Remaining Life Assessment of Coker Heater Tubes

Arun Sreeranganathan, Ph.D., P.E.
Presented by Puneet Agarwal, Ph.D., P.E.

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Overview

- Introduction
  - Coker Heaters
  - Creep
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  - API 579-1 / ASME FFS-1 creep life assessment
  - Basic Screening
  - Medium Screening
  - Advanced Screening ... Testing
- 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-½Mo and 7Cr-½Mo 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

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

\[ \dot{\varepsilon}_c = A \sigma^n \exp\left(\frac{-Q}{RT}\right) \]  Bailey-Norton steady state creep law

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

- \(W\) 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 to 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 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
    – UT 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

$$n L = \frac{1}{\dot{\varepsilon}_{co} \Omega_m}$$

LMP (US Customary Units)

$$\log_{10} n L = \frac{1000 \times LMP(n S_{eff})}{(n T + 460)} - C_{LMP}$$

- Total damage fraction

$$D_{c total} = \sum_{n=1}^{N} \frac{n t}{n L}$$

- 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
Basic Screening Assessment

Screening assessment for service-accumulated creep damage. Requires basic design information and “Worst Case” operating details.

- Calculations based on single, worst-case values for temperature, pressure, and corrosion rate
- Conservative
- Allows focus of inspection effort and tube replacement on critical heaters
- Fast turnaround/relatively low cost
Medium Screening Assessment

Screening assessment to quantify the service-accumulated creep damage

- Calculations based on best definition of operating history including; temperature, pressure, and corrosion rate
- Incorporates more detailed temperature and pressure history
- Recommended if the screening assessment predicts significant creep damage accumulation
- Less conservative than single value basis
- Requires more details from previous operations and inspection data
- Usefulness contingent on data quality and availability
- Reasonable turnaround times, improved results precision at a slightly higher cost
Typical Process Data

- Temperature °F
- Pressure psig
Medium Screening Method

Instead of a yearly calculation of damage, available process data can be used to calculate and **sum the daily accumulated damage**.

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<th>σ ksi</th>
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Uncertainties

NPS 6 x 0.280 9Cr-1Mo Minimum Material Properties

Estimated Life (years)

Temperature °F
Advanced Screening Assessment

Creep Testing...
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 your tubes
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 (Furnace 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 psi
- Corrosion Rate: 3 mpy
Case Study: Fire-side Specimen

9Cr-1Mo Fire-side hoop specimen A

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

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

1152°F 5.22ksi

1200°F 5.61ksi

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an employee-owned company
Case Study: Fire-side Specimen

9Cr-1Mo
Fire-side hoop specimen D

1372°F
1.71 ksi

1372°F
2.57 ksi

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

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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
  - Sulfidic Corrosion
  - 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

347H SS microstructure prior to exposure
347H SS microstructure after exposure
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
- 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
Concluding Remarks

• Creep is becoming more and more relevant as heaters age and profit margins are pushing process limits
• Useful life can be prolonged with a combination of 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
Acknowledgments

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  ▪ Technology Advisor, Valero Energy
Contact Information

Puneet Agarwal, Ph.D., P.E.
Stress Engineering Services, Inc.
Puneet.Agarwal@stress.com
www.stress.com

Creep voids in 9Cr-1Mo steel
Thank You!