Remaining Life Assessment of Coker Heater Tubes

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

Coking.com®
October 17-20, 2016 Mumbai, India

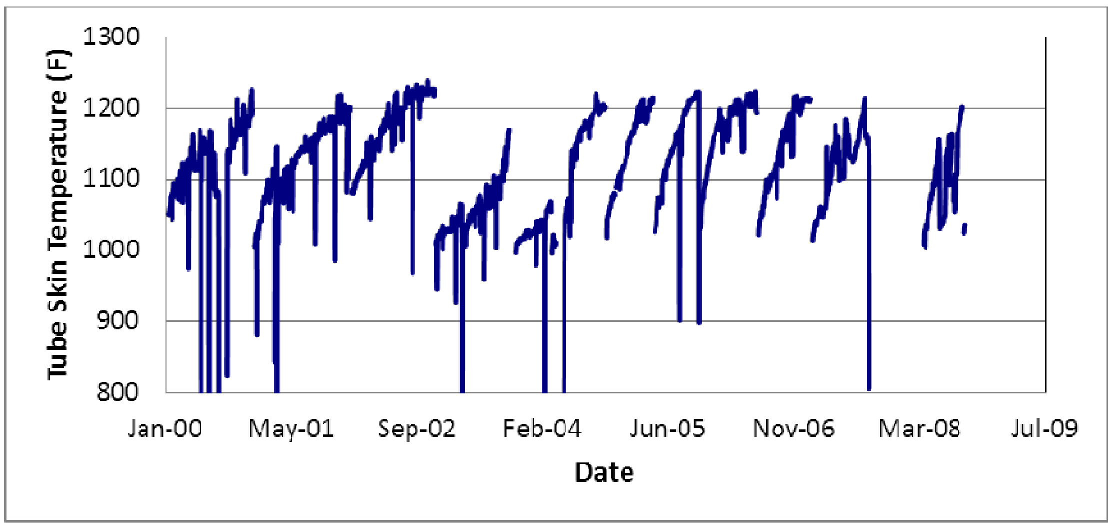
Taking on your toughest technical challenges.

Overview

- Introduction
  - Coker Heaters
  - Creep
- Remaining Life Assessment
  - 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?

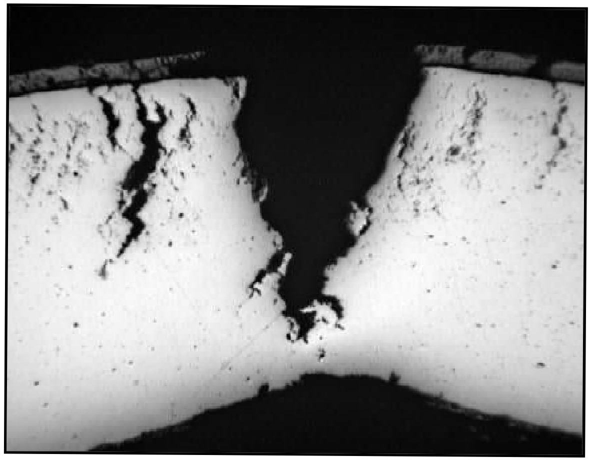
- Time-dependent permanent inelastic strain in materials when subjected to stresses below yield at elevated temperatures

$$\varepsilon_c = f(\sigma, t, T)$$

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

Bailey-Norton steady state creep law

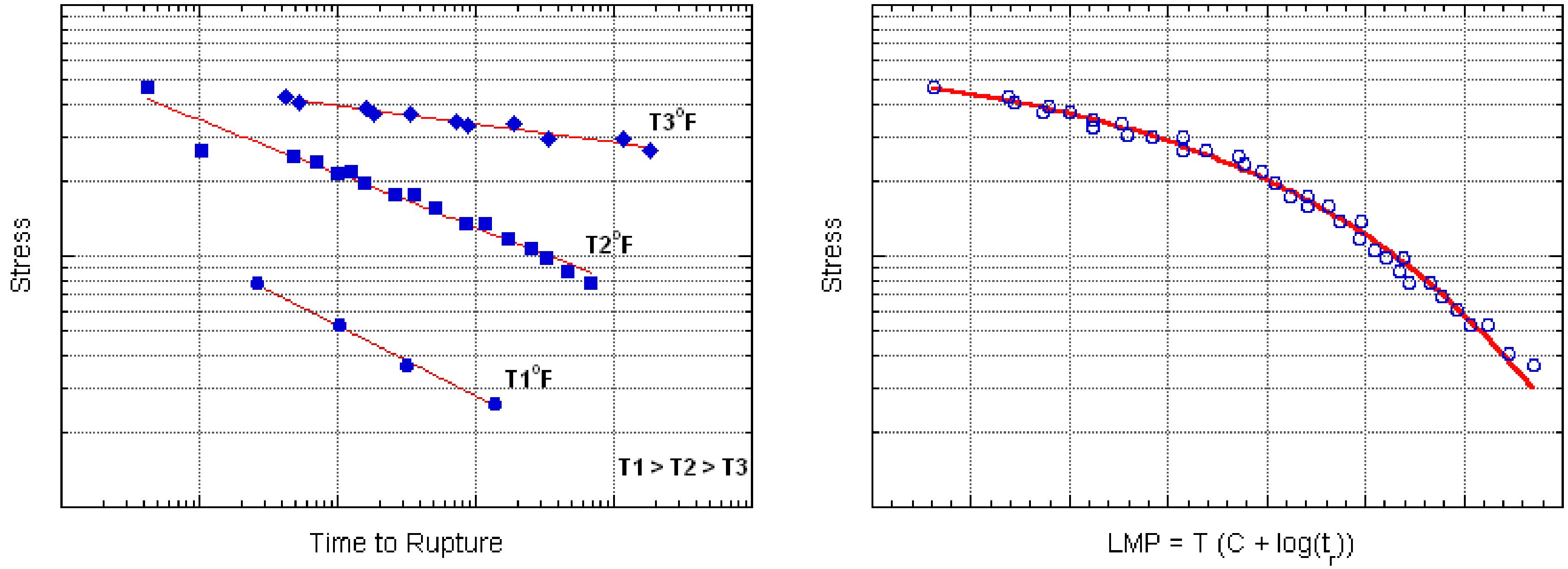
- Creep properties are determined from stress-rupture tests and/or accelerated creep tests



