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Wind Turbine Gearbox Failure Modes – A Brief

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Outline

- Gearbox Reliability Collaborative (GRC)
- Gearbox Failure Database
- Recorded Incidents Summary
- Detailed Damage of one GRC Test Gearbox
- Observations

DOE 1.5 MW Turbine. *Photo by Lee Jay Fingersh, NREL/PIX* 17245

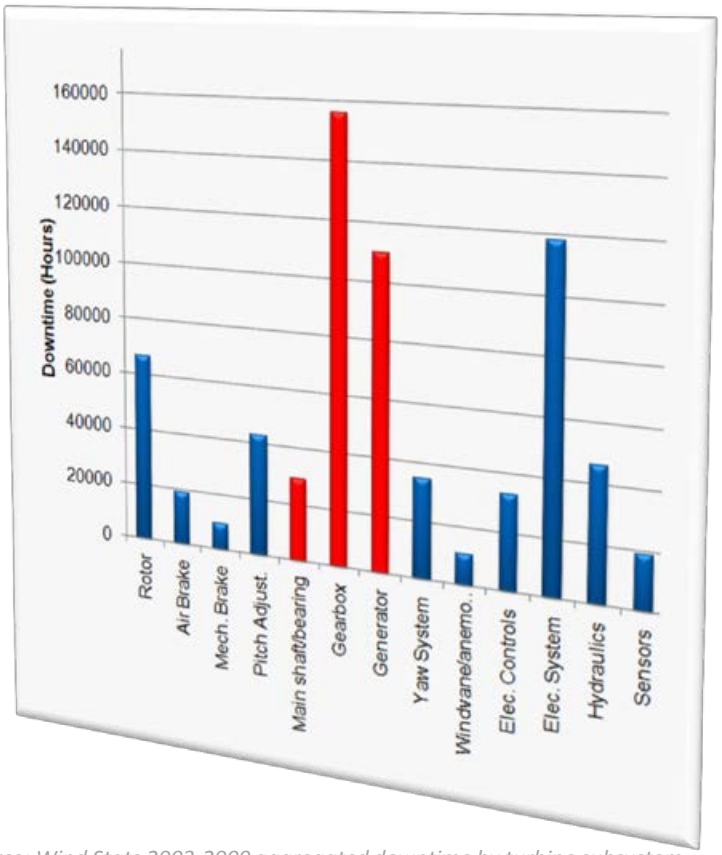
Gearbox Reliability Collaborative

- Wind turbine gearboxes are not always meeting 20-year design life

- Premature failure of gearboxes increases cost of energy
  - Turbine downtime
  - Unplanned maintenance
  - Gearbox replacement and rebuild
  - Increased warranty reserves

- The problem
  - Is widespread
  - Affects most Original Equipment Manufacturers
  - Not caused by manufacturing practices

- Need to improve gearbox reliability and reduce turbine downtime



Source: Wind Stats 2003-2009 aggregated downtime by turbine subsystem

GRC Technical Approach

- Technical Approach
  - Modeling and analysis
  - Field test
  - Dynamometer test
  - Condition monitoring
  - Failure database
- Goal
  - To improve gearbox reliability and increase turbine uptime, which in turn will reduce the cost of energy

