Qualification of an On-Line Bearing and Gear Health Monitoring Technique for In-Service Monitoring of Aircraft Engines and Helicopter Transmissions

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Making Machinery More Effective

Outline

- Introduction
  - Aircraft availability depends on engine & transmission health
  - Why bearings and gears fail
  - Oil Debris Monitor sensor
- Qualification Process
  - How to set debris limits, assess damage severity
  - Early research results, characteristic debris accumulation, initial condition indicators
  - Validate the limits using empirical test data
- Sources of Aircraft Engine & Transmission ODM Test Data
  - Bearing and gear rigs; engine and helicopter test stands
  - Pre-flight aircraft data
- In-Service Condition Indicator Qualification
  - Eurofighter Typhoon / EJ200
  - Pilatus PC-12 / PWC PT6A

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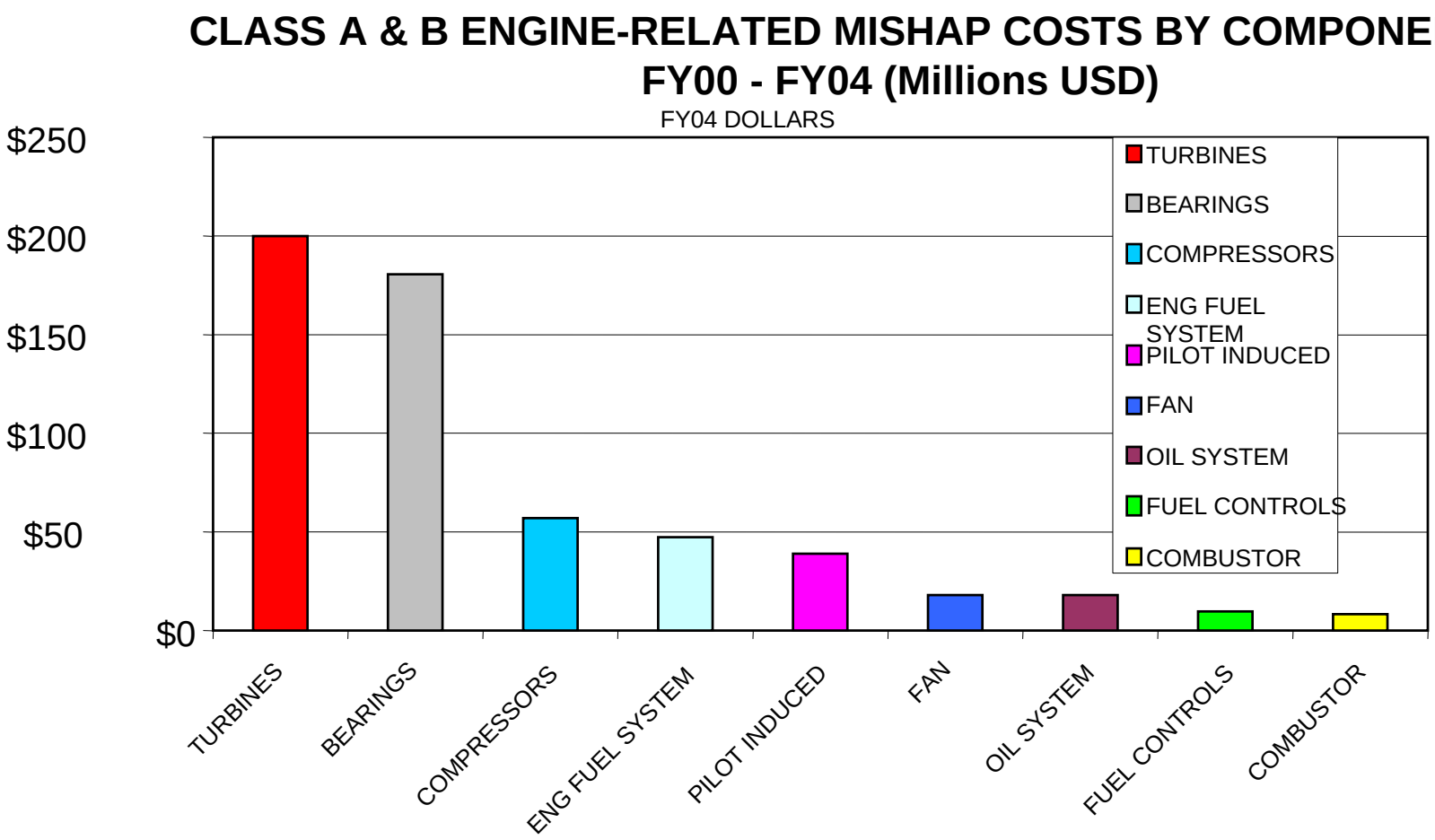
The Cost of Aircraft Engine Failures



