Effective Use of Large Wear Debris Particle Trends To Detect Key Failure Modes of Wind Turbine Gearboxes

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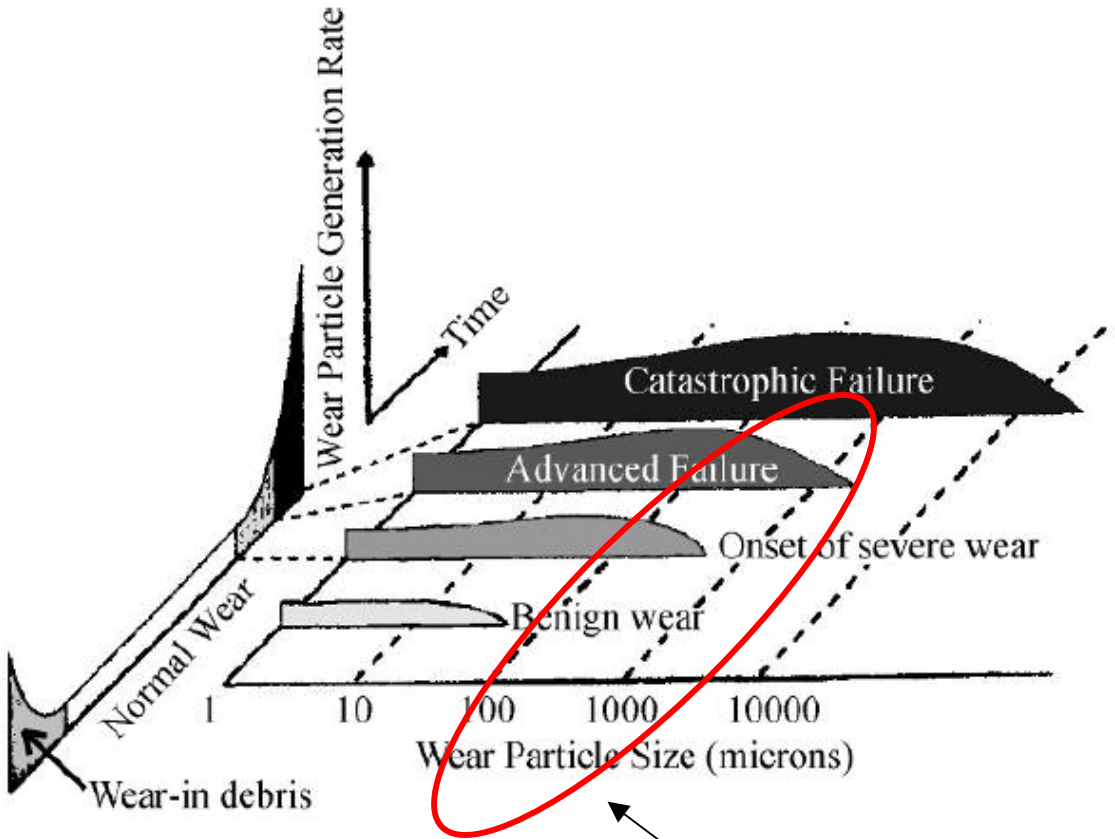
Broomfield, Colorado, Oct 8-9, 2009

Making Machinery More Effective

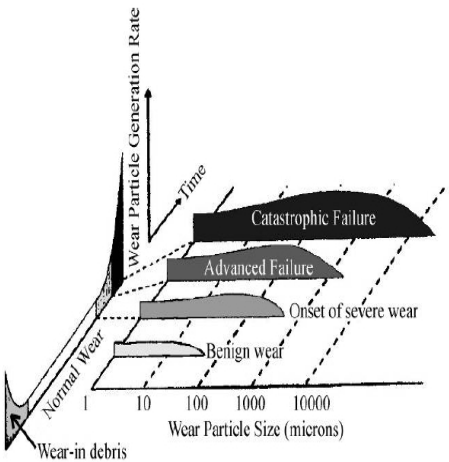
Wear Debris Characterization



Bearing Spall & Gear Pitting
Particle Size Range of Concern

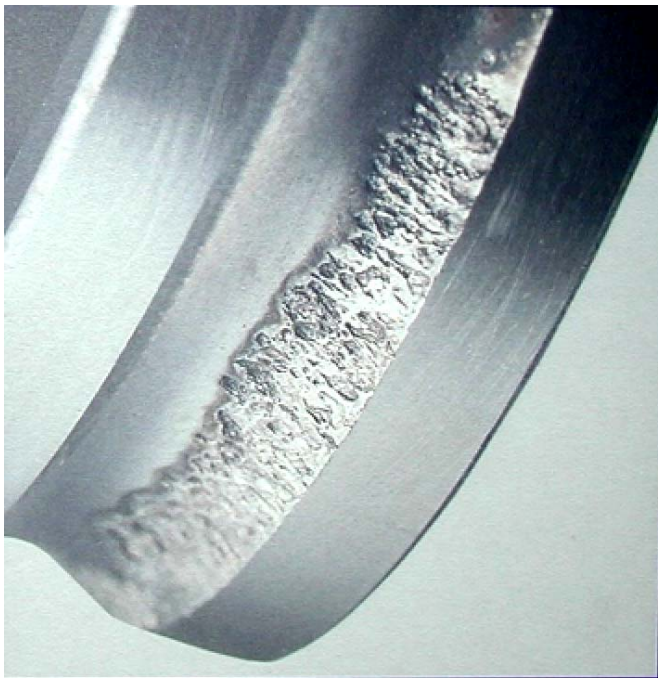
(reference: "Condition Monitoring for Offshore Wind Farms (CONMOW)", ECN Doc # ECN-E—07-044 / CORR0701)

Wear Debris Characteristics – Key Notes



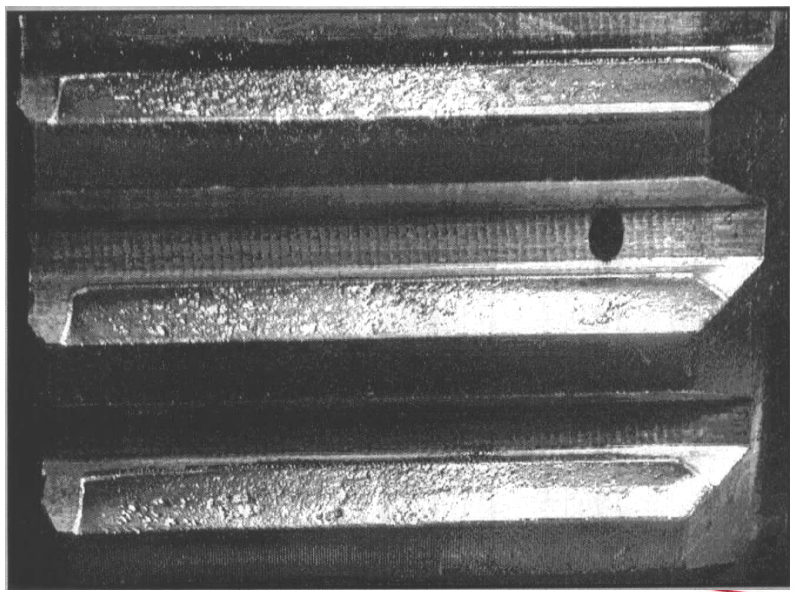
- Chart illustrates wear debris observations from many different wear modes that include polishing, rubbing, abrasion, adhesion, grinding, scoring, pitting, spalling, etc.
- Predominant modes of bearing and gearing failures that shed debris are spalling and pitting which do produce large types of debris ranging from 100 to 1000 micron or greater while machines are still capable of operating
- Rotating equipment that contain rolling element bearings and gears made from hard steel tend to produce this kind of large wear debris that eventually leads to failure of the machine

