Flexible Operations Impact on Steam Turbine Failure Modes and Best Practices

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Industry Trends

Steam Turbine
  – More cycling
    • Two-shifting
  – Reduced minimum loads
  – Fast Starts
  – Re-powering of vintage coal assets
  – Higher inlet temperatures
  – Combined cycle application

Generator
  – Along for the ride!
US Coal Fired Unit
Ultra Minimum Load Operation
# Flexible Operations Impact on Steam Turbine Failure Modes

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**Significant Impact**

**Moderate Impact**

**Minor or No Impact**

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STEAM TURBINE FAILURE MECHANISMS
Key Steam Turbine Mechanisms

- **High Cycle Fatigue** – Vibration
- Creep - Steady stress at elevated temperatures
- **Environmental** - Stress Corrosion Cracking (SCC)
- **Low Cycle Fatigue** – Thermal and mechanical Cycling
- **Foreign Object Damage** - Flow path liberation
- Embittlement – Time and temperature exposure
- **Erosion** – Water droplet and solid particle
- **Rubbing** – Axial and Radial
- **Event Driven** – Water Induction, Overspeed
Minimum Load Considerations

• Primary Failure Mechanisms
  – High cycle fatigue (stall flutter)
  – Solid particle and water droplet erosion

• Secondary Failure Mechanisms
  – Stress corrosion cracking

• Operational Concerns:
  – Turbine differential expansion
  – Increased vibration levels
  – Turbine water induction
  – Boiler issues
  – Overheating at LP exhaust
Cycling Considerations

• Primary Failure Mechanisms
  – Low cycle fatigue cracking of rotor, blades, casing, generator
  – Rotor bow and rubbing
  – Solid particle erosion

• Secondary Failure Mechanisms
  – High cycle fatigue cracking
  – Water droplet erosion

• Operational Concerns:
  – Vibration
  – Turbine water induction
  – Differential expansion
  – Boiler issues
  – Overspeed
HIGH CYCLE FATIGUE (HCF)
Partial Arc Admission - HP inlet

- Control Stage Blading Issue
- Shock Loading
  - Increased steady loading
  - Impact entering the arc excites blade modes (usually first mode)
- Nozzle Passing Frequency Concerns
  - Impulse blading
  - High nozzle exit velocities
- Operation and/or design changes may be required to correct this issue
Campbell Diagram – Hold Speeds
Stall Flutter – LP Blading

- Flow separation produces vibrations
- Occurs in last stage of LP under low load and high back-pressure conditions
- Conditions of concern:
  - Longer blade designs with lower first blade mode frequencies
  - High air in-leakage
  - Summer periods where backpressure control is challenged
  - Potential for increase in failure mode with shift towards load cycling
EROSION – SPE AND WATER DROPLET
Solid Particle Erosion

• First few stages of HP and IP blading
• Damage caused by high velocity rust particles striking blading
• Surface roughness deteriorates fatigue strength and performance
• Low load operation leads to valve throttling
• Operator Awareness
  – Minimize startups/load swings - dislodge particles
  – Operate in sliding pressure mode - reduces throttle pressure which keeps velocities down
Tenon SPE
Nozzle Plate and Block SPE
SPE Coatings

- Tungsten Carbide
- Chromium Carbide
- Titanium Nitride
LP Water Droplet Erosion

• Surface roughness caused by droplets reduces fatigue properties
• Reduces mass of tuned blades
• Repair Considerations
  – Blade frequency testing and trending
  – Stellite repair and/or stellite solid nose bar
  – Flag stellite
  – Blade replacement
• Operator Awareness
  – Keep reheat temperatures at design level
  – Low load operation - boiler droop lowers reheat and throttle temperatures
  – Operational trends to reduce minimum loads

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Erosion Rates are Non-Linear
LOW CYCLE FATIGUE
Low Cycle Fatigue

• Primarily driven by On/Off Cycles – areas with stress concentrations are of highest concern
  – Startup/shutdown cycles
    – Thermal stresses → ΔT; HP & IP vs LP
    – Mechanical stresses → σ = mrω²
• Can be exacerbated by specific startup/shutdown practices
  – Improper or inadequate soak times
Rotor Peripheral Cracks

• Operational
  • Increasing vibration levels over weeks
  • 1X and 2X components increasing with time
  • Shifts in critical speeds
  • Higher critical speed amplitudes
  • Inconsistent phase and vector change in static unbalance

• Outage
  • MT of “J” hook areas
  • Eddy Current (ET)
  • Ultrasonic's
IP Rotor Inlet Cracking
Low Pressure Rotor Shaft End Cracking
Casing Cracking

• High steam to metal temperature differential (≈600°F)
Nonuniform Steam Inlet Design

- First Major Inspection
- Crack 17” length x 1” depth
- 40,000 hours
- 1,000 on/off cycles
RUBS – RADIAL AND AXIAL
Clearances

• Trade off between performance and operability for radial clearances
• Set seal clearances appropriate for mode of operation
• Hard seal rubs can lead to blade looseness, rotor bowing, and bearing babbitt fatigue
• Axial clearances must be maintained to avoid differential expansion limitations
Simple Shaft System Critical Speeds

- 304.8 mm Diameter
- 50.8 mm Thick
- Centered, Rigid Disk

- 660.4 mm
- 50.8 mm

- First Mode $(i=1)$
- Second Mode $(i=2)$
- Third Mode $(i=3)$

- Isotropic Bearing

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Integral Shrouded Blades (Looseness)
Babbitt Fatigue
Inadequate Axial Clearances

Dimension "A"

Axial Clearance (mils)

Subsequent Damage at 8R

Check critical clearances prior to the tops being placed on!
THE EXTENT OF DAMAGE WHEN RUBS OCCUR

There are several factors that influence the extent of any damage resulting from a rub event. Depending on the severity, these factors can lead to metallurgical changes in addition to dimensional deviations. The majority of the rub damage is caused by high intensity heating due to friction. The heating is not uniform around the circumference of the rotor or stator, resulting in non-uniform heat penetration. The rotor cross section in Figure 1 below shows an example of the variation that can be seen in shaft heating around the circumference at a specific axial location. The width of the orange bar corresponds to depth of heating, with section cuts taken at 3 locations.

Figure 1 – Example Variation of Heating Depth in Rotor Cross Section
Rotor Straightening Options

• Hot Spot Rotor diametrically opposite the bow
• Machine plastically deformed material at the bow and weld repair
• Re-machine journals and critical rotor diameters to new centerline
• Re-heat treat deformed areas – limited success
Rotor Bow Repairs

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EVENT DRIVEN – WATER INDUCTION, OVERSPEED
Water Induction Common Causes

• Extraction Sources
  – Leaking Feedwater Heater Tubes
  – Level Control Failures
  – Poor design – heater drains
  – Obstructed extraction line drains

• Main Steam Sources
  – Inadequate drains or not at low point
  – Fast start after boiler trip
  – Attemperator spray malfunctions

• Steam Seal Systems
  – Auxiliary source issues
  – Clogged gland seal header or inadequate drains
  – Operational
Turbine Trip Protection

• Worst case is overspeed event with severe damage
• Potential problem indications:
  – Slow or sticky steam valve operation
  – Delays in rolling down to turning gear due to valve leakage
  – Delays in valve closure
• Mitigation?
  – Valve testing
  – Routine overspeed testing
  – Routine maintenance
  – Sampling and analysis of hydraulic oil
  – Thorough testing to any newly installed turbine trip system
  – Trip on Reverse Power
Thank you – Questions?