Source: Forster, Thompson, Toms, & Horning, "Assessing the Potential of a Commercial Oil Debris Sensor as a Prognostic Device for Gas Turbine Engine Bearings" ISHM August 2005

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Why Bearings Fail

- **Bearings fail in-service due to**
  - **Over Rolling Debris**
    - **Solids contamination**
  - **Corrosion Pitting**
    - **Chemical contamination**
  - **Mechanical Damage**
    - **Dimensional discrepancies**
    - **Manufacturing defects**
    - **Damage during shipping, install**
  - **Classic Fatigue**

- **Subsequent damage progression results in metallic particles being released into lubricating oil**

Source: FAG Bearings / Aerospace Applications

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MetalSCAN Oil Debris Monitor

- On-line full-flow ODM sensor fitted in lube oil line
- Detects 100% of particles above minimum particle size
- Measures number, size, mass of ferrous & non- ferrous debris
- Detects spall initiation, progression, rate
- Quantifies damage severity and remaining useful life

MetalSCAN™

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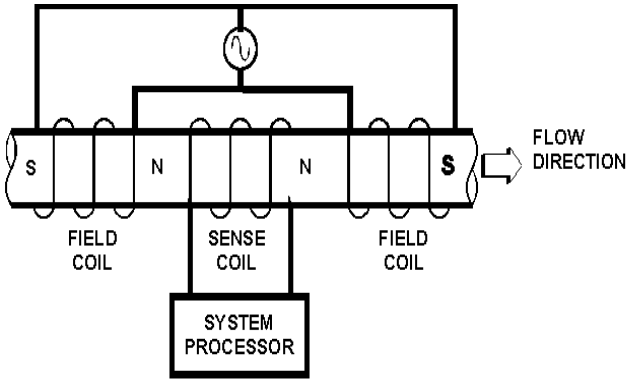
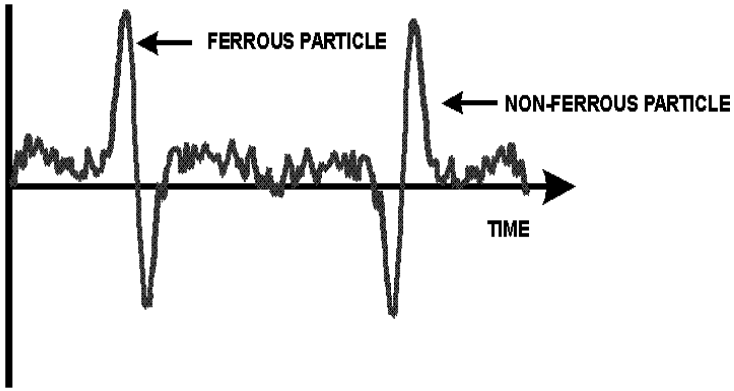
ODM Principles of Operation

- **Metallic debris flows through the field coils creating a current in the sense coil**
- **Processor computes particle size and mass based upon signal amplitude**
- **Ferrous particles and non-ferrous particles are distinguished based upon signal direction.**