Bearing & Gear Surface Fatigue Failure Modes



Bearing Spalling Damage

Gear Pitting Damage



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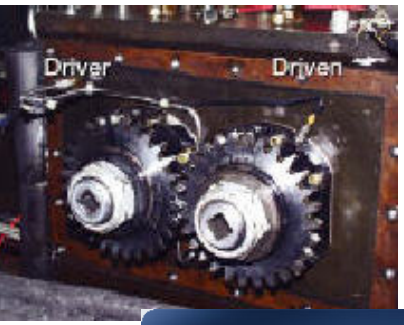
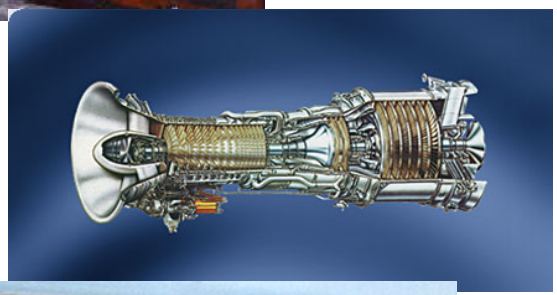
Effective Use of Large Wear Debris Particle Trends





- Various examples of on-line wear debris monitoring will be illustrated for rotating machines:

  - bearing & gear test rigs
  - aero-derivative gas turbines
  - helicopter gearboxes
  - wind turbine gearboxes

- All examples illustrate the use of large wear debris to detect early damage and track the severity of damage of bearing and gear failures

Oil Debris Monitor (ODM) Characteristics

- On-line, full-flow sensor fitted into lube oil system
- Based on inductive sensing technology
- Detects 100% of particles above minimum particle size threshold
- Detects both ferrous and non-ferrous metallic particles
- Quantifies metallic particle counts and rates

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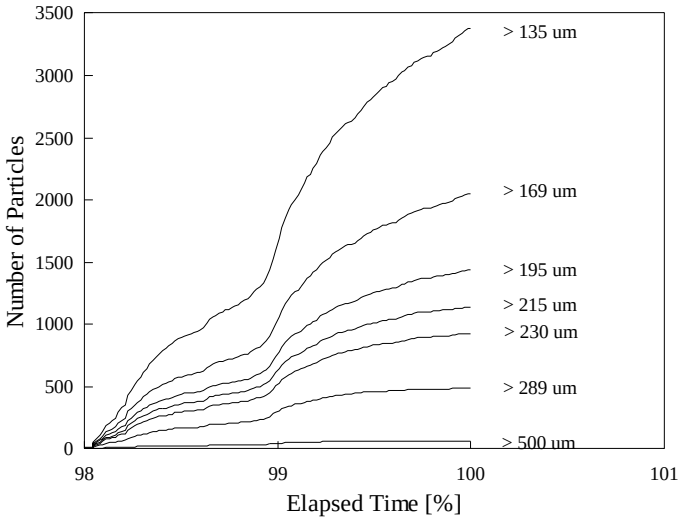
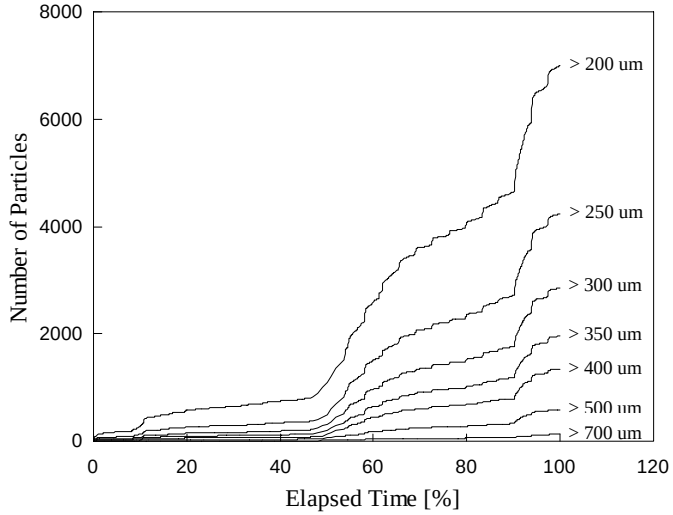
NRC / P&W Bearing Test Rig Cases

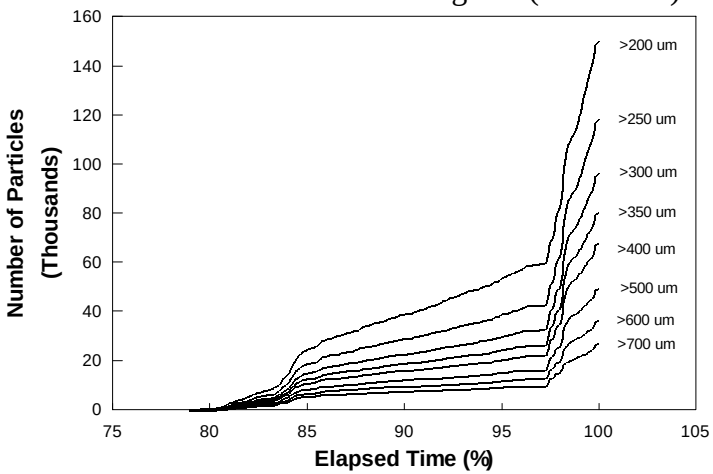
Ferrous Wear Debris Particle Trends



Small-scale bearing test (D=40 mm)



Large hybrid bearing test (D=200 mm)



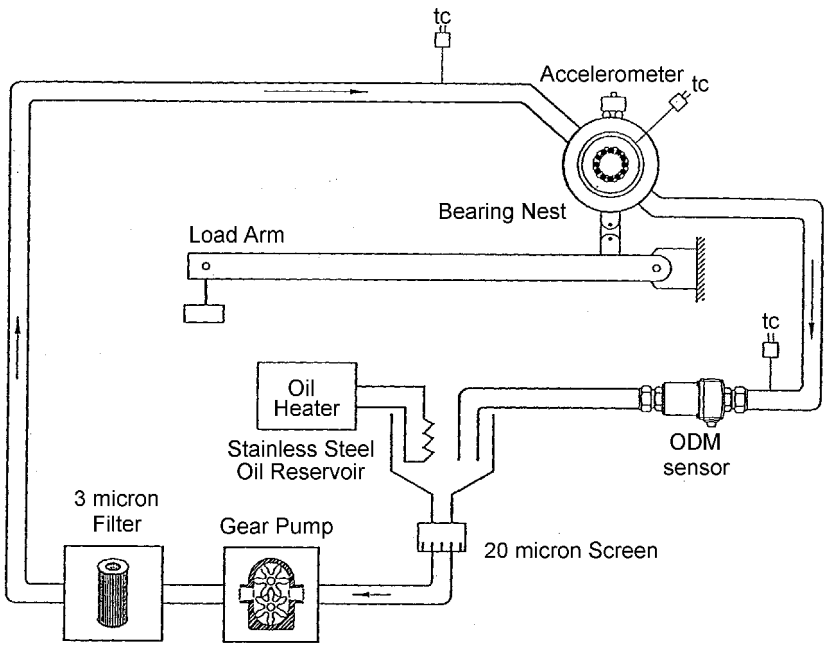
Large-scale bearing test (D=360 mm)

- Key observations:
- Rate of debris generation is dependent on load & speed
- Quantity of debris is dependent on bearing size
- Particle size distribution is independent of bearing size

Reference : *"In-Line Oil Debris Monitor (ODM) for the Advanced Tactical Fighter", SAE 961308, Muir D et al*