Field Test

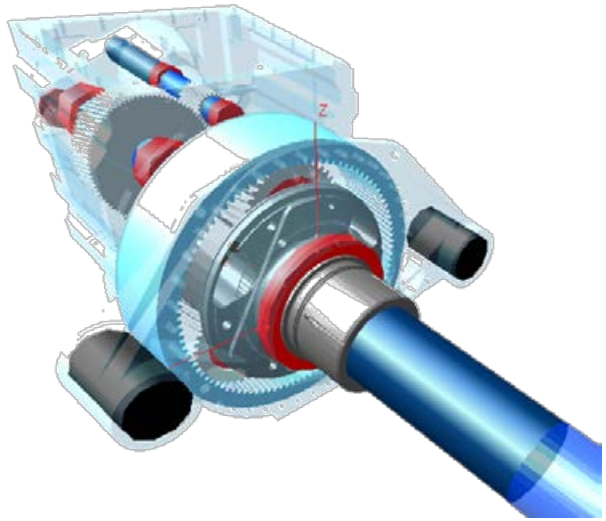
Test Turbine at NREL/PIX19022

Dynamometer Test

NREL Dynamometer/PIX16913

Analysis

- Load cases
- System loads
- Internal loads

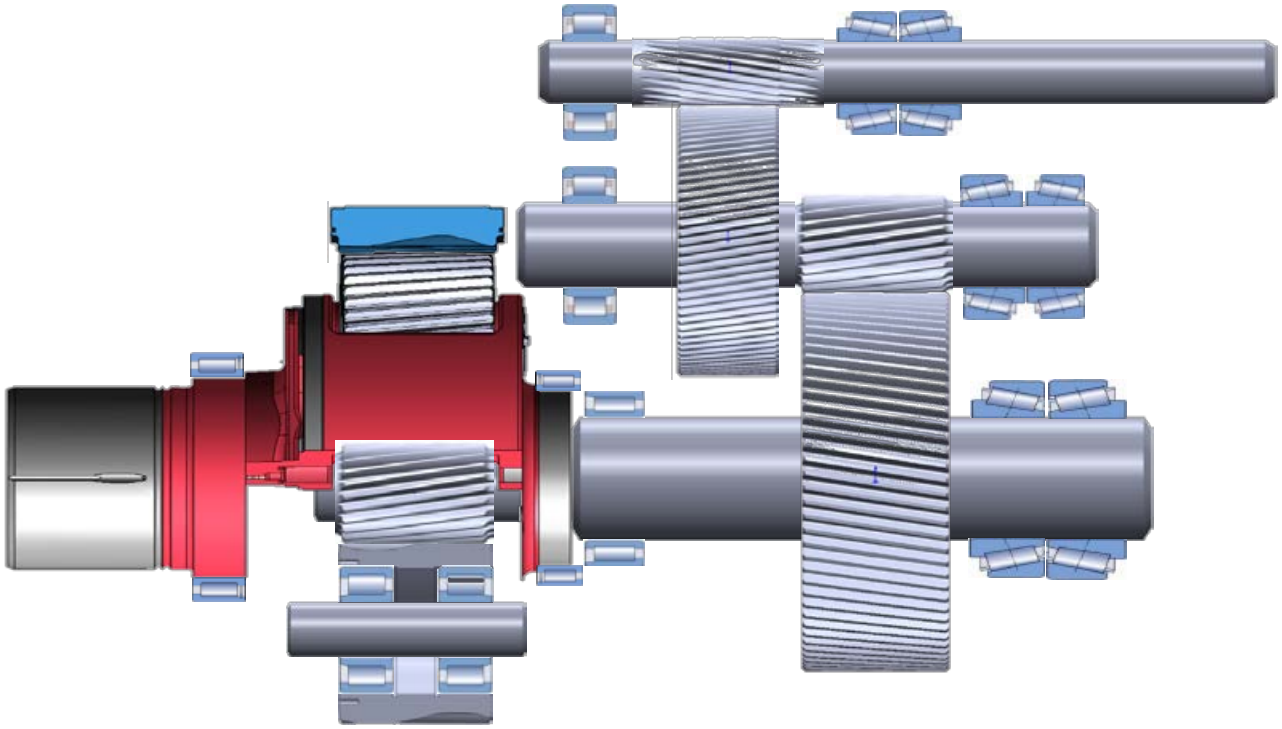


Gearbox Failure Database

- Gearbox problems = expensive uncertainty
- Quantify magnitude and cost of the problem
- Focus research accurately
- Aid root cause analysis and correction
- Provide objective record of improvements

