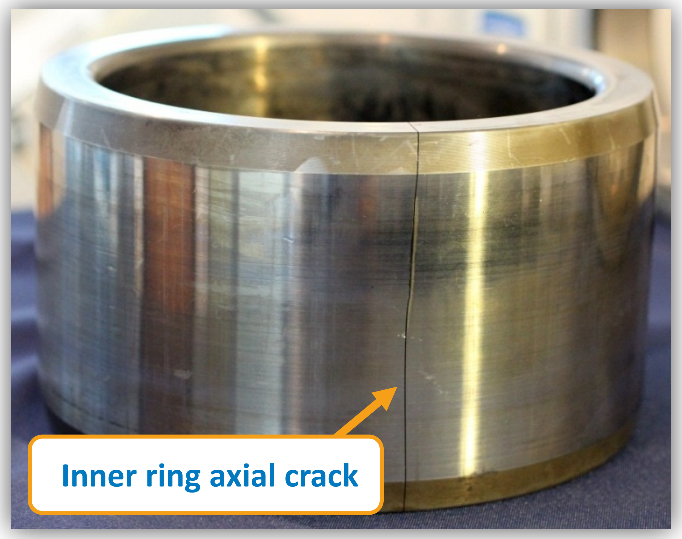
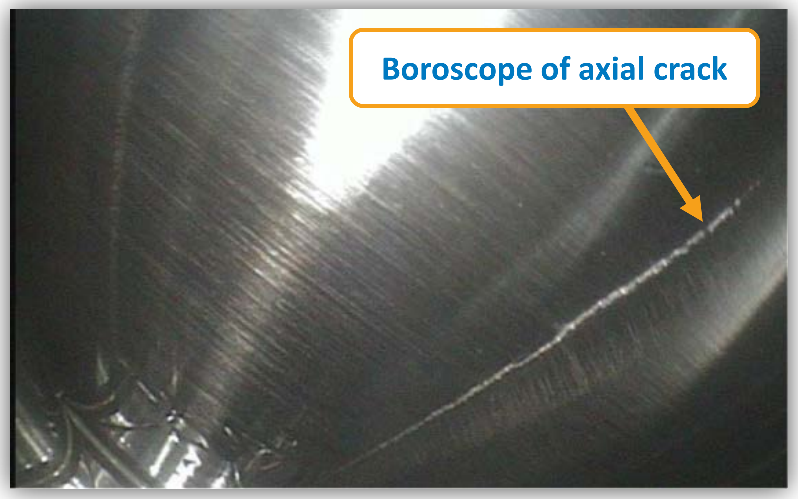
Key Failure Modes – Bearing Axial Cracks

- **Widespread problem with unknown root cause**
  - Topic of research
  - Some OEMs are moving to case carburized bearings
- **Occurrences typically on inner race of cylindrical roller bearings (CRBs)**
  - Current rating standards do not cover this failure
  - White etching areas (local hardening) seem to serve as nucleation points