Roller Element Bearing Test Rig Case 1

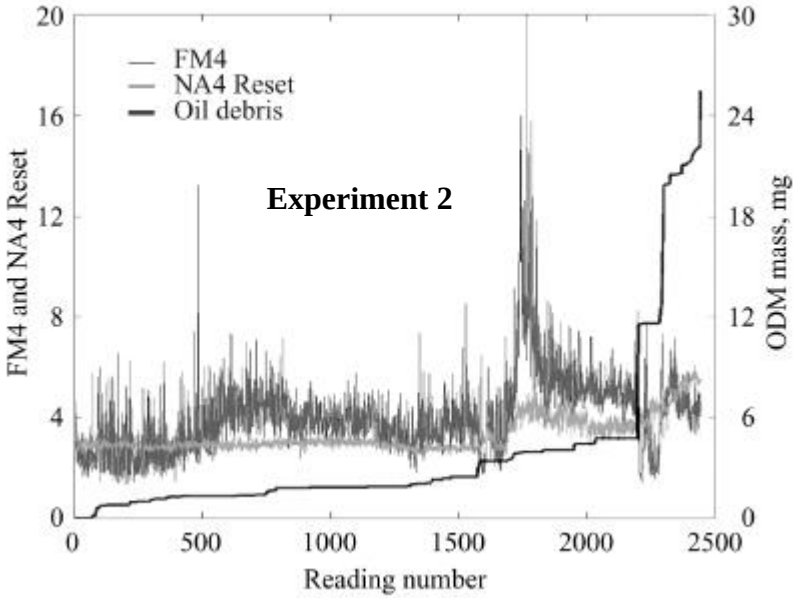
Small-Scale Bearing Damage



Reference : *"In-Line Oil Debris Monitor (ODM) for the Advanced Tactical Fighter", SAE 961308, Muir D et al*

NASA Spur Gear Test Rig Cases

Ferrous Wear Debris Particle Trends



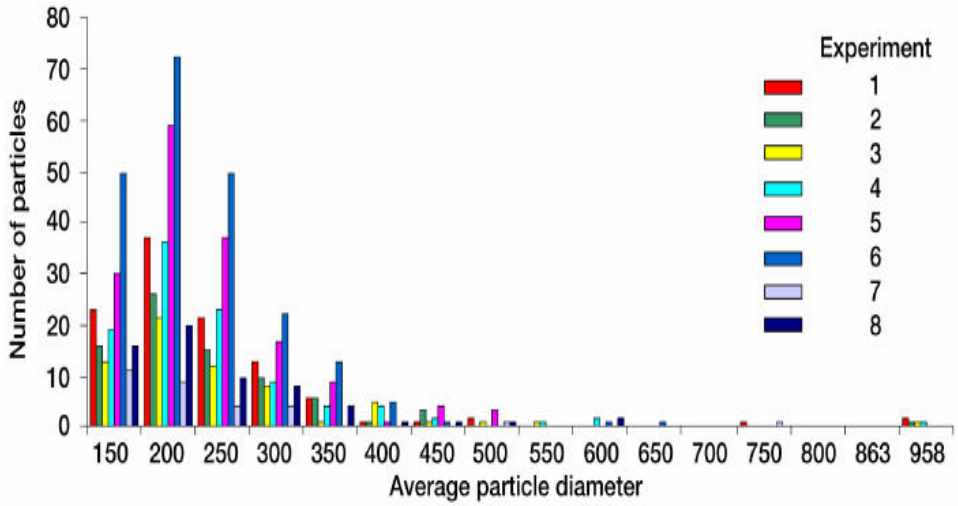
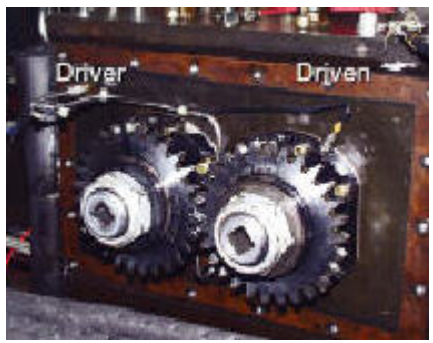


Figure 5.—Spur rig experiment after pitting damage was observed.

Increasing damage on gear tooth



- Pattern of failure for surface fatigue of gears is similar to bearings

Reference : *"Investigation of Gear and Bearing Fatigue Damage Using Particle Distributions", NASA/TM – 2004-212883, Dempsey P et al*

NASA Spur Gear Test Rig Case

Spur Gear Tooth Damage

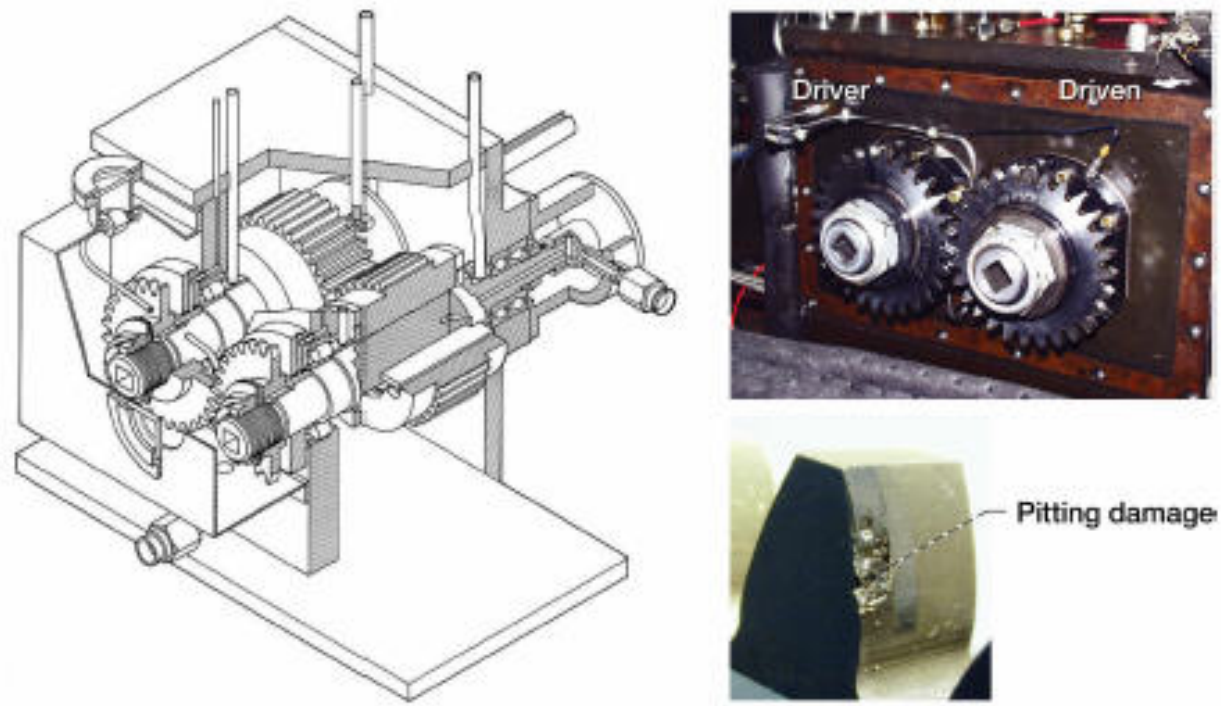
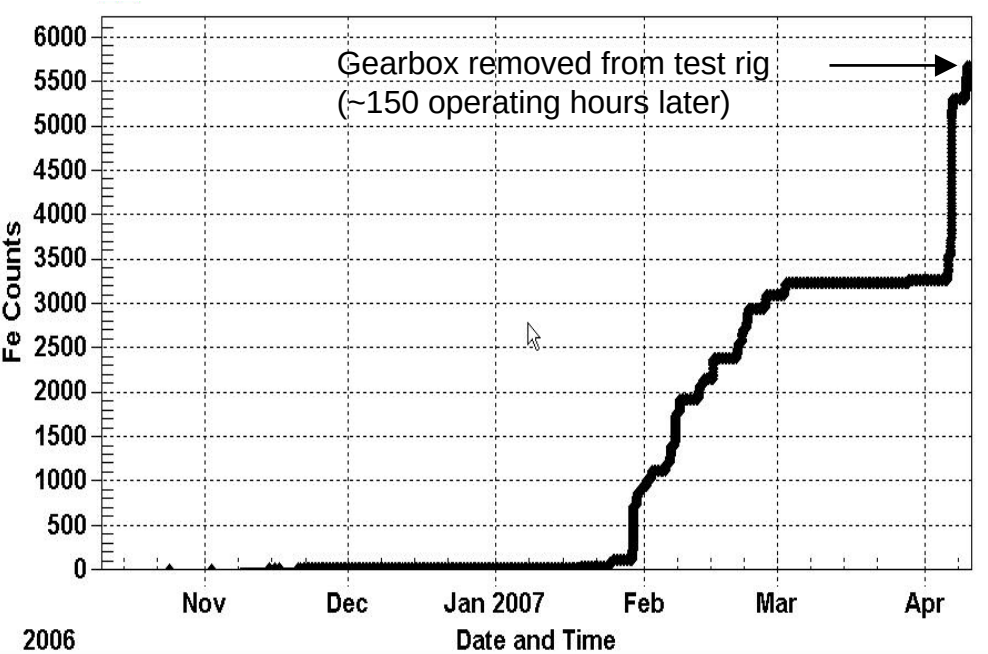
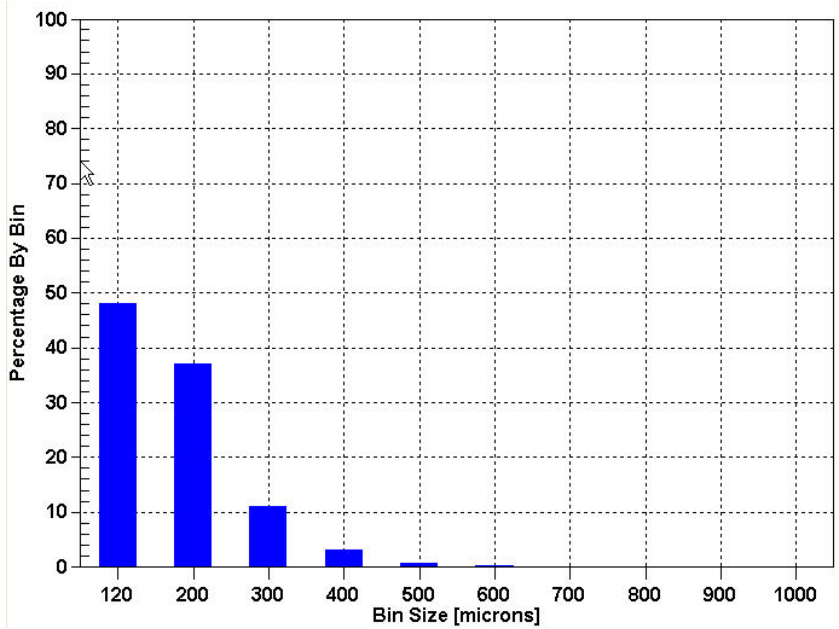