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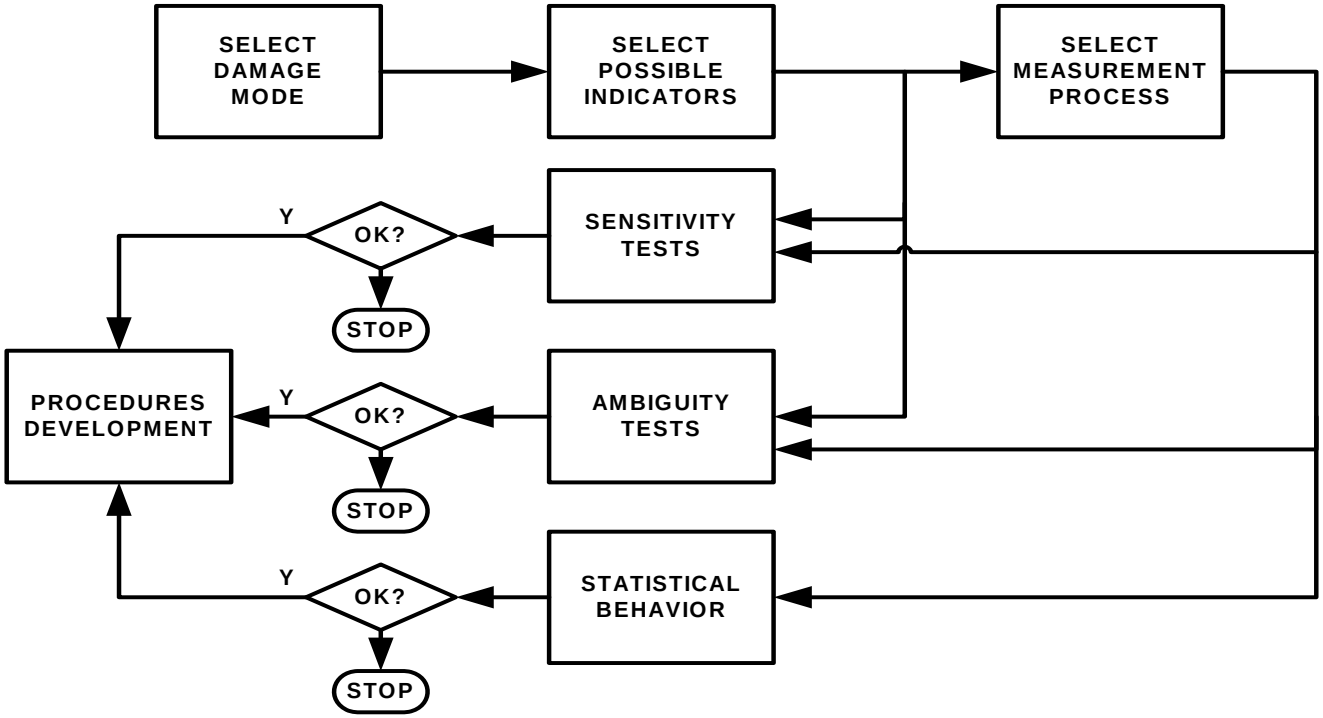
Condition Indicator Development Process

- Condition Indicator Development
  - Determine measurements that quantify wear and damage severity



- Establish Limits & Guidelines
  - Theory validated by empirical data

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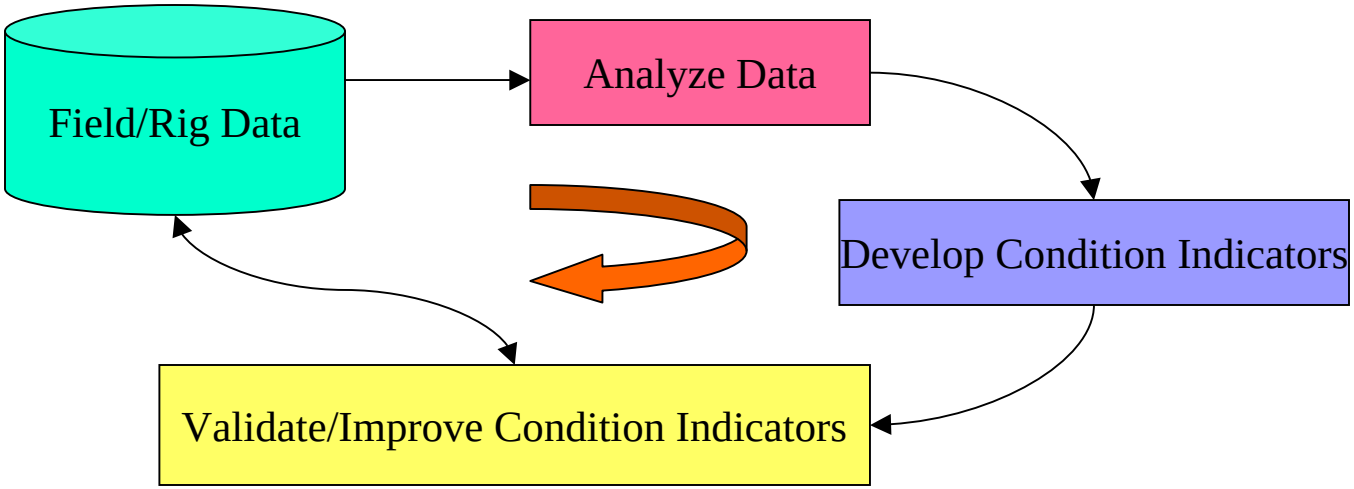
Qualification Process

- ODM Qualification Process
  - Correlate debris quantity with actual damaged components
  - Validate with spall checks, FDA, teardown reports, field data



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Early Research Results

- Joint program between GasTOPS, National Research Council Canada, and Pratt & Whitney in the early 1990s
- Aircraft bearing test rigs: bearings were run to failure
- Data from over 40 bearings (2” to 18” in diameter; ball and roller)
- Initial spall generates a few particles ranging small to large in size
- Early damage progression is a series a spall growth events, which are seen as bursts of particles
- Later stage failure: damage is more progressive / accelerated
  - Rate is dependent on load and speed
  - Quantity is dependent on size of bearing
  - Particle size distribution is independent of bearing size
- Reliable alarm limits can be based upon accumulated quantity
- Can correlate spall size to quantity of debris