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

$$LMP = T(C + \log t_r)$$



STRESS ENGINEERING SERVICES INC. an employee-owned company

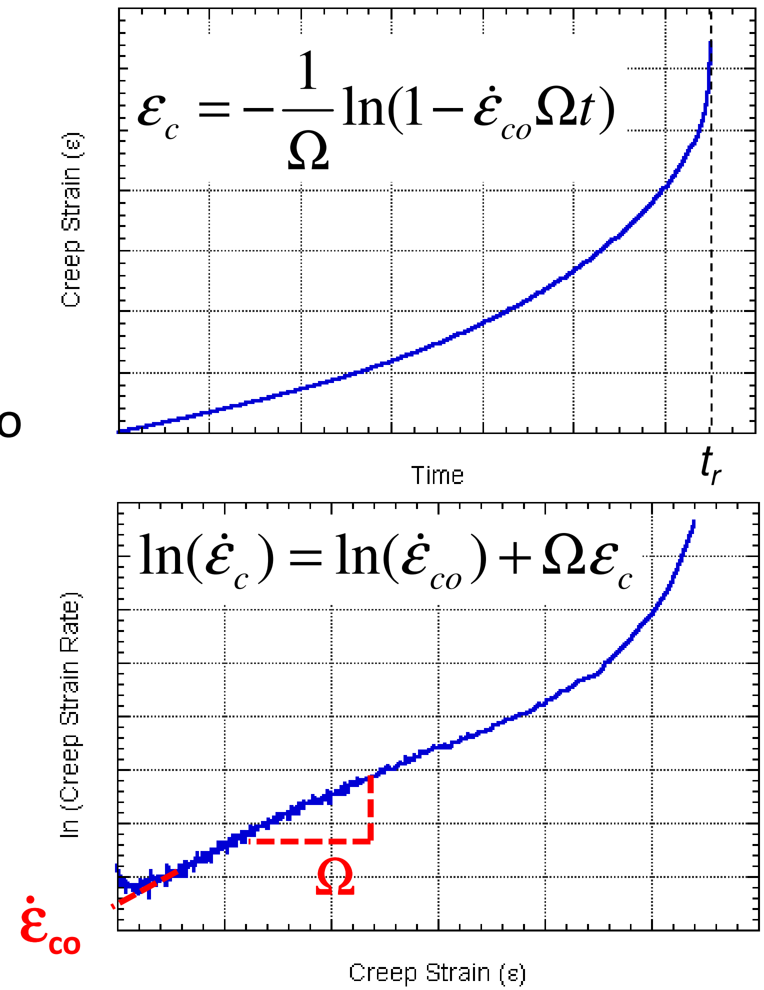
MPC Omega Method

- 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

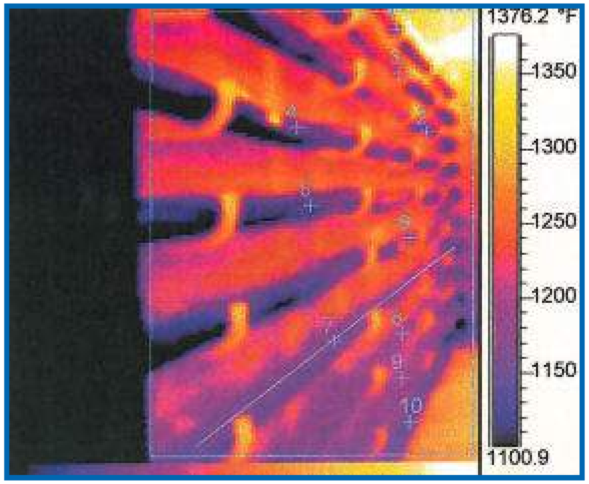
- Both LMP and Omega are fairly easy to use and are applicable to a number of engineering alloys
- LMP and MPC Omega are not the only methods available model creep behavior
  - These are the only two methods provided in API 579-1 / ASME FFS-1
- Neither methods are any more accurate than some of the other 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



STRESS ENGINEERING SERVICES INC. an employee-owned company

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

STRESS ENGINEERING SERVICES INC. an employee-owned company

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

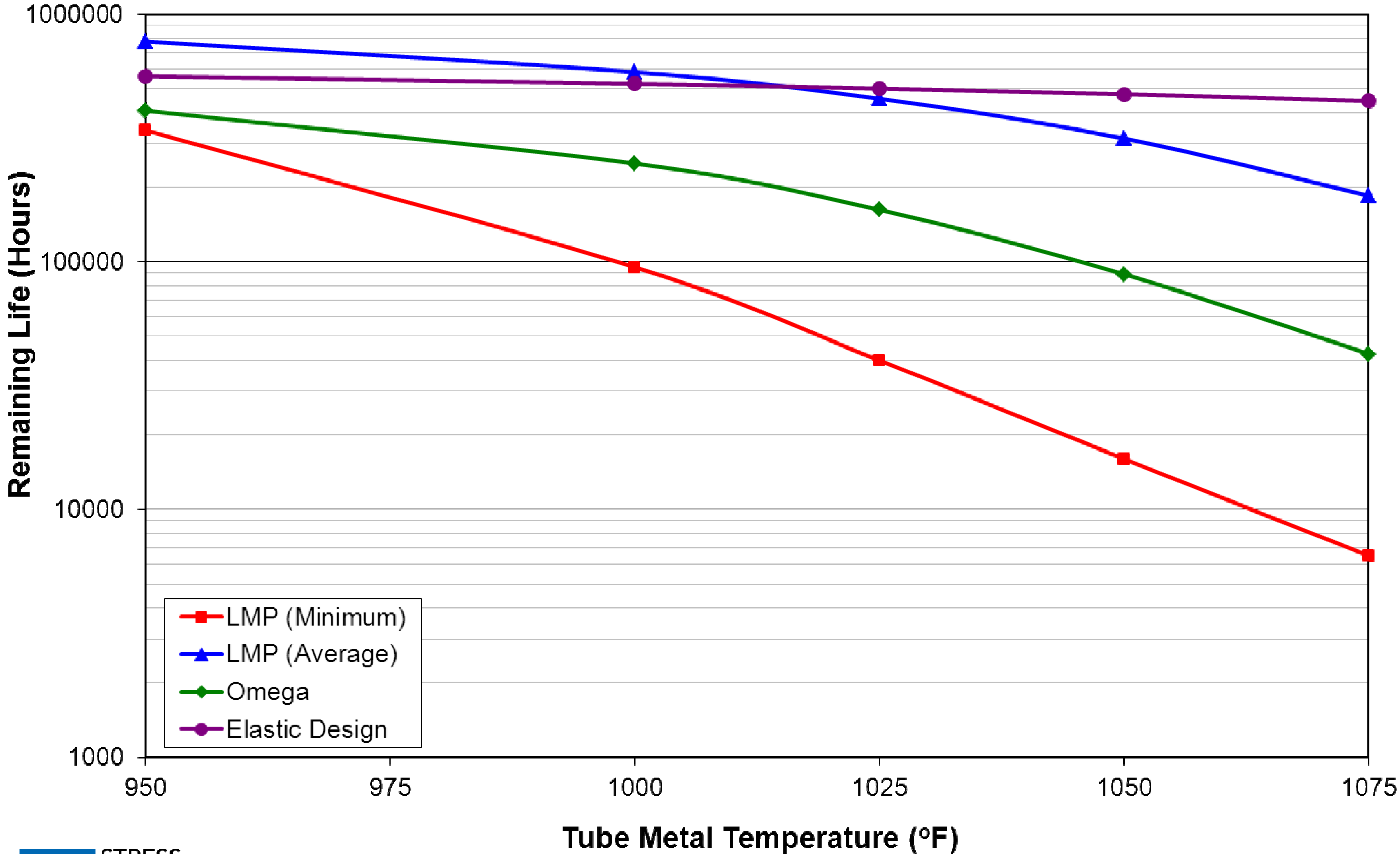
$$ D_{c}^{total} = \sum_{n=1}^{N} \frac{{}^{n}t}{{}^{n}L} $$

- 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)

STRESS ENGINEERING SERVICES INC.