Figure 1.—Spur gear fatigue test rig.

Reference : *"Investigation of Gear and Bearing Fatigue Damage Using Particle Distributions", NASA/TM – 2004-212883, Dempsey P et al*

Helicopter Gearbox Test Rig Case 1
Ferrous Wear Debris Particle Trend





- Rig test of AH-64 drive-train at US Navy Patuxent River transmission test facility
- 200 hour high stress component qualification test
- No chip detector alarm
- Teardown confirmed damage limited to input shaft bearing of right nose gearbox

Data is presented by permission from NAVAIR

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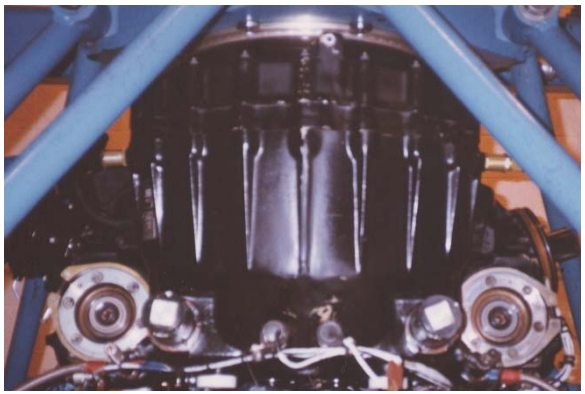
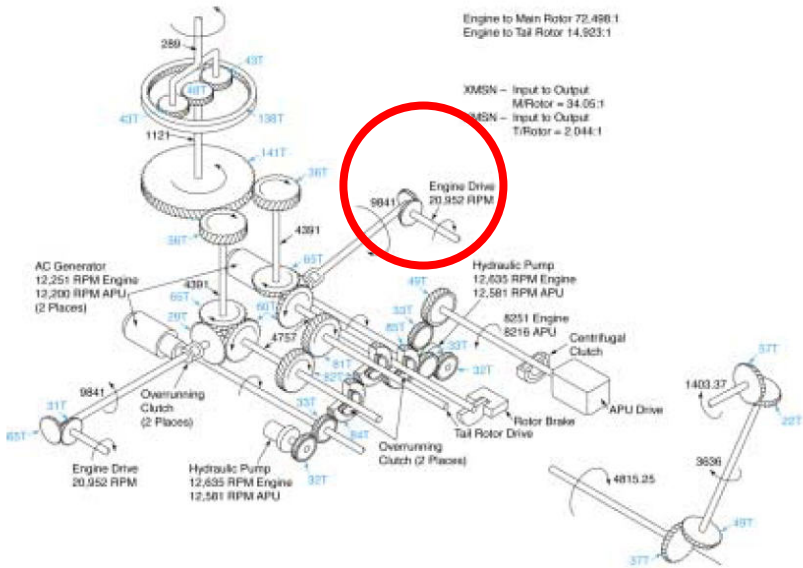
Helicopter Gearbox Test Rig Case 1
Right Nose Gearbox Input Shaft Bearing Damage





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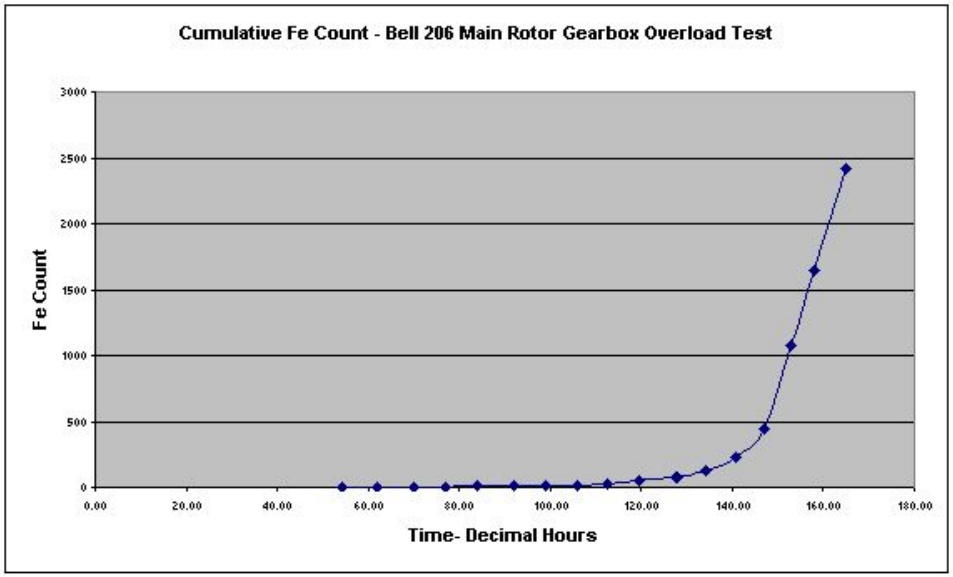
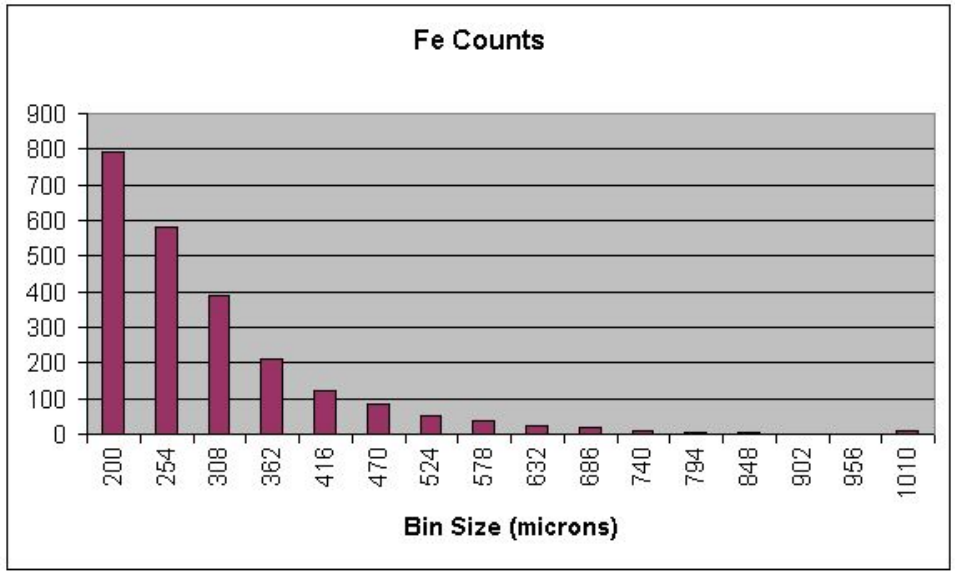
Helicopter Gearbox Test Rig Case 2
Ferrous Wear Debris Particle Trend





