Reformer Tube Inspection
and
Remaining Life Assessment as per
API 579-1/ASME FFS-1

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Basics *Quick view on reformer heater tube operation*

Reformer tubes are used for cracking hydrocarbon (natural gas) to produce hydrogen and carbon dioxide either in presence of steam (called steam reformer) or in presence of oxygen (auto-thermal reforming).

Steam reforming reaction:

$CH_4 + H_2O \rightleftharpoons CO + 3\ H_2$ (700 – 1000°C)

Auto-thermal reforming reaction:

$2CH_4 + ½O_2 + CO_2 \rightarrow 4H_2 + 3CO + H_2O$ (900 – 1000°C)

Hydrogen generation is an endothermic reaction, takes place in presence of catalysts (nickel monoxide).

RLA *Reformer tube inspection*

- The reformer tube life is influenced by operating temperature
- It is experienced that 10 to 20°C overshoot can lower the tube life substantially.
- Reformer tubes are therefore one of the most focused inspection activities during the turnarounds.
- The increased demand for production requires higher flow rates. Shorter reaction time of cracking necessitates increased furnace temperature.

Primary reformer materials

- Reformer tubes (HPMA, G4852, KHR35CT, HP39W)
- Inlet header (P22, 321H, 347H)
- Inlet tube/pigtail/hairpin (P22, 321H, 347H)
- Outlet tube/pigtail/hairpin (800H)
- Hot outlet header (800H)
- Cold outlet header (Low alloy steel, P22, internal refractory lined)

EVOLVE by TCR

Reformer tube failures

- Failures due to creep rupture
- Short term overheating and bowing
- Thermal shocks
- Internal carburization and metal dusting
- Metallurgical degradations
- Design aspect and support system

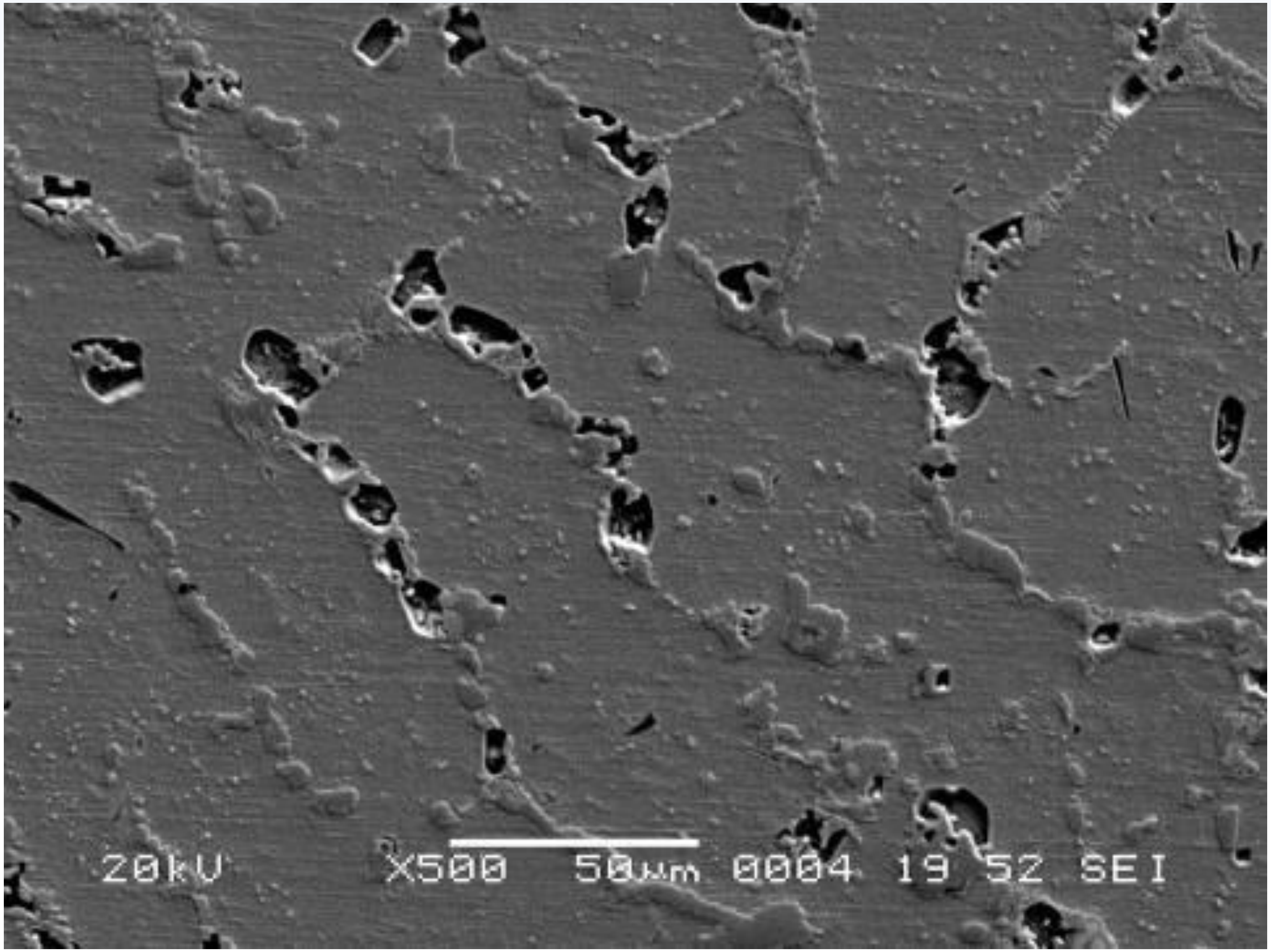
Creep (Elevated service temperature components)

Creep failures occur in hot-section components as a result of continuous exposure of high temperature and stress during operation.

Unacceptable dimensional changes, creep rupture and local failure by creep-crack growth constitute failures.

EVOLVE by TCR

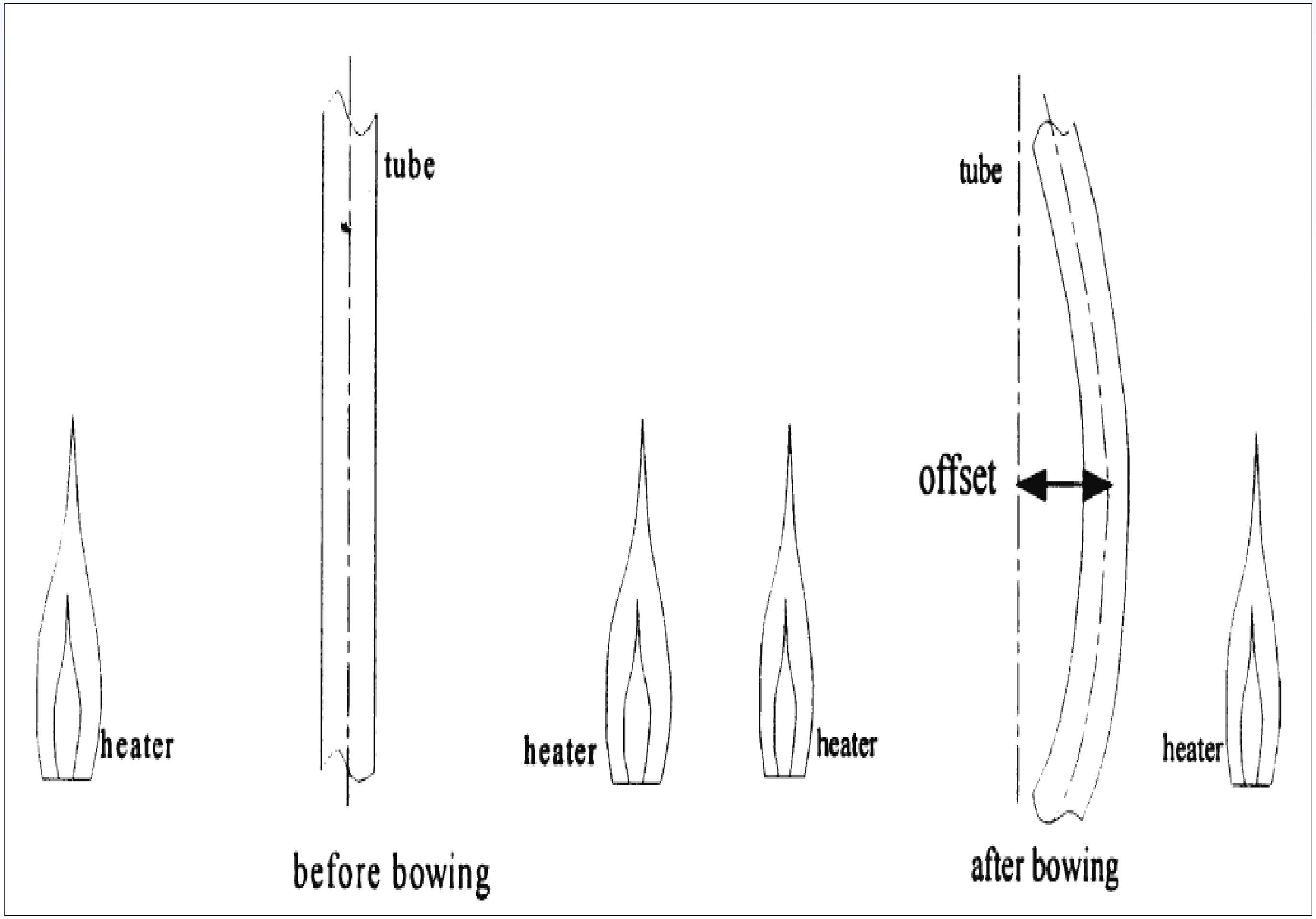
SEM creep damage



Bowing of reformer tube

- As the reformer furnace operation is taken at high temperature and pressure due to thermal expansion and contraction at elevated temperature and due to prolonged exposure to high temperature the microstructure of the material is subjected to degraded and bending or bowing of the tubes occur.

