ANALYSIS OF COKE DRUM CRACKING FAILURE MECHANISMS &
COMMENTS ON SOME PUBLISHED RESULTS

Coke Drum Reliability Workshop
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J Aumuller, P. Eng.
Z Xia, Ph. D., P. Eng.

EDA
Engineering Design & Analysis Ltd.

UNIVERSITY OF ALBERTA
• Coke Drums

Coke drums are large pressure vessels used in oil sands plants & refineries for the recovery of hydrocarbon product from reduced bitumen

- 30 feet Ø x 90 feet height
- operate to 50 psig, 900 °F, cyclic

Construction materials
- composite plate construction, 1” nominal thickness consisting of
  - TP 410S stainless steel cladding
  - carbon steel or low alloy carbon steel (CS, C -½ Mo, Cr - Mo)

Problem – cracking of shell, attributed to presence of bulges and low cycle fatigue
• Coke Drum Bulging
• Why stress determination
  • vessel bulging and cracking attributable to mechanical mechanism rather than metallurgical
  • primary mechanical failure mechanism is
    → low cycle thermal strain cycling

• What are
  • the various loadings
  • their nature
  • contribution to the proposed failure mechanism
COKING.COM 2009
COKER DRUM CRACKING

**Graph:

- **Pressure**
- **Oil in**
- **Water quench**
- **Coke out**

**Time in [hours]:**

<table>
<thead>
<tr>
<th>Operating Step</th>
<th>Temp [°C]</th>
<th>Pressure [kPa]</th>
<th>Duration [hrs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Test</td>
<td>104</td>
<td>241</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>Vapor Heat</td>
<td>316</td>
<td>241</td>
<td>3</td>
</tr>
<tr>
<td>Oil Fill – Coking</td>
<td>482</td>
<td>241</td>
<td>11 – 15</td>
</tr>
<tr>
<td>Steam Quench</td>
<td>177</td>
<td>241</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Water Quench</td>
<td>93</td>
<td>241</td>
<td>3</td>
</tr>
<tr>
<td>Unhead</td>
<td>38</td>
<td>0</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Decoke</td>
<td>38</td>
<td>0</td>
<td>1 – 3</td>
</tr>
<tr>
<td><strong>Total Time</strong></td>
<td></td>
<td></td>
<td>24 – 28</td>
</tr>
</tbody>
</table>
Shell OD Strain - Measured

NB - the measured strains are not necessarily damaging
• Coke Drum Vasing, “Hot”, “Cold” Spots, & Transients

• vasing action is a nominal response
  • bitumen filling, water filling occur over same repeating nominal time period, nominal temperature range → plug flow nature

• drum vasing also occurs
  • during coke cool-down due to insulating effect as coke forms, liquid → solid
  • water quench addition

• localized distortions superimposed
  • system hydraulics cause channel flow & deviations in temperature → strain, stress
• Comments on available published data
  • Field data validity
    • temperature data likely okay, except where insulation is left off
    • strain data is highly suspect – fundamental errors in methodology
      • thermal strain, $e_{TH}$ is
        • inconsistently accounted for, or
        • not accounted for entirely
    • evaluation of strain gauge readings is incorrect
      • closed form expressions are not appropriate, equivalent strain expression premised on 2D model; however, 3D strain state is present
    • no data measured at most susceptible locations
• Comments on available published data
  • base material failure is accelerated likely due to HEAC
    • field & published data regarding base material failure –
      • proceeds rapidly in comparison to clad layer failure, months versus years
  • dependant on operational specifics
• Temperature loading – understanding the fundamentals
  • for isotropic material, temperature increase results
    • in uniform strain
    • no stress when body is free to deform
  • the total strain in a body, \( e_T \) is composed of two components
    • mechanical portion = \( e_M \) [due to pressure, weight, + others]
    • thermal portion = \( e_{TH} \)
  • then, \( e_T = e_M + e_{TH} \)
    • when thermal growth is constrained, \( e_T = 0 \) \( \Rightarrow \) \( e_M = - e_{TH} \)
    • since \( e_{TH} = \alpha \cdot \Delta T \), where \( \alpha \equiv \) coefficient of thermal expansion or CTE and, the coke drum is in a biaxial stress state, then

\[ \sigma_{TH} = - E \cdot \alpha \cdot \Delta T / (1 - \mu) \]
• Temperature loading [cont’d]
  • thermal expansion in coke drum is constrained due to several mechanisms
    • skirt structure
    • cladding – base material differential expansion due to mismatch in coefficient of thermal expansion, CTE

<table>
<thead>
<tr>
<th></th>
<th>100 F [in/in/F]</th>
<th>800 F [in/in/F]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTE-clad</td>
<td>6.0E-6</td>
<td>7.1E-6</td>
</tr>
<tr>
<td>CTE-base</td>
<td>6.6E-6</td>
<td>8.9E-6</td>
</tr>
</tbody>
</table>

• ΔT between adjacent parts of the structure due to varying exposure to incoming streams, i.e. bitumen [hot] and quench water [cold]
• Temperature loading [cont’d]