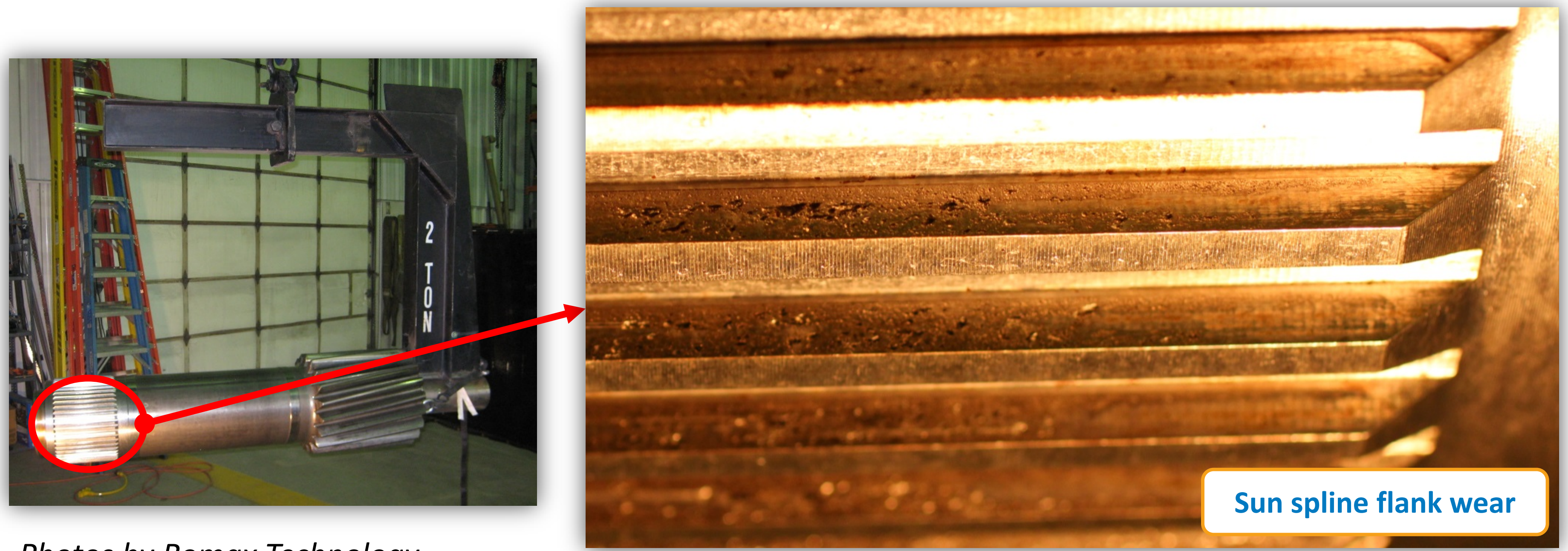




Photos by Romax Technology

Note About Sun Splines

- **Commonly show signs of fretting and pitting**
  - Difficult to lubricate
- **Not a common failure mode**
  - Debris generated is ideally flushed away with minimal consequential damage to gears and bearings