Bowing of reformer tube



Schematic drawing of bowing of reformer tube

Acceptable up to 1.5XOD as long as not wedging (OISD)

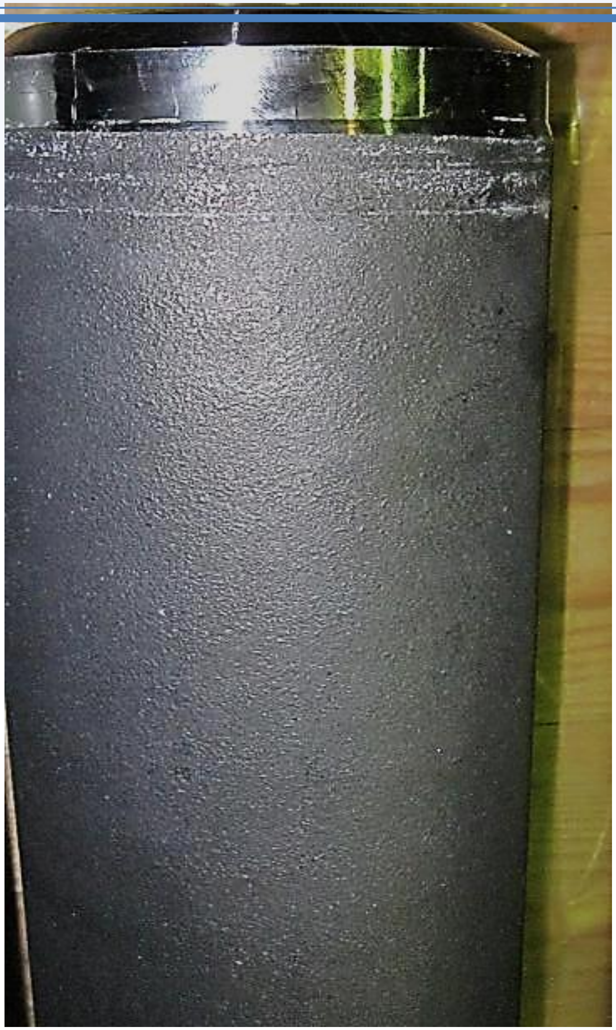
EVOLVE by TCR

Baldness in reformer tubes (Oxidation)

- Corrosion and oxidation resistance of most materials conventionally used in steam cracking industry relies on formation of a protective chromia (Cr_2O_3) layer.

- It is noticed that the scale formed on 25Cr-35Ni has a rapid initial growth rate , but at a certain point, intrinsic stresses causes the scale to spall off. New oxide is formed on the spalled areas, and chromium from the alloy is rapidly consumed.

Baldness in reformer tubes *Fuel / air ratio*



Comparison between two reformer tubes for showing baldness

Baldness: oxidation damage

- The carbides grow at the grain boundary with ageing.
- At the outer surface reacts with the oxygen in the furnace environment, when the Chromium depletes because of the grain boundary carbide precipitation, the oxides form on the outer surface of tube.
- Thus the oxidation at the outer surface led the Cr depletion region near outer surface.
- The variation of Cr concentration in the matrix from outer to the inner edge of the service expose tube is generally observed to be more at the outer surface.

EVOLVE by TCR

Internal carburization

- Internal carburization can be caused by process upset
- Severe carburization can lead to brittle failure

Internal carburization

- Internal carburization can be caused by process upset
  - Degradation of catalyst
  - Imbalance of Feed and steam
  - Upstream process upset
- Carburization extent: it is observed up to 50% of wall thickness (from ID side)
- Carburized layer is not sound wall, and hence does not bear the internal pressure
- Severe carburization can lead to brittle failure
  - Brittle fracture can occur during idling time essentially during pressure test, DP test for catalyst check
- Relative magnetic permeability measurements are helpful
- MOCs: Kubota developed AFTALLOY (Al and Si added proprietary grade)

Thermal shock

- Sudden change in temperature causes thermal shock that may result in abrupt, catastrophic failure of tubes.

Localized overheating

➤ *Direct flame impingement*:

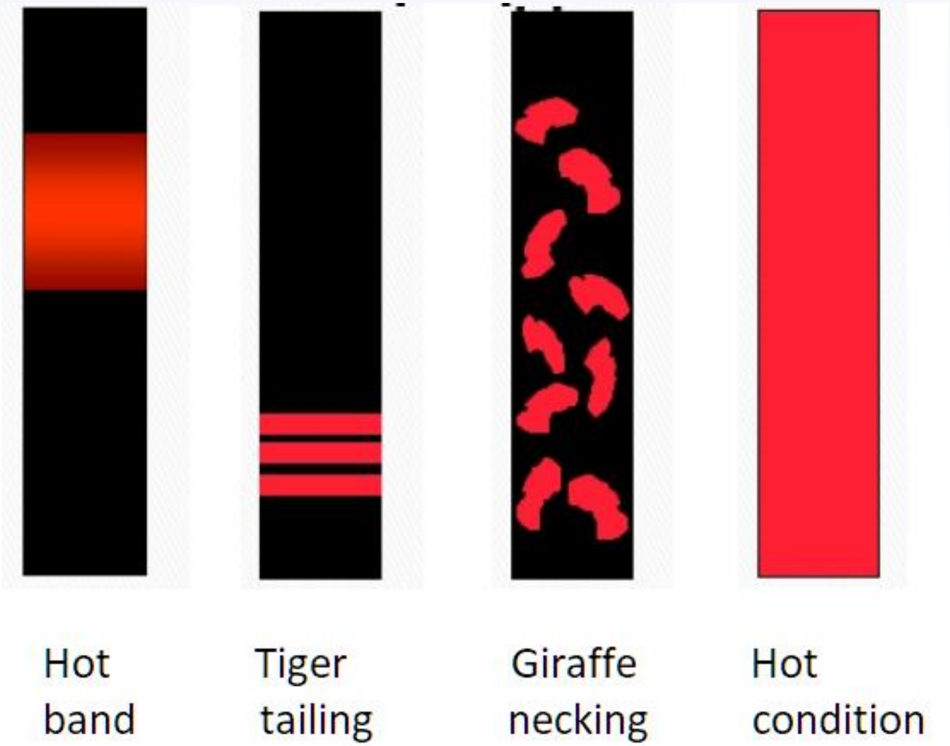
- Mis-alignment of burners and / or their clogging creating disturbance in flue gas path can lead to direct flame impingement to the tubes.
- As a result, tubes tend to damage locally by overheating.

EVOLVE by TR

Deteriorated catalyst

- *Overheating by choking of catalyst:*

- The nickel monoxide catalyst used in cracking of hydrocarbons is generally in pellet form.
- Due to ageing or increased flow rate, the catalysts undergo rubbing and relative movement of particles making them more friable.
- The fine particles settle down and choke the gas path such that a localized channel would get form and passage of gas gets completely resisted.



Metallurgical degradation

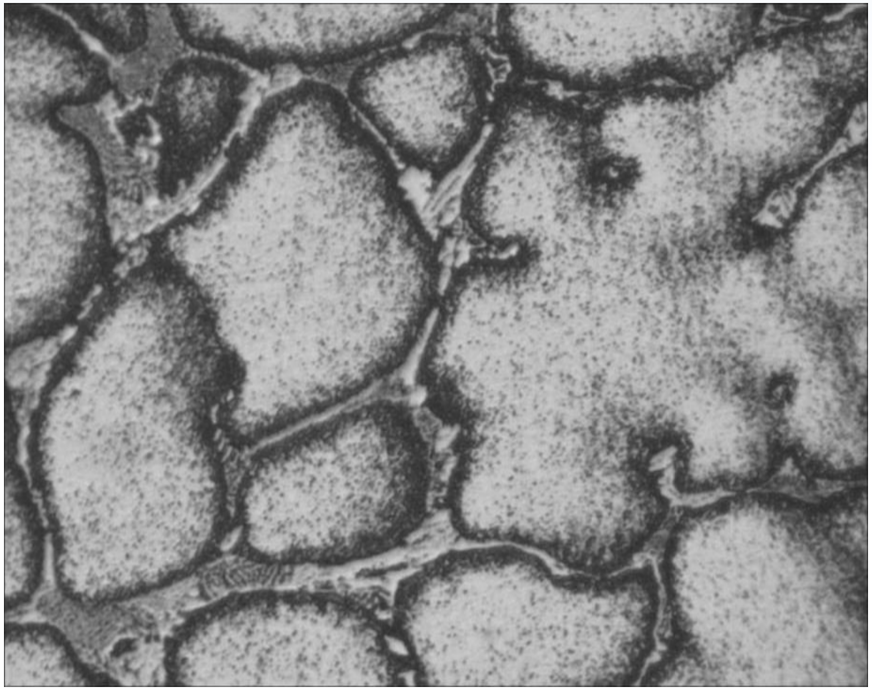
- The carbide coarsening mechanism is temperature and time dependent phenomena. Higher the temperature faster is the coarsening of carbides.

- For temperature exposure between 700-800°C, the primary carbides tend to get transformed from their eutectic morphology to compact blocks.

- Between 800-900°C the secondary carbides tend to coalesce and they get reduced in number due to carbon diffusion to the primary carbides.

- When the material is exposed between 900-1000°C the secondary carbides also tend to disappear over a Prolonged exposure and primary carbide appear blocky, continuous in nature as shown in Figure 1. This results in reduction in creep rupture strength

Metallurgical degradation



Formation of compact blocky carbides

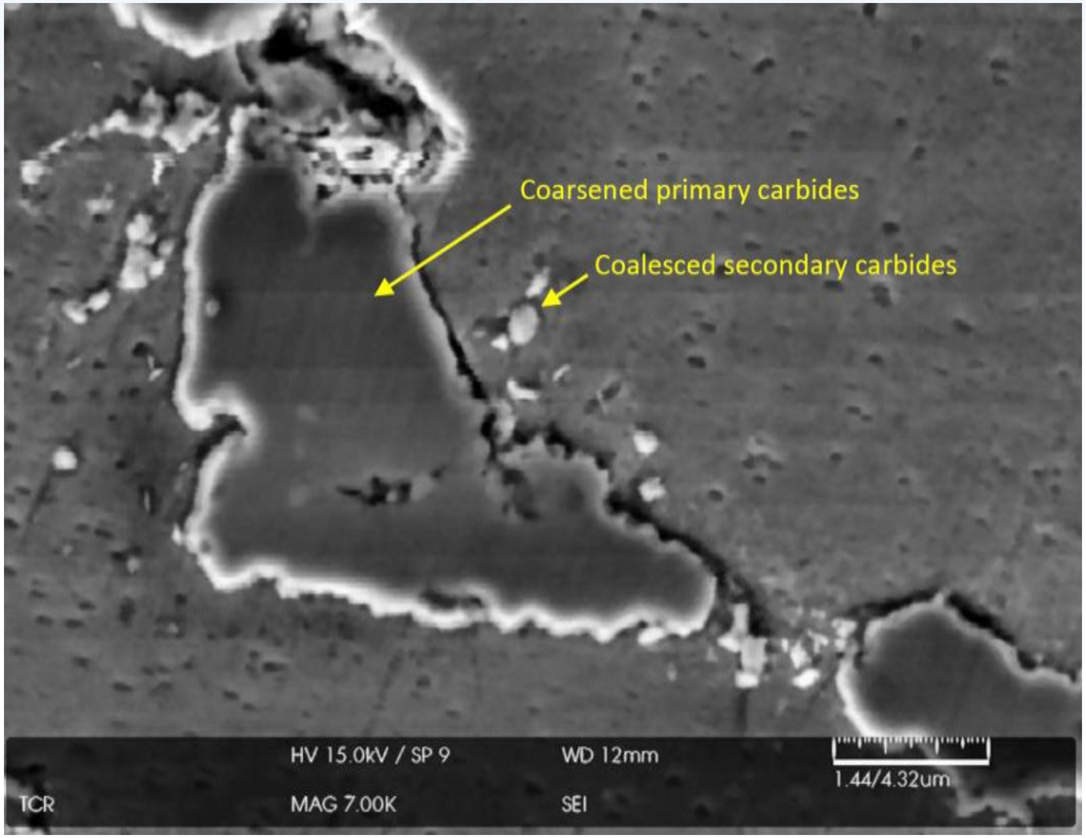
Secondary carbides

Primary carbides

With aging at 800°-900°C the secondary carbides tend to coalesce and they get reduced in number with diffusion to primary carbides.