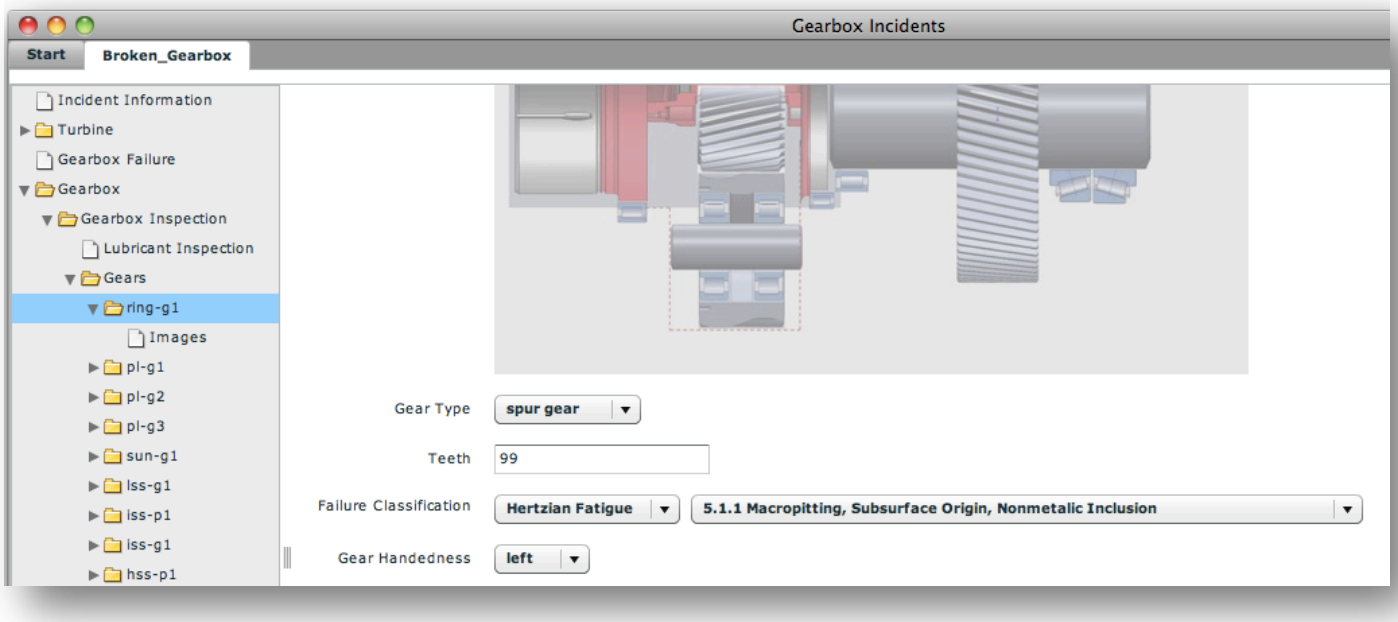
Gearbox Failure Database (*Cont.*)

- **Collect information from gearbox rebuilds**
  - In shop and on tower
  - Existing data from papers, Excel spreadsheets, etc.
  - Share ‘sanitized data’ within the group
- **Analyze and close loop when solutions are identified**



Gearbox Failure Database *(Cont.)*

- Structured data collection: navigation tree
- Visually oriented: wireless image transfer from camera to correct fields in software
- Embedded failure codes library



Recorded Incidents Summary [1]

- 37 incidents: 36 with bearing and 22 with gear failures

Quantity	Component	Code	Description
1	bearing	5.4.3	Hertzian Fatigue, Micropitting, Edge of Raceway
1	bearing	6.1.1	Wear, Adhesion, Mild
3	**bearing**	**6.1.3**	**Wear, Adhesion, Severe (Scuffing)**
4	**bearing**	**6.2.1**	**Wear, Abrasion, Two-body**
10	**bearing**	**6.2.2**	**Wear, Abrasion, Three-body**
1	bearing	6.2.3	Wear, Abrasion, Polishing
14	**bearing**	**8.1.1**	**Cracking, Roller and Ring Cracks, Hardening Cracks**
2	bearing	8.1.2	Cracking, Roller and Ring Cracks, Grinding Cracks
1	gear	3.1	Overload, Fracture, Brittle
1	gear	4.1	Bending Fatigue, Low Cycle
2	gear	5.3	Hertzian Fatigue, Subcase Fatigue
6	**gear**	**6.4**	**Wear, Fretting-Corrosion**
2	gear	4.2.1	Bending Fatigue, High Cycle, Root Fillet Cracks
3	**gear**	**4.2.2**	**Bending Fatigue, High Cycle, Profile Cracks**
2	gear	6.1.1	Wear, Adhesion, Mild
1	gear	6.2.2	Wear, Abrasion, Moderate
4	gear		not found

Top Failure Modes for Bearings [2]

- **Cracking: 8.1.1 roller and ring hardening cracks**
  - Generally inter-granular with the crack running from the surface of a roller or a ring toward its center of mass in a relatively straight line
  - Cracking in heat treatment usually occurs during or after quenching due to localized stresses caused by non-uniform cooling or unequal transformation of austenite to martensite.

Top Failure Modes for Bearings [2]

- **Abrasion: 6.2.1, 6.2.2 two-body and three-body**
  - Two-body: embedded particles or asperities on one bearing surface abrade the opposing bearing surface
  - Three-body: abrasion due to loose contaminants
  - Abrasion scratches or gouges on bearing surfaces are in the direction of sliding. Under magnification, scratches appear as parallel furrows that are smooth and clean
  - Usually caused by contamination of lubricant by hard, sharp-edged particles. Common contaminations are sand, rust, machining chips, grinding dust, weld splatter, and wear debris.