an employee-owned company

Example: Remaining Life Results



STRESS ENGINEERING SERVICES INC.
an employee-owned company

Basic Screening Assessment

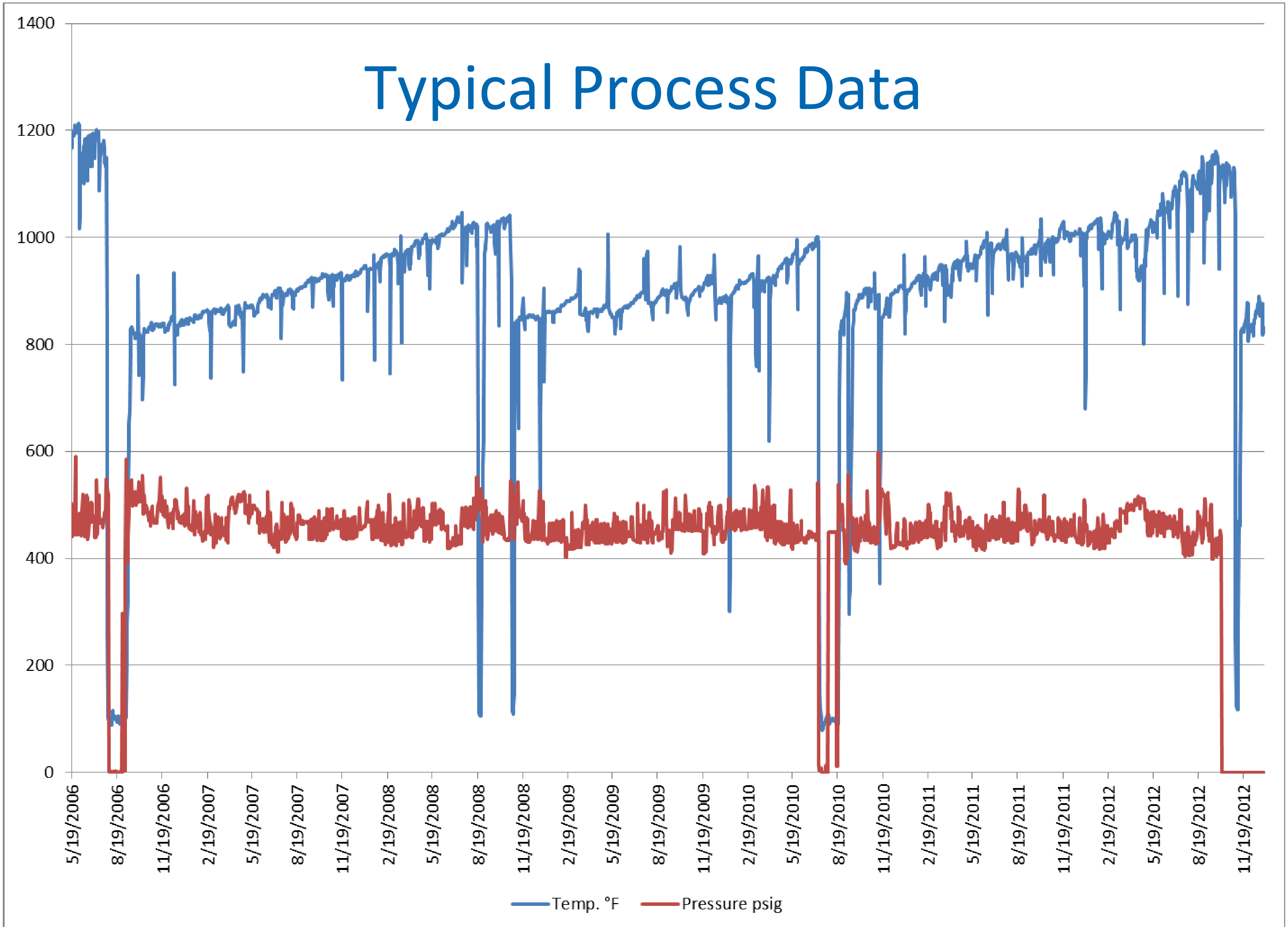
Screening assessment for service-accumulated creep damage. Requires basic design information and “Worst Case” operating details.

- 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



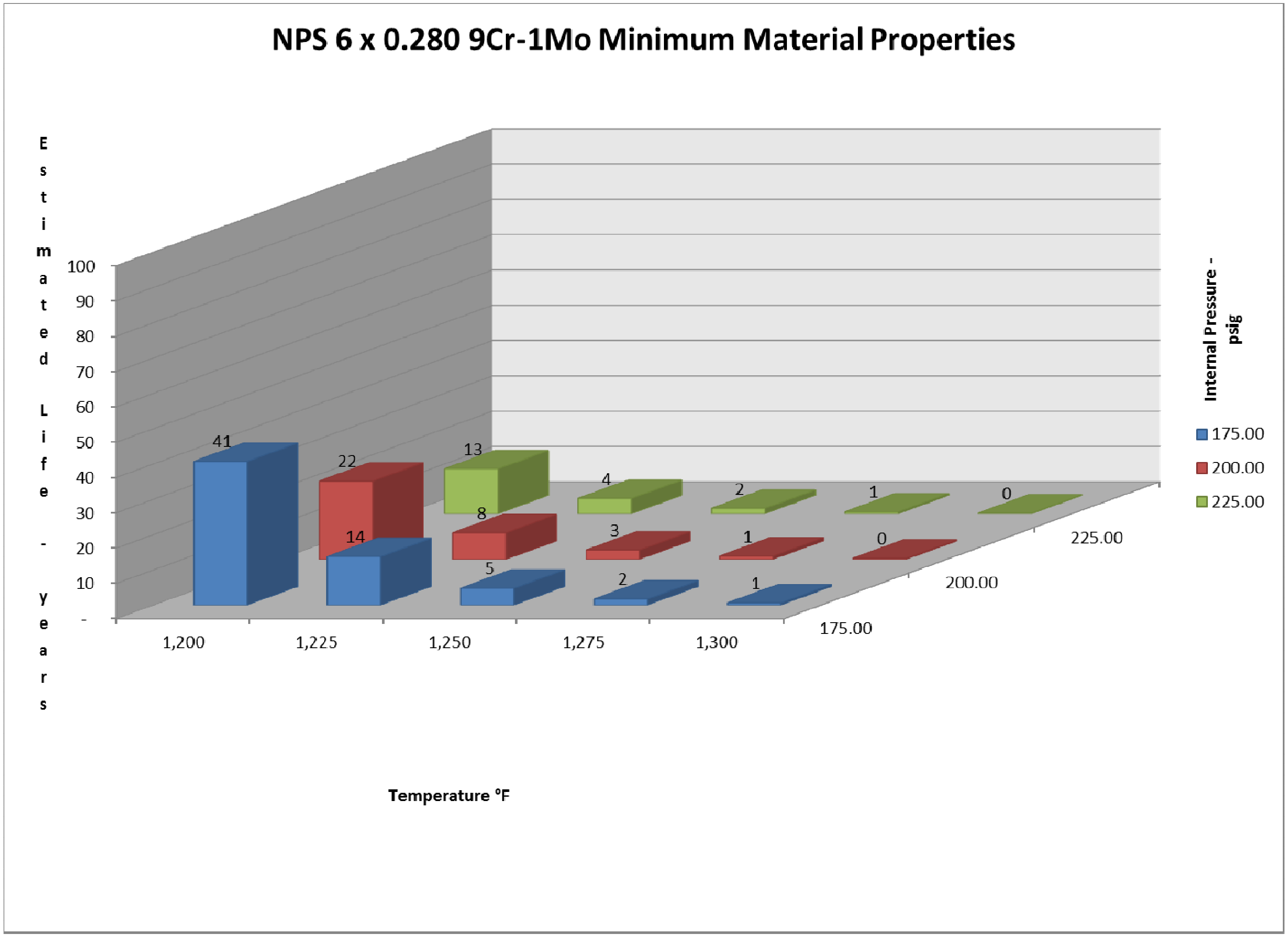
Typical Process Data
1400
1200
1000
800
600
400
200
0
5/19/2006
8/19/2006
11/19/2006
2/19/2007
5/19/2007
8/19/2007
11/19/2007
2/19/2008
5/19/2008
8/19/2008
11/19/2008
2/19/2009
5/19/2009
8/19/2009
11/19/2009
2/19/2010
5/19/2010
8/19/2010
11/19/2010
2/19/2011
5/19/2011
8/19/2011
11/19/2011
2/19/2012
5/19/2012
8/19/2012
11/19/2012
Temp. °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***.