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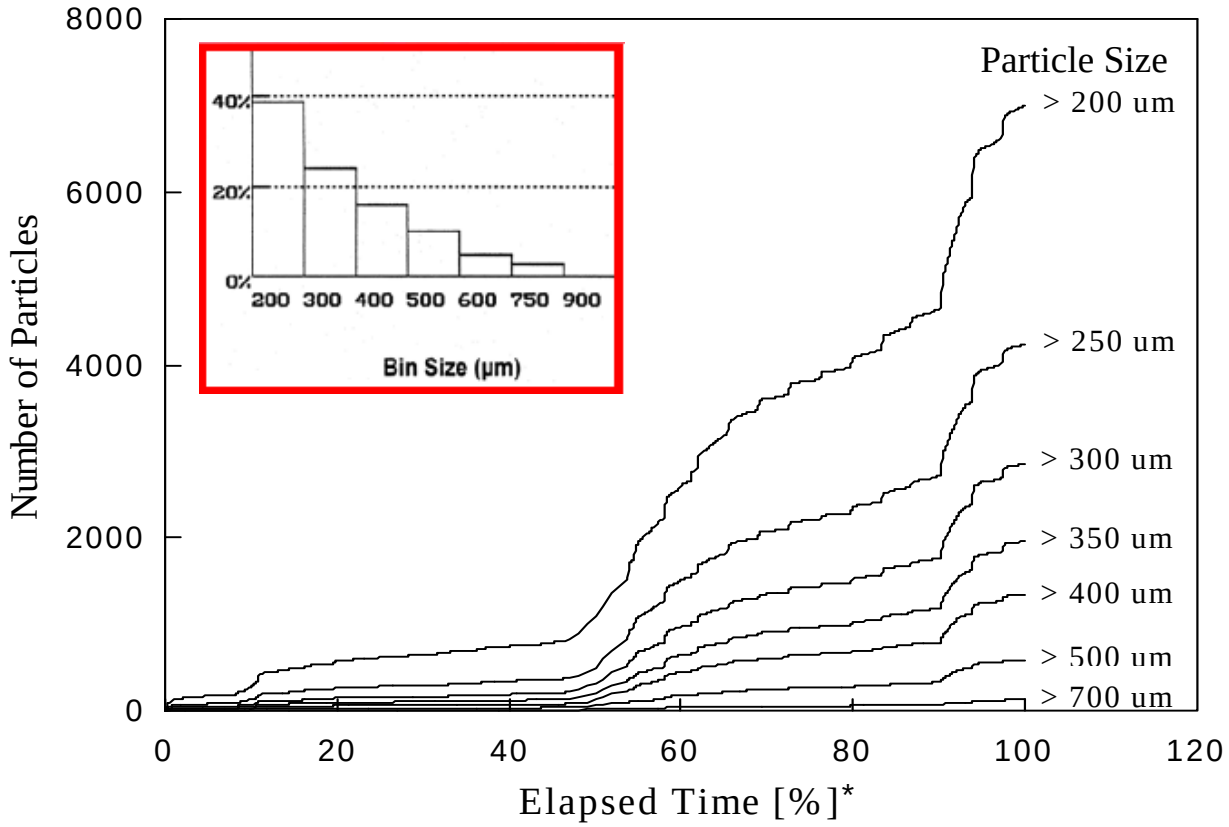
Characteristic Debris Accumulation



Source: JL Miller (Pratt & Whitney) and D. Kitaljevich (GasTOPS Ltd.), **In-line Oil Debris Monitor for Aircraft Engine Condition Assessment,** IEEE 2000

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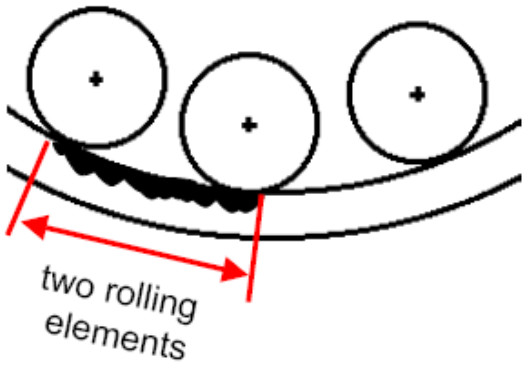
Initial Condition Indicator – Total Mass

- **Critical spall arc length: 2 rolling elements ($\theta c = 360°/N$)**
  - **When 2 elements fit in spall track, get a jump in vibration**
- **Mass of debris shed is a function of spall width, depth, length, material density; proportional to ball, pitch diameter**
- **Mass rate is function of load, speed, temp**