EVOLVE by TCR

Metallurgical degradation



Scanning electron micrograph:

With aging at 800°-900°C the secondary carbides tend to coalesce and they get reduced in number with diffusion to primary carbides.

Remaining Life Assessment

RLA *What is Remaining Life Assessment*

The heater tubes are built with certain assumption on nominal design and reasonable life of operation, generally about one or two decades.

At end of this period tubes are either replaced or life is extended.

The tube replacement is generally planned when failure rate increases.

What is important is: DAMAGE MECHANISM causing failure.

RLA *Approaches*

A fairly accurate remaining (residual) life assessment can be performed for CREEP rupture failures through destructive tests. This include Accelerated Stress Rupture test.

Similarly, Non-destructive Test approach for RLA is also adopted based on metallurgical condition assessment of tube and correlating the CREEP strength to applied stress.

RLA *How is it derived*

RLA is an output of quantitative figure derived from:

- Estimate of accumulated tube damage (the life fraction used up) based on operating pressure, the tube metal temperature, and the corrosion rate and the exposed service life.
- Available knowledge of the actual rupture strength of a given tube, this is generally provided by the alloy manufacturer.
- In absence of parametric creep rupture data, accelerated stress rupture tests may be adopted.

RLA *Destructive test approach*

Part I

Laboratory analyses

RLA *Laboratory analyses*

- Dimensional measurement
- Macrostructural observation
- Microstructural observation
- Accelerated stress rupture test

RLA *Laboratory analyses*

Dimensional measurement

Thickness measurement

– outer surface oxidation rate

- Inner surface metal dusting (carburization)

Increase in outer diameter

Creep Curve: Basic Concepts

Creep properties are generally determined by means of a test in which a constant uniaxial load or stress is applied to the specimen and the resulting strain is recorded as a function of time.

EVOLVE by TCR

RLA *Laboratory analyses*

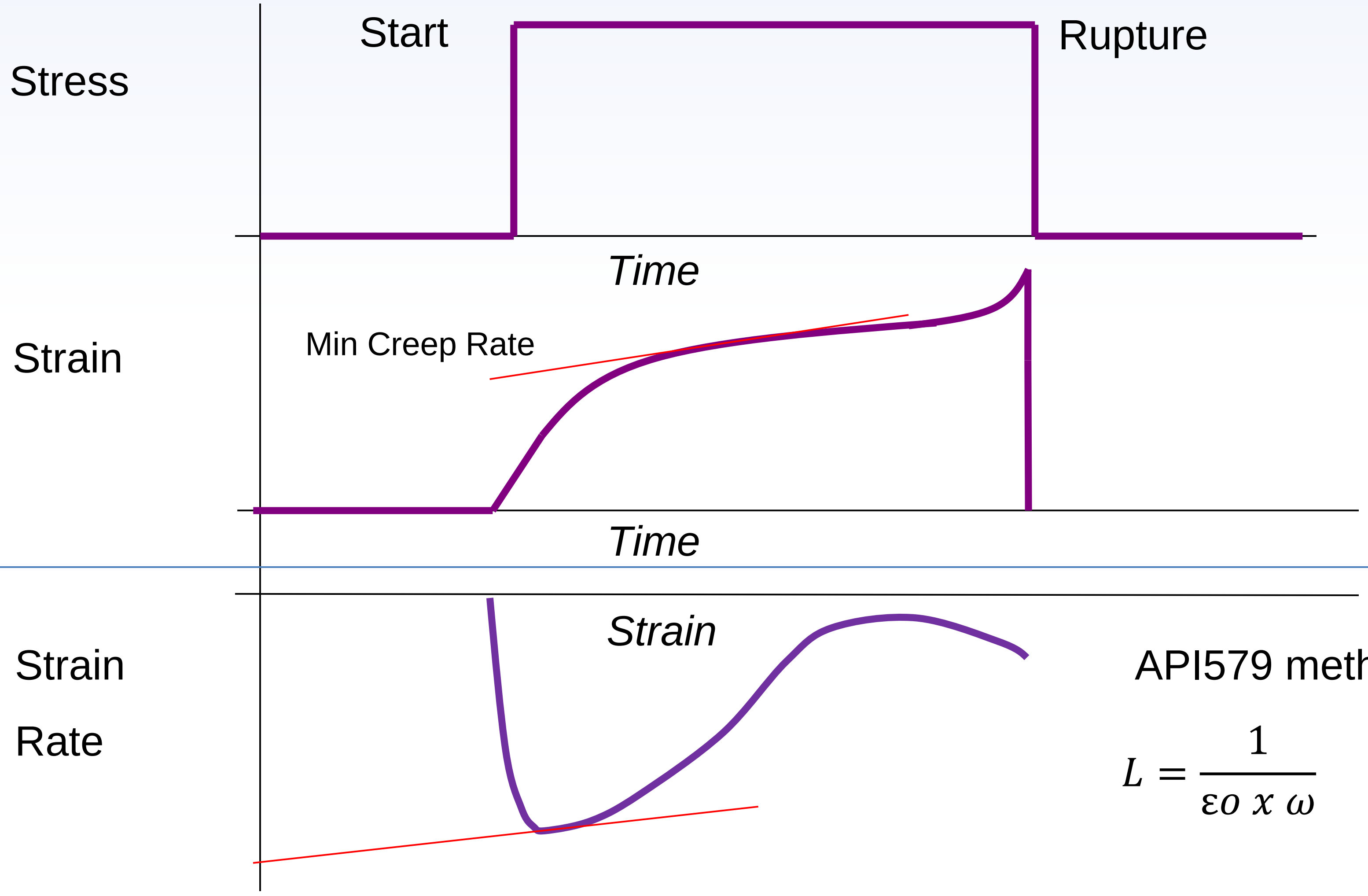
Accelerated stress rupture test

- Similar to tensile test preparation, specimens are prepared and subjected to tensile loading (constant load) at pre-selected elevated temperature.
- Generally 2 or 3 tests are performed at different temperatures and/or stress

Creep rupture test

- Usually a tensile bar
- Dead load applied
- Strain is plotted with time
- Test usually ends with rupture (failure)

