LOW LOAD OPERATIONS FOR THERMAL PLANTS

TWO CASE STUDIES

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LOW LOAD OPERATION OF THERMAL ASSETS

- Historically, Radiant Thermal Plants were dispatched base load.
- Some cyclic, flexible operation was required.
- Today’s power markets are requiring more flexible operations, more operation at low load and more understanding of the impacts on equipment degradation/wear-out.
- This presentation will present 2 case studies where engineering software for detailed modeling of boiler/HRSG steam systems has been applied.
- These case studies address the impacts of low load operation and also can be used to troubleshoot power plants where operation at full load has not been achieved due to a combination of design and performance problems.
CASE 1. NEW COAL-FIRED CFB

- CFB (Circulating Fluidized Bed) with 265,000 lbs/hr & 409 psig design capacities (Operating Phase I).
- Expected to run second phase with higher pressure at 950 psig. (Operating Phase II)
- Since then, numerous commissioning events causing trips and failures as well as more significant damage to pressure parts and refractory.
- The units had high temperatures out of the recycle cyclone exceeding the design and protective limits of 920 C (1688 F) early in plant operation.
- Resulted in restricted operating loads of about 40% of full power operation (100,000 lbs/hr).
- Failures in pressure parts continue to occur.
CASE 1. LOW LOAD EVALUATION OF CFB
CASE 1. CFB GENERAL ARRANGEMENT

Furnace and BackPass Screen Tubes
CASE 1. CFB SCREEN TUBE FAILURES

Screen tubes show creep damage and graphitization in metallurgical tests.

High tube temperatures are the cause (>640°C/1184°F vs 250°C expected).

Water treatment vendor gave temperature range of 1100-1400°F.
CASE 1. SCREEN TUBE FAILURE LOCATIONS

Area of failures
CASE 1. CFB SYSTEM MODELING – GAS/COMBUSTION PROCESS
CASE 1. CFB SYSTEM MODELING – WATER/STEAM PROCESS
CASE 1. BACK PASS SCREEN TUBE

- 100% Power – 240 KPPH 3% steam
- 38% Power - 255 KPPH 1.79% Steam

- 100% Power – 265 KPPH 3.3% steam
- 38% Power - 87 KPPH 1.65%
CASE 1. FLUID VELOCITY CONDITIONS – 35% STEAM LOAD – TUNED

<table>
<thead>
<tr>
<th>Variable</th>
<th>SI Unit</th>
<th>38% Steam Load - Design Case</th>
<th>38% Steam Load - Tuned</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FW Grate BackPass Data</td>
<td>RW BackPass Cav</td>
</tr>
<tr>
<td>Mass Flow H2O - Outlet</td>
<td>ton/hr</td>
<td>122.6</td>
<td>78.4</td>
</tr>
<tr>
<td>Temp. H2O - outlet</td>
<td>°C</td>
<td>233</td>
<td>233</td>
</tr>
<tr>
<td>Press. H2O - outlet</td>
<td>bar</td>
<td>29.68</td>
<td>29.68</td>
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<tr>
<td>Outlet Content Steam by Mass</td>
<td>%</td>
<td>1.34</td>
<td>1.94</td>
</tr>
<tr>
<td>Inlet velocity H2O</td>
<td>m/s</td>
<td>0.19</td>
<td>0.12</td>
</tr>
<tr>
<td>Outlet velocity H2O</td>
<td>m/s</td>
<td>0.32</td>
<td>0.25</td>
</tr>
<tr>
<td>Overall usage factor</td>
<td>-</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Temp. metal</td>
<td>°C</td>
<td>237</td>
<td>237</td>
</tr>
<tr>
<td>Xmartinel</td>
<td>-</td>
<td>7.32</td>
<td>5.29</td>
</tr>
<tr>
<td>Pass Time</td>
<td>s</td>
<td>17.2</td>
<td>58.85</td>
</tr>
<tr>
<td>Circulation Ratio</td>
<td>-</td>
<td>74.45</td>
<td>51.66</td>
</tr>
<tr>
<td>Inlet y Steam content ratio by vol</td>
<td>%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Outlet y Steam content ratio by vol</td>
<td>%</td>
<td>43.01</td>
<td>52.25</td>
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</table>
CASE 1. FLUID VELOCITY CONDITIONS – 80% STEAM LOAD – TUNED

