High Temperature Oxidation and Corrosion of Gas Turbine Materials in Burner Rig Exposures

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Integrated Gasification Combined Cycle (IGCC) Plants:

Combined Cycle Plants
- Higher efficiency (coupling steam and gas turbines (GTs))

IGCC
- Syngas from solid fuels
- Integration of gas cleaning to meet environmental legislation

GT lifetime limited by
- Hot corrosion: alkali metals, $SO_x$
- Erosion: particles
- Deposition: particles, vapour
- Creep and fatigue
- Synergistic effects
Background

Traditionally, industrial gas turbines operate on natural gas / oil-derived fuels
- Low in ash, alkali metals, etc
- Increasing fuel cost

Alternative fuels
- Gasified coal & biomass
- Lower calorific value syngases
- More ash, S, alkali metals, etc

Higher gas operating temperatures
- Increase power plant efficiency

Result:
- Components exposed to hotter, dirtier combusted gas stream
UK/US Collaboration on Advanced Materials for Low Emission Power Plants

5 year project established between:
- UK Department of Energy and Climate Change (DECC)
- US Department of Energy (DOE)

Project aims:
- Study new gas turbine operating environments
- Study response of materials for hot gas path components
  - Quantifying & ranking materials’ corrosion resistance
  - Creating an information database for future models

Talk aims:
- Describe burner rig exposures designed to simulate GT environments
- Assess corrosion of current state-of-the-art materials
**Experimental Details: Materials**

Under this programme:
- 24 materials systems exposed:
  - 8 state-of-the-art alloys (bare or coated)
  - 9 corrosion resistant/bond coatings
  - 2 thermal barrier coatings

4 tests:
- Combustion gas environments simulating 4 different fuels
- Up to 1000 hours
- In a high velocity burner rig
- Total of nearly 700 air-cooled samples exposed

Focus on 4 materials & 3 tests

<table>
<thead>
<tr>
<th>Material</th>
<th>Ni</th>
<th>Cr</th>
<th>Co</th>
<th>Al</th>
<th>Ti</th>
<th>Ta</th>
<th>Mo</th>
<th>W</th>
<th>B</th>
<th>C</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haynes 230</td>
<td>57</td>
<td>22</td>
<td>5</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>14</td>
<td>0.015</td>
<td>0.1</td>
<td>Si: 0.4, Mn: 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>La: 0.02, Fe: 3</td>
</tr>
<tr>
<td>IN939</td>
<td>48</td>
<td>22.5</td>
<td>19</td>
<td>1.9</td>
<td>3.7</td>
<td>1.4</td>
<td>-</td>
<td>2</td>
<td>0.009</td>
<td>0.15</td>
<td>Nb: 1, Zr: 0.09</td>
</tr>
<tr>
<td>IN738LC</td>
<td>62</td>
<td>16</td>
<td>8.5</td>
<td>3.4</td>
<td>3.4</td>
<td>1.7</td>
<td>1.7</td>
<td>2.6</td>
<td>0.01</td>
<td>0.11</td>
<td>Nb: 0.9, Zr: 0.05</td>
</tr>
<tr>
<td>CM247LC</td>
<td>62</td>
<td>8.1</td>
<td>9.2</td>
<td>5.6</td>
<td>0.7</td>
<td>3.2</td>
<td>0.5</td>
<td>9.5</td>
<td>0.015</td>
<td>0.07</td>
<td>Hf: 1.4, Zr: 0.015</td>
</tr>
</tbody>
</table>
**Experimental Details: Test Conditions**

Syngas upper contaminant limits determined:
- Extrapolated from current NG limits
- Corrected for reduced fuel calorific content
- Variables standardised for ease of comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulates</td>
<td></td>
<td>Contaminated Diesel</td>
<td>IGCC</td>
<td>H2-rich IGCC</td>
</tr>
<tr>
<td>Entry Gas Temp.</td>
<td>°C</td>
<td>1180</td>
<td>1180</td>
<td>1250</td>
</tr>
<tr>
<td>Gas Velocity</td>
<td>ms⁻¹</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Dust Type</td>
<td></td>
<td>-</td>
<td>-</td>
<td>Sieved PF fly ash</td>
</tr>
<tr>
<td>Dust Load</td>
<td>ppm.mg⁻¹.h⁻¹</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>SOₓ</td>
<td>vppm</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>HCl</td>
<td>vppm</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H₂O</td>
<td>vol.%</td>
<td>8.7</td>
<td>8.7</td>
<td>~20</td>
</tr>
<tr>
<td>Na</td>
<td>ppb</td>
<td>125</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>K</td>
<td>ppb</td>
<td>125</td>
<td>125</td>
<td>125</td>
</tr>
</tbody>
</table>