Top Failure Modes for Bearings [2]

- **Adhesion: 6.1.3 severe adhesion (scuffing)**
  - Severe adhesion or scuffing is transfer of material from one bearing surface to another due to welding and tearing
  - Damage typically occurs in areas of slip in narrow or broad bands along the direction of sliding. It may occur in localized patches with load concentrations
  - Scuffing areas appear to have a rough or matte texture, which under magnification, appears to be torn or plastically deformed.

Top Failure Modes for Gears [3]

- **Fretting Corrosion: 6.4**
  - Fretting corrosion is deterioration of contacting gear tooth surfaces caused by minute vibratory motion
  - It occurs between contacting surfaces that are pressed together and subject to cyclic, relative motion of extremely small amplitude. Under these conditions, lubricant is inadequate to replenish, permitting metal-to-metal contact and causing adhesion of surface asperities
  - Fretting corrosion damages gear teeth by forming ruts along lines of contact.

Top Failure Modes for Gears [3]

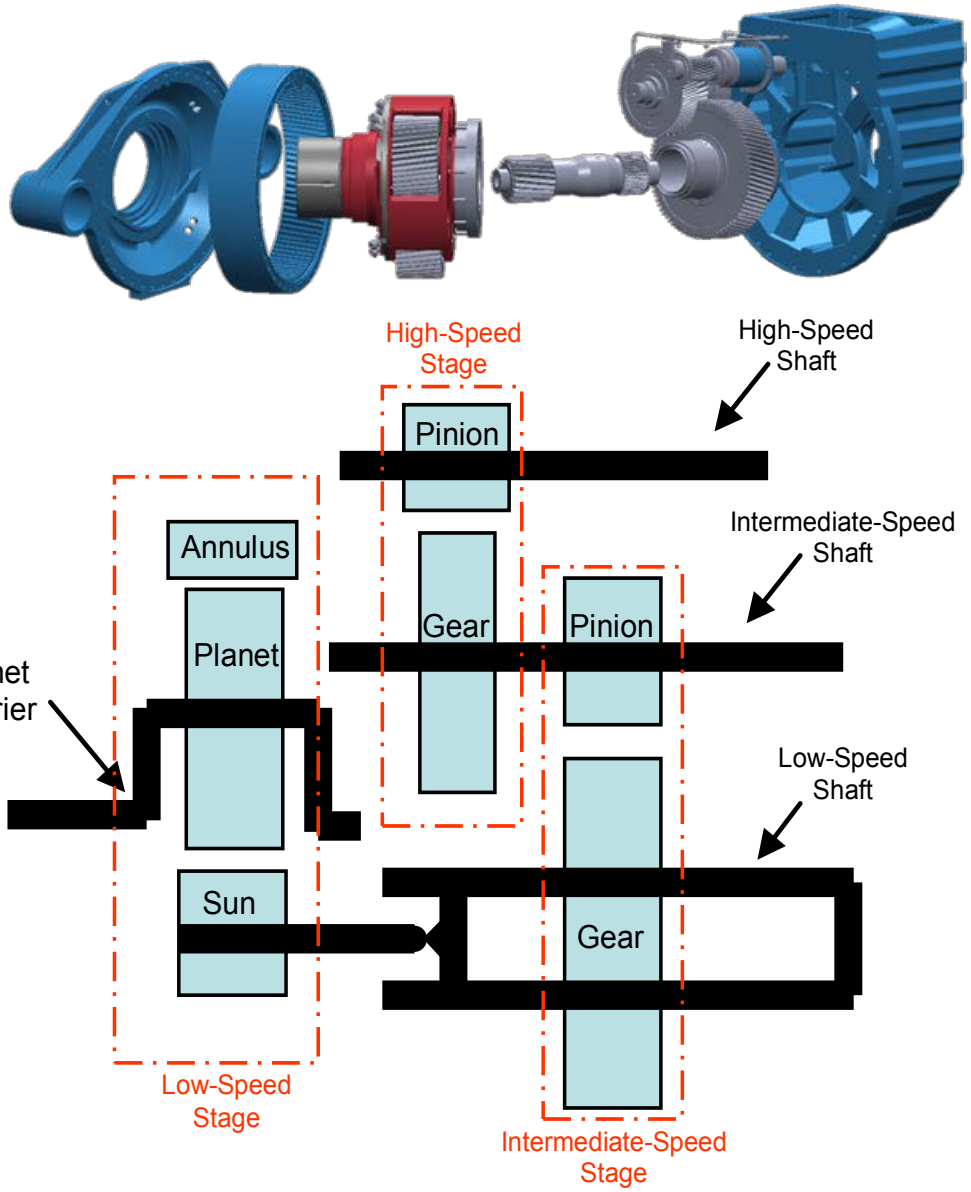
- **Bending Fatigue: 4.2.2 High-Cycle**
  - It consists of three distinctive stages: crack initiation, propagation and fracture
  - During stage 1 no gross yielding of the gear teeth occurs. However, local plastic formation may occur in regions of stress concentrations or areas of discontinuities. The end of this stage is symbolized by the formation of microcracks inside grains.

