Steam side Scale exfoliation problem in Saudi Electricity Company / EOA Superheater and Reheater

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QPP had experienced tube failures in the 2rySH, 3rySH and 2ryRH and outlet leg that is attributed to tube external exfoliation.

The origin of the problem in both 3rySH and 2ryRH is due to higher than expected tube metal temperature. The 2rySH problem is attributed to uncontrolled desuperheater spray during start-up.

Under certain conditions, oxide scale that forms on the outside and inside surfaces of superheater tubes and pipes may break loose and exfoliates. It also suspected that an excessive internal oxide scale exfoliation which cause complete or partial plugging of the steam flow path.
What is Scale Exfoliation

- High temperature steam reacts with internal metal surfaces to form a hard tenacious scale.

- Scale growth rate is a function of material of construction, temperature, unit start-up and shutdown cycles.

- Because of the difference of coefficients of thermal expansion, expansion and contraction during start-ups loosens the scale causing it to exfoliate (flakes)

- The exfoliation process is a mechanical process and due of some stress effect
Scale Generation

- After starting the boiler operation, oxides scales generates and start growing

- \( \text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + \text{O}^{2-} \)

- \( \text{Fe}^{++} + \text{O}^{2-} \rightarrow \text{Fe}_y\text{O} \)

- Outer layer is generated by the diffusion of \( \text{Fe}^{++} \) to steam side (magnetite \( \text{Fe}_3\text{O}_4 \) and hematite \( \text{Fe}_2\text{O}_3 \))

- Inner layer is generated by the diffusion of \( \text{O}^{2-} \) magnetite, hematite and other chemical elements which are ingredients of original material.
There is no stress and no crack in scale during boiler operation.

Boiler shut-down and start-up, thermal stress arise at the scale–metal boundary due to the difference of thermal expansion coefficient between scale and metal.

Scale is thin and fragile, the thermal stress makes cracks only in the scale.

Number /size of the cracks and other parameters influence on the adherence force of scale.

Scale exfoliation will take place after many thousands of hours of services.
# Scale exfoliation process parameters

<table>
<thead>
<tr>
<th>Thermal Stress</th>
<th>Major Parameters</th>
<th>Influence on Scale Exfoliation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature drop</td>
<td>Yes (Proportional factor)</td>
</tr>
<tr>
<td></td>
<td>Scale thickness</td>
<td>Yes (Proportional factor)</td>
</tr>
<tr>
<td></td>
<td>Shut down/Start up rate</td>
<td>No</td>
</tr>
<tr>
<td>Adherence Force</td>
<td>Number/Size of cracks</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Corrosion at scale-metal boundary</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Scale Accumulation

- Scale accumulation seems random except under the condition that there are some technical/design reasons.

- Majority of scale accumulations happen at the boundary of inner/outer layers.

- New scale generation starts on fresh surfaces after next start-up.
Parameters of scale accumulation are summarized in the following table:

<table>
<thead>
<tr>
<th>Major Parameters</th>
<th>Influence on Magnitude of Accumulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale Thickness</td>
<td>Yes (In general, the scale of an old power plant is thick.)</td>
</tr>
<tr>
<td>Area of Exfoliation</td>
<td>Yes (Proportional factor)</td>
</tr>
</tbody>
</table>
Scale Accumulation monitoring

- There are more than one way to monitor the scale accumulation recommended:
  - Ultrasonic Thickness examination by EMATS (Electromagnetic Acoustic Transducer System)
  - In every outage at least 10% of the SH/RH should RT (X-ray) Inspected to the trend of scale
Scale exfoliations Damages

- 20 - 30 % of scales are exfoliated in one shut down and start-up process, possibility of complete plugging should be considered.
- It can cause long term overheating and creep damage
- It can cause long term overheating
- Fire side corrosion because of higher tube temperature.
- In case of RH this flaking particles may go through to intermediate turbine and damage the blades
Measures to be taken when scale exfoliation Occur

- The boiler can be subjected to purging operation to get rid of the scale flakes during the shut-down period.

- **If scale accumulation ratio over 50% tubes** should be cleaned out by mechanical means (Bend tubes to be removed temporarily and reinstalled).

- **Upgrade the material** to SA-213 TP347FHG with shot peening to resist internal scale exfoliation
QPP Exfoliation Problems

- **QPP Boiler Specification**
  - In 1994, Qurayyah Power Plant Unit 2 had experienced premature tube failures in the 3rySH and 2ryRH outlet leg that is attributed to tube external exfoliation.
  - The origin of the problem in both 3rySH and 2ryRH is due to higher than expected tube metal temperature.

- In 2002, unit-4 QPP had experienced tube failures in the 2rySH, attributed to tube external exfoliation, desuperheater spray during start-up.

- August 2007, first tube failure was experienced at unit-3 2ryRH and outlet leg that is attributed to tube external exfoliation.
Flaking or thick scale were observed near fractured area.