Alarm limit $Q_{ALARM} = K\ (360°/N)\ D\ d$

- **Q = Quantity of debris detected**
- **K = Constant (bearing type)**
- **N = Number of rolling elements**
- **D = Bearing pitch diameter**
- **d = Rolling element diameter**



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Engine, Gearbox, & Bearing Rig Data

- **Bearing and Gear Component Rigs**
  - National Research Council of Canada – small scale bearing rigs
  - Pratt & Whitney & GasTOPS – full scale aircraft bearings
  - AFRL 40mm Bearing Rigs - test bearing materials and fluids
  - NASA Glenn Research Center Component Rigs
    - Hybrid bearing, Tapered roller bearing, Spur gear, Spiral bevel gear

- **Engine & Transmission Test Stands**
  - NASA OH-58 Kiowa Helicopter – main rotor transmission test stand
  - CAF Sea King Helicopter – engine & gearbox test facilities
  - DTSO Bell 206 Helicopter – main rotor transmission test stand
  - F22 Raptor - F119 engine pre-flight tests
  - AH-64 Apache Helicopter - transmission test stand

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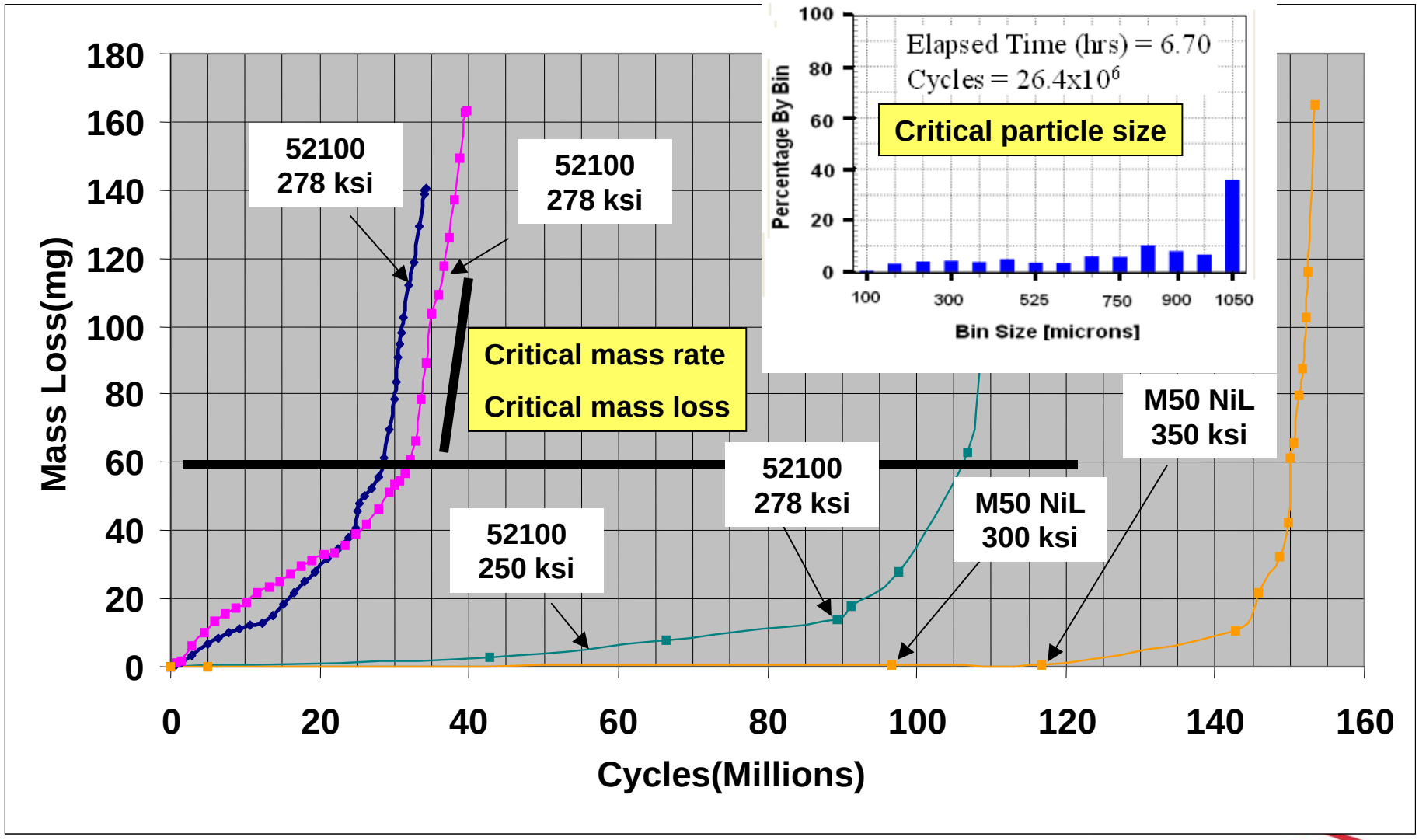
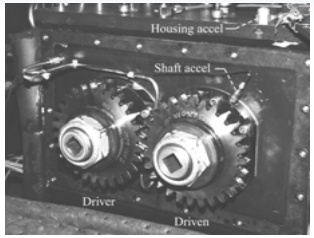
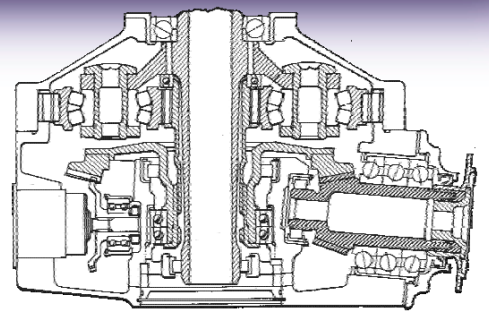
AFRL Bearing Rig: M50 NiL Propagation Rates