Top Failure Modes for Gears [3]

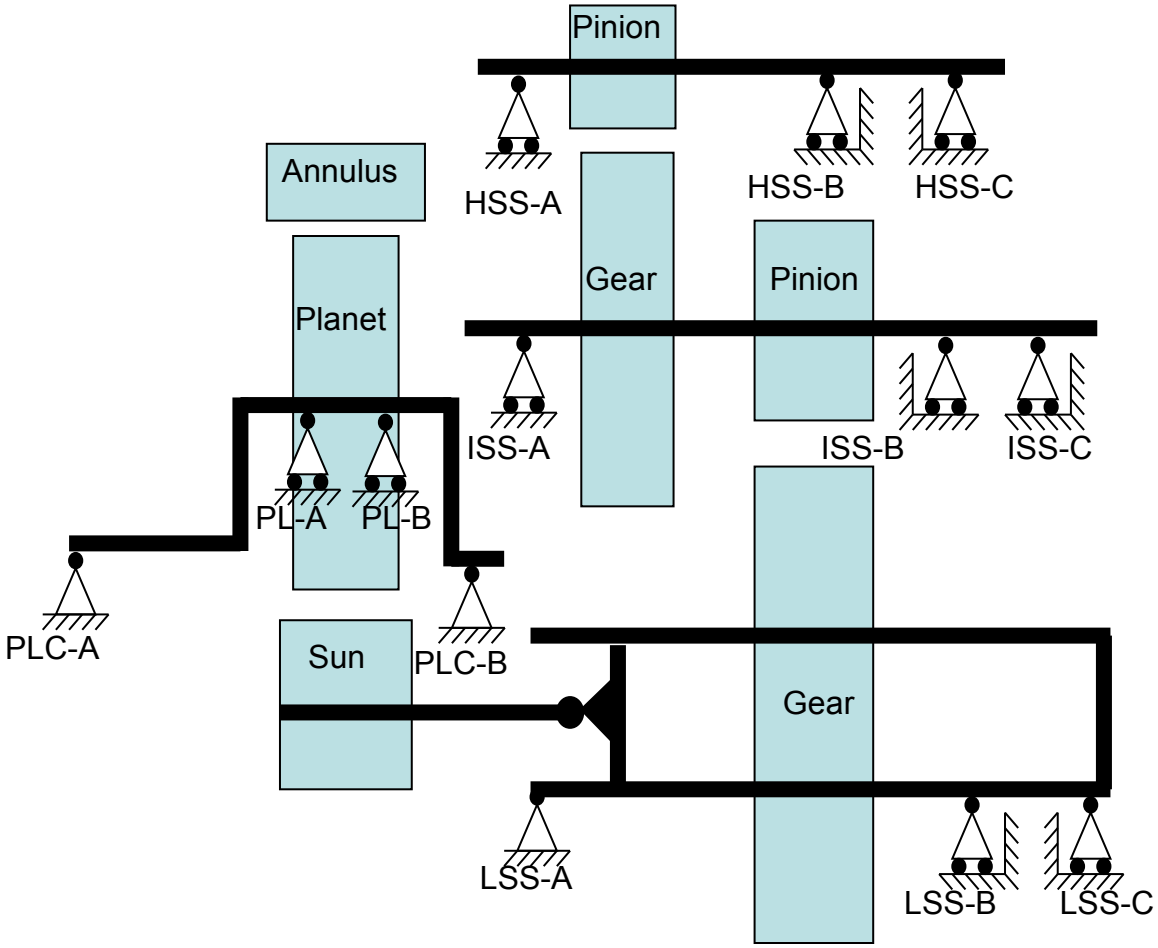
- Stage 2 begins when the crack turns and grows across grain boundaries (transgranular) in a direction approximately perpendicular to the maximum tensile stress. Plastic deformation is confined to a small zone at the leading edge of the crack. As a result, the cracked surfaces usually appear smooth without signs of gross plastic deformation
- Sudden fracture occurs during stage 3. It may be ductile, brittle or mixed-mode depending upon material toughness and magnitude of applied stress
- High-cycle bending fatigue occurs when cyclic stress is less than the yield strength of the material and the number of cycles to failure is greater than 10,000.

