Remaining Life Assessment of Coker Heater Tubes

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Overview

- Introduction
  - Coker Heaters
  - Creep
- Remaining Life Assessment
  - API 579-1 / ASME FFS-1 creep life assessment
- Creep Testing
  - Tube removal guidelines
  - Test Procedure
  - Case study
- Other Damage Mechanisms
- Concluding Remarks
Coker Heaters

• Operating conditions typically different from other fired heaters due to coking of radiant tubes
• Industry moving towards heavier/cheaper crudes
  ▪ Larger quantities of vacuum residue
• Throughput limited by fouling
  ▪ Frequent decoking cycles
Coker Heaters

- Creep is one of the most prominent damage mechanisms in coker heaters
- 9Cr-1Mo steel is the workhorse alloy in the refining industry
  - 5Cr-$\frac{1}{2}$Mo and 7Cr-$\frac{1}{2}$Mo in radiant sections of few old furnaces
  - Upgrades to austenitic stainless steel series or Incoloy 800H/HT are now common
What is Creep?

- **Time-dependent** permanent inelastic strain in materials when subjected to **stresses below yield** at **elevated temperatures**

\[ \varepsilon_c = f(\sigma, t, T) \]

\[ \dot{\varepsilon}_c = A \sigma^n \exp\left(\frac{-Q}{RT}\right) \]

- **Creep properties** are determined from **stress-rupture tests** and/or **accelerated creep tests**

Bailey-Norton steady state creep law
Larson-Miller Parameter

- Time-Temperature parameter developed in the early 1950s by F. R. Larson and J. Miller in order to extrapolate short-term rupture test results to long-term predictions

\[ LMP = T(C + \log t_r) \]
MPC Omega Method

- Based on the concept that strain rate is a direct gage of creep damage

\[ \dot{\varepsilon}_c = \dot{\varepsilon}_{co} \exp(\Omega \varepsilon_c) \]

- Practical engineering alloys used in high temperature applications display little or no primary or secondary creep, residing in the tertiary range for most of their lives

\[ \Omega \] is the creep damage coefficient and defines the rate at which the strain rate accelerates with increasing strain

- It is not required to run creep tests to rupture

\[ t_r = \frac{1}{\dot{\varepsilon}_{co} \Omega_m} \]
Modeling Creep Behavior

• Both LMP and Omega are fairly easy to use and are applicable to a number of engineering alloys
• LMP and MPC Omega are **not** the only methods available model creep behavior
  ▪ These are the only two methods provided in API 579-1 / ASME FFS-1
• Neither methods are any more accurate than some of the other approaches that have been proposed
  ▪ Manson-Haferd
  ▪ Orr-Sherby-Dorn
  ▪ Monkman-Grant
Why Do Creep Life Assessment?

• Determine how much life is remaining in the tubes
• Screen for creep damage prior to shutdowns to prevent/limit costly inspection/testing
• Determine if the furnace can be operated at higher temperatures
  - Higher EOR (end of run) temperatures are often desired in coker heaters to reduce the frequency of decoking cycles
  - Creep life assessment can show where operating limits should be set to maximize throughput vs. risk of failure
Inputs for Heater Tube Assessment

- **Design Data**
  - Material of construction
  - Tube size and schedule

- **Service History**
  - Tube metal temperatures
    - Thermocouple data and/or infrared data
  - Pressure
    - Inlet pressure and pressure drop
  - Corrosion
    - Corrosion rate and replacement history
    - Retirement thickness
  - Upsets
API 579-1 / ASME FFS-1 Creep Life Assessment

- Part 10 provides assessment procedures for pressurized components operating in the creep range.
- Methodologies are provided to compute accumulated creep damage at each time increment where the component is subjected to a specific stress-temperature combination.
  - Rupture data in terms of Larson-Miller parameter
  - MPC Project Omega data
- Based on a linear damage accumulation model.
Remaining Life Calculations

- Remaining life calculated for each time increment $n t$

**MPC Omega**

\[ nL = \frac{1}{\dot{\varepsilon}_{co}\Omega_m} \]

**LMP (US Customary Units)**

\[ \log_{10} nL = \frac{1000 \times LMP(nS_{eff})}{(nT + 460)} - C_{LMP} \]

- Total damage fraction

\[ D_{c}^{total} = \sum_{n=1}^{N} \frac{n t}{nL} \]

- Creep life is fully consumed when the accumulated creep damage fraction equals 1.0
  - API 579-1 / ASME FFS-1 adds a safety margin (useful life consumed at $D = 0.8$)
Example: Remaining Life Results

The graph shows the remaining life results as a function of tube metal temperature (°F). The x-axis represents the tube metal temperature, while the y-axis shows the remaining life in hours. Different lines represent different models or scenarios:

- LMP (Minimum)
- LMP (Average)
- Omega
- Elastic Design

The data indicates a clear trend where the remaining life decreases as the tube metal temperature increases.
Why Do Creep Testing?

- Precise description of the furnace operating history is not available
  - Reliable assessments cannot be made without accurate history
- Tubes have (or are suspected to have) suffered in-service degradation
  - Visual indications of creep damage are not always present
- Life assessment based on API 579-1 / ASME FFS-1 creep properties predicted that the tubes are near end of life
  - Testing provides creep properties specific to tubes being analyzed
Guidelines for Tube Removal

• Sample from the areas exposed to the highest temperature regions that will be remaining in service
  ▪ Use combination of IR data, thermocouple data, tube visual inspection, thickness measurements, and bulging checks (visual, strapping, lamping, and/or crawlers)

• Clearly mark the tubes before removal
  ▪ Location in the heater (asset number, pass, elevation, distance to closest thermocouple, etc.)
  ▪ Fire-side & back-side (if applicable)

• Testing the wrong tubes could be worse than not testing at all!