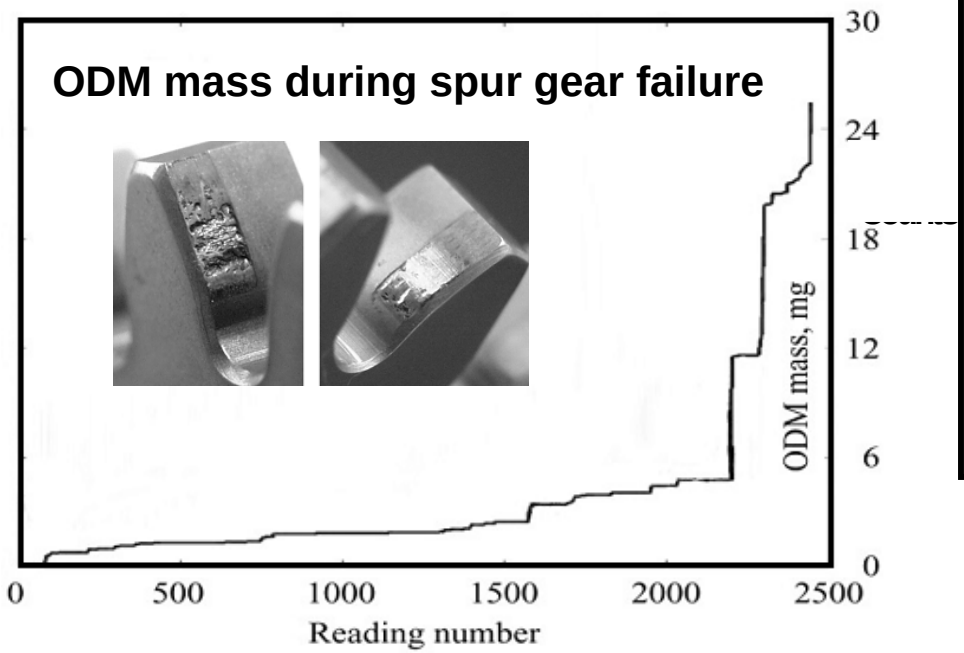


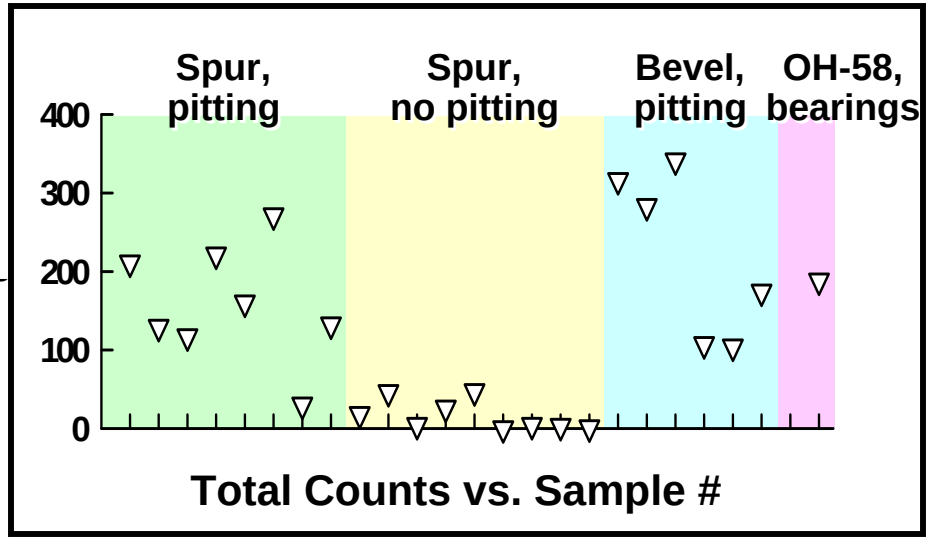


NASA Glenn Test Rigs



- Goal to quantify debris generation during bearing & gear wear
- Test Methods: Spur gears (17 tests), Spiral bevel gears (6 test), OH-58 helicopter transmission (2 tests), and others
- Measured debris progression, total counts, total mass, mean particle size