Thermal Expansion vs Temperature for Various Materials of Construction

Temperature [°F] vs CTE [10^-6 / °F] for:
- C 1/2Mo
- 1 1/4 Cr
- 2-1/4 Cr
- 410S
- N06625
- Temperature loading [cont’d]

E (Young's Modulus) vs Temperature

- C 1/2Mo
- 1 1/4 Cr
- 2-1/4 Cr
- 410S
- N06625
• Temperature loading [cont’d] - Temperature - Stress Profile Comparisons
• Nature of Drum Failures
  • Low Cycle Fatigue – $\frac{da}{dN}$
    • characterized by high strain– low cycle
      • exacerbated by presence of code acceptable defects
      • cladding crack failure initiation < 1,000 ~ 2,000 cycles
      • cladding crack propagation thru thickness ~ 2,500 cycles
  • Environmentally assisted fatigue – $\frac{da}{dt}$
    • exposure of base material to hydrogen assisted mechanism
    • short time to through failure – hours to months
    • cleavage surfaces evident
Number of Drums Reporting 1st Through Wall Crack – API Survey

• Nature of Drum Failures – cont’d
  • Upper bound strain
    • measured strain range, $\Delta \varepsilon = 2,500$ ue $\sim 3,400$ ue
    • calculated possible, $\Delta \varepsilon = 5,140$ ue $\sim 14,400$ ue

• measurements fall well below values governed by system parameters
• system parameters indicate that strains repeat and will cause failure at susceptible locations
• ε - N Low Cycle Strain Life Curve for SA 387 12 Plate [2¼ Cr – 1Mo]

<table>
<thead>
<tr>
<th>ε</th>
<th>2,570</th>
<th>3,400</th>
<th>5,140</th>
<th>7,200</th>
<th>14,400</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>100,000</td>
<td>25,000</td>
<td>4,800</td>
<td>2,500</td>
<td>900</td>
</tr>
<tr>
<td>Years</td>
<td>274</td>
<td>68</td>
<td>13</td>
<td>7</td>
<td>2.5</td>
</tr>
</tbody>
</table>

- extremes
- failure can occur within 2.5 years
- potential service life of 274 years
- actual performance of unit is function of system specifics

* Sonoya, K., et al., ISIJ International v 31 (1991) n 12 p 1424 - 1430
• \( \sigma - N \) Low Cycle Strain Life Curve per ASME VIII Div 2

<table>
<thead>
<tr>
<th>( \varepsilon )</th>
<th>2,570</th>
<th>3,400</th>
<th>5,140</th>
<th>7,200</th>
<th>14,400</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma )</td>
<td>77.1</td>
<td>102.0</td>
<td>154.2</td>
<td>216.0</td>
<td>432.0</td>
</tr>
<tr>
<td>( N )</td>
<td>10,000</td>
<td>4,200</td>
<td>1,200</td>
<td>550</td>
<td>70</td>
</tr>
<tr>
<td>Years</td>
<td>27</td>
<td>11.5</td>
<td>3</td>
<td>1.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

• ASME VIII Div 2 S – N chart is not appropriate for service life determination
• Influence of Internal Defects
  • Code allows internal defects

• For material thickness over ¾ inch to 2 inch, inclusive [19 mm to 50.8 mm]
  • Maximum size for isolated indication is ¼ “ [6.4 mm] diameter
  • Table limiting defect size is given in ASME VIII Div 1
• Stress at Internal Defects

Stress at internal defect
Stress at clad
Stress at OD surface
• largest strains/stresses at
  • clad
  • internal defects
  • local distortions
• maximum range of strains & stresses known due to system parameters
Conclusions

- field measurement techniques problematic
  - thermal strain interpreted as mechanical strain
  - measured strains well below upper bound strains
  - strains at internal defects inaccessible, no measurement
  - strains at material interface inaccessible, no measurement

- upper bound approach determines maximum strains obtainable
  - strain level, # of exposure incidents governed by system hydraulics
  - strain level, # of exposures govern service life
  - local shell deformations will further affect strain levels
  - crack initiation function of clad & base material integrity
  - through-wall base material failure related to HEAC susceptibility
• Evaluation

• improve field measurement techniques
• improve design procedures –
  • ASME VIII Div 1 not adequate to address complex loadings
  • more detailed & accurate estimation of stress required
  • need to consider more than material yield strength properties
• material selection opportunities – less expensive options for same performance
• preventative maintenance & repair opportunities identifiable
• Follow up work opportunities

  • develop improved field stress measurement technique
  • detection of internal defects and assessment technique
  • assessment of influence of local shell distortions
  • material constitutive modeling for better FEA modeling
  • characterization of base material performance in HEAC environment
  • identify alternative clad materials
  • develop appropriate design methodologies for coke drum

• Joint industry program – to leverage industry & NSERC resources
• Contact

• Dr. Zihui Xia, University of Alberta
  • zihui.xia@ualberta.ca
  • T: 780 492 3870

• John Aumuller, EDA Ltd.
  • aumullerj@engineer.ca
  • T: 780 484 5021