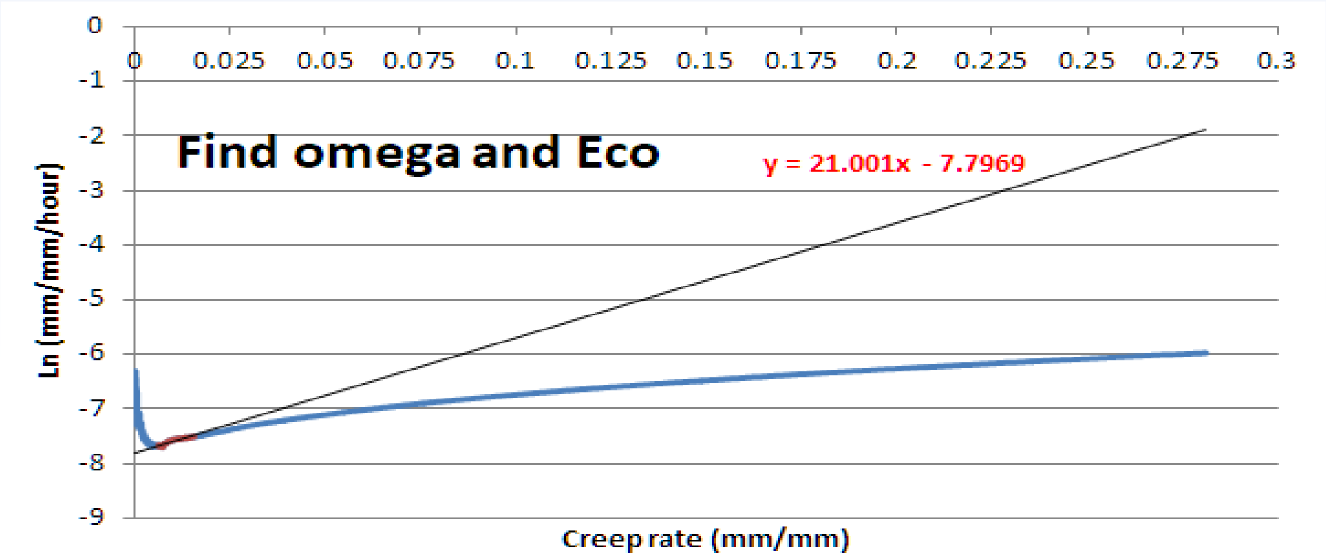
Creep curves

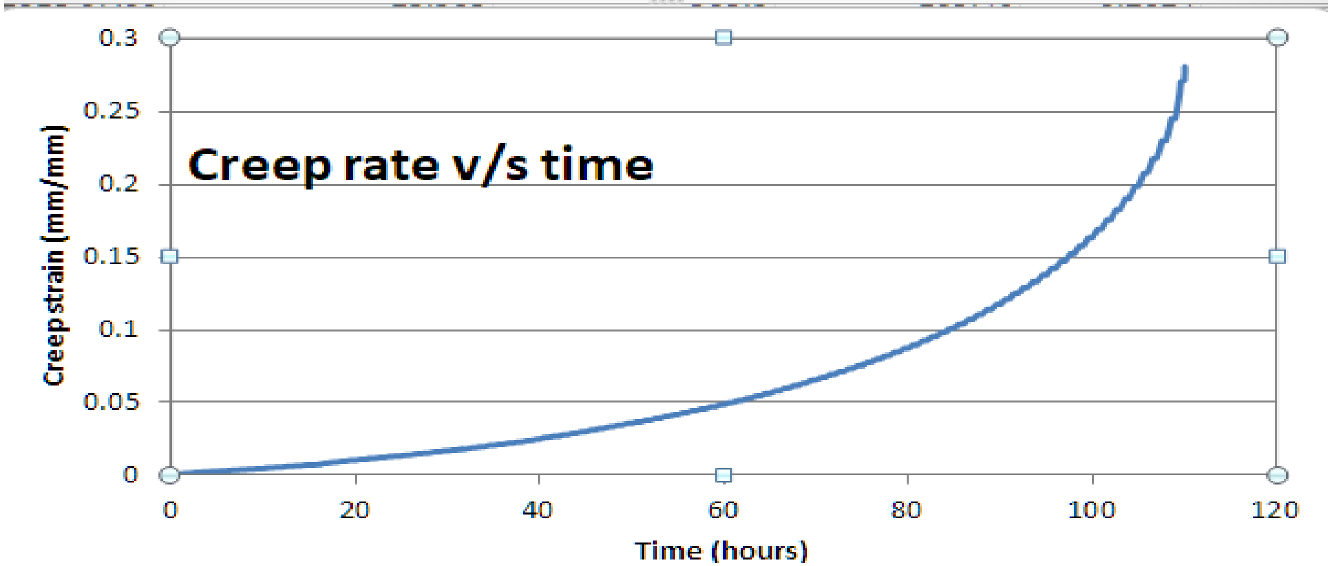


API579 method

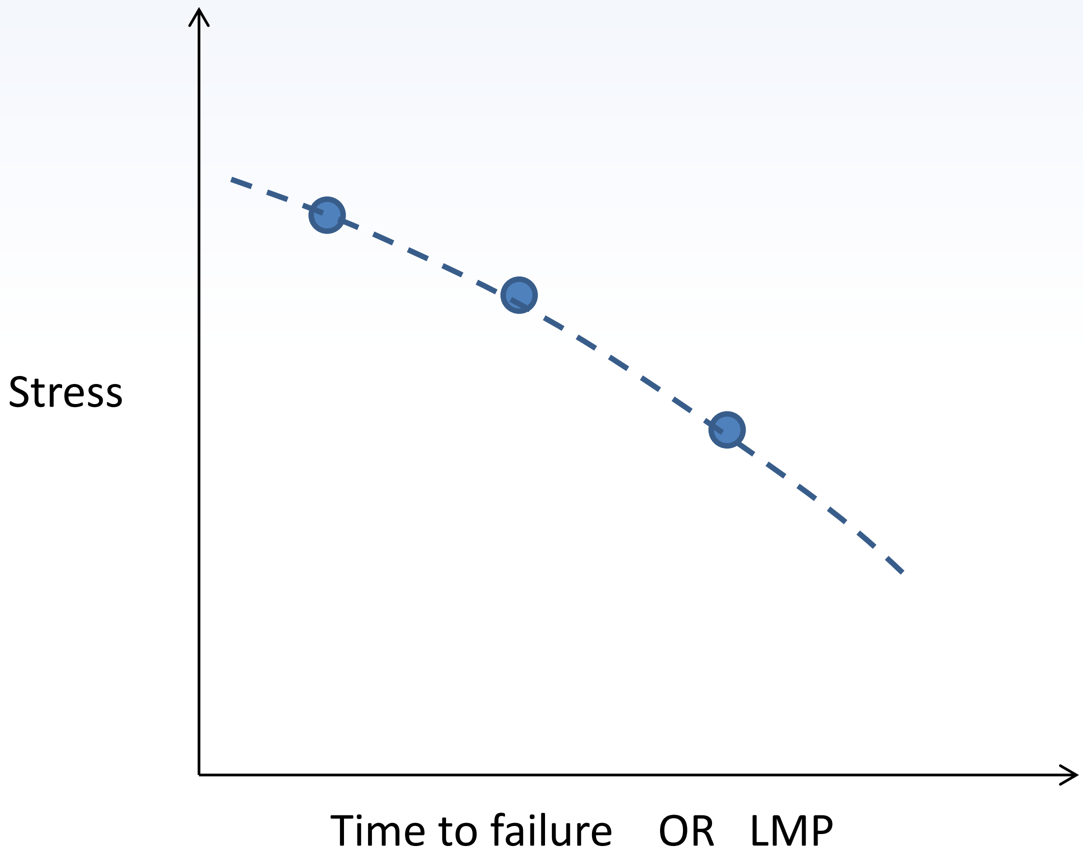
$$L = \frac{1}{\varepsilon o \ x \ \omega}$$

Mechanisms of Creep





RLA *Laboratory analyses: ASR*



Plotted when test temperature is constant

Plotted when test temperature is varied

As stress decreases, time to rupture increases

As temperature decreases, time to rupture increases

A fair degree of accuracy can be gained with lower stress values and higher test temperature regimes

RLA *Laboratory analyses*

Use of accelerated stress rupture test results

- Having multiple test results handy, prepare the stress v/s LMP curve.
- Interpolate the actual (operating) stress and determine LMP
- Determine the residual time by averaging the trend on tube metal temperature using LMP equation

$$LMP = (T + 273) \times (C + \log_{10} t)$$

where, LMP is determined from stress rupture curve, T is temperature in °C, t is the residual life in hours and 'C' is material constant – generally between 20 to 30.

RLA *NDT Approach*

Part II

Shutdown inspection on reformer heater tubes and remaining life assessment approach

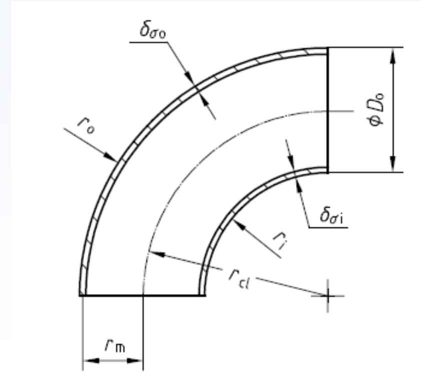
Present scenario of inspection

During turnarounds generally following activities are targeted:

- Maintenance of burners and their alignments
- Maintenance of refractory, hot gas manifold chambers
- Visual inspection of reformer tubes
- Scanning for detection of internal fissure in reformer tubes
- Outer diameter measurement of tubes
- Random dye penetration tests of inlet / outlet pigtail joints

Present scenario of inspection

General criteria for tube replacement:



$$\sigma_i = \frac{2r_{cl} - r_m}{2(r_{cl} - r_m)} \sigma$$

- Tube bowing condition
  - Stresses increase at intrados

- Visual appearance / marking of localized heating
- Ultrasonic attenuation, e.g. tubes exhibiting highest dB value or exceeding 64 to 70 dB
- Calculated creep strain based on outer diameter measurements, tubes exceeding 3% are generally prioritized

Present scenario of inspection

Still missing the outcome of inspection

- What is remaining life ?

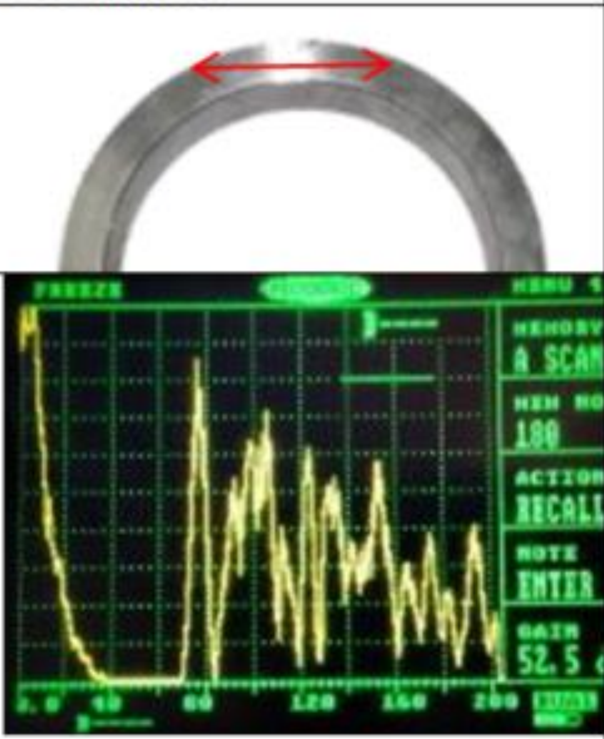
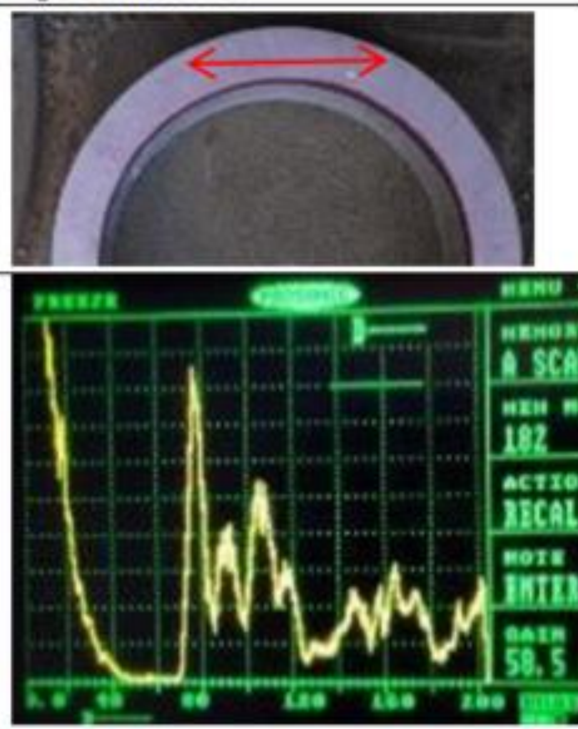
The answer lies to in-depth understanding of damage causing mechanisms, responsible to tube failure