					damage$_m$	damage$_a$			
δ	σ ksi	LMP	life$_m$ hrs	life$_a$ hrs	1.9%	0.8%			
								Temp. °F	Pressure psig
0.400	2.276	52295.46	1,832,148	4,240,896	0.001%	0.001%	3/19/2002	1150	444
0.400	2.276	52295.26	2,216,246	5,129,973	0.001%	0.000%	3/20/2002	1146	444
0.400	2.276	52295.06	2,344,507	5,426,858	0.001%	0.000%	3/21/2002	1144	444
0.400	2.277	52294.86	2,176,177	5,037,223	0.001%	0.000%	3/22/2002	1146	444
0.400	2.277	52294.66	2,606,582	6,033,487	0.001%	0.000%	3/23/2002	1142	444
0.400	2.277	52294.45	6,315,109	14,617,660	0.000%	0.000%	3/24/2002	1124	444
0.400	2.277	52294.25	8,141,255	18,844,662	0.000%	0.000%	3/25/2002	1118	444
0.400	2.277	52294.05	949,405	2,197,600	0.003%	0.001%	3/26/2002	1164	444
0.400	2.277	52293.85	760,960	1,761,403	0.003%	0.001%	3/27/2002	1169	444
0.400	2.277	52293.65	1,259,030	2,914,293	0.002%	0.001%	3/28/2002	1158	444
0.400	2.278	52293.45	674,267	1,560,735	0.004%	0.002%	3/29/2002	1171	444
0.400	2.278	52293.25	671,626	1,554,621	0.004%	0.002%	3/30/2002	1172	444
0.400	2.278	52293.05	885,510	2,049,701	0.003%	0.001%	3/31/2002	1165	444
0.400	2.278	52292.85	1,466,214	3,393,864	0.002%	0.001%	4/1/2002	1154	444
0.400	2.278	52292.65	3,557,240	8,233,988	0.001%	0.000%	4/2/2002	1136	444
0.400	2.278	52292.45	413,574	957,305	0.006%	0.003%	4/3/2002	1182	444
0.400	2.278	52292.25	413,812	957,855	0.006%	0.003%	4/4/2002	1182	444

Uncertainties



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

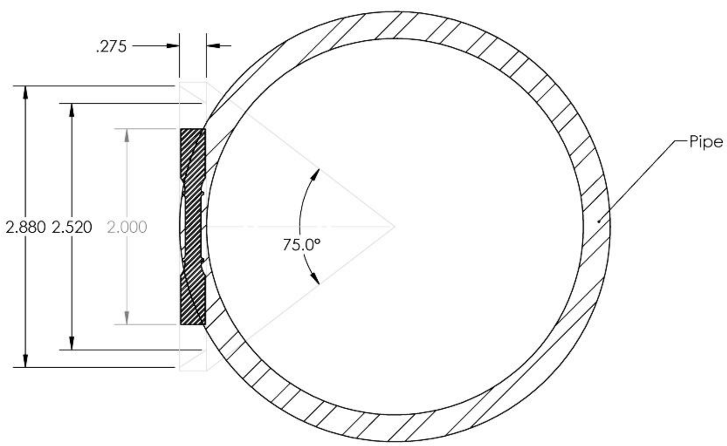
Guidelines for Tube Removal

- 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



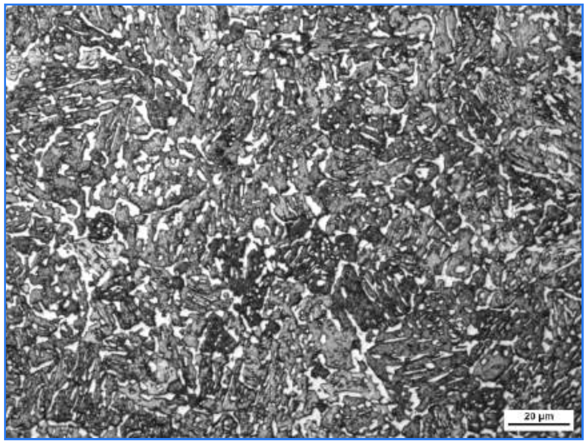
STRESS ENGINEERING SERVICES INC.

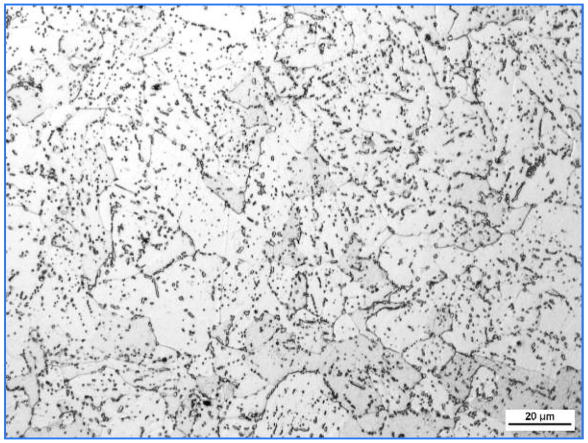
Creep Testing: Omega vs. LMP

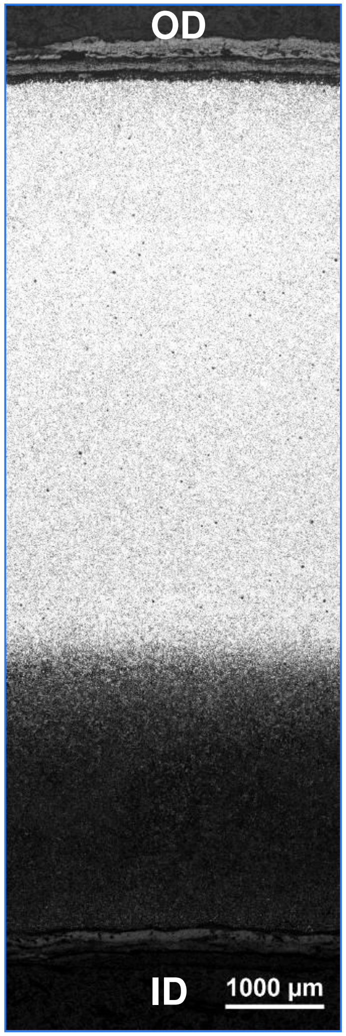
- Omega method requires testing in two stages
  - Initial creep rate (ICR) more sensitive to changes in temperature and stress compared to Omega
    - Determine initial creep rate (ICR) at test conditions close to operating conditions
    - Determination of Omega requires further acceleration of test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

