Steam Turbines in Combined Cycle: Reliability & Performance Improvement Solutions

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Agenda

- D-11 Fleet Issues
- Known Reliability and Performance Issues
  - N2 Packing Casing
    - N2 Joint Leakage
    - Casing Ledge Cracks
  - HP casing joint leakage
  - Diaphragm Creep Distortion (diaphragm dishing)
  - Bowed rotors
  - Seal Rubs and Clearance Issues
  - L-0 Blade Cracking and Erosion
- A-10 Fleet Issues
- Alstom HP-IP Blade
  - Shim Migration
  - Root Cracking
D-11 Fleet

- About 200 units across US & Canada installed in late 1990’s early 2000’s
- Installed in combined cycle plants with 2 gas turbines
- Two basic D11 configurations
  - 207FA- 11 HP stages, 7 IP, DFLP 762 mm (30”), 851 mm (33.5”) or 1016 mm (40”) LSB
  - 209FA- 10 HP stages 8 IP, DFLP 851 mm (33.5”) or 1067mm (42”) LSB
- Units manufactured by GE, Toshiba, Hitachi but have GE nameplate
Elevated N2 Leakage

- Joint leakage caused by:
  - Preload reduced from relaxation of 422 stainless studs at 1050°F
  - Casing thread creep damage
- Distorted casing makes disassembly difficult
- Opened joint causes leakage across seals
- Offset hooks due to out-of-round condition
- Performance losses due to open joint

1050°F and 1905 psig
Typical on HP side

1050°F and 550 psig
Typical on IP side
Elevated N2 Leakage

- Opening inspection of N2 casing joint indicates leakage

FEA shows N2 joint open in operation
Elevated N2 Leakage

Upgraded Joint Hardware

- Upgrade joint studs to Inconel
- Utilize double nut arrangement
- Ethos Upgrade removes reliance on casing material to maintain sealing
- OEM upgrade (Inconel studs and single nut design)
  - Significant creep damage appears after 5 to 7 years due to reliance on original casing material, causing leakage and difficulty in disassembly.
- Ethos upgrade (Inconel studs and double nut design)
  - Ensures sealing for 10 years, while allowing for ease of assembly and disassembly
  - After 10 years casing thread repair is avoided
  - Performance improvement due to long term joint closure
A TIL was released in 2008 alerting customers of cracking in the N2 casing of D-11 units.

Cracks initiated in the main fit fillet radius from low cycle fatigue and creep rupture damage due to high stress concentration in a high temperature location.

OEM fillet radius in this location 0.375”

Ethos solution is a generous undercut radius that reduces stress on the N2 fit area.

N2 Casing Cracking
Casing Joint Leakage

- Determine required repairs for leaking outer casing joints
- Increase in stud preload
- Changes to stud and nut materials
- Joint distortion analysis
  - What gap is permissible
  - Scrape or machine
A TIL was released in 2007 alerting customers to diaphragm dishing issues found in D-11s.

Diaphragm dishing:
- Hot stages of HP and IP distort axially due to creep distortion at nozzle weld tie-in
- Leads to axial rubs with packing and rotor

Ethos Solution:
- Prep diaphragm entrance side for strengtheners
- Weld strengthener inline with nozzle LE to minimize flow disturbance
- TE tie-in weld if needed from creep damage
- Repair vane trailing edges if required
- Stress-relieve repair
- Machine packing cell to true up packing fit
- Restore axial location w/deviated packing
- Repairs completed within outage window
Causes for Bowed Rotors

- Rubbing during start up / shut down
- Casing distortion
- Water induction
- Foreign object damage / mechanical failure
- Improper inlet temperature control
- Improper slow roll techniques
- Rotor thermal stability / growth problems

- All contribute to one of two causes of rotor bow:
  - Residual Stresses
  - Creep/Plastic Deformation
Common Straightening Methods

- Hung rotor / vertical stress relief
  - Usually only half of original TIR removed by stress relieving
- Heat lathe
  - Similar results as hung rotor method as creep and plastic deformation is not addressed
- Localized heating / hot spotting
  - Residual stresses introduced may relax at different rates than existing stresses
  - Danger of overshooting or local tempering from poor heat input control
- “Throwing” of journals
  - Requires deviated bearing diameter to maintain acceptable clearance
  - Bow may continue to increase over time
  - Interchangeability of spare bearings affected
EE Horizontal Method

- Incoming inspection
  - Visual and dimensional, including detailed TIR
  - Check hardness
  - Metallographic samples
  - NDT for cracks
  - Magnetic memory measurement (MMM)
- Finite Element Analysis
- Engineering evaluation
- Straightening procedure
  - Orient with high spot on top
  - Heat desired areas for localized stress relieving
- Evaluate TIR, iterate
  - Apply external force during subsequent iterations
- Outgoing MMM
EE Horizontal Method

Horizontal Method Results:

<table>
<thead>
<tr>
<th>TIR (inch)</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.011</td>
<td>Max TIR before straightening</td>
<td>.077”</td>
</tr>
<tr>
<td>0.002</td>
<td>Max TIR after straightening</td>
<td>.002”</td>
</tr>
</tbody>
</table>
D-11 Conventional Packing Wear

- HP Conventional Packing:
  - Avg. horizontal wear = 35 mils
  - Avg. top wear = 15 mils
  - Avg. bottom wear = 60 mils

- IP Conventional Packing:
  - Avg. horizontal wear = 15 mils
  - Avg. top wear = 20 mils
  - Avg. bottom wear = 65 mils

- Wear on bottom segments is significantly greater than top and sides

- Similar wear pattern on tip seals
D-11 Packing Rubs

- Heavy rubs at lower half horizontal joint

- Although clearances are generally larger on the bottom, the wear is substantial at all locations
Rotor Vibration from Seal Rubs

- HP-IP rotor very flexible
  - Sensitive to midspan rubs
  - High amplification factor (> 24)
- If rotor trips on high vibration (7.5 mils P-P)
  - Max displacement at seals: 0.156 P-P
  - Seal rubs
    - 78 mils minus operating clearance
    - Any casing distortion reduces seal clearance

Max Deflection at Critical Speed 0.156” Peak to Peak Orbit
Seal Improvement: Retractable

- Seal developed to upgrade OEM seals to avoid wear during start-up and shut-down
- Additional clearance during start-up and shut-down
- Reduced vibration during start-up
- Mitigated risk of shaft seal and tip seal rubs
- Operating clearance is maintained between outage cycles
- Incorporate elliptical clearance – top & bottom
Tip Brush Seals

- The Brush Tip Seal applies EthosEnergy’s brush technology at the blade tip
- Features
  - Integrated flexible and compliant metallic brush element
  - Improved leakage control over OEM design
  - Reduced clearance for improved sealing effectiveness
  - Minimize seal wear during all operating periods
34.5” and 40” L-0 Cracking

- TIL Issued 2011
- Cracking is due to low cycle fatigue (LCF)
  - Starts and stops
  - Cracks at transition points on fingers

- 40” Ti LSB
  - Titanium is “notch sensitive”
    - Stress Concentration Factor for Ti higher for same geometry compared to stainless steel

- 34.5 LSB (12 Cr Jethete M152)
  - Cracking in same area as 40 Ti
  - Same improvements needed as with 40 Ti LSB
34.5” and 40” L-0 Cracking

- Geometry modification removes sharp corners pressure/suction sides at all finger transitions
- Surface treatment process creates beneficial compressive surface stress 10X deeper than traditional
- Combination of geometry change and surface treatment provides reduced cyclic stress
- Greater than 4X cycle guarantee on 40” Ti blades vs OEM configuration
Due to the length of the LSB and higher moisture content at the exhaust end, LSB are prone to leading edge erosion damage.

Ethos can repair the leading edge damage using either weld build up or bar nose insert techniques (depending on the extent of the damage).
A-10 Frame

- Axial Seal Rubs
  - N2 & N3 location occurrence – long rotor condition
  - Excessive leakage at higher loads limits turbine output
- Long Flexible HP rotor
  - Seal Wear
  - Rotor vibration from rubs
- Same LP blades as D-11 (34.5” M152 and 40” Titanium L-0)
- Difficult to set radial clearances and align
  - Tops-on alignment used by some customers
Alstom HP/IP Blade Design Issues

- Cracks observed in blade root fillets
- No locking blades or entrance slot
- Blades assembled tight at shroud
- Shims assembled with clearance at blade root
- Lab evaluation & RCA
  - Thermal-mechanical fatigue
  - Austenitic blade material – thermal expansion rate
  - High peak stress in blade fillet & LCF
  - Skew angle & fillet geometry greatly contribute to stress

Migrated shims

Blade root crack
Improvements

• Material change from Austenitic SS to proprietary material better suited to high temperature/stress environment
  • Reduction in coefficient of thermal expansion
• Optimized geometry – undercut, skew angle & root
  • Centrifugal stress reduction 33%
  • Thermal transient stress reduction 53%
• Forced interference at the covers
• Swaged caulking under the dovetails
• Machined admission slot in the rotor grooves
• Shimless assembly
• Locking blade retained with grub screws

• Expected life reduction for 8 year period
  - OEM 157%
  - Redesign 12%
Summary

- D-11 Reliability Challenges and Solutions
  - N2 Packing Casing leakage / ledge cracks
  - Diaphragm Creep Distortion
  - Bowed rotors
  - Seal Rubs / Clearance Issues
  - L-0 Blade Cracking and Erosion

- A-10 Fleet
  - Similar to D-11

- Alstom HP-IP
  - Blade Shim Migration & Root Cracking
  - Casing out-of-round

- Evaluation criteria – Repair / Replace
  - Performance
  - Reliability
  - Outage cycle

- Upgrades generally designed to be performed within a typical outage window