Role of NDT to identify damages

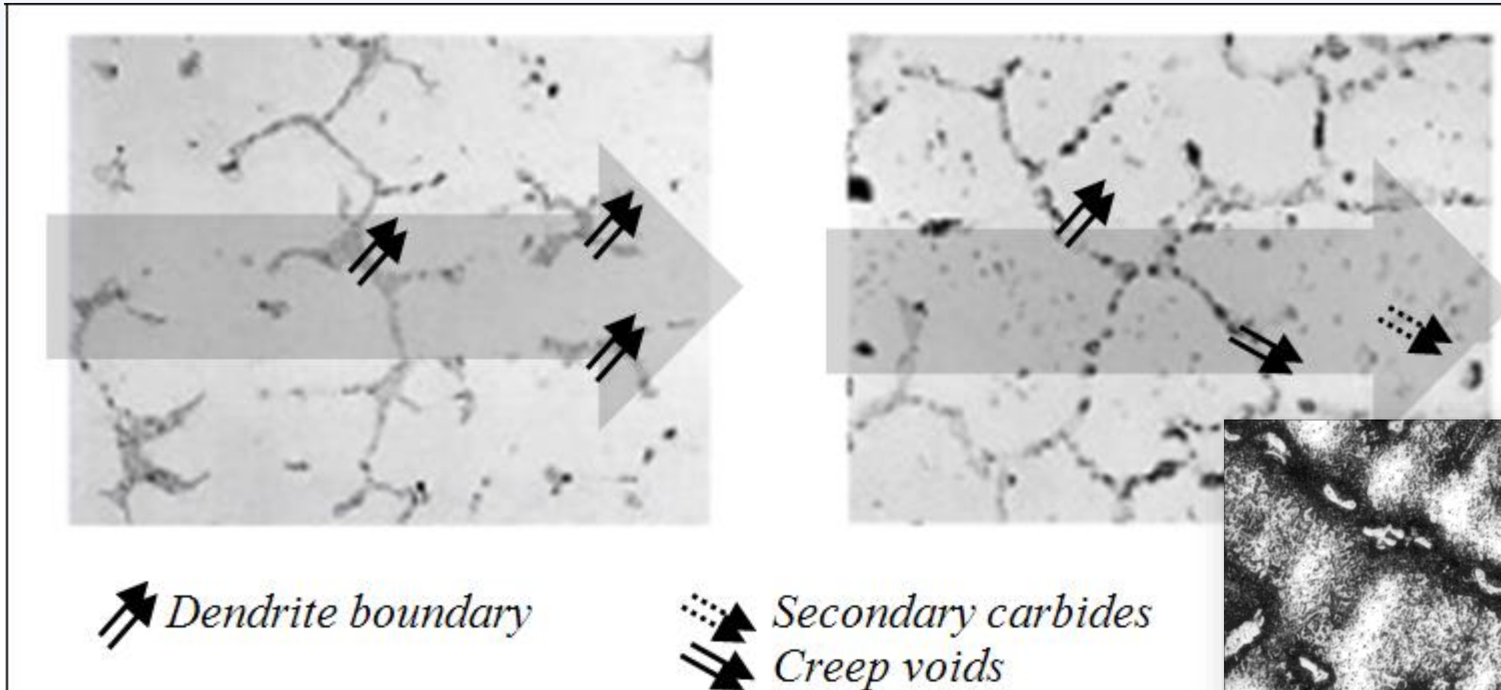
Damage mechanism	NDT method for detection	Information available
Creep damage	Diametric measurements	Often increased diameter by 3 to 6%.
	Ultrasonic scanning for attenuation measurements	Increased attenuation indicating presence of creep voids and / or creep fissures
	Eddy current testing	Detection of creep fissures at later stage.
	Metallography	Creep fissures and void at primary carbide chains, detected generally after 2nd stage damage, when surfaced out to OD
	Radiography	Direct film imaging can detect possible advanced stage of creep fissures
Localized overheating	Pyrometers / Thermovision in operation	Increased skin temperature either by flame / flue gas impingement or damage of catalysts leading to disturbed path of internal gases
	Metallography	Overheated structures around 1000°C for short duration would dissolve the secondary carbide precipitates.
Degradation of catalysts	Pyrometers / Thermovision in operation	Increased skin temperature
	Pressure gauges and on-line readings	Change in pressure between inlet and outlet gases would reflect disturbance of flow and damage of catalysts
External tube oxidation	Visual inspection	By touch and feel, smoothening of surface texture reflects external oxidation
	Thickness measurements	Reduced wall thickness.
Thermal fatigue	Visual inspection and ARTIS	Typical bowing of tubes reflect disturbance in thermo-mechanical stress distribution
	Spring tension / counter weight balance readings at penthouse area	Indicates disturbance in thermo-mechanical stress distribution

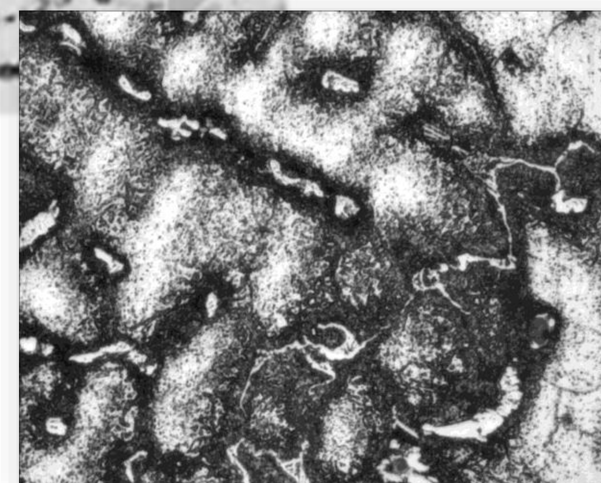
Creep detection by UT

Detection of creep fissures: typical attenuation comparison

Echo response comparison		
New material	*Aged material*	*Material with midwall fissures*
		

Creep detection by UT: Effect of carbides

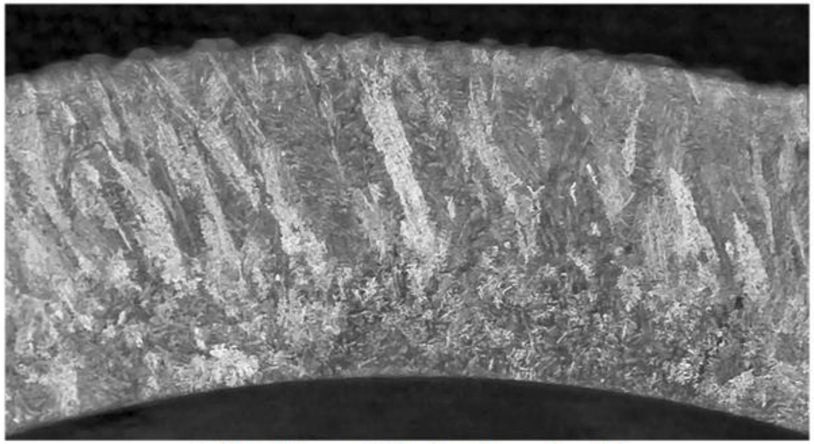




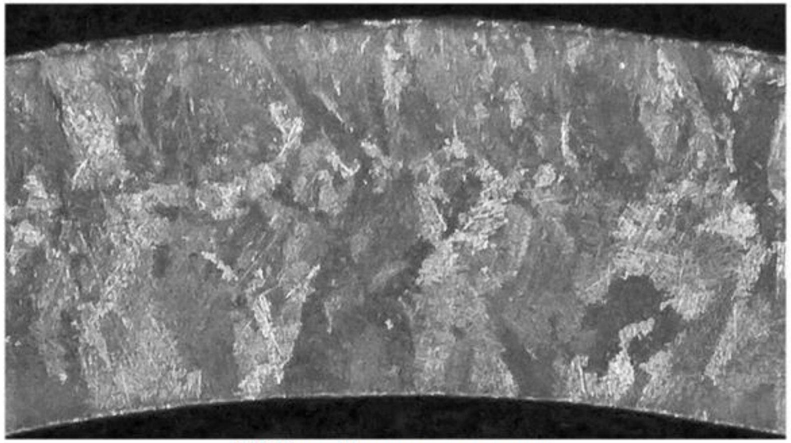
TR Mode ultrasound wave attenuates by:

- Scattering at dendrite boundaries
- Secondary precipitates
- From creep damage, seen as formation of voids
- From interlinked voids (fissures) at mid-wall

Creep detection by UT: Effect of macro-structure



Columnar at OD, Equiaxed at ID

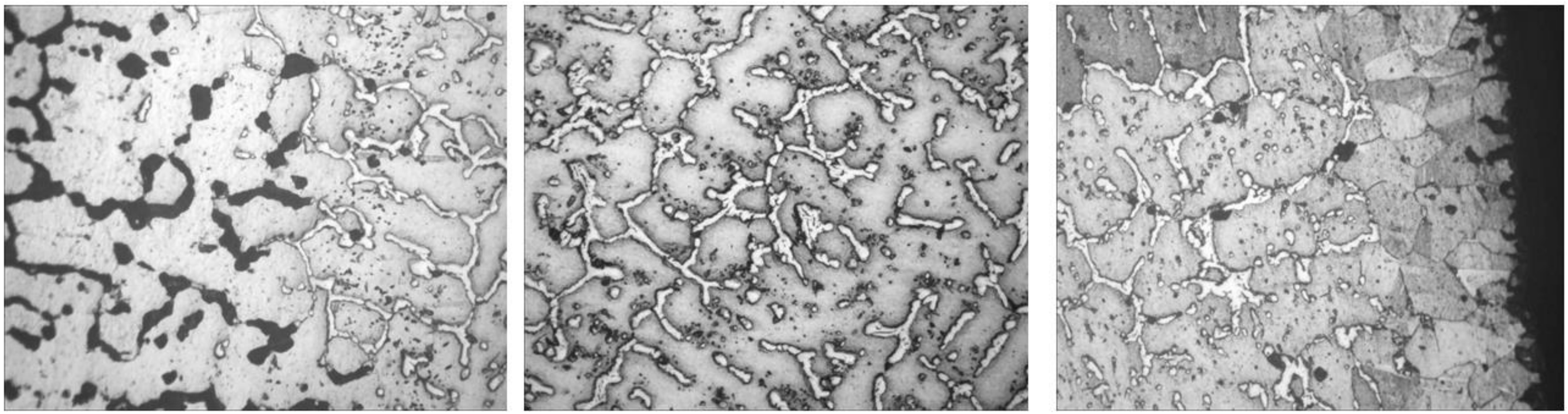


Fully columnar structure

TR Mode ultrasound wave attenuation also differs with

- Fully columnar grain to Equiaxed and Columnar macrostructures

Creep detection by UT: Effect of carbides

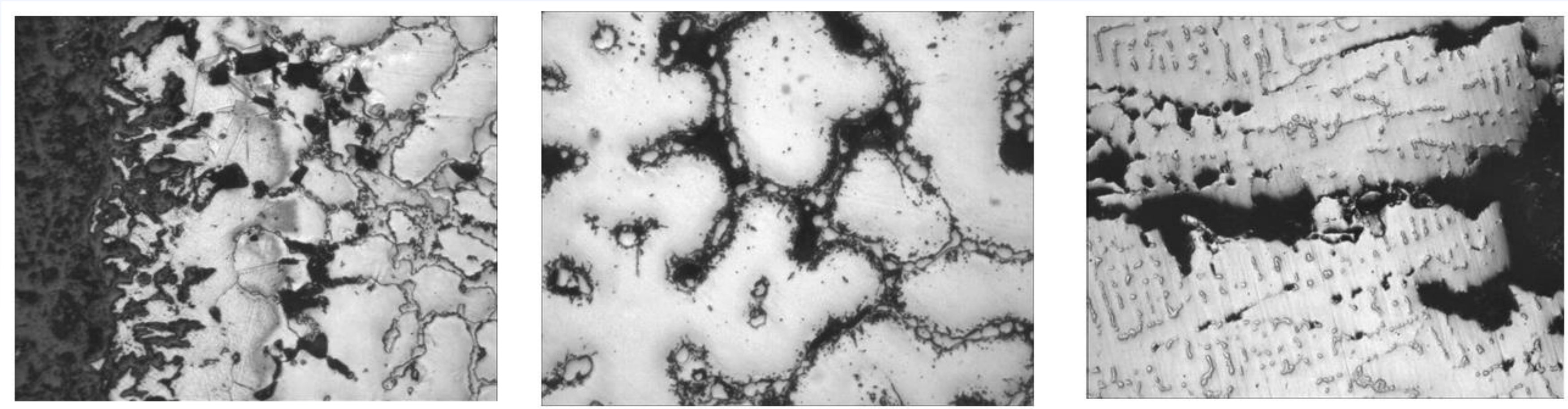


Alloy:KHR35CT, 100X, service exposed material (125000h),

Observation: creep voids are along primary carbide. Isolated creep cavities are at core along with tendency for carbide coarsening.