- Rig test of a B206 main rotor gearbox at DSTO test facility
- 150% overload stress test

Data is presented by permission from the Australian Defense Science & Technology Organization

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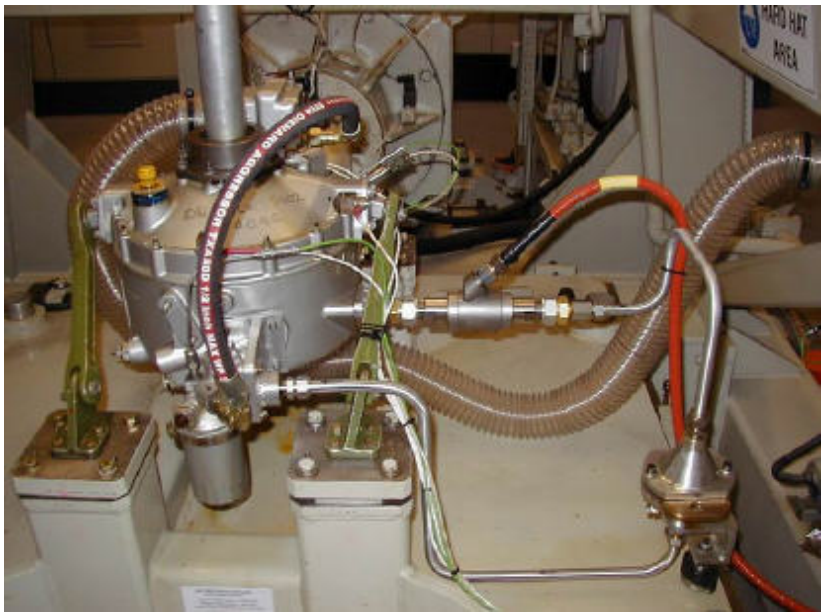
Helicopter Gearbox Test Rig Case 2
Main Transmission Planet Bearing Damage



- Test teardown showed damage limited to planet bearing

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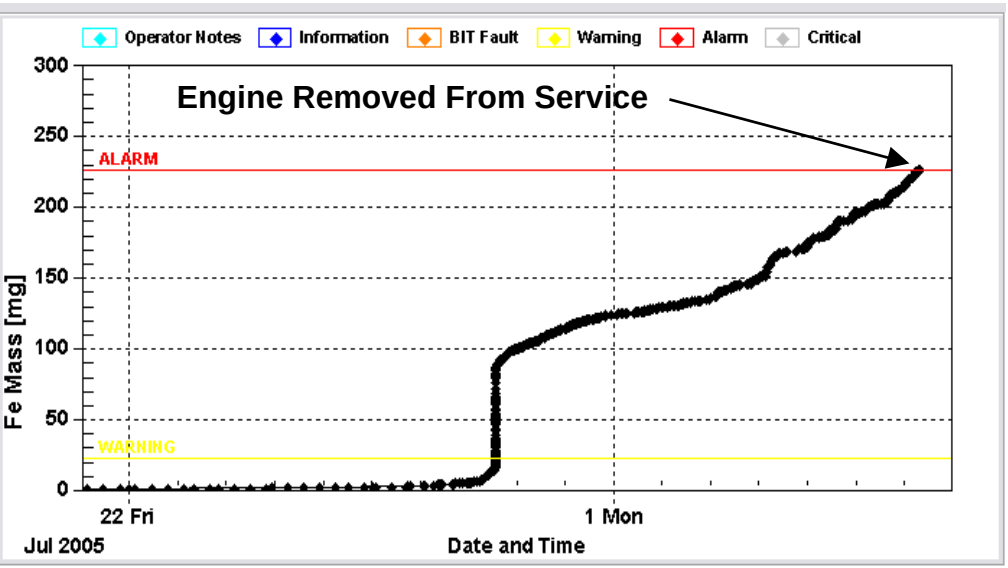
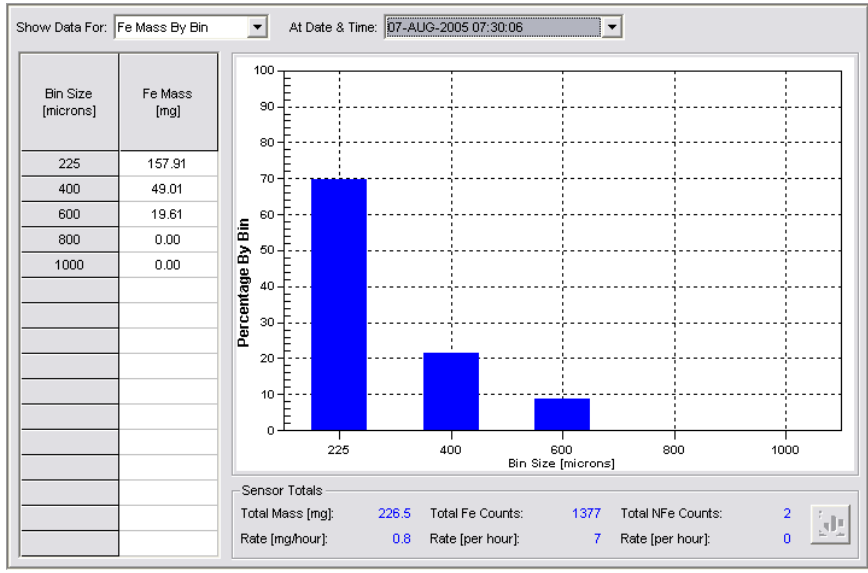
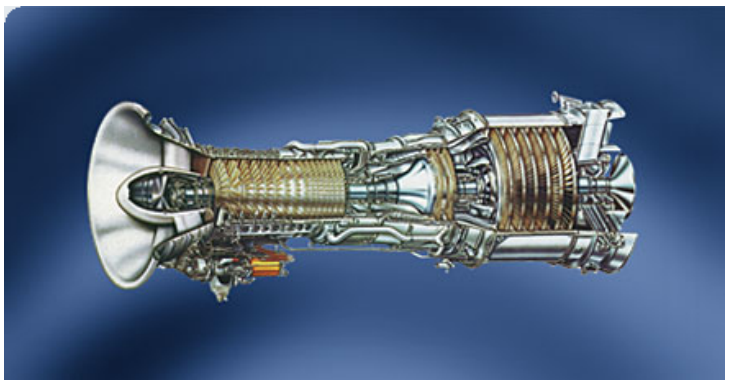
Aero-derivative Gas Turbine Case 1
Ferrous Wear Debris Particle Trend