Source: NASA Glenn Research Center, Cleveland, OH.
Ref: P.Dempsey, A. Afieh, D. Lewicki, H. Decker, et al.

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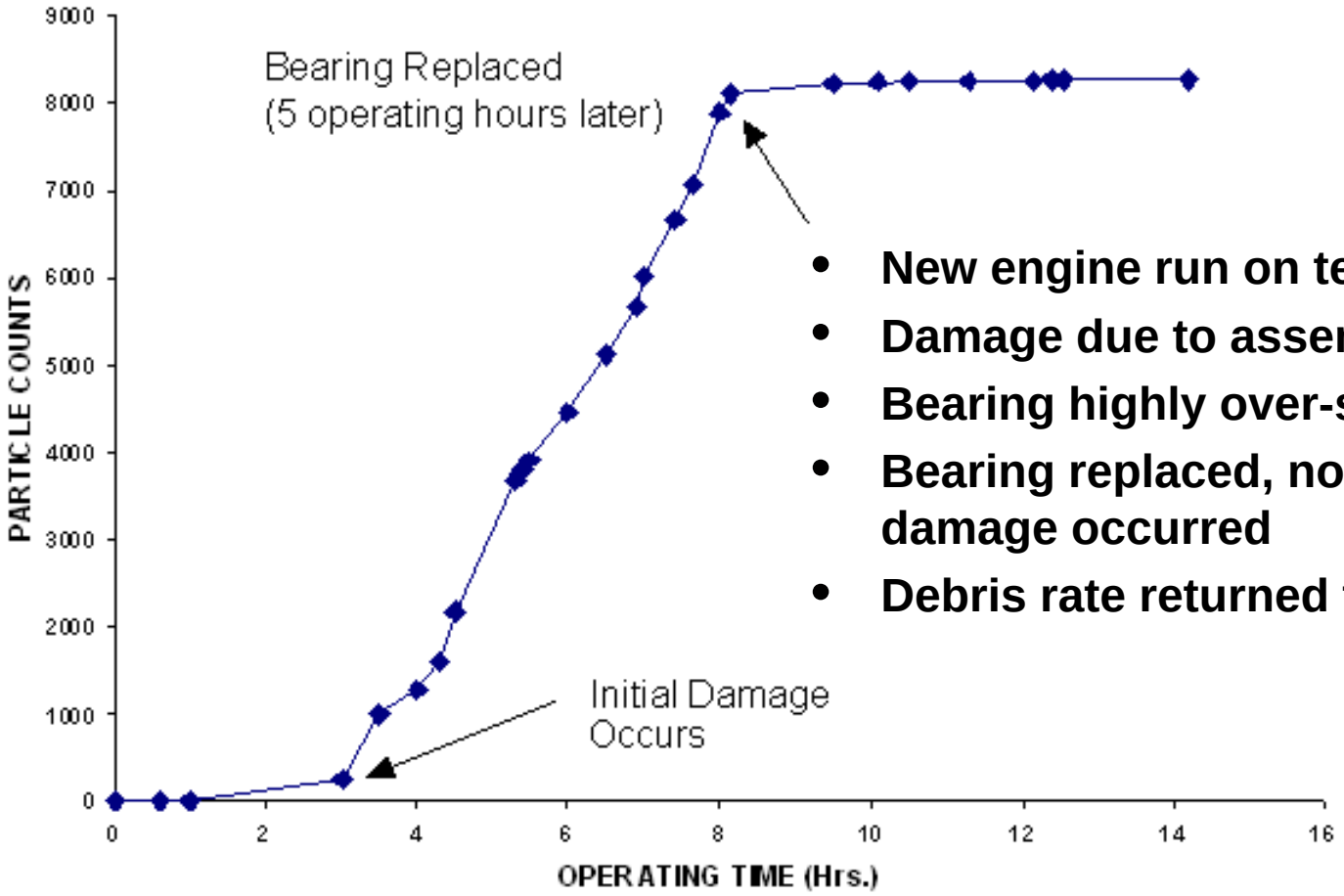
F119 Engine / F22 Aircraft Pre-Flight Tests