Sound attenuation measured is 60 to 64 dB

Creep detection by UT: Effect of carbides

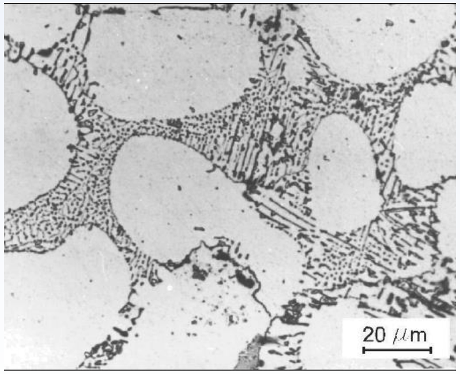


Alloy HK40, Service exposed 29 years,

Primary carbides at dendritic grain boundaries. Outer and inner edges show oxidation cracking. Aligned cavities are observed along primary carbide at core. The secondary carbides are nearly absent within the grains.

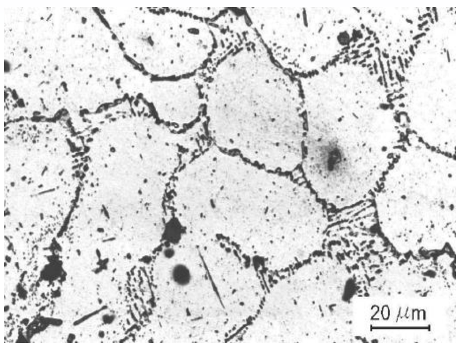
Sound attenuation measured is 56 to 62 dB

Microstructural degradation v/s Ultrasound attenuation



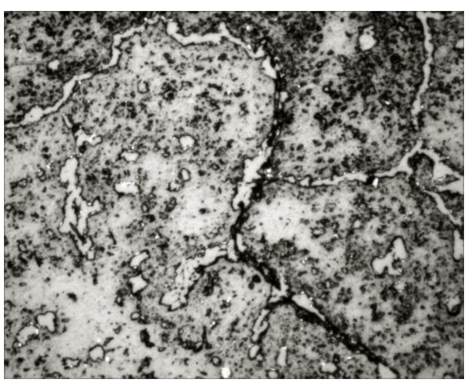
The microstructure of unused IN519 tubes is shown in Figure left, having dendritic columnar austenite grains oriented perpendicularly to tube walls.

Attenuation level: 35 – 55 dB



Upon aging, the structure degrades. The original morphology of eutectic carbides gets modified after exposure at elevated temperatures.

Attenuation level: 55 – 62 dB



At life fraction near to 80 - 95%, the microstructure is coarsened secondary carbides with presence of inter dendritic micro fissures.

Attenuation level: 62 – 72 dB

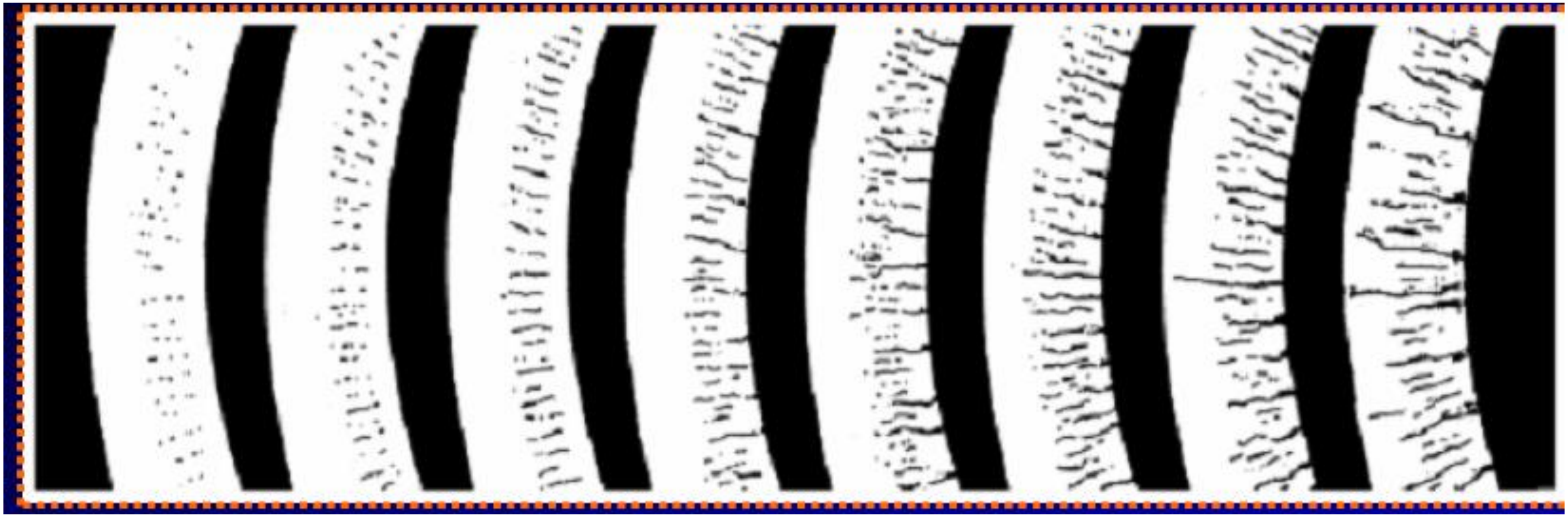
Severity Classification (Statistics based on general Reformer Tube grade material)

Class - 1	Class - 2	Class - 3	Class - 4	Class - 5
Sound Metal (in as cast condition)	Creep Voids Micro Fissures Inner Wall	Aligned voids & fissures between ID & mid-wall	Voids & creep Fissures mid-wall to OD, greater	Macro cracking with > 75% through wall thickness
No Damage	Slight Damage	Moderate Damage	Severe Damage	Critical Replacement needed
-	After 40% Life.	After 55% Life	After 75% Life	After 100% Life
Class - 1	Class - 2	Class - 3	Class - 4	Class - 5

EVOLVE by TCR

Progressive creep cracking (Reformer tubes)

Creep damage initiates from mid-wall
Balance between temperature gradient and internal working pressure



ARTiS model for integrated approach

Test	Index (higher is worse)			
	0 (least aged)	1	2	3 (most aged)
General visual examination	Good condition with no significant abnormality.	Apparent change in weld or apparent offset or abnormal coloration	Apparent localized bulging or shiny surface	Presence of crack, bulged with craze pattern
Visual baldness	Good surface roughness	Smooth surface texture on touch and feel	-	-
Bowing of tubes	< 0.1X of tube diameter	Up to 0.5X of tube diameter	Up to 0.8X of tube diameter	Up to 1X tube diameter
Ultrasonic attenuation*	Up to 50 db	Up to 58 db	Up to 70 db	> 70 db
Creep strain	< 2%	2 to 3 %	3 to 5 %	> 5%
Microstructural condition	Microstructure without any significant grain coarsening	Dilation of secondary carbides towards grain boundary with coarsening of primary grain boundary carbides	Presence of isolated or oriented creep voids preferably normal to principle stress direction	Presence of interconnected, parallel micro cracks normal to principle stress direction
Overall index	Sum of individual indexing			

Automated Reformer Tube Inspection System (ARTiS)

ARTiS is abbreviated to Automated Reformer Tube Inspection System.

This is a robotic crawler to aid ultrasonic testing of reformer tubes in a more systematic manner and provide tabular and interactive digital output.

The method follows same principle of manual scanning.
While crawling it measures:

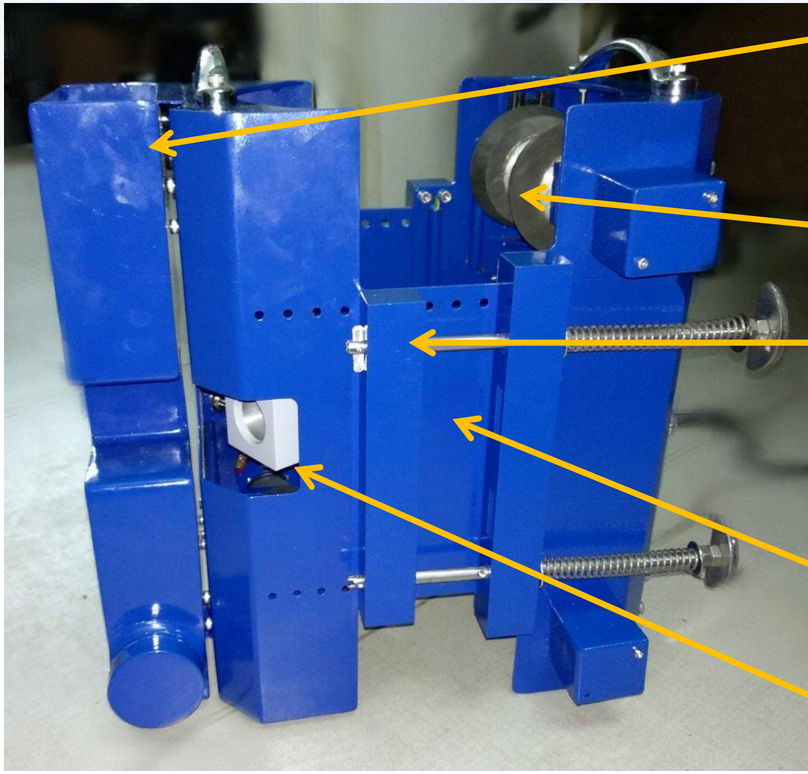
- Ultrasonic creep fissure detection
- Outer diameter of tube
- Tube bowing assessment

The outcome of inspection is more systematic and traceable throughout the tube height.