- Only last 35 days shown.
- After rapid rise of debris engine power reduced to 80% to slow damage progression to reach scheduled maintenance period
- No change detected by vibration or scavenge temperature
- *SECONDARY DAMAGE avoided*

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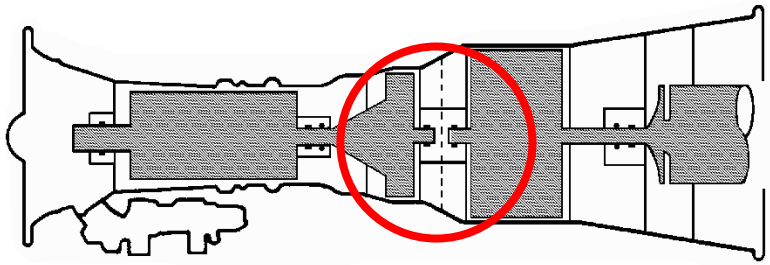
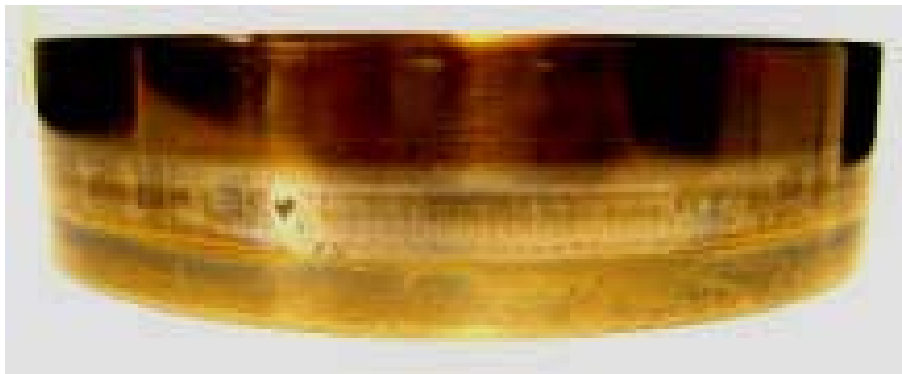
Aero-derivative Gas Turbine Case 1
Main Shaft Bearing Damage



- **Damage to #5 and #6 bearings**.



Bearing Inner Race

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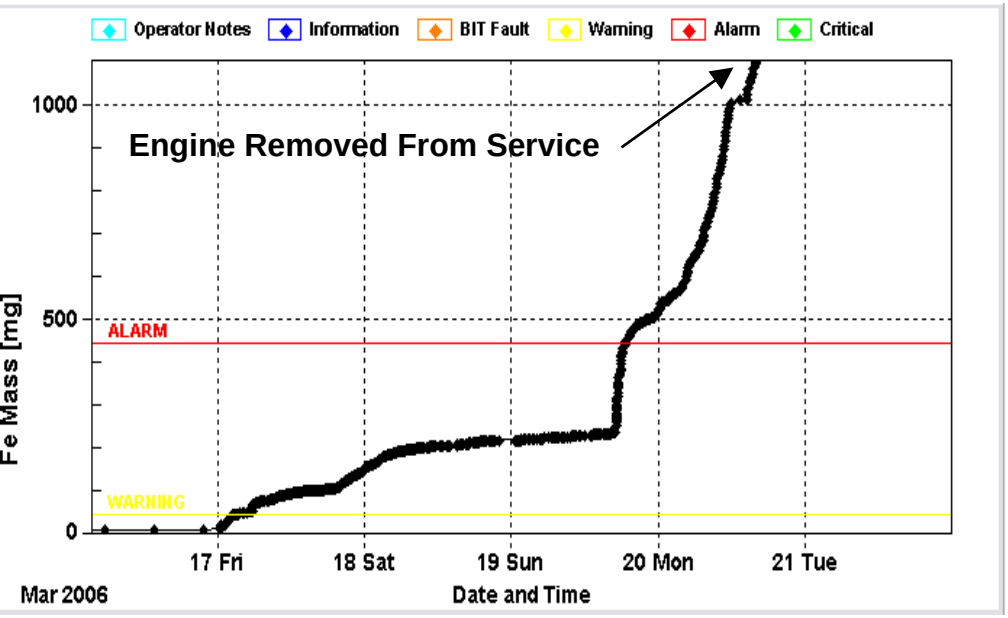
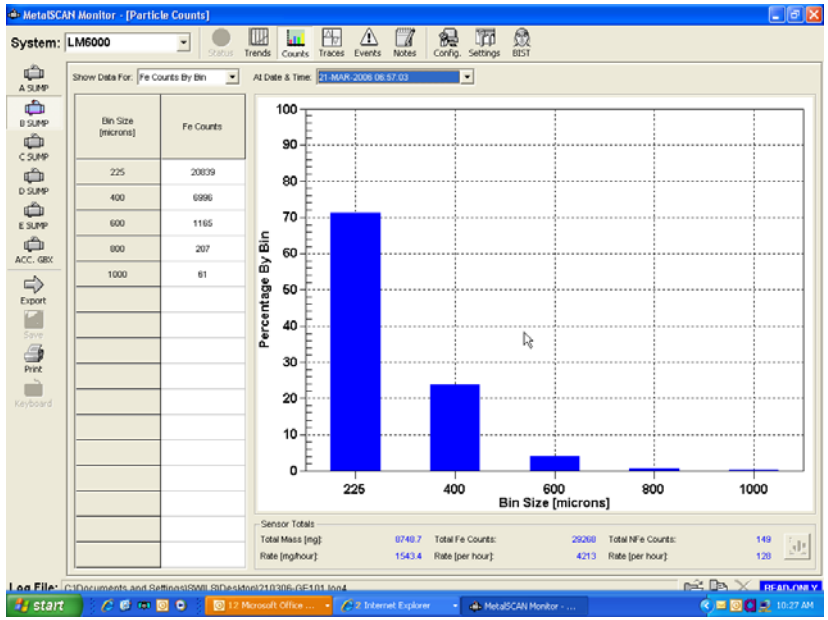
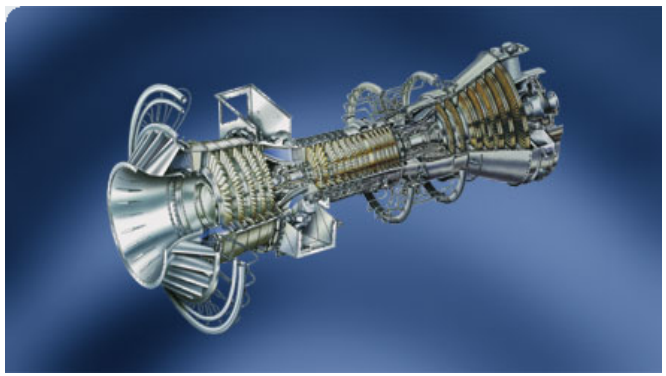
Aero-derivative Gas Turbine Case 2