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Comment on Accelerated Tests

- Large metal losses:
  - Up to 2-3 mm in 1000 hours
  - Why?
- Burner rig runs an accelerated test
  - Operates under atmospheric pressure
  - But need the same alkali sulphate dew points as a real gas turbine
  - Therefore need more salt in the system
  - Increases the vapour pressure in the gas stream
  - Increases the deposition flux
- Therefore much higher corrosion rates than in standard gas turbines

\[
\dot{m} = \beta_i \frac{p_i - p_{s,i}}{p} \rho_g
\]

\[
\beta_i = ShD_i / d
\]

\[
p_{s,i} = p_n \exp \left[ A_i - \frac{B_i}{T + C_i} \right]
\]

$m$, flux of condensed gaseous component, $i$
$
\beta_i$, mass transfer coefficient of component, $i$
$p_i$, partial pressure of component, $i$
$p_{s,i}$, saturation pressure of component, $i$
$p$, flue gas pressure
$\rho_g$, flue gas density
$Sh$, Sherwood number
$D_i$, diffusion coefficient of component, $i$
d, diameter on which component, $i$, condenses
$p_m$, $10^5$ Pa
$A_i$, $B_i$, $C_i$, constants
$T$, absolute temperature
Experimental Details: Burner Rig

Samples exposed for:
- 300 hours
- 700 hours
- 1,000 hours
Experimental Details: Statistical Assessment of Damage via Image Analysis

Thermocouple measures cooling air exit temp. Cooling air in

Hot air out

<table>
<thead>
<tr>
<th>Data Point Number</th>
<th>∆GM /µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

The graph shows the ∆GM /µm values plotted against data point number. The distribution of values is represented with a standard normal probability plot.
Results:
Samples Pre- and Post-Exposure

Pre-exposure

Post-exposure
Image Analysis Results: The Effect of Exposure Time

Good Metal Loss for CM247LC after Test 2 exposure at 755 °C

Good Metal Loss for CM247LC after Test 2 exposure at 955 °C

Change in Good Metal with Time (Test 2 exposure, 955 °C)

- ΔGM /µm,
- Probability /%,
- Time /hours

- 300 hours
- 700 hours
- 1000 hours

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SEM & EDX Results:
The Effect of Exposure Time (Test 2, 955 °C)

300 hours

700 hours

1000 hours

Al, Co, Cr, S, Hf, Ni, O

90 µm

100 µm

100 µm
SEM & EDX Results:
The Effect of Exposure Time (Test 2, 955 °C)

- 300 hours
- 700 hours
- 1000 hours
Image Analysis Results:
The Effect of Test & Exposure Temperature

Cumulative Probability $\Delta G_M$ after 1000 h exposure (955 °C)

Effect of Test on CM247LC GML (1000 hour exposure)

Cumulative Probability $\Delta G_M$ after 1000 h exposure (755 °C)
Conclusions

- The severity of the corrosion and oxidation conditions varied between the three tests
  - Test 2 (IGCC conditions including ash particles) appeared least aggressive
  - Impacting fly ash removed corrosive deposits?
- Different types of hot corrosion seen
  - Type I: internal oxidation & sulfidation, lower incubation GMLs
  - Type II: pitting, higher incubation GML
  - Mixed mode
- CM247LC has a high fraction of Al
  - Should provide good oxidation protection
    - Areas of incubation seen in Type I
  - However, performs poorly under hot corrosion conditions
    (cf. Haynes 230, IN939, IN738LC)
  - Effect of low Cr content
Looking Forward

UK-US Project
• 20 systems being characterised
• Developing a greater understanding of the distribution of corrosion damage around samples

Moving on the H2-IGCC (Framework 7) project
• Assess different combusted syngas environments
• Study state-of-the-art and advanced materials systems
Acknowledgements

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• the Department for Business, Enterprise and Regulatory Reform,
• Alstom Power and Siemens (UK).

US activities funded by:
• Department of Energy
• Siemens Power Generation Inc.
b) Probability /
\[ \Delta GM \text{ /µm} \]

- 300 hours
- 700 hours
- 1000 hours

Mount
Damaged regions
Sample
Reference notch
SEM & EDX Results:
Effect of Exposure Temperature (700 h, Test 3)