• Tube sample should be a minimum of 18” long if cold cut, or 24” long if torch cut
Accelerated Creep Testing

• Five specimens from each tube
  ▪ Four hoop specimens from the fire-side
  ▪ One axial specimen from the back-side
• The back-side specimen is a reference sample intended to represent, to the degree possible, a sample with minimal creep damage
• Specimens are typically nickel plated to limit oxidation
Creep Testing: Omega vs. LMP

• Omega method requires testing in two stages
  ▪ Initial creep rate (ICR) more sensitive to changes in temperature and stress compared to Omega
    – Determine initial creep rate (ICR) at test conditions close to operating conditions
    – Determination of Omega requires further acceleration of test conditions

• LMP can be obtained by:
  ▪ Testing to rupture
  ▪ Predicting the time to rupture once a clear tertiary behavior is observed

• Materials that have not been thermally stabilized in service may not conform to the Omega model
Case Study: Background

- Coker heater commissioned in 1982
- Tube Material: 9Cr-1Mo (SA213-T9)
- Tube Size: 3” Sch. 160
- Pressure: 450 psig
- Corrosion Rate: 3 mpy
Case Study: Fire-side Specimen

1152°F 5.22ksi
1200°F 5.61ksi

\[ t_r = \frac{1}{\dot{\varepsilon}_{co} \Omega} = 1914 \text{hrs.} \]

\[ \varepsilon_c = -\frac{1}{\Omega} \ln(1 - \dot{\varepsilon}_{co} \Omega t) \]

\[
\begin{array}{|c|c|c|}
\hline
\text{Parameter} & \text{Value} & \text{Error} \\
\hline
m1 & 0.0018857 & 2.5052e-5 \\
m2 & 9.5194 & 0.099264 \\
m3 & 5.4901e-5 & 1.2617e-7 \\
Chisq & 0.00023981 & NA \\
R & 0.99965 & NA \\
\hline
\end{array}
\]
Case Study: Fire-side Specimen

\[ \varepsilon_c = -\frac{1}{\Omega} \ln(1 - \dot{\varepsilon}_{co} \Omega t) \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Error</th>
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<tbody>
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<td>m1</td>
<td>0</td>
<td>0.0031734</td>
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<tr>
<td>m2</td>
<td>9.5399</td>
<td>0.044198</td>
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<tr>
<td>m3</td>
<td>0.0007499</td>
<td>2.453e-6</td>
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<tr>
<td>Chisq</td>
<td>0.0031218</td>
<td>NA</td>
</tr>
<tr>
<td>R</td>
<td>0.99896</td>
<td>NA</td>
</tr>
</tbody>
</table>

1372°F 1.71ksi
1372°F 2.57ksi
Case Study: Remaining Life

- Plenty of creep life left in the tube at EOR temperatures less than 1275°F
- Test results show some scatter
- Back-side specimen test results lie within the scatter
Case Study: Omega vs. LMP

\[ LMP = (T + 460)(20 + \log t_r) \times 10^{-3} \]
Other Damage Mechanisms

• Creep is not the only damage mechanism in coker heaters
  ▪ Carburization
  ▪ Sigma Phase (Stainless Steels)
  ▪ External Oxidation
  ▪ Sulfidation
  ▪ Brittle Fracture
  ▪ Erosion

• Any of these damage mechanisms can lead to tube failures before creep life is consumed
  ▪ Some might interact with creep, accelerating rupture
Carburization

- Coke deposits promote carburization on the ID
  - Carbon combines with carbide-forming elements in the alloy to form internal carbides
  - Occurs in CS, Cr-Mo alloys, 300 and 400 series SS typically above 1100°F
  - Reduces ambient temperature ductility, toughness, and weldability of the alloy

Brittle fracture in carburized 9Cr coker heater tube
Sigma Phase Embrittlement

- Iron-Chromium intermetallic phase that forms in ferritic and austenitic stainless steels when exposed to 1050°F - 1800°F
  - Causes loss of ductility and embrittlement below 250°F - 300°F
  - May affect creep properties and reduce creep ductility
External Oxidation

• Conversion of metal to oxide scale in the presence of oxygen
  ▪ Metal loss increases with increasing temperature

• Flame impingement causes localized heating
  ▪ Increased oxidation on the OD
  ▪ Increased coke formation on the ID
Erosion

- Tubes in Coker furnaces require frequent decoking processes to remove ID deposits (coke)
- Steam air and spall decoking are regularly used in refinery operations
  - Localized thinning at areas of high velocities decoking
  - Return bends are particularly affected
  - All alloys are susceptible
Challenges Predicting Life

• Establishing Life Limiting Degradation Mechanisms
• Defining Operating Conditions
  ▪ Measuring tubes metal skin temperatures
  ▪ Considering all applied loads and stresses affecting the tubes
• Selecting Material Creep Strength and Ductility
  ▪ Industry data (literature)
  ▪ Sampling and mechanical testing
• Gathering Inspection Data and Setting Variables Affecting Remaining Life Calculation
  ▪ Corrosion rates
  ▪ Time increment
Concluding Remarks

• Creep becomes more and more relevant as heaters age and profit margins push process limits
• Useful life can be prolonged with a combination of adequate inspection program, life assessment calculations and process changes
• Accelerated creep testing can be employed to shift the operating history of the tubes
• Other possible damage mechanisms must not be overlooked
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Creep voids in 9Cr-1Mo steel