Life Prediction of Critical Turbine Components Using Prognosis

By

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Safe Life LCMM Philosophy (1/1000 probability of crack initiation)

-3σ = Mean/2.45

Life to crack initiation

Frequency of Failures

Log Cycles or Time to Crack Initiation

All components are retired

Mean

- All components are retired at the mean value of the normal distribution.
- The distance from the mean to the point where the curve starts to decrease is -3σ, which is Mean/2.45.
Remaining Life of Safe Life
Expired Discs

USAF Study
XactLIFE System Architecture (Patent Pending)

- Engine Operational Data
  - Data Analysis and Filtering
    - Combustor Model
      - Engine Modeling
        - Thermodynamic Analysis
          - Component Geometry
            - Material Information
              - Engine Design Parameters
                - Finite Element Model
                  - Finite Element Solver
                    - Probabilistic Analysis
                      - Microstructural Damage Model
                        - XactLIFE™
                          - Output Results
                            - GUI
                              - REMAINING LIFE
                                - OVERHAUL & INSPECTION INTERVALS
                                  - DISTORTION & CRACKING
                                    - SURFACE CONDITION

Legend:
- User Input
- Software Process
• Determine the **temperature** and stress profiles that the components are exposed to in a specific engine operating environment

• Consider the effect of operating loads on crack initiation life in different rotors

• Identify the most fracture prone rotor

• Determine the primary and secondary fracture critical locations of the rotor(s) and predict a safe operating interval for the engine

• Consider the effect of NDI detection limit/uncertainties on the future safe operation of the engine and select the most appropriate NDI technique for inspecting the individual rotor locations.

• Design new NDI probes if necessary
Temperature Profile Frame 5 blade/Disc
Combined

Bladed Disc

Stand Alone Disc
Jethete M152 Hardness Behavior

![Graph showing the hardness behavior of Jethete M152 as the temperature increases from 400°C to 800°C. The hardness decreases significantly above 600°C.](graph.png)
Jethete M 152 Stainless Steel

C 0.08 – 0.13 wt%
Cr 11.0 – 12.5 wt%
Mo 1.5 – 2.0 wt%
V 0.25 – 0.4 wt%
Ni 2.0 – 3.0 wt%

Disc bore hardness was 380HV and all that can be concluded is that the disc rim temperature is less than 500ºC
No noticeable change in secondary carbide morphology below 500°C (Schinkel et. al., ASM International, 1983). No over-temperature exposure or rim temperature does not exceed 500°C during service.
Replica technique is only good if surface connected cracks are present
### XactLIFE Based Frame 5001P Disc Creep Life (Mid-East Client)

<table>
<thead>
<tr>
<th>Rim Temp. °C</th>
<th>Rim Life In Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>415 °C (predicted)</td>
<td>360,000 (predicted)</td>
</tr>
<tr>
<td>450 °C (assumed)</td>
<td>100,000 (assumed)</td>
</tr>
<tr>
<td>500 °C (assumed)</td>
<td>20,000 (assumed)</td>
</tr>
</tbody>
</table>

*In this case lower bound creep crack initiation life was estimated to be 360,000 hours*
Lessons Learned

- Accurate assessment of the disc rim temperature is vital for assessing the residual life range available for life extension for a specific engine operating environment.
- Rim temperature can only be determined through gas path modeling and heat transfer analysis.
- Hardness checks and replica assessment only indicate whether the discs have been subjected to any over-temperature effects during service.
- Replicas can only be used to detect any surface connected flaws.
- Return to service interval prediction involves detailed engineering assessment of the engine as a whole.
PROGNOSIS BASED SAFE INSPECTION INTERVAL OR RETURN TO SERVICE INTERVAL PREDICTION FOR W-101 ENGINES

PDVSA Fleet, Maracaibo, Venezuela
LIFE CYCLE MANAGEMENT OF TURBINE DISCS/SPACERS MIL-STD-1783

- Assumes that a crack already exists in as manufactured discs.
- The minimum detectable crack size is governed by the detection limit of the NDI technique used during overhaul.
- Prediction of crack propagation interval (CPI), using crack growth analysis techniques.
- Safe inspection interval (SII) defined as half of the CPI.
- Disc inspection after every SII.
- Return the disc back to service if no crack is detected.

**Graphical Representation:**

- **CPI**
- **Dysfunction Crack**
- **SII = 1/2 CPI**
- **Initial Crack Size, \(a_i\) (Minimum Detectable Crack)**
- **Inspection Cycles or Time**
  - **1st Inspection**
  - **2nd Inspection**
  - **3rd Inspection**
W-101 Turbine Configuration