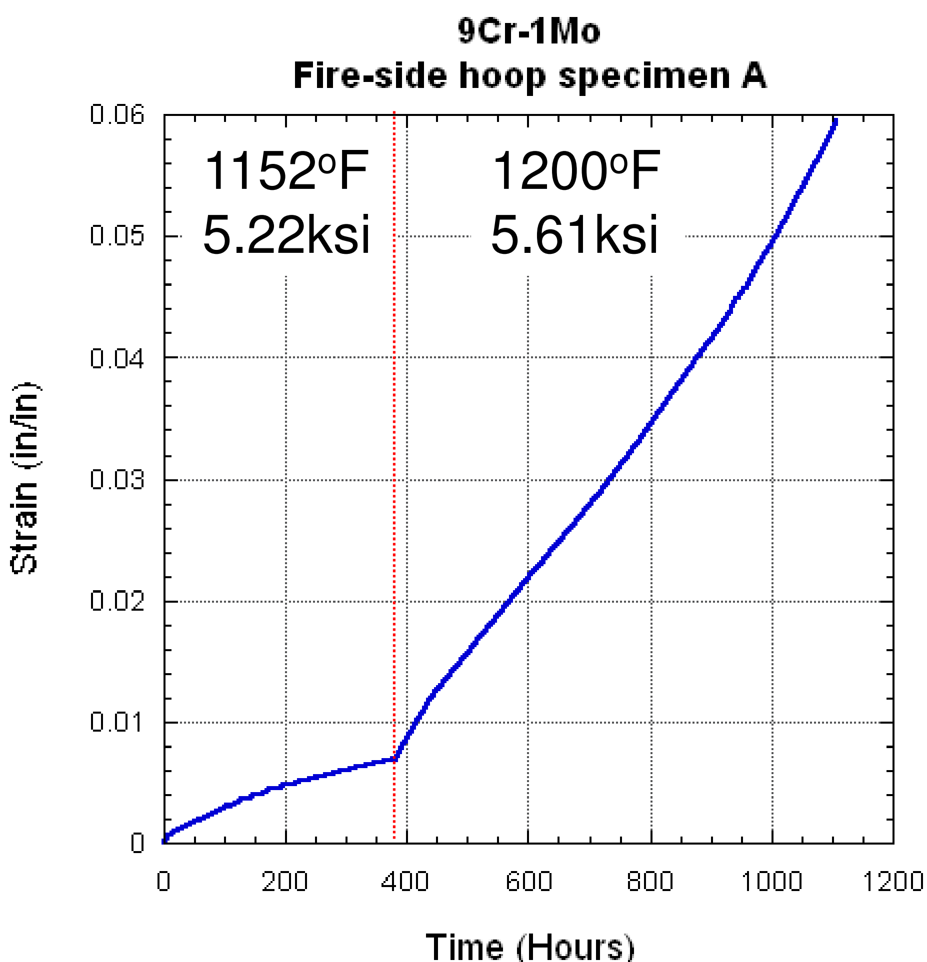
- Coker heater commissioned in 1982
- Tube Material: 9Cr-1Mo (SA213-T9)
- Tube Size: 3” Sch. 160
- Pressure: 450 psi
- Corrosion Rate: 3 mpy

