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

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• 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
• Major loadings identified

  • pressure, live weight, dead weight
    • pressure is nominally constant over operating cycle - cyclic
    • live weight load from bitumen feed, quench water - cyclic
    • dead weight load is constant

  • mechanical load due to coke crushing
    • as drum contracts, load due to restraint created by solid coke
      residual mass – cyclic, global

  • temperature load due to varying temperature of incoming
    streams – cyclic, variable, global & localized

  ➔ appears to be most damaging load mechanism ➔
• Contribution to failure
  • pressure, live weight, dead weight
    • not likely due to design stresses well within elastic region, no evidence that stresses exceed elastic
  
  • mechanical load due to coke crushing
    • feasible load, but not sufficiently severe
    • laser scan results do not generally support this mechanism
    • incremental distortion not evident

• temperature load due to varying temperatures of incoming streams – cyclic, variable, global & localized aspects during operational cycle
→ magnitude & distribution consistent with nature of failures
• Character of temperature loading is complex

  • variation and variability in fluid stream temperatures & impacts on drum metal temperature [DMT]
    • vapor heat [~ 550 °F], nominally causes uniform rise in DMT; however, vapour heat temperature can vary widely per operator intervention – can go directly from steam to oil-in step → thermal shock

  • oil-in [~ 750 °F to 900 °F], nominally causes uniform rise in DMT
    • as bitumen solidifies and cools, uniform effects give way to localized effects
• Character of temperature loading is complex [cont’d]

• water quench [~ 250 °F]
  • extreme thermal shock imposed on DMT
    • ~ 850 °F → 250 °F - oil-in & water quench temperatures
  • highly variable DMT due to flow channeling imposing hot & cold spots upon the drum shell that are also time variable, i.e. \( T = T(x, y, z, t) \) or \( T(\theta, z, t) \)

→ **highest potential impact on shell structural integrity**
Shell OD Strain - Measured

-200
0
200
400
600
800
1000
1200

0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0

strain in [ue]

0
200
400
600
800

Vapor heat

Oil in

Steam test

Water quench

time in [hours]

NB - the measured strains are not necessarily damaging
• Coke Drum Vasing -

- an effect of temperature loading
- occurs during oil-in operational step
  - condensation heats up lower elevations sooner than upper
  - differing temperatures in axial direction cause variable radial growth in drum
  - distortion in drum shell \( \rightarrow \) stresses – but where?
• Coke Drum Vasing -

  • drum vasing also occurs during
    • coke cool-down due to insulating effect as coke forms, liquid \( \rightarrow \) solid
    • water quench addition
  • vasing action is a nominal response
    • bitumen filling, water filling occur over same repeating nominal time period, nominal temperature range \( \rightarrow \) plug flow nature
  • localized distortions superimposed
    • system hydraulics cause channel flow & deviations in temperature \( \rightarrow \) 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

$\rightarrow$ thermal stress, $\sigma_{TH} = -E \cdot \alpha \cdot \Delta T / (1 - \mu)$
• 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</th>
<th>800 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

![Graph showing thermal expansion vs temperature for various materials of construction. The graph plots CTE (10^-6/°F) against temperature (°F). The materials include C 1/2Mo, 1 1/4 Cr, 2-1/4 Cr, 410S, and N06625.]
• Temperature loading [cont’d]

E (Young's Modulus) vs Temperature

E - [10^6 psi]

Temperature [°F]

C 1/2Mo
1 1/4 Cr
2-1/4 Cr
410S
N06625
• Nature of Drum Failures
  • Low Cycle Fatigue – $da / dN$
    • characterized by high strain–low cycle
      • exacerbated by presence of code acceptable defects
      • cladding crack failure initiation $< 1,000 \sim 2,000$ cycles
      • cladding crack propagation thru thickness $\sim 2,500$ cycles
  • Environmentally assisted fatigue – $da / dt$
    • 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, $\Delta \varepsilon = 2,500 \text{ ue} \sim 3,400 \text{ ue}$
  - calculated possible, $\Delta \varepsilon = 5,140 \text{ ue} \sim 10,080 \text{ ue}$

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

<table>
<thead>
<tr>
<th>$\varepsilon$</th>
<th>N</th>
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<tbody>
<tr>
<td>2,570</td>
<td>100,000</td>
</tr>
<tr>
<td>3,400</td>
<td>25,000</td>
</tr>
<tr>
<td>5,140</td>
<td>4,800</td>
</tr>
<tr>
<td>7,200</td>
<td>2,500</td>
</tr>
<tr>
<td>10,080</td>
<td>1,500</td>
</tr>
</tbody>
</table>

| Years | 274 | 68 | 13 | 7 | 4 |

- extremes
- failure can occur within 4 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

- ASME VIII Div 2 S – N chart is not appropriate for service life determination

\[
\begin{array}{c|cccccc}
\varepsilon & 2,570 & 3,400 & 5,140 & 7,200 & 10,080 \\
\sigma & 77.1 & 102.0 & 154.2 & 216.0 & 302.4 \\
N & 10,000 & 4,200 & 1,200 & 550 & 180 \\
\end{array}
\]
• Influence of Internal Defects
  • Code allows internal defects

• For material thickness over 3/4 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

![Graph showing stress at different locations over time](image-url)
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
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