Ferrous Wear Debris Particle Trend

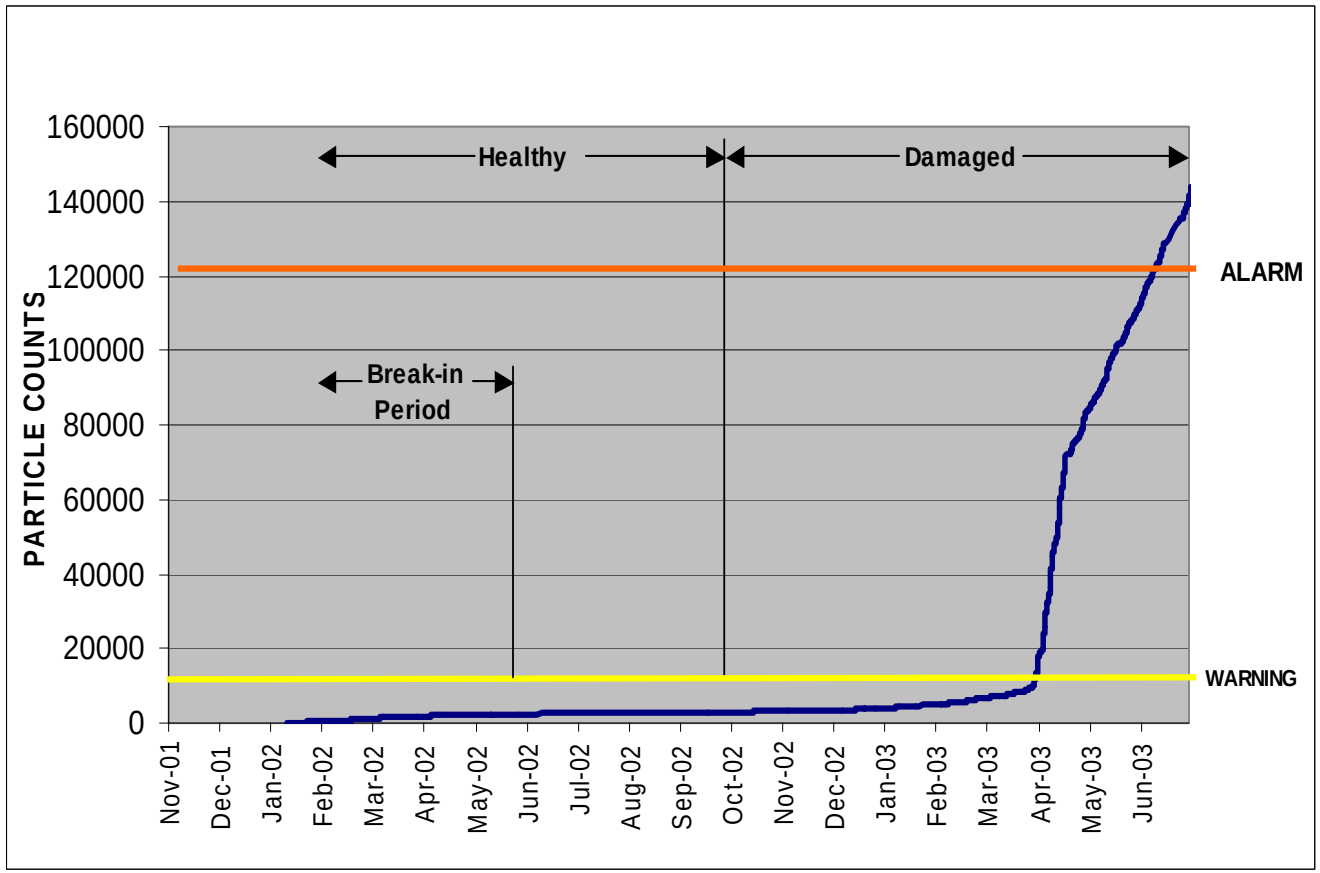






- Only last 4 days shown
- Due to high prices for power, customer ran engine past alarm limit at reduced load with close monitoring
- Engine tripped on high lube oil temperature
- Damage limited to bearing. SECONDARY DAMAGE avoided

Wind Turbine Gearbox Case 1
Ferrous Wear Debris Particle Trend



Wear debris particle sizes observed over 225 um

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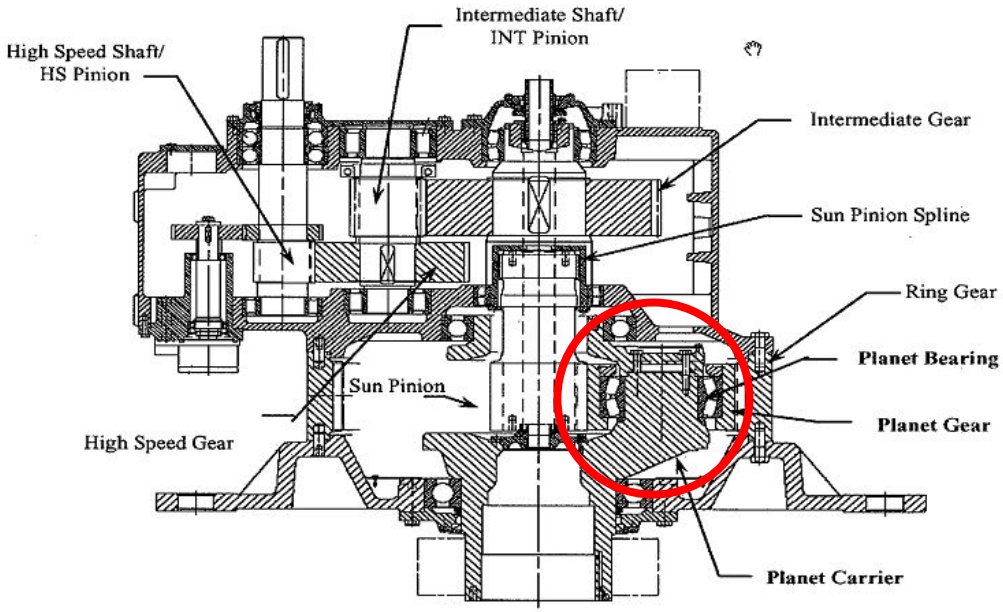
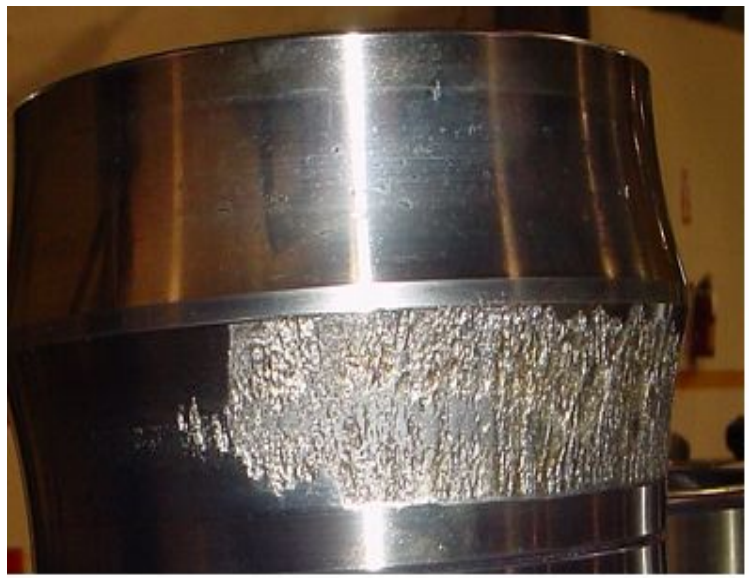
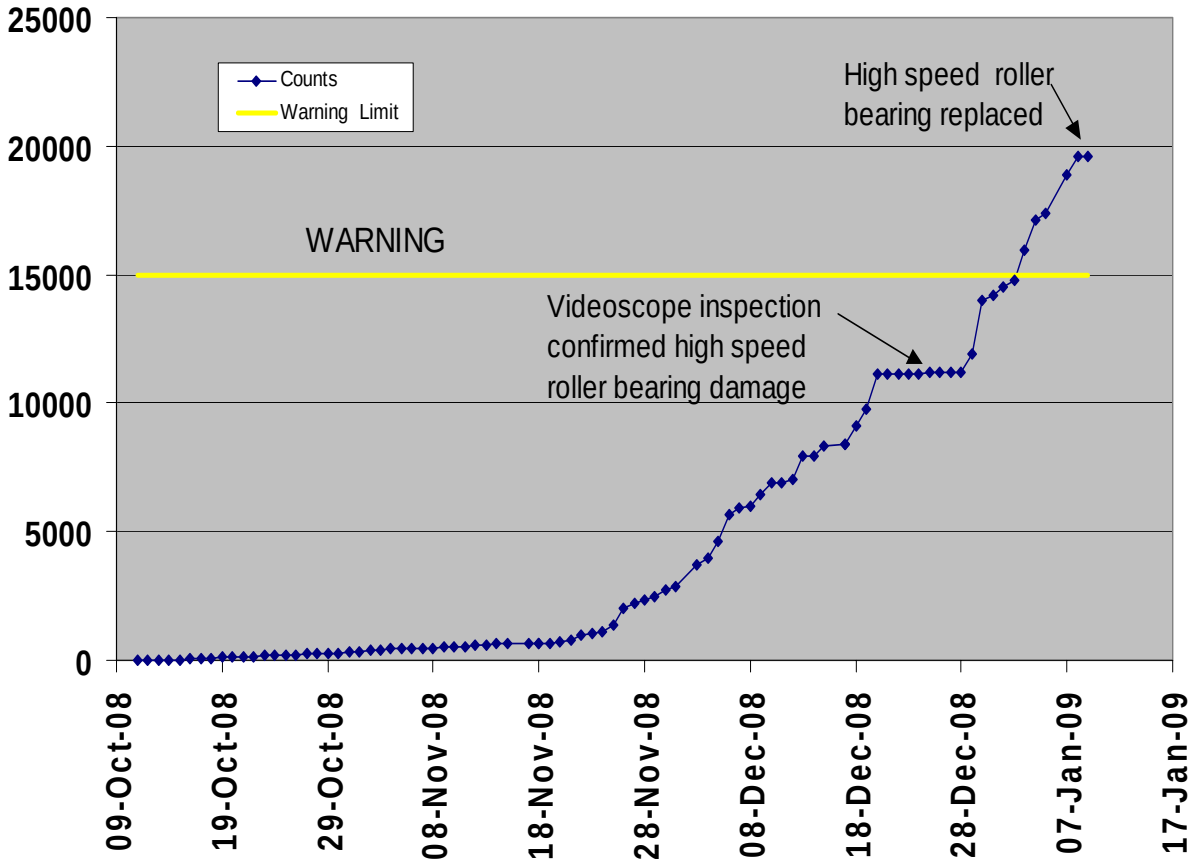
Wind Turbine Gearbox Case 1
Planetary Stage Bearing Damage