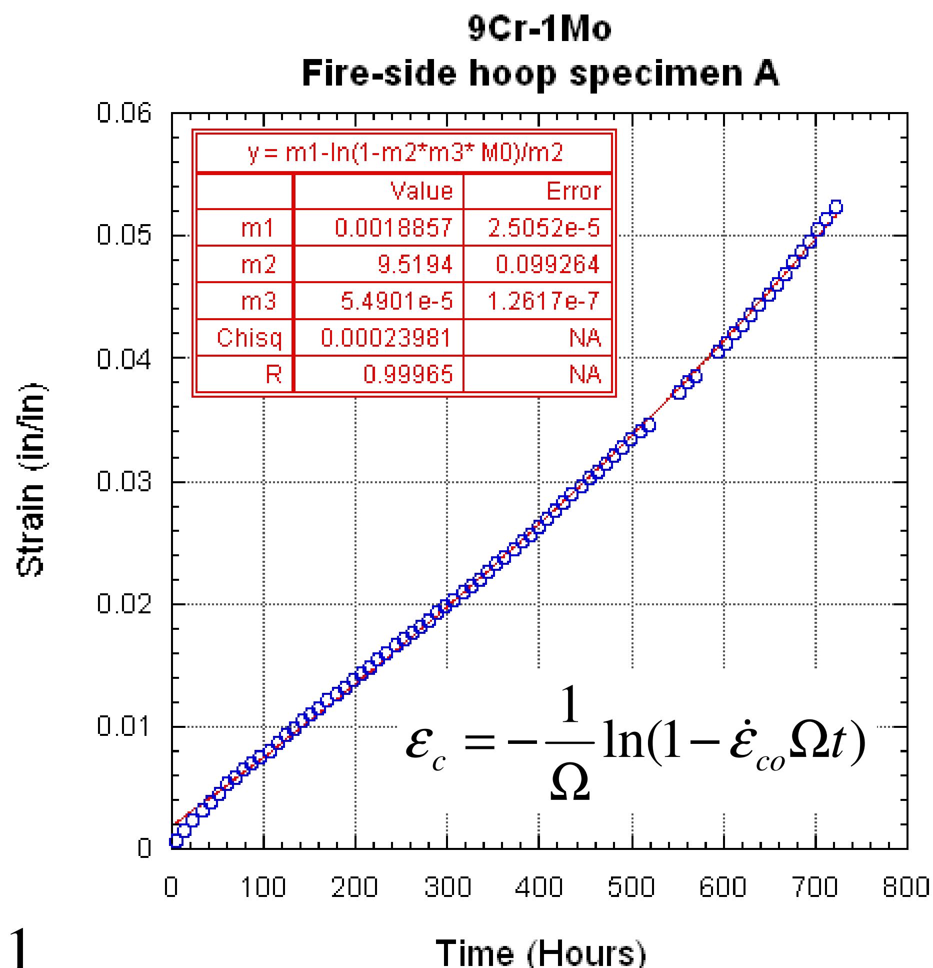






Case Study: Fire-side Specimen



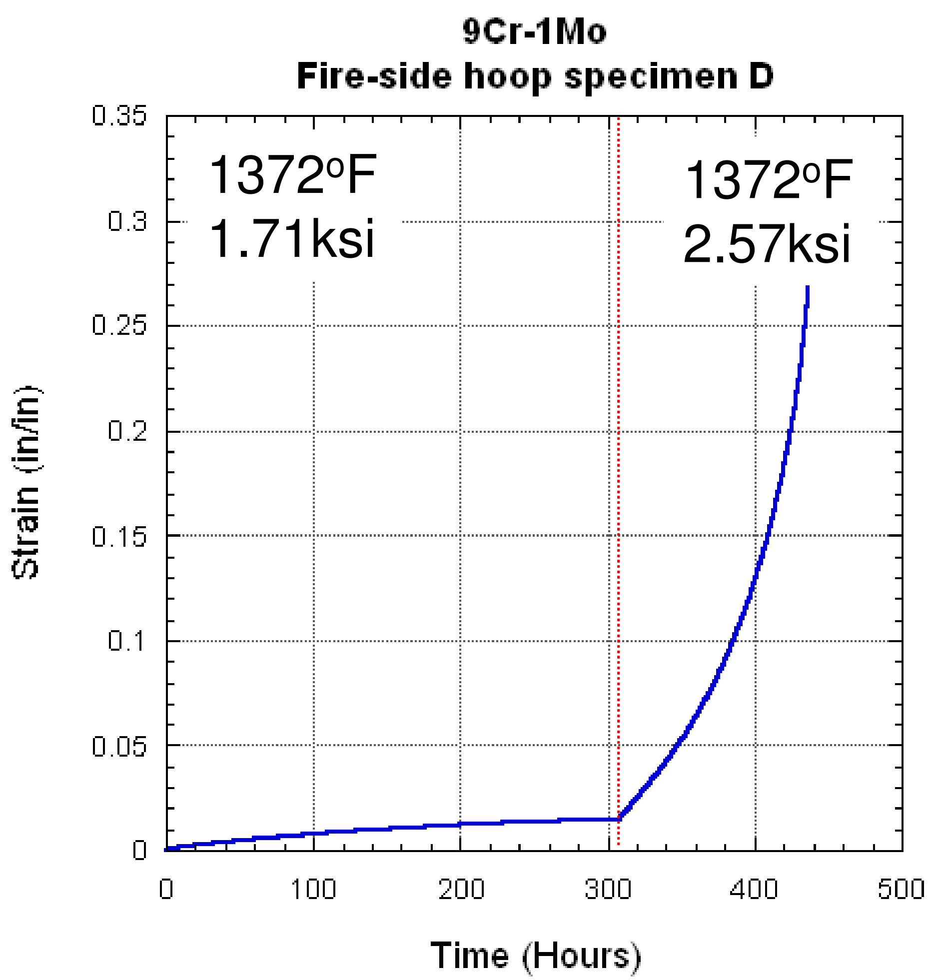


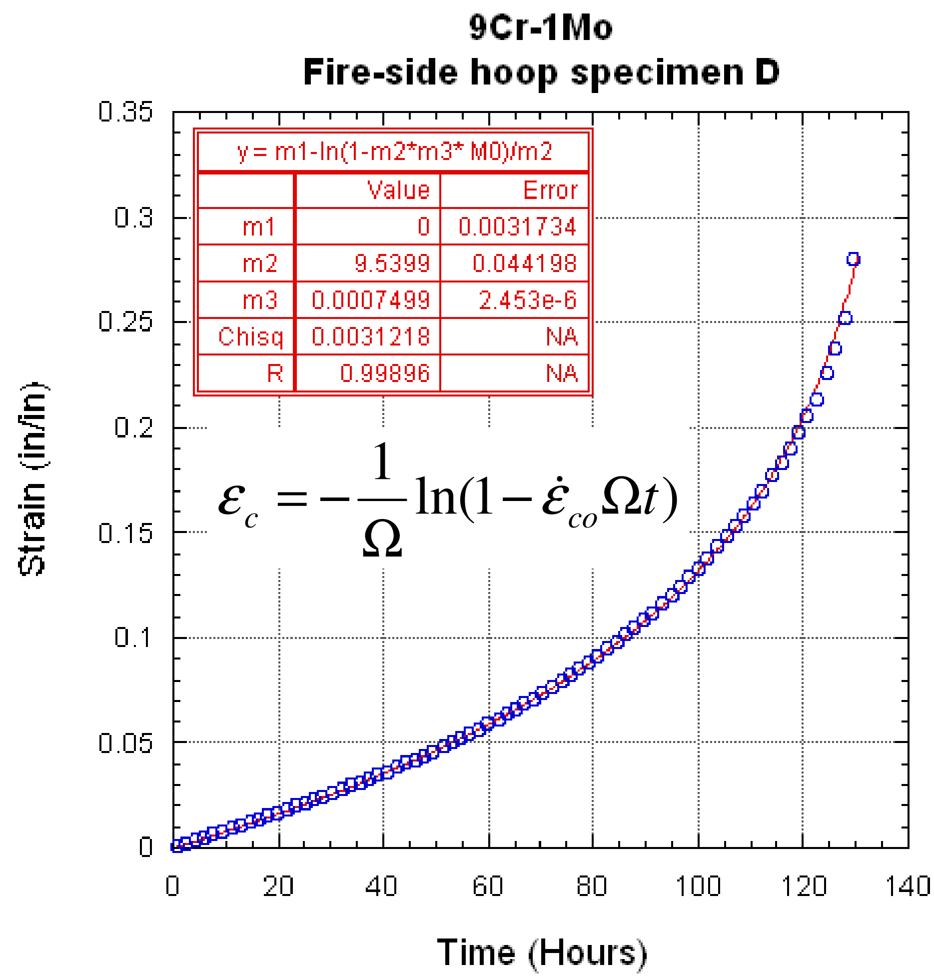
	Value	Error
m1	0.0018857	2.5052e-5
m2	9.5194	0.099264
m3	5.4901e-5	1.2617e-7
Chisq	0.00023981	NA
R	0.99965	NA

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

$$t_r = \frac{1}{\dot{\varepsilon}_{co}\Omega} = 1914 hrs.$$

Case Study: Fire-side Specimen



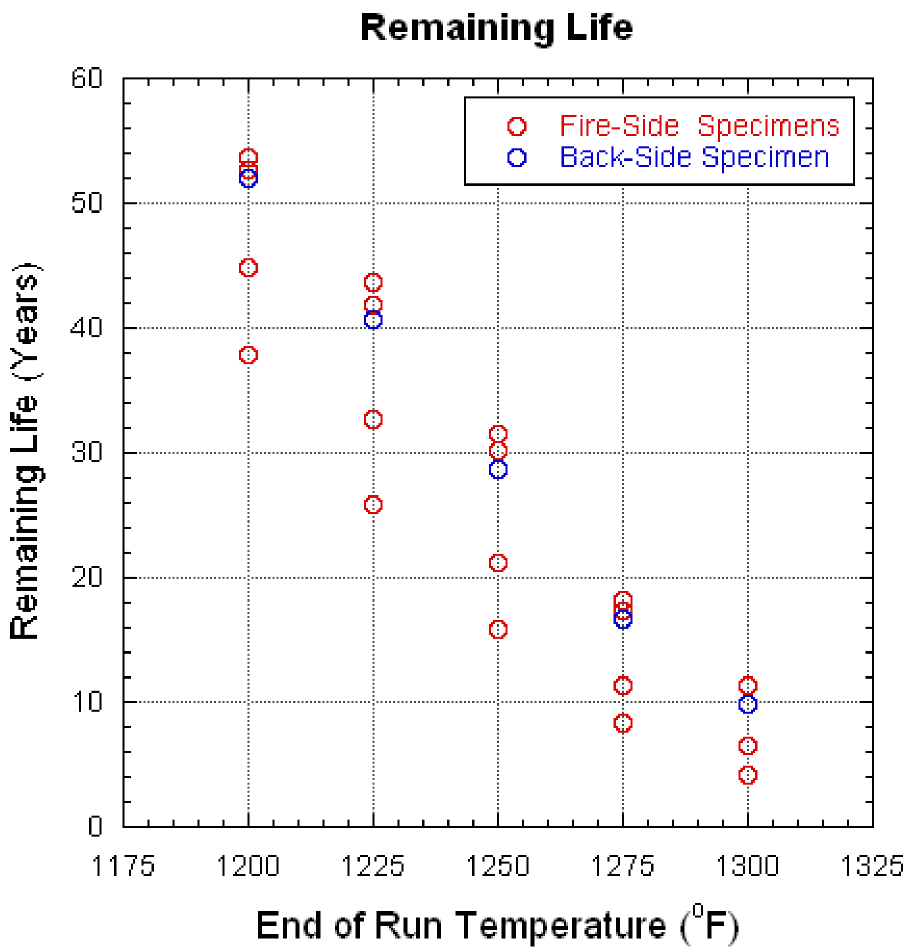


STRESS ENGINEERING SERVICES INC.