- New engine run on test stand
- Damage due to assembly error
- Bearing highly over-stressed
- Bearing replaced, no secondary damage occurred
- Debris rate returned to normal

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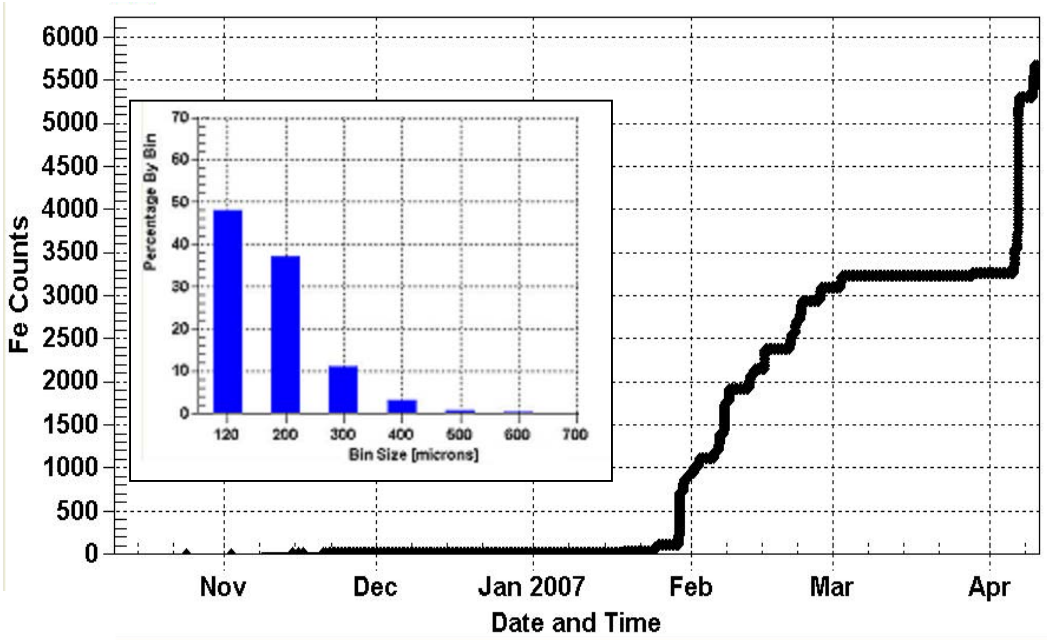
AH-64 Apache Helicopter Transmission

- **Application:** Naval Air Station at Patuxent River
  Helicopter Transmission Test Facility
- **Condition Indicator: Total Mass**
  - Right nose gearbox sensor detected high quantity of wear debris
- **Damage Verification**
  - Filter Debris Analysis (XRF) showed M50 in right NGB, 100x mass LNGB
  - Teardown showed one roller over 50% of contact surface had spall; early signs in other rollers and race



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In-Service CI Qualification

- **Application: Eurofighter Typhoon / EJ200**
- **Condition Indicators**
  - **Total Mass Accumulation Level and Rate**
  - **Large Particle Accumulation Level and Rate**

- **EJ200 Debris Database**
  - **3 Bench Test Engines**
  - **7 Flying Development Engines**
- **Validation**
  - **Bearing rig tests used for initial condition indicator limits**
  - **Correlated MetalSCAN mass rate to legacy debris monitor limits**
  - **Database of wear debris data (MetalSCAN, MCD and oil filters) of healthy and faulted engines used for ongoing limit verification**

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In-Service CI Qualification

- **Application: Pilatus PC-12 / PWC PT6A Engine**
- **Condition Indicators**
  - **Level 1 Threshold - Total Particle Count Threshold**
    - **Minimum count to allow for new engine break-in**
  - **Level 2 Threshold - Short Term Particle Count Rate**
    - **Cockpit *CAUTION* for aircraft on ground**
  - **Level 3 Threshold - Medium Term Particle Count Rate**
    - **Cockpit *ALARM* for aircraft on ground and in air**

- **Validation**
  - **Normal engine oil contamination rates evaluated in test cells**
    - **Over 100 Production Engines and 50 Repair/Overhaul Engines**
  - **Over 350 in-service aircraft**

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Summary

- A mature, commercially-available in-line ODM sensor provides quantitative diagnostic and prognostic information about bearing and gear damage
- Over the past 15 years, ODM diagnostic condition indicator formulas have been verified by military and government organizations (DND, AFRL, NASA) and by the OEMs
- Verification process uses parameters including:
  - Critical mass loss
  - Critical mass rate
  - Critical particle size
- GasTOPS is working with AFRL to enhance prognostic capabilities of the ODM sensor algorithms for aircraft engine bearing applications

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