GRC Test Gearbox

- A 750-kW wind turbine gearbox
- One planet and two parallel stages, floating sun
- Pressurized lubrication for all but the planet gears and the ring gear.



Bearing Nomenclature



Acronym	Definition
PLC	Planet Carrier
PL	Planet
LSS	Low-Speed Shaft
ISS	Intermediate-Speed Shaft
HSS	High-Speed Shaft

Test History

1. Completed dynamometer run-in test
2. Sent for field test: experienced two oil losses
3. Stopped field test
4. Retested in the dynamometer under controlled conditions.

NREL 2.5 MW Dynamometer. *Photo by Lee Jay Fingersh, NREL/PIX 16913*

Real Damage [4]

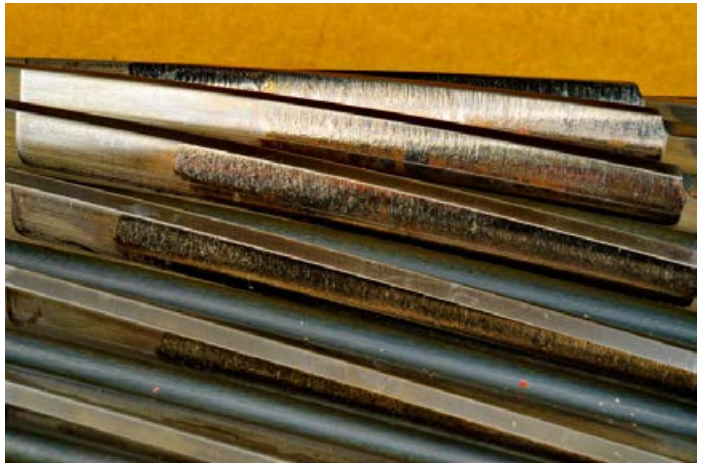
Failure #	Component / Location	Mode	Severity
1	HSS Gear Set	**Scuffing**	Severe
	(HSS Gear and HSS Pinion)		
2	HSS Downwind Bearings	Overheating	Mild
	(IR and Rollers)		
3	ISS Gear Set	**Fretting Corrosion**	Severe
	(ISS Gear and Pinion)	**Scuffing**	
	(All Teeth)	**Polishing Wear**	
	(Sun Spline)		
4	ISS Upwind Bearing	Assembly damage	Moderate
	(IR)	Plastic deformation	
		Scuffing	
		False brinelling	
		Debris dents	
		Contact Corrosion	
5	ISS Downwind Bearings	**Assembly damage**	Severe
	(OR Spacer for both Bearings)	Plastic deformation	
		Dents	
6	Annulus/Ring Gear, or Sun Pinion	Scuffing and polishing	Moderate
		Fretting Corrosion	Severe
7	Planet Carrier Upwind Bearing	**Fretting Corrosion**	Severe
	(Container and OR)		

Real Damage (*Cont.*)

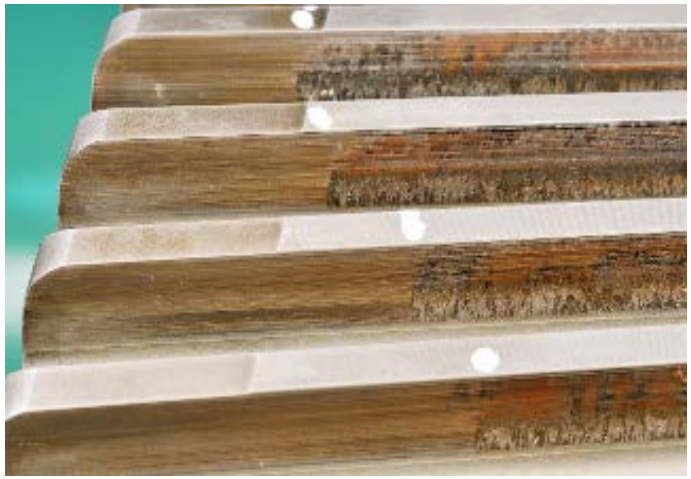
9	Oil Transfer Ring for Planet Carrier	Polishing	Mild
	(Bore)		
10	LSS	**Scuffing**	Severe
	(Shaft and O-ring Seal Plate)		
11	LSS Downwind Bearings	**Abrasion**	Severe
	(Locknut)		
12	HSS Shaft	Miaslignment	Mild