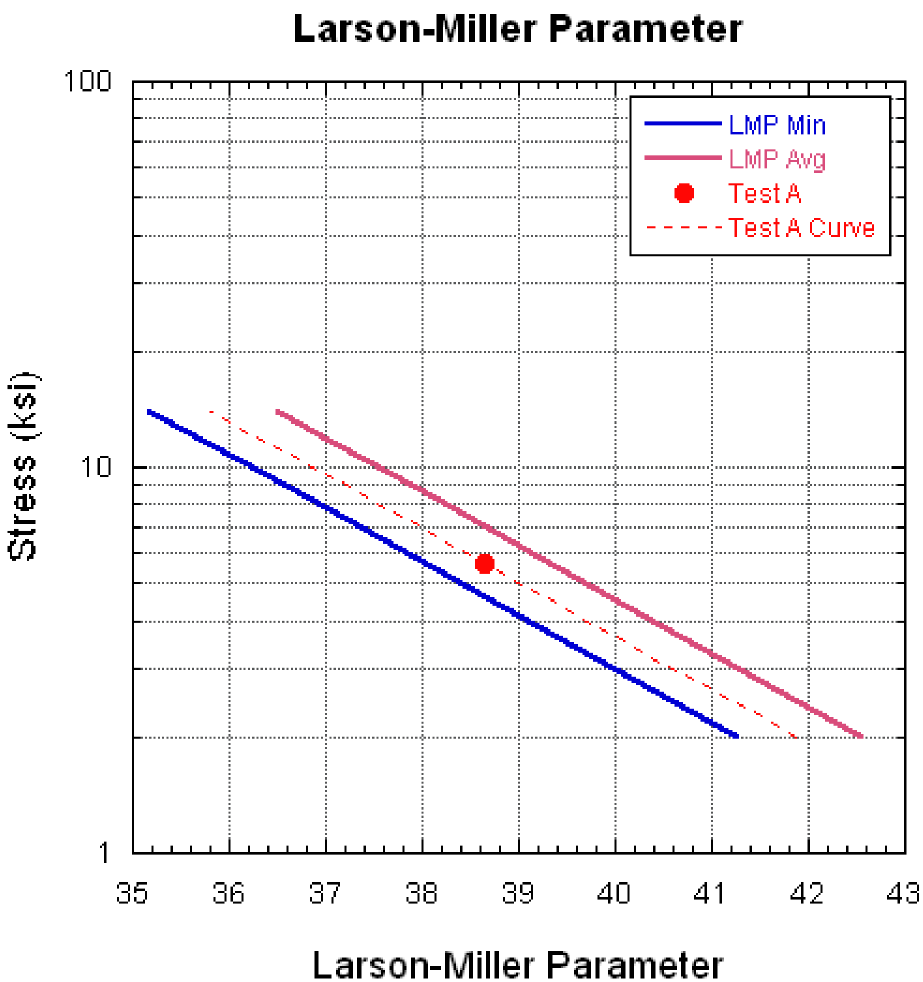
an employee-owned company

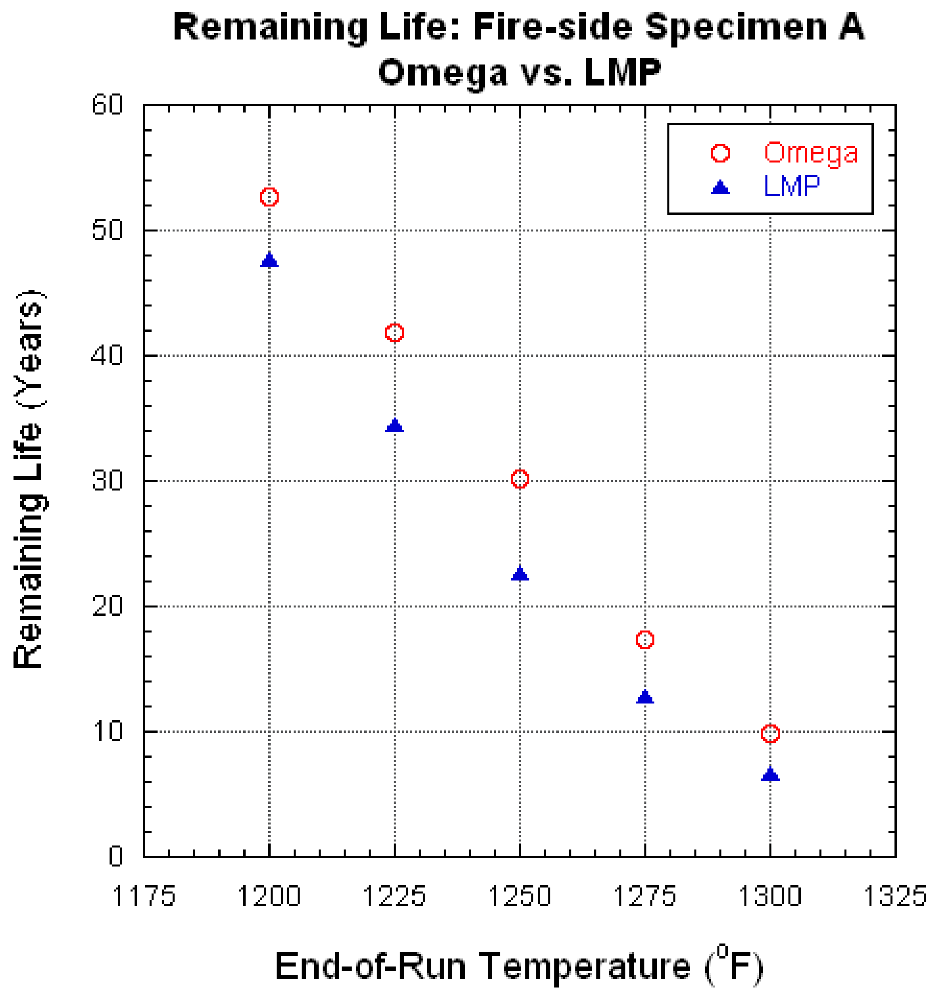
Case Study: Remaining Life

- 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



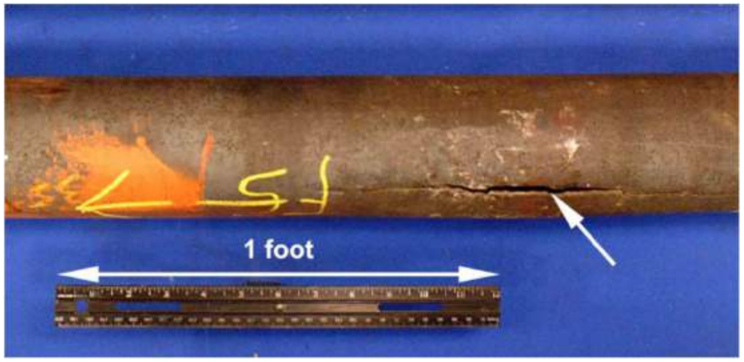


$$LMP = (T + 460)(20 + \log t_r) \times 10^{-3}$$

STRESS ENGINEERING SERVICES INC. an employee-owned company

Other Damage Mechanisms

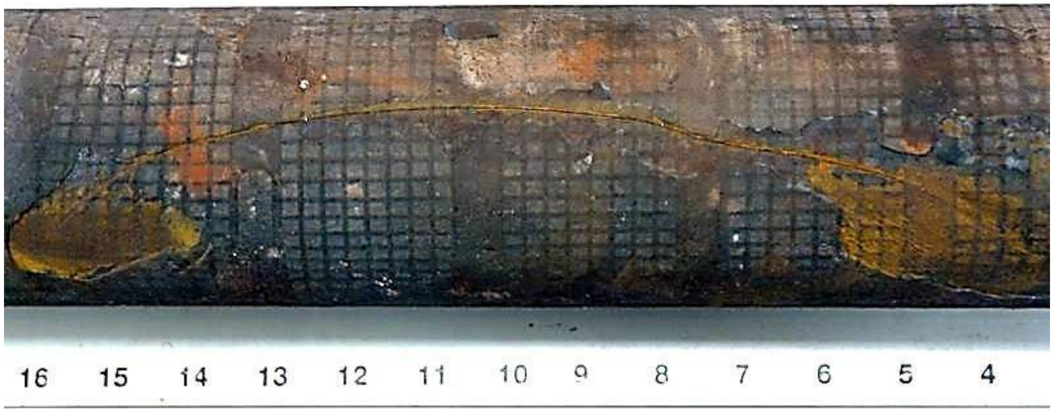
- Creep is not the only damage mechanism in coker heaters
  - Carburization
  - Sigma Phase (Stainless Steels)
  - External Oxidation
  - Sulfidic Corrosion
  - Brittle Fracture
  - Erosion