<table>
<thead>
<tr>
<th>Variable</th>
<th>SI Unit</th>
<th>80% Steam Load - Design Case</th>
<th>80% Steam Load - Tuned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flow H2O - Outlet</td>
<td>ton/hr</td>
<td>N/A</td>
<td>133.8</td>
</tr>
<tr>
<td>Temp. H2O - outlet</td>
<td>°C</td>
<td>N/A</td>
<td>236</td>
</tr>
<tr>
<td>Press. H2O - outlet</td>
<td>bar</td>
<td>N/A</td>
<td>31.01</td>
</tr>
<tr>
<td>Outlet Content Steam by Mass</td>
<td>%</td>
<td>N/A</td>
<td>2.44</td>
</tr>
<tr>
<td>Inlet velocity H2O</td>
<td>m/s</td>
<td>N/A</td>
<td>0.2</td>
</tr>
<tr>
<td>Outlet velocity H2O</td>
<td>m/s</td>
<td>N/A</td>
<td>0.46</td>
</tr>
<tr>
<td>Overall usage factor</td>
<td>-</td>
<td>N/A</td>
<td>0.8</td>
</tr>
<tr>
<td>Temp. metal</td>
<td>°C</td>
<td>N/A</td>
<td>242</td>
</tr>
<tr>
<td>Xmartinel</td>
<td>-</td>
<td>N/A</td>
<td>4.4</td>
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<tr>
<td>Pass Time</td>
<td>s</td>
<td>N/A</td>
<td>13.14</td>
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<tr>
<td>Circulation Ratio</td>
<td>-</td>
<td>N/A</td>
<td>41</td>
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<tr>
<td>Inlet y Steam content ratio by vol</td>
<td>%</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td>Outlet y Steam content ratio by vol</td>
<td>%</td>
<td>N/A</td>
<td>56.91</td>
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CASE 1. CFB BOILER EVAPORATOR CIRCULATION

<table>
<thead>
<tr>
<th>Operating Condition</th>
<th>Circulation Ratio</th>
<th>Furnace Tube Outlet Velocity</th>
<th>Backpass Tube Outlet Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I 100%</td>
<td>23</td>
<td>4.6 m/s</td>
<td>0.38 m/s</td>
</tr>
<tr>
<td>Phase II 100%</td>
<td>17.3</td>
<td>2.95</td>
<td>0.21</td>
</tr>
<tr>
<td>Phase II 38%</td>
<td>39.2</td>
<td>1.7</td>
<td>0.16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Phase I 100%</th>
<th>Phase II 100%</th>
<th>Phase I 70%</th>
<th>Phase II 70%</th>
<th>Phase I 38%</th>
<th>Phase II 38%</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Steam %</td>
<td>2.39</td>
<td>3.05</td>
<td>1.87</td>
<td>2.72</td>
<td>1.37</td>
<td>2.03</td>
</tr>
<tr>
<td>North Flow</td>
<td>290.98</td>
<td>211.31</td>
<td>273.04</td>
<td>193.4</td>
<td>270.36</td>
<td>176.3</td>
</tr>
<tr>
<td>North Velocity</td>
<td>0.44</td>
<td>0.26</td>
<td>0.38</td>
<td>0.23</td>
<td>0.32</td>
<td>0.19</td>
</tr>
<tr>
<td>South Steam %</td>
<td>3.63</td>
<td>4.42</td>
<td>2.77</td>
<td>3.70</td>
<td>4.94</td>
<td>2.35</td>
</tr>
<tr>
<td>South Flow</td>
<td>194.5</td>
<td>155.58</td>
<td>189.95</td>
<td>152.22</td>
<td>172.02</td>
<td>133.36</td>
</tr>
<tr>
<td>South Velocity</td>
<td>0.30</td>
<td>0.22</td>
<td>0.32</td>
<td>0.2</td>
<td>0.25</td>
<td>0.16</td>
</tr>
</tbody>
</table>
CASE 1. BACKPASS SCREEN TUBE CONDITIONS

• The North and South backpass wall tubes both feed into a single 12 inch outlet header while the side walls each have their own outlet header.