Automated Reformer Tube Inspection System (ARTiS)

Comparison	Manual method	ARTiS
Requirement of scaffolding	Needed	Not needed
Cost of scaffolding	At actual	Nil
Time required for erection and removal of scaffolding	1 to 2 days	Nil
Requirement of D.M. water	Continuous	Limited
Spillage and wetting of surrounding during test	Uncontrolled	Nil
Time of test (3 persons team)	3 to 5 days for 100 tubes	2 to 3 days for 100 tubes
Resolution of test result	1.5 - 2.0 meters	0.1 meter
Outer diameter measurement	One or two locations manually	Every 0.1 meter
Tube bowing	Qualitative judgment or by plumb measurement, additional time	Quantitative measure during UT scan
Safety consideration	Higher risk (elevated work area)	Lower risk (platform area)
Reporting	Manual data entry	Software based with statistical data analysis

Crawler components



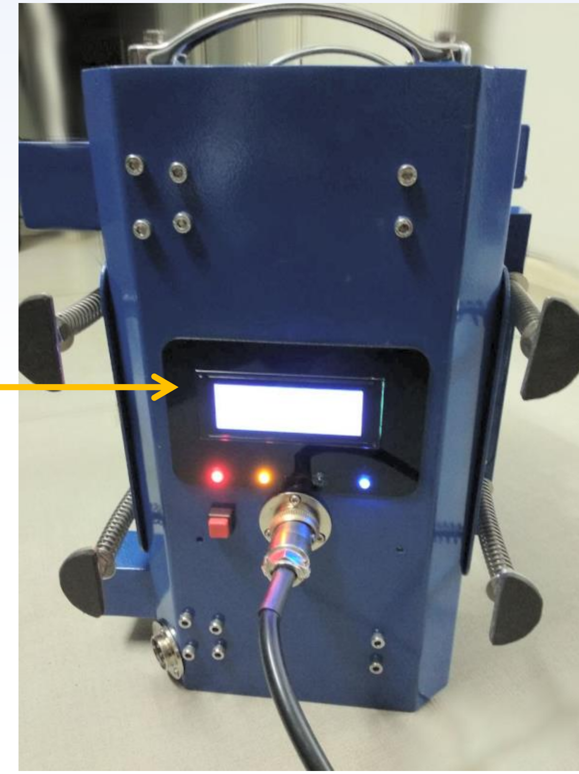
Water tank with pump

Drive

OD measurement

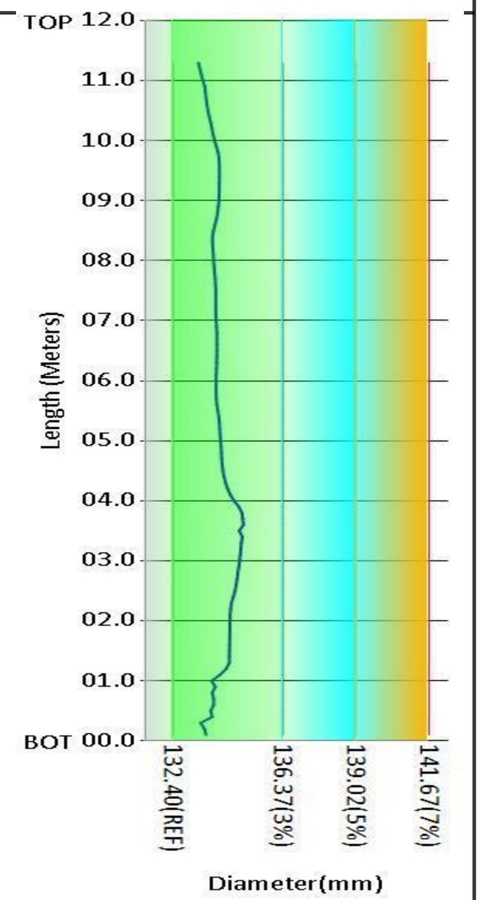
Adjustable arm

UT Probes



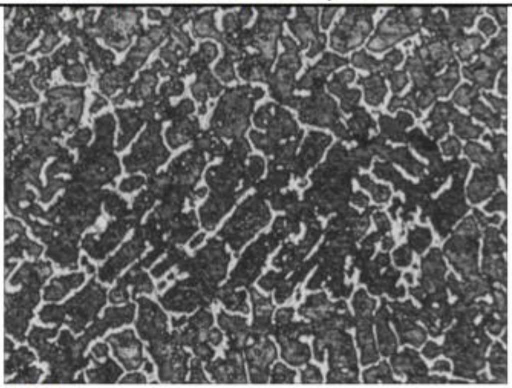
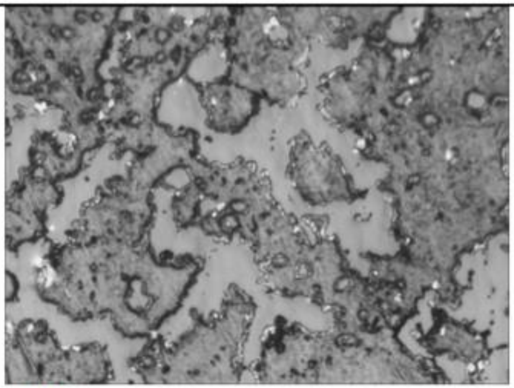
Automated Reformer Tube Inspection System (ARTiS)

Tube number: Row 1 - Tube 5				
Distance From Top	Measured OD	Creep %	Avg dB	TMT °C
01 - 02 M	132.18	1.674	56.643	901.3
02 - 03 M	132.35	1.809	57.571	901.5
03 - 04 M	132.40	1.849	58.643	901.8
04 - 05 M	132.55	1.963	58.357	902.6
05 - 06 M	132.55	1.965	57.357	902.6
06 - 07 M	132.53	1.945	57.000	902.4
07 - 08 M	132.62	2.018	57.000	903.0
08 - 09 M	132.44	1.877	56.929	902.0
09 - 10 M	132.22	1.705	56.500	901.5
10 - 11 M	132.17	1.668	56.429	901.2
11 - 12 M	132.27	1.746	56.000	901.8
12 - 13 M	132.14	1.646	56.000	901.0



Sample Data

Automated Reformer Tube Inspection System (ARTiS)

Average Attenuation(db)	53.8	
Attenuation category	Grade II	
Bowing (mm)	13.2	
Thickness (mm)	13.50	
Permeability (µ)	01.62	
DP Test	No relevant discontinuity found.	
Microstructure	 100X	 400X
comments	Microstructure shows network of primary and secondary precipitates including carbides in the matrix of austenite in a cast structure. The primary and secondary precipitates have coarsened.	
Measured hardness (BHN)	161, 163, 164	
Accumulated damage %	06.80	
Level 1 assessment	Passes up to current operating life Passes up to next 4 years of service life	
Nomenclature(RefOD): Measured average diameter at first 1 meter on top of tube (Measured OD): Average outer diameter measured for segment (Creep %): Increase in diameter when compared to nominal outer diameter (Avg db): Average ultrasonic attenuation value for segment (TMT): Effective tube metal temperature calculated that would cause current damage level		

Automated Reformer Tube Inspection System (ARTiS)

What if Level 1 criteria are not satisfied?

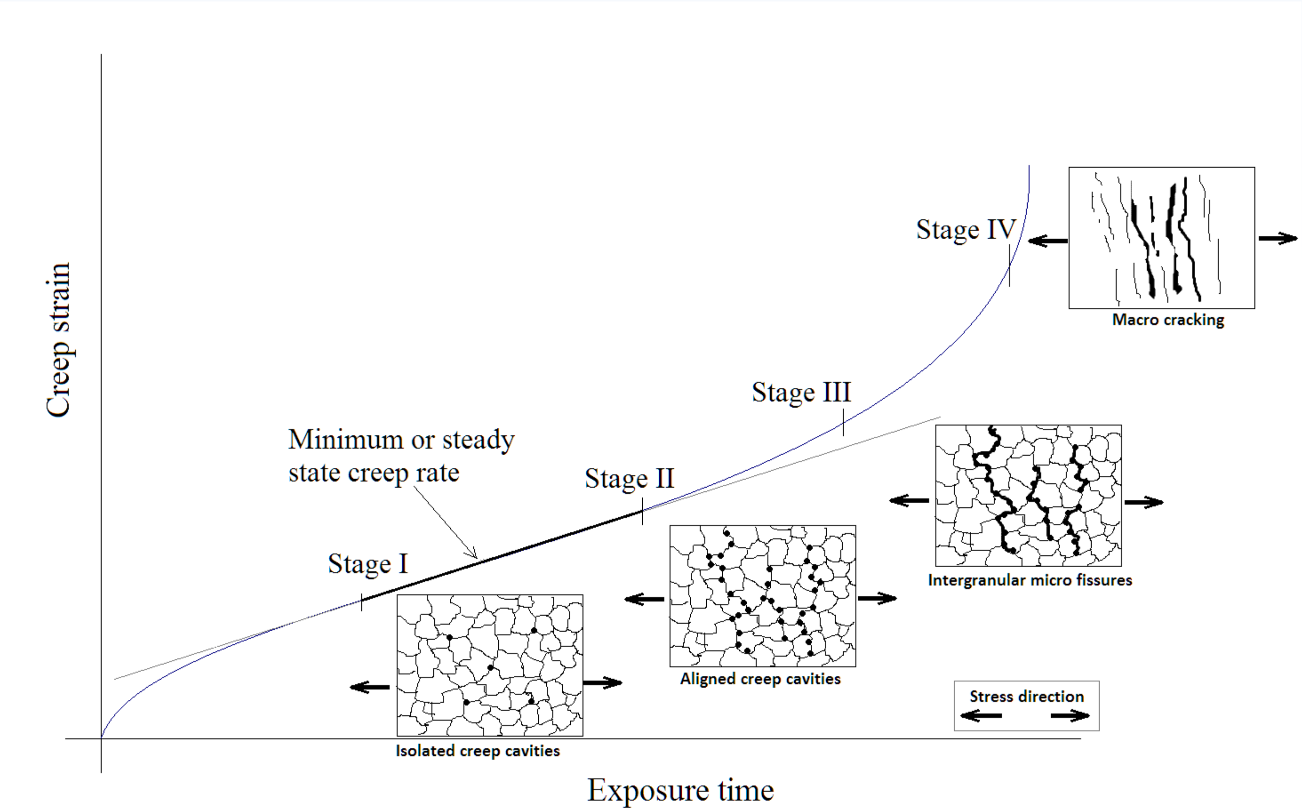
Level 3 assessments require determination of remaining life based on the inspection results used for the Level 1 assessment. The assessment approach is based on the calculation of accumulated creep strain till the date of operation. For the evaluation, operating parameters are to be obtained from time to time since the commissioning till the date of assessment.

These data include original dimensions of the tubes, the start of run and end of run temperatures for each time interval. The start and end of run conditions for each of the time intervals long with measured tube metal temperatures during operation and pressure variations becomes the input parameters for life assessment calculations. The changes / variation in pressure and tube metal temperature are generally associated with catalyst changeovers. All these data are difficult to obtain and often not traceable.

On certain reformer designs, the tube metal temperatures for all of the tubes are not feasible to measure which is the major influencing factor for creep life. It is therefore, necessary to calculate that effective tube metal temperature for individual tube is to be used for future life calculations. The effective tube metal temperature is defined as the temperature that caused the present level of creep damage to the tubes in terms of creep strain (i.e. increase in diameter) accommodating all occasional changes in tube skin temperatures as well as thermal cycling.

The creep strain used for calculations is necessarily a steady state creep rate of increase (i.e. stage II as shown in the creep curve >> *Next slide*.)

Automated Reformer Tube Inspection System (ARTiS)



The creep strain to be used in calculations is necessarily a steady state creep rate.