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Brief History Lesson

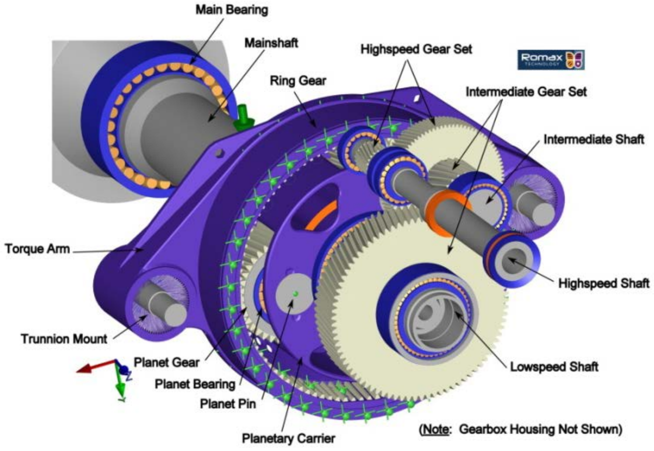
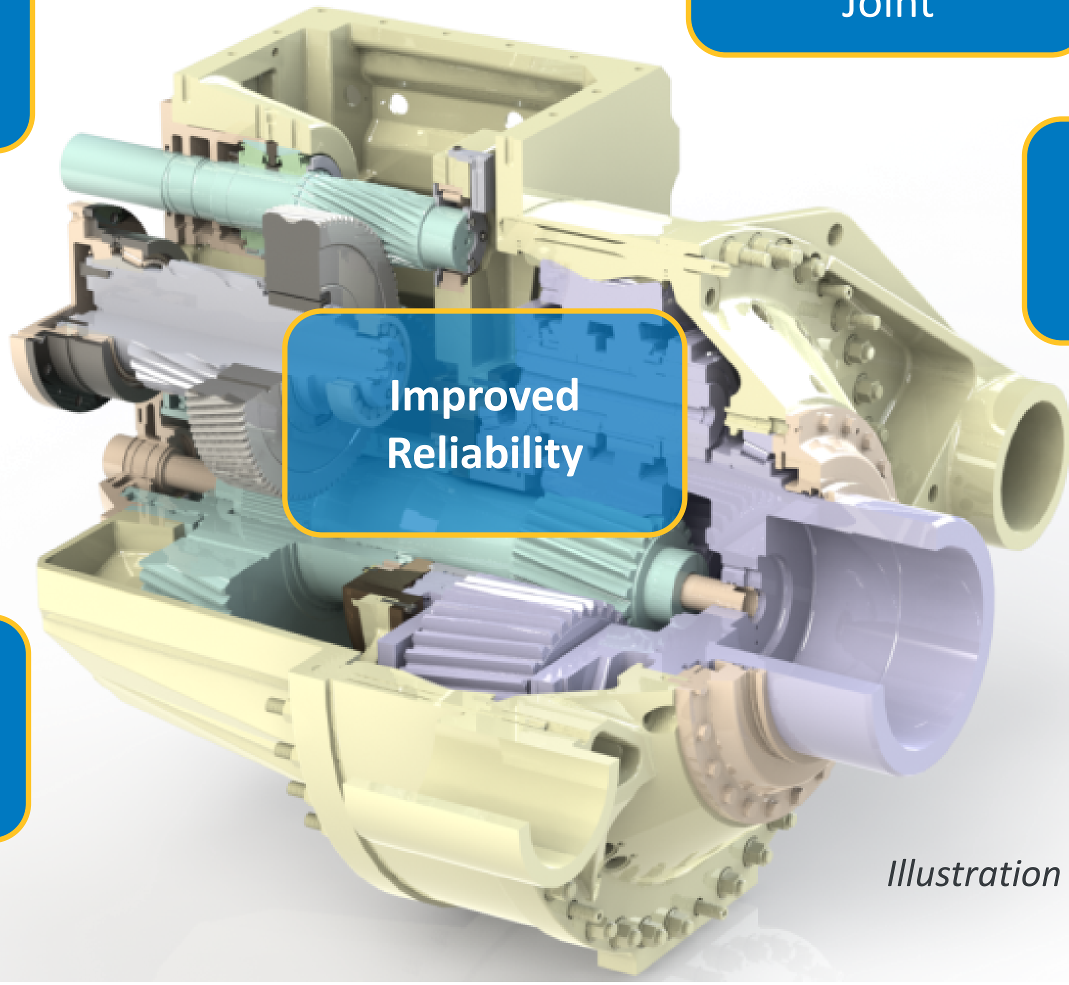


Illustration by Romax Technology

- **GRC Gearbox 1 and 2**
  - Gearbox 1: Dynamometer and in-field testing
  - Gearbox 2: Dynamometer testing

- **Key Items:**
  1. Misalignment between carrier and ring gear
     - Application: rotor-bending moments
     - Design: operating radial internal clearance in planet carriers (PLCs)
  2. Poor load share between upwind and downwind planetary bearings
     - Application: torque load with carrier windup and planetary pin deflection
     - Design: operating radial clearance in the two single-row CRBs
  3. Oil feed into rotating frame (planetary stage)
     - Application: off-axis and transient loads
     - Design: distribution ring sensitivity to carrier misalignment; jams with poor sealing

Key Design Improvements (GRC Gearbox 3)