• There is only one outlet nozzle (12 inch) on the North and South wall outlet header. This is in the center of the header just above the failure zones.

• During full load (100%) operation the north and south backpass walls produce similar amounts of circulating water/steam flow. During low load (38%) operation the south backpass wall produces three times the circulating water/steam flow as the North (screen side) wall. This is likely to produce a significant change in North wall tube circulation especially near the nozzle.

• Screen tube use SA-213 T22 material. Failures occurred in the main body of the tubes as longitudinal cracks. The orientation of the cracks indicated the main pressure hoop stress was acting in the failures. Metallurgical exams (Reference 12) found micro and macro-cracks from creep damage in the tube body using surface replicas. The occurrence of macrocracks indicates crack life expenditures > 40-70%
CASE 1. RECOMMENDATIONS

- Replace Screen tube sections identified by NDE (Reference 12) as at or above Creep Stage 2.
- Add two additional 12 Inch outlet nozzles on each end of the outlet header to connect with the common outlet header from the East and West Backpass Walls.
- Corrections for inlet flue gas flow distributions if possible.
CASE 2. CCGT LOW LOAD OPS EVALUATION
CASE 2. CCGT LOW LOAD OPS EVALUATION

- 2x1 CCGT located in Arizona
- COD 2003
  - GE Frame 7FA GT
  - NEM HRSG designed for heavy duct firing
  - Toshiba ST with RH
- Operating Profile Changes
  - ca 2012, plant was baseloaded for 4 months per yr (summer) infrequently operated otherwise.
  - Changes in western power markets and contracts dictated an evaluation of whether the steam plant could operate at lower load and if so, the cost to be incurred for added wear & tear
CASE 2. 2X1 CCGT WITH HIGH DUCT FIRING

- Steam Cycle Designed to Accommodate a wide range of steam flows to ST (730 kpph to 260 kpph part load (per HRS))

- Steam Turbine (Toshiba) designed to accommodate this wide range of steam flows by requiring large LP last stage blades and annulus areas

- Steam temperature control by desuperheating sprays have sufficient capacity to accommodate this range of operation

- Design for large firing capacity was well executed and the HP SH and RH panel surface areas are well balanced before and after the duct burners.

- Low Load Evaluation was conducted to examine 1x1 operation and impact on key variables

- Other issues include: operability of the plant in simple cycle mode (bypass) and functionality of emissions controls (SCR catalyst) at low loads

- Related issue for the ST is the potential for overheating the LP Turbine due to low steam flow causing recirculation (windate) heating
CASE 2. CCGT 1X1 LOW LOAD EVALUATION

- Key Variables Evaluated:
  - Metal temperatures in the HP SH and RH tubes
  - Limits on DSH sprays (to achieve final steam temperatures required at ST)
  - High Steam Temperatures in HRSG/boiler and high energy (steam) piping
  - High Steam Temperatures at Steam Turbine Inlets
  - Low Pressures in the LP Evaporators - causing high fluid velocity and potential circulation instability
  - Vibration in tube bundles due to vortex shedding at low GT exhaust mass flows

- Assessment performed by combination of engineering analysis by computersimulation of the steam cycle using the KED PPSD™ software coupled with review of operating data supplied by the plant.
CASE 2. PPSD MODEL – FLUE GAS PATH
CASE 2. PPSD – OVERALL STEAM CYCLE
CASE 2. PPSD – HP STEAM SYSTEM
CASE 2. PPSD – IP/RH STEAM SYSTEM
CASE 2. CCGT LOW LOAD EVALUATIONS