Automated Reformer Tube Inspection System (ARTiS)

(T+273) = P / [20 – Log (creep rate)]

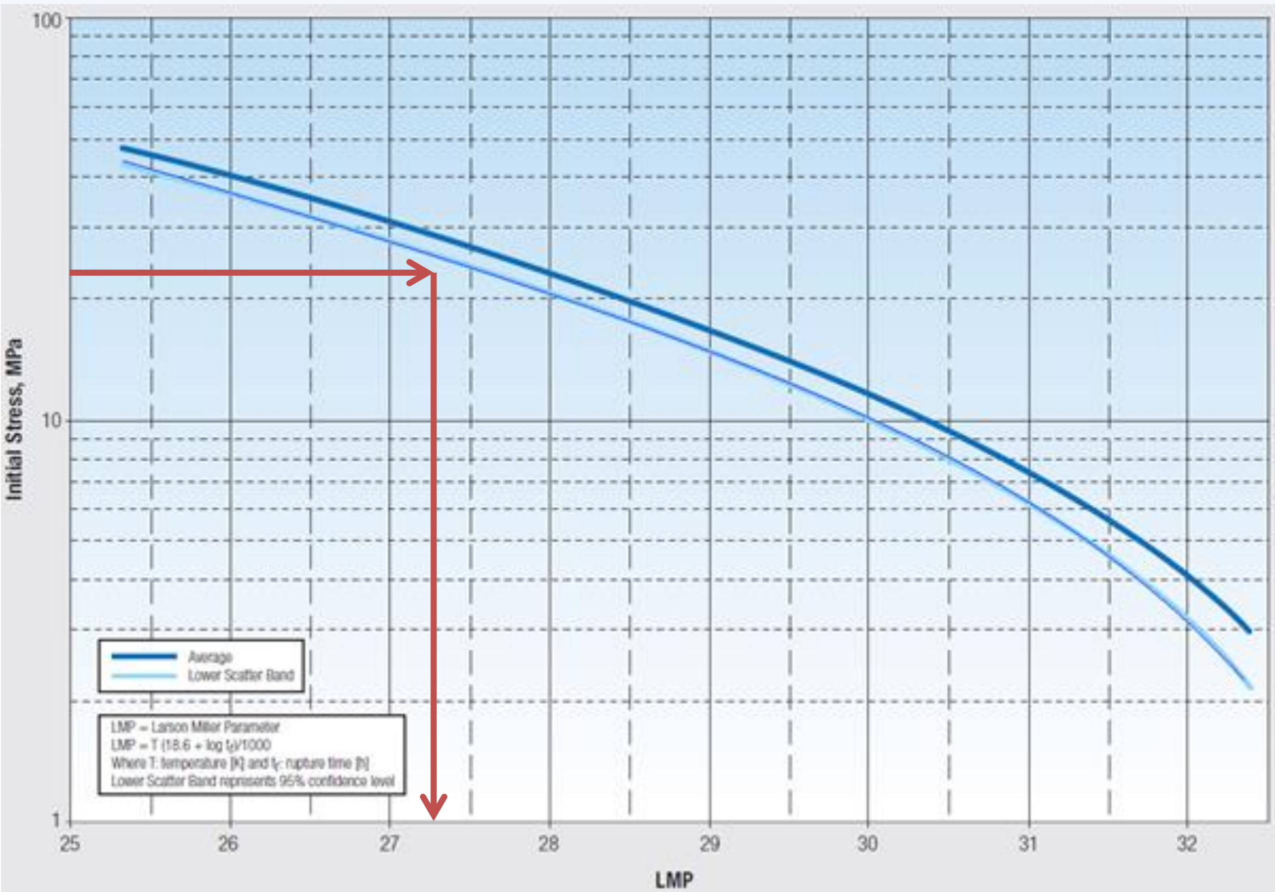
The creep strain is calculated from maximum increase in diameter along length of tube.

Dividing the total creep strain to number of hours the tube is operated.

The creep strain rate along with the initial stress for each interval of loading provides input parameters for calculation of effective tube skin temperature.

The curves for creep strain rate v/s stress are available with service providers through series of actual creep rupture tests.

Automated Reformer Tube Inspection System (ARTiS)



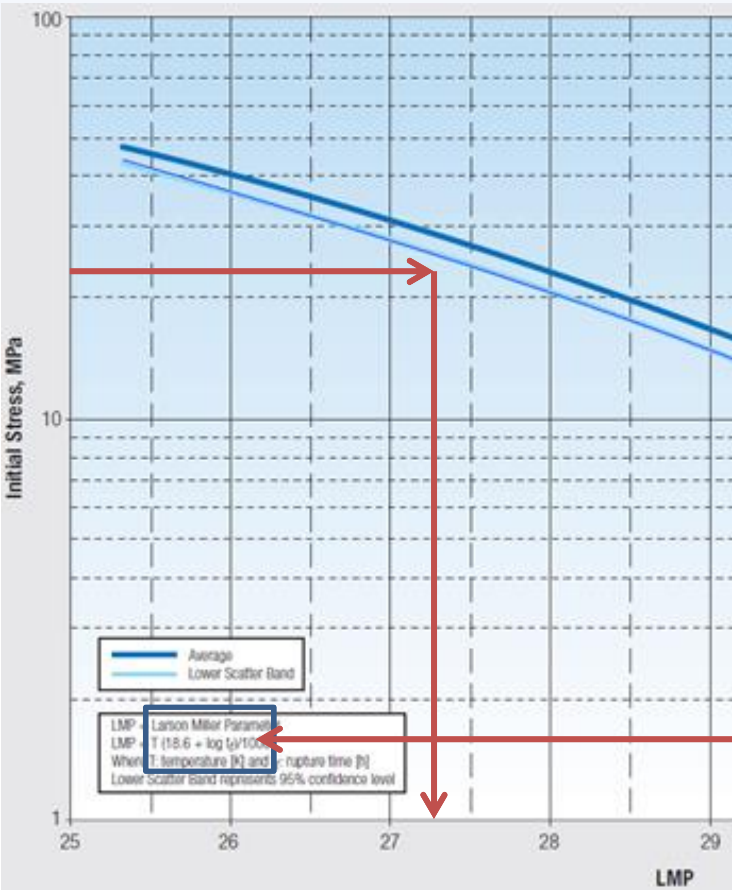
From calculated effective tube metal temperature, new working life (DL) can be calculated.

Data are made available by manufacturer of alloy.

Generally provided with procurement of new tubes.

$$D_L = 10^{\{P / (T\text{-}EFF + 273)\}}$$

Automated Reformer Tube Inspection System (ARTiS)



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…d with

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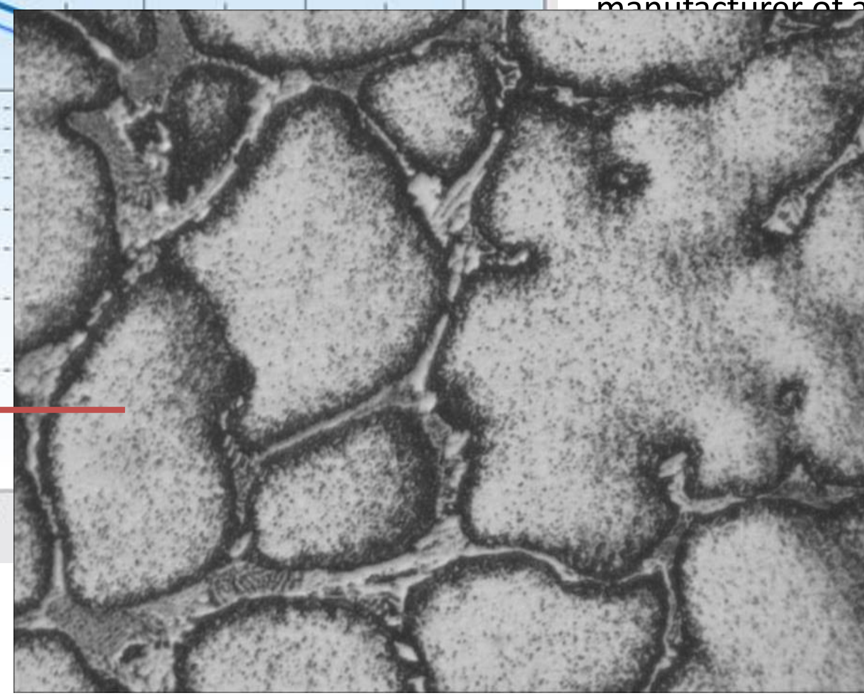

Automated Reformer Tube Inspection System (ARTiS)

API Standard 530 / ISO 13704:2001 (E)

Table A.2 — Life fractions for each period

Operating period	Average stress		Larson-Miller values				Rupture time based on minimum strength		Rupture time based on average strength	
			minimum		average					
	MPa	psi	°C	(°F)	°C	(°F)	a	Life fraction	a	Life fraction
1	48,52	(7 045)	19,06	(34,32)	19,48	(35,09)	54,0	0,02	154,8	0,01
2	54,91	(7 973)	18,83	(33,90)	19,25	(34,66)	13,1	0,05	35,8	0,02
3	56,66	(8 213)	18,77	(33,80)	19,19	(34,55)	15,0	0,14	42,1	0,05
4	68,78	(9 985)	18,41	(33,15)	18,83	(33,90)	4,7	0,43	13,1	0,15
					Accumulated damage =			0,64		0,23

Automated Reformer Tube Inspection System (ARTiS)

Typical output of remaining life with API 579 ASME FFS1 approach

Tube	TEff °C	[A] Predicted retirement at TEff		[B] Predicted retirement at 930°C	
		hours	date	hours	date
1	916	>100000	>Jul 2031	84650	24-10-2029
2	918	>100000	>Jul 2031	64210	25-06-2027
3	925	36470	25-04-2024	27710	26-04-2023
4	923	51800	24-01-2026	37200	26-05-2024
5	920	91220	24-07-2030	59830	24-12-2026
6	923	51070	24-12-2025	36470	25-04-2024
7	**927**	**29170**	**26-06-2023**	**24790**	**25-12-2022**
8	921	68590	24-12-2027	45960	26-05-2025
9	920	84650	24-10-2029	53990	25-04-2026
10	923	48880	24-09-2025	35010	24-02-2024
11	917	>100000	>Jul 2031	69320	24-01-2028
12	920	78810	22-02-2029	50340	24-11-2025
13	915	>100000	>Jul 2031	80270	24-04-2029
14	907	>100000	>Jul 2031	>100000	>Jul 2031
15	921	70780	25-03-2028	46690	25-06-2025
16	907	>100000	>Jul 2031	>100000	>Jul 2031
17	914	>100000	>Jul 2031	86840	23-01-2030
18	910	>100000	>Jul 2031	>100000	>Jul 2031

Automated Reformer Tube Inspection System (ARTiS)

Conclusions

The non-destructive testing of reformer heater tubes has undue emphasis predominantly on ultrasonic attenuation measurements.

Change in microstructural condition such as carbide coarsening, secondary carbide precipitation and depletion / dissolution of carbides from the grains largely affect the ultrasound attenuation mechanism and significantly affect the creep strength of the material.

Microstructural changes are necessarily to be categorized with respect to internal fissures and diameter correlation.

Conclusions

Significant or complete loss of ultrasound energy may be indicative of presence of mid-wall fissures which requires confirmation by radiography and metallography techniques.

The tube life assessment based only on NDT approach has so far remained in isolation, where only a few techniques like diameter measurements and loss of ultrasound energy are considered for judgment.

TCR always believe to work as a team

Thank you