The cause of rupture was presumed to be for aged deterioration caused by long term service at high temperature.
Lap analysis report

Sample Information

Component: 2ry Superheater Tubes
Leaked Location: Panel #43-Tube3
(Boiler rear; 27 August 2007)
Level: Approx. FL+33,000mm
Sampled Tube Location: Panel #43-Tube3
Material: SA213-T12
Dimension: φ 42.7×t4.6mm (tsr=4.44)

Probable Root Cause

The cause of rupture was presumed to be for a short-term overheat caused by something choking inside the tube.
<table>
<thead>
<tr>
<th><strong>Boiler Specification</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Customer</strong></td>
</tr>
<tr>
<td>Saudi Electricity Company</td>
</tr>
<tr>
<td><strong>Unit</strong></td>
</tr>
<tr>
<td>Qurayyah P/S No. 3</td>
</tr>
<tr>
<td><strong>Boiler Type</strong></td>
</tr>
<tr>
<td>MB-FRR</td>
</tr>
<tr>
<td><strong>Steam Press.</strong></td>
</tr>
<tr>
<td>210kg/cm²</td>
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<tr>
<td><strong>Steam Temp.</strong></td>
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<tr>
<td>541/541°C (SH/RH)</td>
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<tr>
<td><strong>Fuel</strong></td>
</tr>
<tr>
<td>Oil and Gas</td>
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<tr>
<td><strong>Start of Operation</strong></td>
</tr>
<tr>
<td>1992</td>
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<tr>
<td><strong>Operation Hours</strong></td>
</tr>
<tr>
<td>116,647 Hours</td>
</tr>
</tbody>
</table>
Sample Information

Component: 2ry Superheater Tubes

Leaked Location: Panel #46-Tube2
(Boiler rear; 30 August 2007)

Level: Approx. FL + 30,600mm

Sampled Tube Location: Panel #46-Tube2

Material: SA213-T91

Dimension: $\phi 42.7 \times 6.9$ mm ($tsr=6.77$)
Conclusion

- Scale exfoliation can be a very serious problem if not monitored.
- Maintenance program should include a schedule for monitoring the scale accumulation in the boiler tubes specially for those boilers working consciously on high load.
- Close monitoring to the boiler performance may give a high indication of scale accumulation rate.
- A flushing procedure should be adopted by the operation in order to clean the tubes from the accumulated scale.
Thank You
The outer layer is generated by the diffusion of Fe$^{++}$ to the steam side and inner generated by the diffusion of O$^{2-}$ to the metal side.

Outer scale consists of magnetite (Fe$_3$O$_4$) and hematite (Fe$_2$O$_3$).

Inner scale consists of magnetite (Fe$_3$O$_4$) and hematite (Fe$_2$O$_3$) and other chemical elements which are ingredients of original material.
- **Steam side Scale exfoliation** in steam plants is a very severe problem which can result in short-term overheating boiler tube failures.
- In addition, the solid particles can cause the solid particle erosion of the inlet stages of the steam turbines (intermediate turbine stages).
Accumulation Rate
## Countermeasure for Scale Exfoliation / Plugging

<table>
<thead>
<tr>
<th>No.</th>
<th>Countermeasure</th>
<th>Scale Generation</th>
<th>Creep Strength</th>
<th>Quenching Resistance</th>
<th>Residual Stress</th>
<th>MHI’s Experience</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
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</tbody>
</table>

**Notes:**
- Detailed explanations and considerations for each countermeasure.
- Potential impacts and benefits analyzed.
- Continuous monitoring and feedback loop for improvement.
In scale which has grown beyond a certain thickness, the outer layer exfoliates due to the difference in thermal expansion between the tube material and the scale during start and stop of the boiler.
1. Shot-peening process

Shot-peening have been employed for 18Cr - 8Ni austenitic stainless steels in order to improve steam oxidation resistance.

In shot peening – process, shot grains impinge onto inner tube surface to form cold-worked layer.

<table>
<thead>
<tr>
<th>Shot-blasting (Grit-blasting)</th>
<th>Shot-peening</th>
</tr>
</thead>
<tbody>
<tr>
<td>To remove scale from inner tube surface</td>
<td>To form cold-worked layer on inner tube surface</td>
</tr>
</tbody>
</table>

Fig 1 Comparison of Shot-blasting and Shot-peening

![Cold-worked layer](100 \mu m)

Photo Microstructure of shot-peened tube on inner surface (ASME TP347HFG)

2. Property of shot-peened tube

Owing to increasing of Cr diffusion in cold-worked layer, the protective Cr$_2$O$_3$ layer forms continuously on the inner surface of shot-peened tube, and acts as a protective layer to suppress steam oxidation.
QPP Tube Failure
Ghazlan U3 IP turbine blades deposits
Ghazlan U3 IP turbine blades damages