• 2014 Initial Low Load Analysis
  • GT Loads to 92 MW (using test data)
  • GT Loads to 67 MW (design data)
• Design Cases
  • Case 5: 94F/27% RH 2 x 75% GT Unfired
  • Case 6: 94F/27% RH 2 x 50% GT Unfired
  • Case 10: 94F /27% RH 1 x 50% GT Unfired
• Operational Cases (Next Slide)
• Future Operations (Subsequent Slide)
• May 2016 Analysis looked at operational data developed during testing for upgraded controls (GE OPFLEX) at 65 MW
CASE 2. FINDINGS – TUBE TEMPS

• Metal Temps
  • HP SH 4 lead tube row temperatures on average can reach the ASME Design temperature of 1102 F under very low load conditions or if efficiency improvements such as AGP upgrades are installed.
  • This does not include any additional temperature rise due to steam side oxide buildup over time or local hotspots in tubes.

• Row-Row Differences
  • Low Load operation increases the tube average temperatures from row to row. This is primarily in HP SH 4 and RH 2. This increased delta T will increase differential thermal expansion and thus tube stresses (tensile). High local stresses combined with high tube temperatures can increase the risk of creep and creep-fatigue damage.
CASE 2. STEAM SEPARATION EQUIPMENT

- HP Steam Drum: Cyclone Separators, Chevron/Mesh
- IP Steam Drum: Simple change of direction (“half” cyclone) plus wire mesh
- LP Steam Drum: Simple change of direction (“half” cyclone) plus wire mesh

Configuration is designed to accommodate the high steam flows of full firing with both cyclone and secondary separators in the HP Drum. At low load operating conditions all the steam pressures are either lower (HP) or the same or lower (IP/LP) than at full power conditions. This improves steam separation in all technologies due to the greater difference in steam and water densities at low pressure.

- For cyclone separators (and change of direction primary separators) lower steam velocities reduce centrifugal forces on water, but this is more than compensated by greater density differences. In addition lower velocities increase effectiveness of impingement and wire mesh separators and reduce forces to carry droplets up in the drum.
CASE 2. TYPES OF STEAM SEPARATORS

<table>
<thead>
<tr>
<th>Type</th>
<th>Approximate Droplet Size Range $\mu$m</th>
<th>Separation System Flow Regime</th>
<th>Typical $F_{x}$ $\frac{1}{\text{kg}^{1/2} \text{s}}$</th>
<th>Typical $\Delta P$ Pa</th>
<th>Two Phase Flow Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity Separator</td>
<td>&gt;10.0</td>
<td>Laminar or Turbulent</td>
<td>.25-15</td>
<td>negligible ~1 velocity head</td>
<td>Any quality but best for low quality slug or annular dispersed flow</td>
</tr>
<tr>
<td>Droplet Diffusion</td>
<td>&gt;10.0</td>
<td>Turbulent</td>
<td>2.5-5</td>
<td>About 1 velocity head</td>
<td>Highly dispersed droplet flow</td>
</tr>
<tr>
<td>Knitted Wire Mesh</td>
<td>&gt;3.0</td>
<td>Turbulent</td>
<td>.8-1.6</td>
<td>25-500</td>
<td>Highly dispersed droplet flow</td>
</tr>
<tr>
<td>Chevron or Impingement Separator</td>
<td>&gt;6.0</td>
<td>Turbulent</td>
<td>.8-3.7</td>
<td>250-500</td>
<td>Highly dispersed droplet flow</td>
</tr>
<tr>
<td>Cyclone Separator</td>
<td>10.0 and up</td>
<td>Turbulent</td>
<td>2.5-1.7</td>
<td>750-7500</td>
<td>Any quality or flow regime</td>
</tr>
</tbody>
</table>
## CASE 2. HP DRUM STEAM VELOCITIES