- Two main root causes:
  - Oil starvation
  - Assembly damage
- Simple triggers may lead to complex damage

Gear Sets



High-Speed Stage Pinion (Severe Scuffing)
Photo from GEARTECH, NREL/PIX 19743

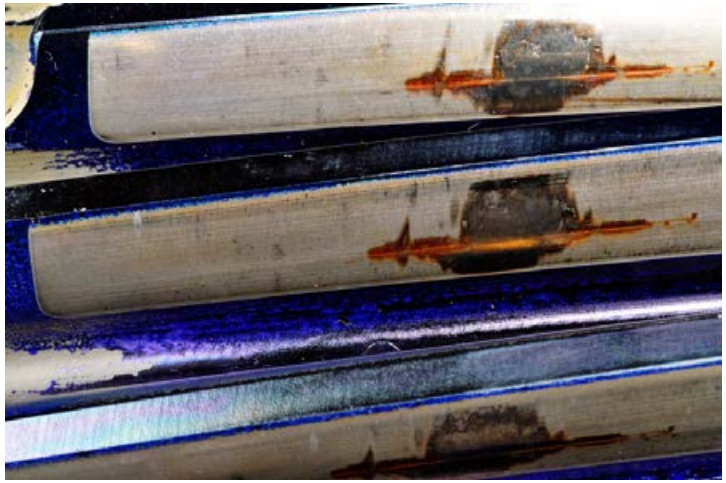


High-Speed Stage Gear (Severe Scuffing)
Photo by Robert Errichello, NREL/PIX 19599

Sun Pinion (Severe Fretting Corrosion)
Photo from GEARTECH, NREL/PIX 19750

Sun Spline (Severe Fretting Corrosion)
Photo from GEARTECH, NREL/PIX 19751

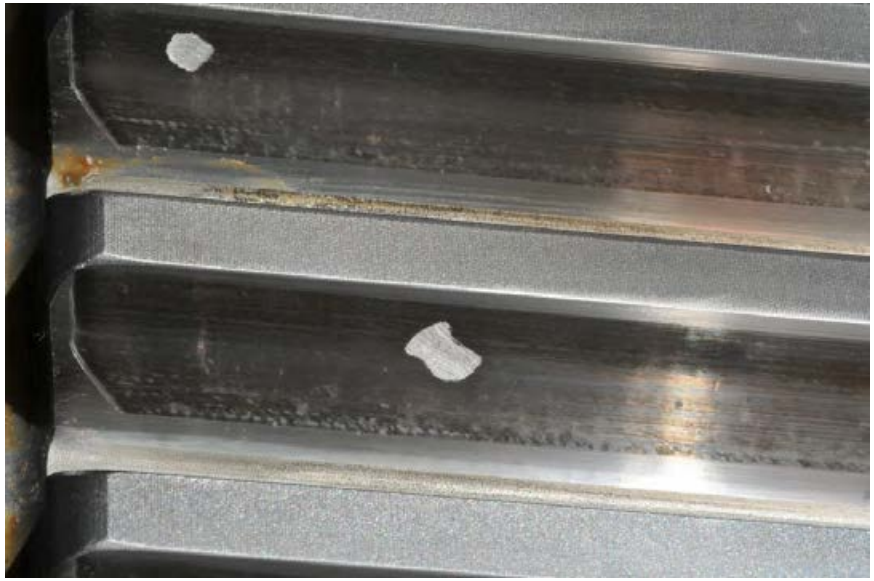
Gear Sets



Intermediate-Speed Stage Pinion
Photo from GEARTECH, NREL/PIX 19745

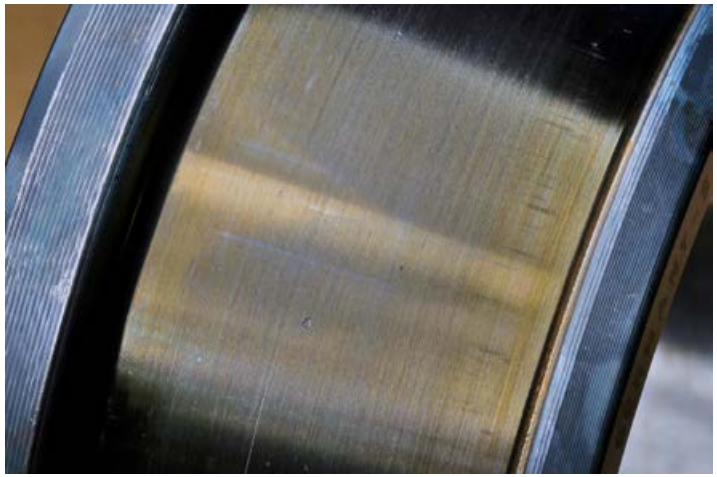
- Failure mode 1: fretting corrosion, severe
- Failure mode 2: polishing wear, severe (local)
- Failure mode 3: scuffing, severe (local)
- Description: Damage was imprinted on all teeth because the gear set had a hunting gear ratio.