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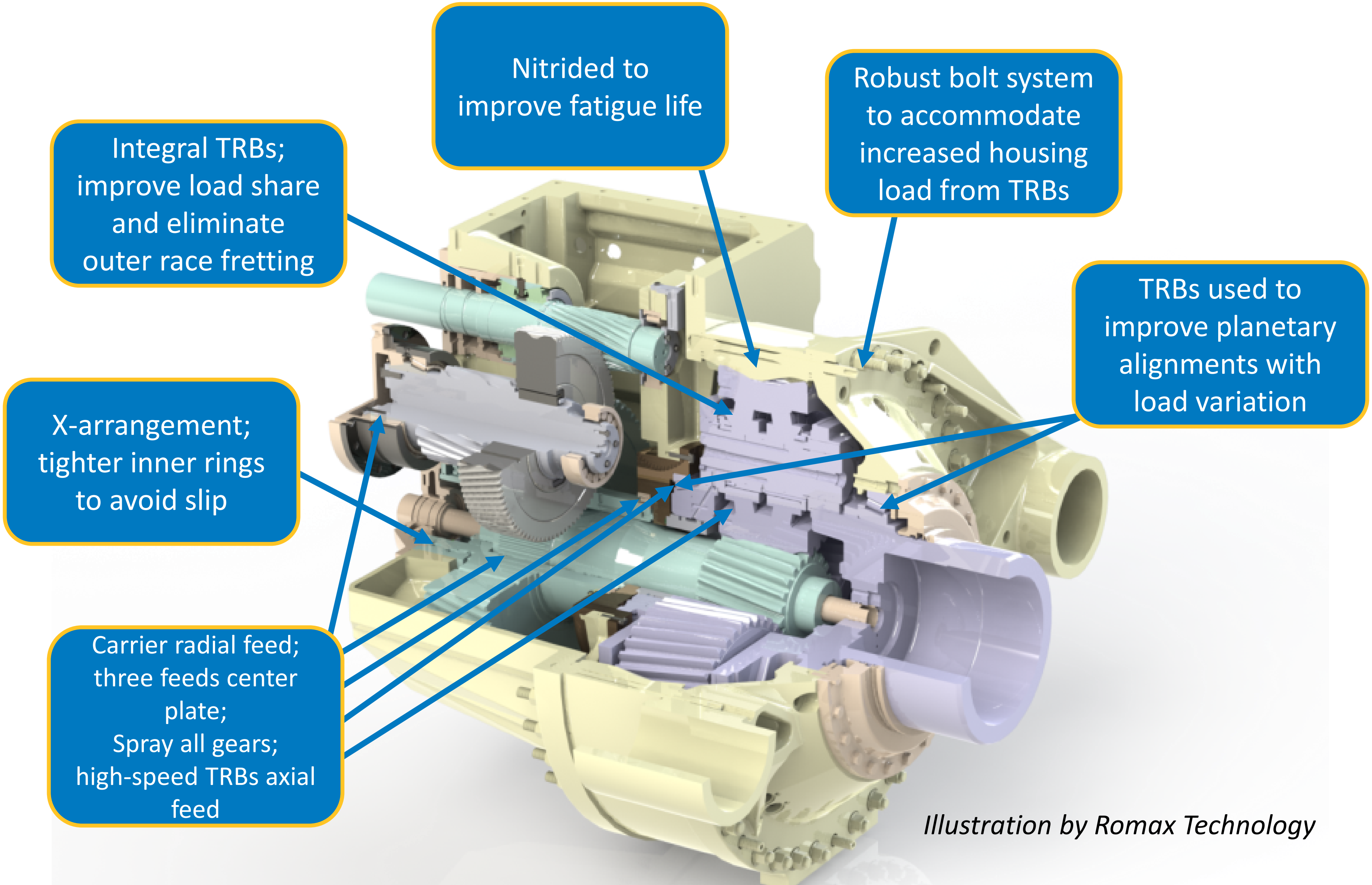
Key Design Improvements (GRC Gearbox 3)



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Test Summary

- Phase 1 (300+ hours of data) included:
  - Gearbox 1 dynamometer test - 125+ signals
  - Gearbox 1 field test
  - Oil loss event led to gearbox damage
- Phase 2 (700+ hours of data) included:
  - Gearbox 2 dynamometer test - 150+ signals
  - Dynamic torque and some dynamic non-torque loads
  - Gearbox 1 dynamometer test
  - Condition monitoring evaluation and gearbox teardown
- Phase 3 (underway) includes:
  - Gearbox 2 retest with high-speed section instrumentation
    - ✓ Field loads (normal power production and transient); generator misalignment
  - Gearbox 3 test
    - ✓ Replace planetary CRBs with preloaded TRBs