<table>
<thead>
<tr>
<th>Case</th>
<th>HP</th>
<th>IP</th>
<th>LP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Power (Case 1)</td>
<td>117.6</td>
<td>85.23</td>
<td>316</td>
</tr>
<tr>
<td>50% Load 1 x 1 (Case 11)</td>
<td>79.1</td>
<td>196</td>
<td>60</td>
</tr>
<tr>
<td>1 x 65 MW (test)</td>
<td>78.16</td>
<td>179</td>
<td>46</td>
</tr>
</tbody>
</table>
CASE 2. POTENTIAL FOR HP ECON STEAMING

- The NEM HRSG economizers are all panelized unlike other HRSG OEMs where upper U bends for tubes are employed.
- A check was done to assess the potential steaming in the final passes of the HP/IP and LP economizers at full and part loads.
- There is little indication of steaming in the final economizers in the HP and LP sections, and only a small potential of some steam at the final feed water piping to the IP Steam drum.
- Flashing downstream of the IP control valve should be monitored for potential wear in valve and piping.
CASE 2. EVALUATION OF VIBRATION POTENTIAL

1 X 1 65 MW GT LOAD TEST

- Blue: Tube
- Red: Acoustic
- Green: Vortex

FREQUENCY (HZ)
CASE 2. FINDINGS – IMPACTS ON ST

- 1 x 1 Low Load operation can significantly increase the risk of high temperatures in the LP Steam Turbine section. This can cause excessive thermal expansion of blades and the rotor.
- 1 x 1 Low Load Operation can also result in damage to the terminal edge of Last Stage Turbine blades from recirculation of hood spray.
CASE 2. FINDINGS – IMPACTS ON DSH

- Simple Cycle Operation in Low Loads (100% steam bypass to condenser) will require tight control of the bypass desuperheaters (HRH) and the steam curtain sprays in the steam turbine.
- Long periods of bypass operation will increase the risk of damage to condenser and steam turbine from control problems.
- The LP Steam bypass to condenser has no desuperheaters and is in excess of enthalpy limits prescribed by standards.
- For startup and shutdown use this is not usually an issue but for extended operation in simple cycle mode modifications to lower enthalpy are recommended.
CASE 2. FINDINGS - IMPACTS ON FAC / LDI

- There seems to be no increased risk of Flow Accelerated Corrosion (FAC) or Liquid Droplet Impingement (LDI), HP Evaporator waterside deposits, Evaporator instability and carryover, cold end gas side deposition or corrosion, or tube/casing vibration at low loads.
CASE 2. FINDINGS – IMPACT ON TEMP CONTROL

- Main Steam and Hot Reheat steam temperature control should not be a problem as a favorable heat transfer surface area balance before and after the desuperheaters is present and adequate spray capacity is installed.
CASE 2. FINDINGS - SUMMARY

- Operating data at 65 MW 1 x 1 operation confirmed these findings.
- PPSD simulation model with the measured GT inputs and ST pressures predicted deuperheating spray flows and steam conditions consistent with measured data.
- Actual GT exhaust gas temperatures were lower than design with the new tuning so tube metal temperatures are consequently lower.
- Spray flows for the HP Steam are within the expected range and below the Tetra recommended limit of 15% of steam flow.
- Inspections of sprays and downstream piping are recommended as preventive actions if low load operations are frequent.
CASE 2. OPERATIONAL TEST CASES

- 335 MW: 2 x 108 MW GT Unfired – 73F
- 335 MW 1 x 110 MW GT Unfired – 73F
- 300 MW: 2 x 92 MW GT Unfired – 90F
- 350 MW: 2 x 114 M GT Unfired – 88F
- 113 MW: 1 x 65 MW GT Unfired – 85F
CASE 2. FUTURE OPERATIONS (DESIGN DATA)

- 1x1 140 MW Gross Output at 70F
- 1x1 150 MW Gross Output at 70F
- 1x1 67 MW Gross Output at 73 F
- 1x1 67 MW AGP
Questions?

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