- Failure mode 1: scuffing, moderate (local)
- Failure mode 2: polishing wear, severe
- Description: Two original, hand dressed macropits are shown. Polishing wear removed all traces of the grind marks and created a wear step at the end of contact.

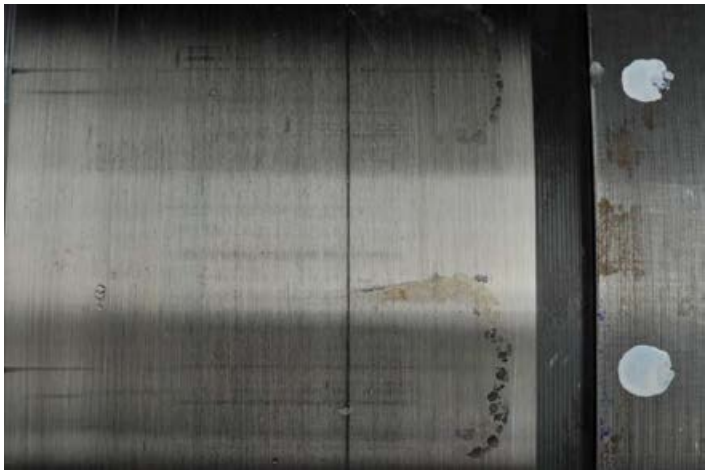


Annulus Gear. *Photo from GEARTECH, NREL/PIX 19749*

Bearings



Bearing HSS-C Inner Raceway (Mild Overheating) *Photo from GEARTECH, NREL/PIX 19744*



Bearing ISS-A Inner Raceway (Mild Contact Corrosion) *Photo from GEARTECH, NREL/PIX 19746*

Bearing ISS-B/ISS-C Outer Raceway Spacer (Severe Assembly Damage) *Photo from GEARTECH, NREL/PIX 19747*

Bearing PLC-A Outer Raceway (Severe Fretting Corrosion) *Photo from GEARTECH, NREL/PIX 19748*

Observations

- **Gear failure database incidents:**
  - 37 among which 36 related to bearings and 22 related to gears => may need to pay attention to both bearings and gears
  - Top bearing failure modes: hardening cracks, abrasion (scratching of surfaces), adhesion (scuffing, welding and tearing of materials)
  - Top gear failure modes: fretting corrosion, high-cycle bending fatigue
- **GRC damaged test gearbox:**
  - Simple causes may lead to complex damage
  - Operation and maintenance improvements are necessary to minimize the possibility of oil loss
  - Additional attention to assembly is needed to avoid damage.

Summary

- Motivation and technical approach for the GRC
- Motivation, objectives, approach and features of the gearbox failure database
- Summary of incidents recorded in the database and detailed damage of one GRC test gearbox, along with some discussions
- Be careful with generalization of the results obtained based on the database, as population is still small

References

1. Link, H.; LaCava, W.; van Dam, J.; McNiff, B.; Sheng, S.; Wallen, R.; McDade, M.; Lambert, S.; Butterfield, S.; Oyague, F. (2011). Gearbox Reliability Collaborative Project Report: Findings from Phase 1 and Phase 2 Testing. 88 pp.; NREL Report No. TP-5000-51885.
2. GEARTECH, Bearing Failure Analysis – A Textbook for the Bearing Failure Analyst.
3. GEARTECH, Gear Failure Analysis – A Textbook for the Gear Failure Analyst.
4. Sheng, S. (2011). "Wind Turbine Gearbox Condition Monitoring Round Robin." presented at the 2011 Wind Turbine Condition Monitoring Workshop, Broomfield, CO, September 19-21, 2011.
5. GEARTECH, GEARTECH Report No. 2443 – Failure Analysis of NREL Field Test Gearbox No. 1, January 21, 2011.

Thank You!

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Photo from HC Sorensen, Middelgrunden Wind Turbine Cooperative, NREL/PIX 17855

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