Photo by Jeroen van Dam, NREL 19257

April 2009
Oct 2009
July 2010
Nov 2010
Jan 2011
July 2013
July 2014

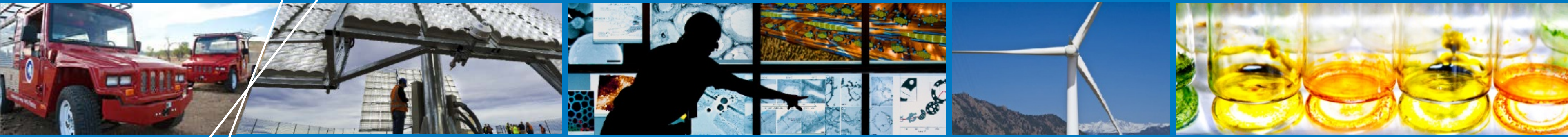
Key Findings

- Three-point drivetrain design sensitive to nontorque loads
  - Nontorque load (bending) disturbs load sharing among planetary gears and between planet-bearing rows
  - Main shaft misalignment can cause pitting on the ring gear
  - Non-torque load (thrust) affects planet carrier position
- Controller adjustments to reduce torque spikes
- External gauges can indicate tooth contact pattern
- High bearing skidding risks at low torque
- On-line particle counting can be used for run-in
- Reliability improvement needs a comprehensive approach that can include:
  - Design and testing
  - Metallurgy and material
  - Operation and maintenance

http://www.nrel.gov/wind/grc/publications.html

Schedule

- **Main housing, ring gear, shafts and gears, and so on**
  - Contract award August 2013
  - Instrumentation installation April 2014
  - Gearbox acceptance/completion May 2014
- **Planet gear/bearings**
  - Planet inners manufactured September 2013
  - Planet inner strain gages calibrated October 2013
  - Planet gears manufactured December 2013
  - Delivery to gearbox manufacturer January 2014
- **Dynamometer testing**
  - Gearbox 2 with added HSS instrumentation, September 2013
  - Gearbox 3, June 2014

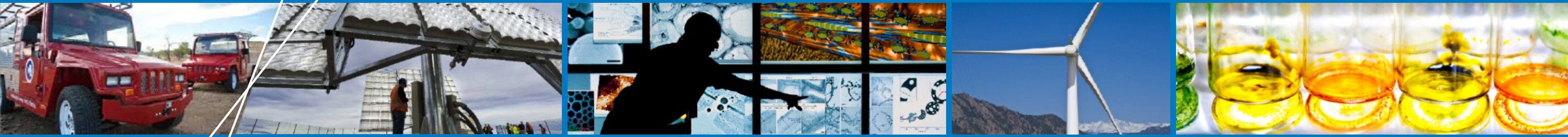


Next Steps

GRC – FY14 and Beyond

- **Draw down current GRC 750-kW project**
  - Complete build and test of gearbox 3
  - Validate design tools used for design improvements → increase in L_{10} life for gearbox bearings
- **Launch new GRC 1.5 project**
  - Field test 1.5-MW turbine (highest interest to GRC members)
    - ✓ Offers of in-kind cost share from industry
  - Gather main shaft (input) and high-speed shaft (reaction) loads
    - ✓ Focused measurement and modeling → NREL reference load distribution
    - ✓ Needed by industry for design improvements
  - Use 2.5-MW dynamometer, U.S. Department of Energy (DOE) 1.5-MW turbine, and NWTC controllable grid interface (CGI) as stepping stones to conduct field testing in wind farm(s)

Meet Industry Desires with Applied Testing, Analysis, and Modeling



Several Other Reliability R&D Activities

Testing

- Field testing of commercial megawatt scale and small (under 100 kW) wind turbines
- Dynamometer testing facilities: 250 kW, 2.5 MW, and 5 MW
- Static and fatigue tests of blades
- Grid compliance testing: a 7-MW controllable grid interface (CGI)
- Multimegawatt energy storage testing capability under development