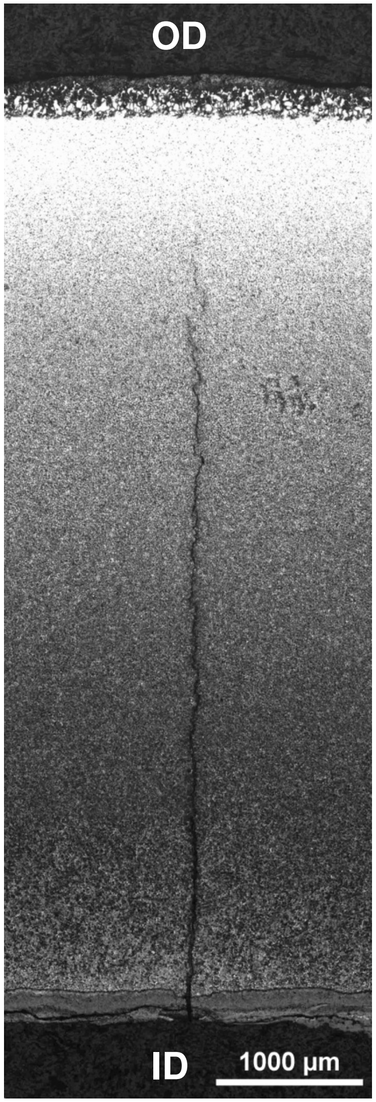
- Any of these damage mechanisms can lead to tube failures before creep life is consumed
  - Some might interact with creep, accelerating rupture

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

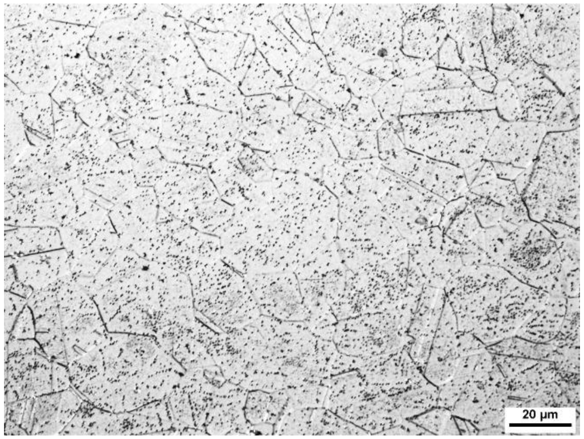


Brittle fracture in carburized 9Cr coker heater tube

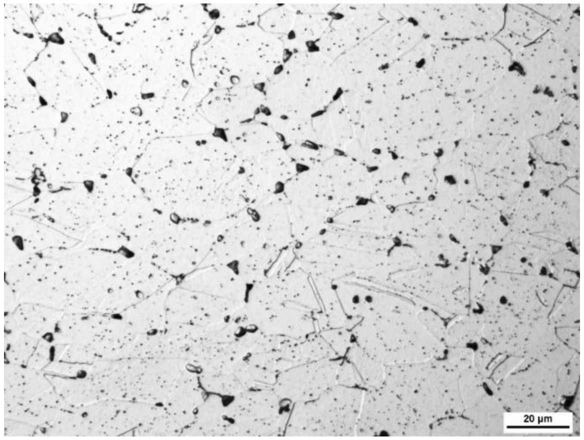


Sigma Phase Embrittlement

- 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



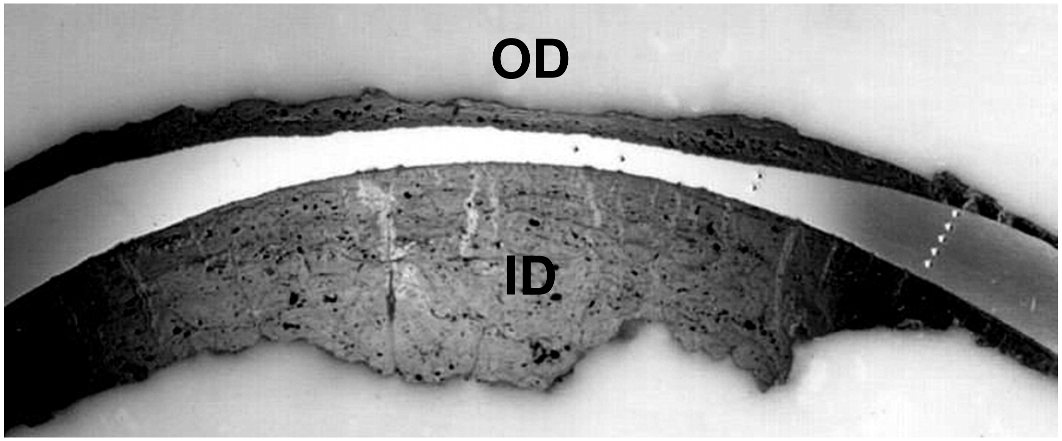
347H SS microstructure prior to exposure



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

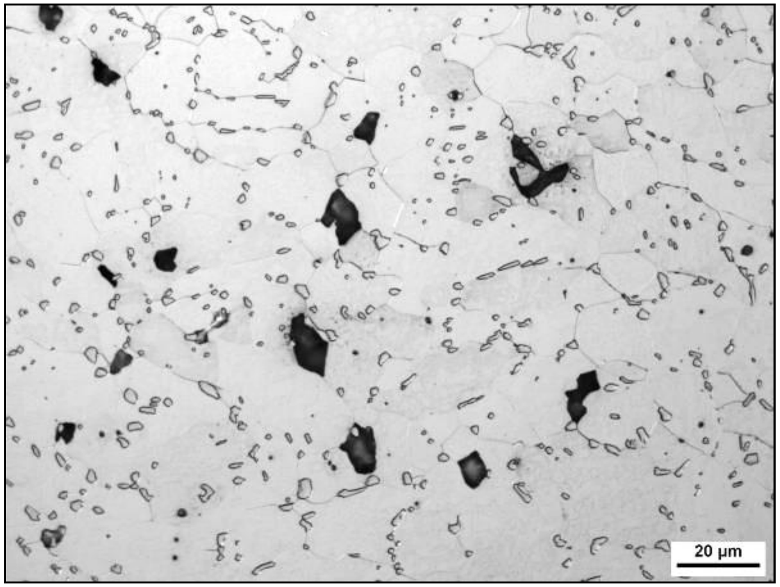
- Creep is becoming more and more relevant as heaters age and profit margins are pushing process limits
- Useful life can be prolonged with a combination of life assessment calculations and process changes
- Accelerated creep testing can be employed to shift the operating history of the tubes
- Other possible damage mechanisms must not be overlooked

Acknowledgments

- Antonio Seijas
  - Sr. Fixed Equipment Engineer, Phillips 66 - Refinery Business Improvement
- Mike Urzendowski
  - 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!