SINGLE SHAFT GAS TURBINE
9950 HP
SPEED 6300 RPM

HOT SECTION ROTOR

Stage 1  Stage 2  Stage 3  Stage 4  Stage 5

SOURCE: TURBINE MANUAL
EXTENDED DAMAGE TO THE TURBINE HOT SECTION
LIFE CYCLE MANAGEMENT OF TURBINE DISCS

CRACK AT THE FIRTREE BOTTOM SERRATION DETECTED DURING OVERHAUL INSPECTION
IDENTIFICATION OF CRACK INITIATION AND PROPAGATION MECHANISMS
Brittle Creep Fracture in Discaloy
- Stress-temperature profile of the part (boundary conditions)
- Identification of fracture critical location (crack nucleation / initiation based)
- Determine ‘a’ v/s K Correlation
- Choose damage evolution models (Short CCGR and Long CCGR)
- Conduct creep crack growth based safe inspection interval or overhaul interval prediction analysis
Probability of Detection Of Disc Cracks Using LPI
Safe Inspection Interval Prediction for LPI Technique Using Prognostics

Graph: \( a \text{ (mm)} \) vs. \( t \text{ (hr)} \) for creep Analysis

- \( y \)-axis: \( A \text{ (mm)} \)
- \( x \)-axis: \( t \text{ (hr)} \)

Data points show a steady increase in \( A \) over time, indicating creep behavior.
Probability of Detection of Cracks Using LPI and ECI
Safe Inspection Interval Prediction for ECI Technique Using Prognostics

(a (mm) vs. t (hr) for creep Analysis)
PFM Analysis Using ECI Technique

No. of Disks = 436
Median = 565881.49 Hours
0.100 % F = 118551.60 Hours
Lambda = 13.25
Dzeta = 0.51

Lognormal Analysis for Safe Inspection Intervals

Cumulative Probability (%)

Number of hours to dysfunction

Normal Deviates
- Use RFC based life cycle management philosophy to maintain discs and NOT DESIGN LIFE APPROACH. Fleet life increased from 150,000 hours to 300,000 hours

- It allows utilization of the crack initiation life of each and every individual part rather than only 1 in 1000 parts allowed by the Design life approach. Only retire discs when a crack is detected or wear is excessive.

- Select appropriate inspection technique to suit user needs

- Prognosis based LCMM saves users close to 50% on overhaul costs
What We Do Differently in Prognosis

- **Residual Life Assessment Using XactLIFE**
  - Precisely define the temperature gradient from bore to rim for the specific engine operating environment through engineering analysis
  - Use FE methods to determine thermal-mechanical stress gradients
  - Use physics based damage models to predict fracture critical locations and compute crack initiation life for a specific user
  - Use hardness checks and replication only for rough verification of T

- **Inspection Interval Prediction Using XactLIFE**
  - Predict a safe return to service interval for the specific user taking into account consequences of any flaws that may be missed during inspection or introduced during manufacturing or present as a metallurgical defect
  - Define quantitative NDI requirements for the user
  - Select most suitable NDI techniques for inspection and design probes if necessary

- **XactLIFE Based Reliability Assessment and Risk Mitigation**
  - Conduct probabilistic analysis taking into account material variability, usage variability and inspection uncertainly
  - Quantify engine reliability for future safe engine operation
Cost Savings

- Disc replacement costs are deferred on long term basis. In the case of W-101 fleet, PDVSA deferred $40 Million investment by more than 10 years.

- Overhaul costs are reduced by as much as 45-50% of the regular overhaul costs. PDVSA saved $2.5 Million per year in reduced overhaul costs for the W-101 fleet.

- Other repair costs can also be reduced significantly
Prognostics Health Management

Level 1
- LCM-ES/Prognostics
  - In-Service PROGNOSIS Engine
    - MISSION PROFILE ANALYSIS
    - COMBUSTOR MODEL
    - OFF DESIGN ENGINE ANALYSIS
    - THERMODYNAMIC MODELING
    - NON LINEAR SOLVER BASED FE ANALYSIS
    - MICROSTRUCTURE BASED DAMAGE ANALYSIS

Level 2
- Output Results
  - GUI
    - DISTORTION & CRACKING
    - CRACK BEHAVIOR
    - SURFACE CONDITION
    - REMAINING LIFE OVERHAUL & INSPECTION INTERVALS

Level 3
- Performance Monitoring
  - Efficiency
  - TIT/TET
  - Torque
  - Compressor Input Pressure
  - Outside Temperature
  - Fuel Flow
  - Compressor Discharge Pressure
  - Engine Speed
  - Bleed Condition

- Health Monitoring
  - Trending and Pattern Recognition

Level 4
- Input Data
  - GUI
  - COMPONENT MODEL
  - IN-SERVICE OPERATING DATA
  - MATERIAL PROPERTIES

Level 5
- Reasoning And Neural Networks based Real Time Correlation

Level 6
- LPI
  - Eddy Currents
  - Ultrasonic
  - Impedance Spectroscopy
  - LPI
  - Acoustic Emission

Level 7
- Diagnosis
  - Sensors Based Data
    - External & Internal
    - Major Events & Faults
  - Repair & Overhaul Decisions
    - In-Service Inspection
    - Non Destructive Evaluation

Level 8
- Structural Transfer Functions
  - Overtemp
  - Overspeed
  - VIB Sensors
  - PMT
  - Optical

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