Inner Race

Wind Turbine Gearbox Case 2
Ferrous Wear Debris Particle Trend



Wear debris particle sizes observed over 260 um

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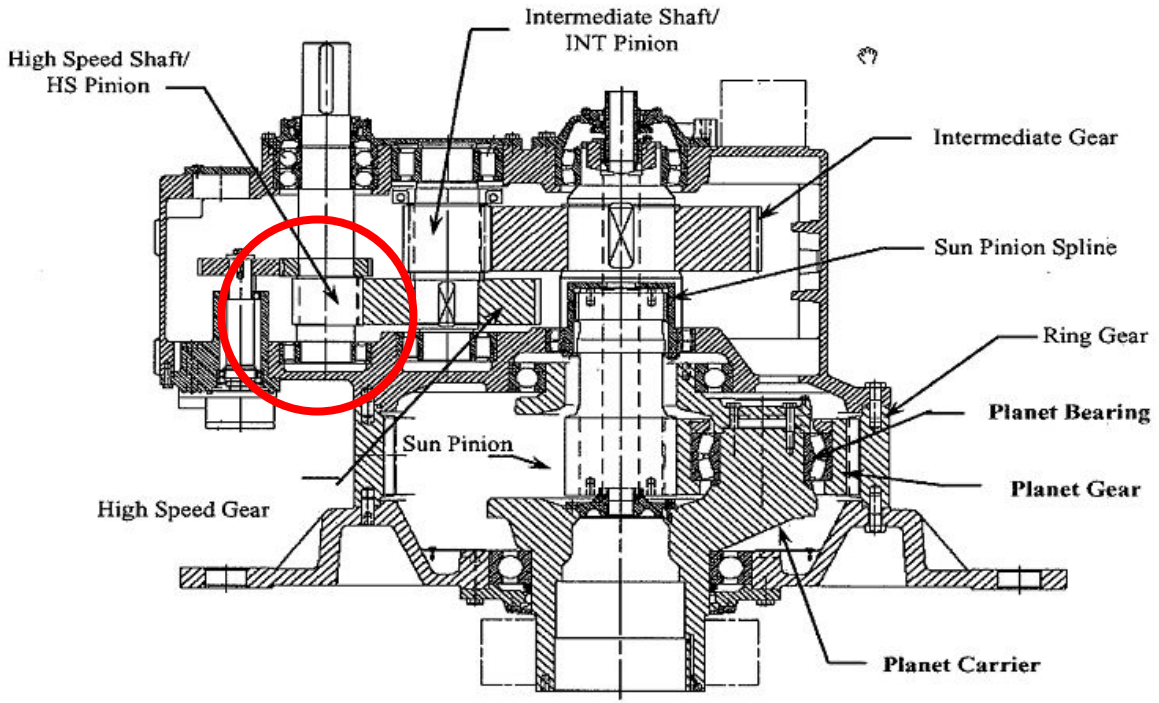
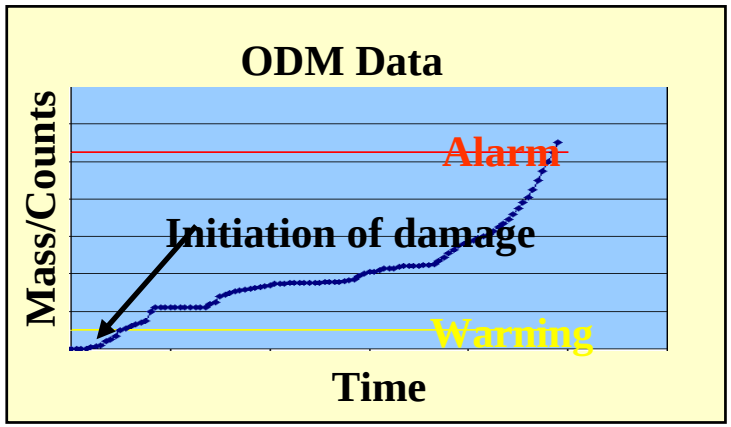
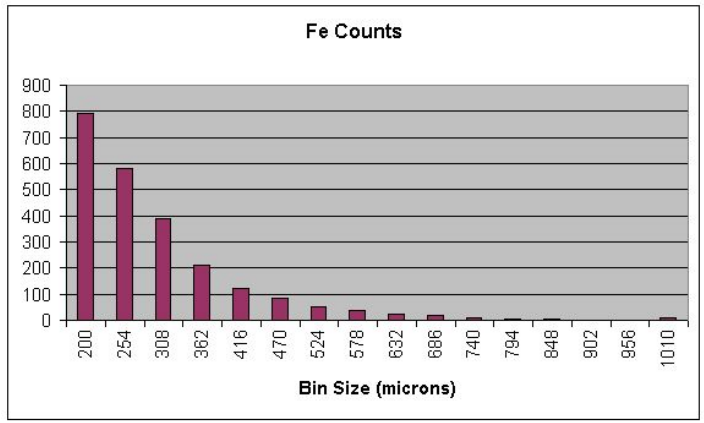
Wind Turbine Gearbox Case 2
High Speed Stage Bearing Damage



Inner Race

Large Wear Debris Trends - Summary





- Accumulated particle mass/count trends of large wear debris particles have been proven capable of monitoring the condition of bearings and gears in critical rotating machinery
- Large wear debris particles have provided (1) sufficient early indications of bearing spall and gear pitting surface fatigue wear and (2) quantification of the severity of damage progression to avoid failure
- Even at early stages of significant bearing & gear damage, large wear debris particles greater than 200 um are generated

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