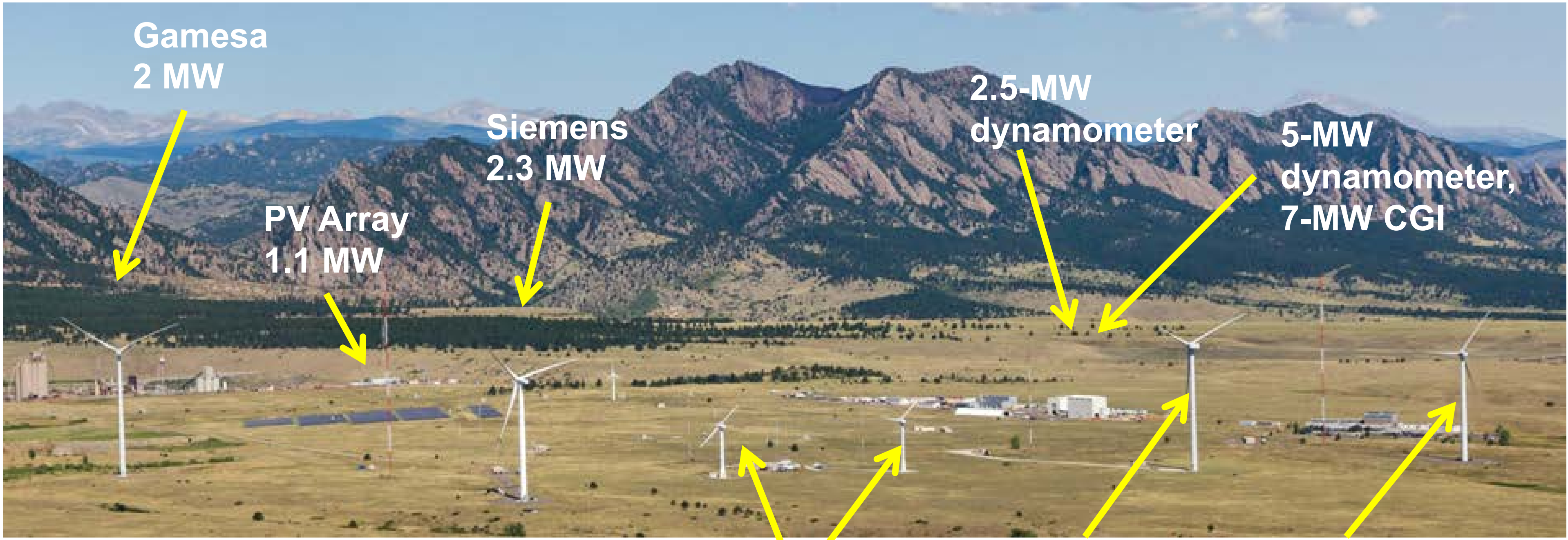


Photo by Vahan Gevorgian, NREL

Data Collection and Modeling

- **Gearbox reliability database => drivetrain major subsystems/components reliability database => O&M research [3,4]**
  - Highlight failure locations, failure modes, and possible root causes
  - Opportunities: data sharing and solution packages (from fault detection to maintenance recommendation) R&D, and so on
- **Historical operational and expense cost data and major component replacements data collection [5]**
  - Collected by DNV KEMA and GL GH for NREL and the combined data represents 10 GW of U.S. capacity
  - Opportunities: results update and validation, and so on
- **Offshore O&M cost modeling [6]:**
  - Energy Research Center of the Netherlands (ECN) tool purchased by NREL and baseline studies for U.S. offshore project conducted
  - Opportunities: data sharing and model validation, and so on

References

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5. Lantz, E. "Operations Expenditures: Historical Trends and Continuing Challenges." Presented at AWEA Wind Power Conference, May 5–8, 2013, Chicago, IL. NREL/PR-6A20-58606.
6. Meadows, R. Offshore O&M Cost Drivers - A U.S. Case Study, NREL Report No. TP-5000-58908 (*forthcoming).*

Thanks for your attention!

Special thanks to the U.S. Department of Energy and the GRC project partners.

HC Sorensen, Middelgrunden Wind Turbine Cooperative, *Photo by HC Sorensen, NREL 17855*

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