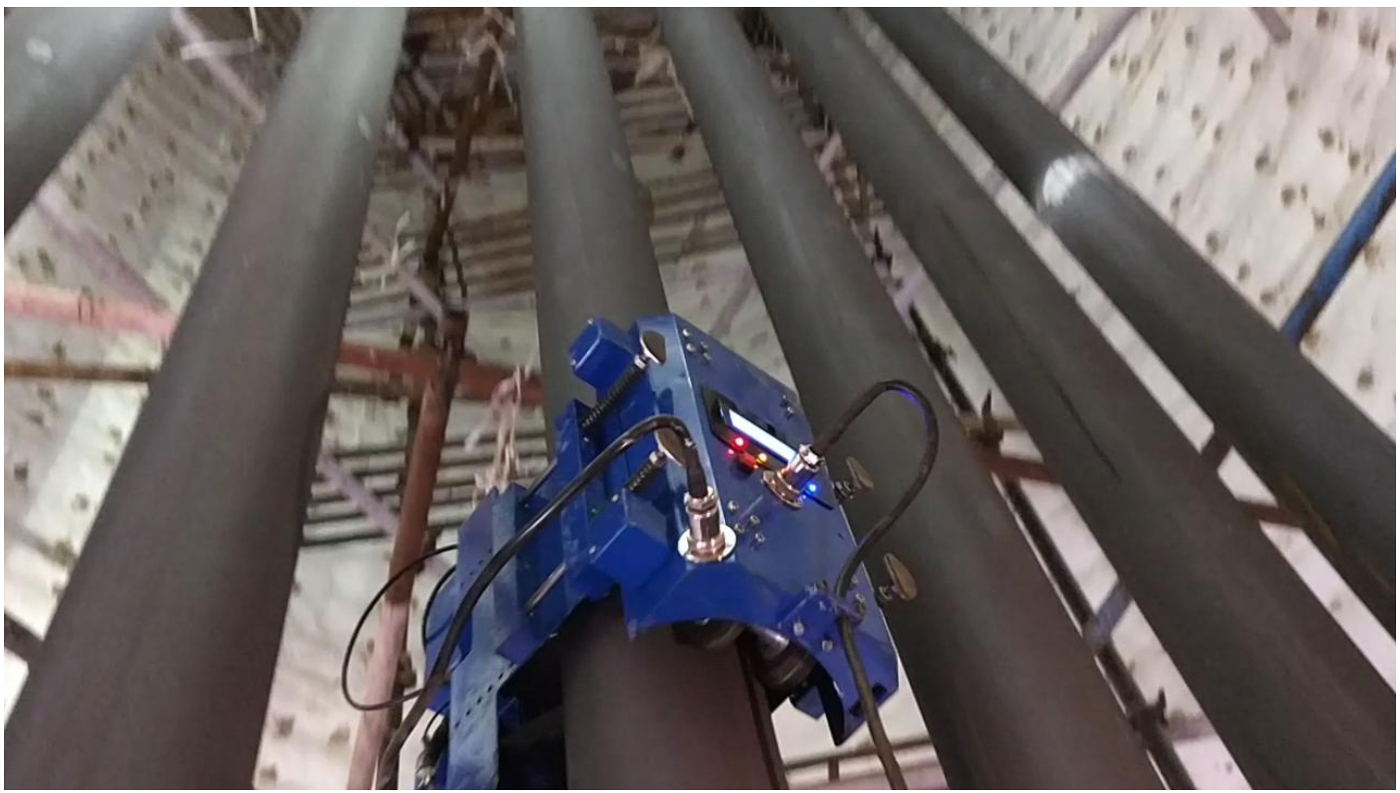
Reformer Tube Inspection
and
Remaining Life Assessment as per
API 579-1/ASME FFS-1



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Importance of tube inspection

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

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Reformer tube damage mechanisms

- Metallurgical degradations and failures due to creep rupture
- Excessive bowing and wedging with other tube
- Oxidation
- Thermal shocks
- Localized overheating
- Damaged catalyst
- Design aspect and support system

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Creep (Elevated service temperature components)

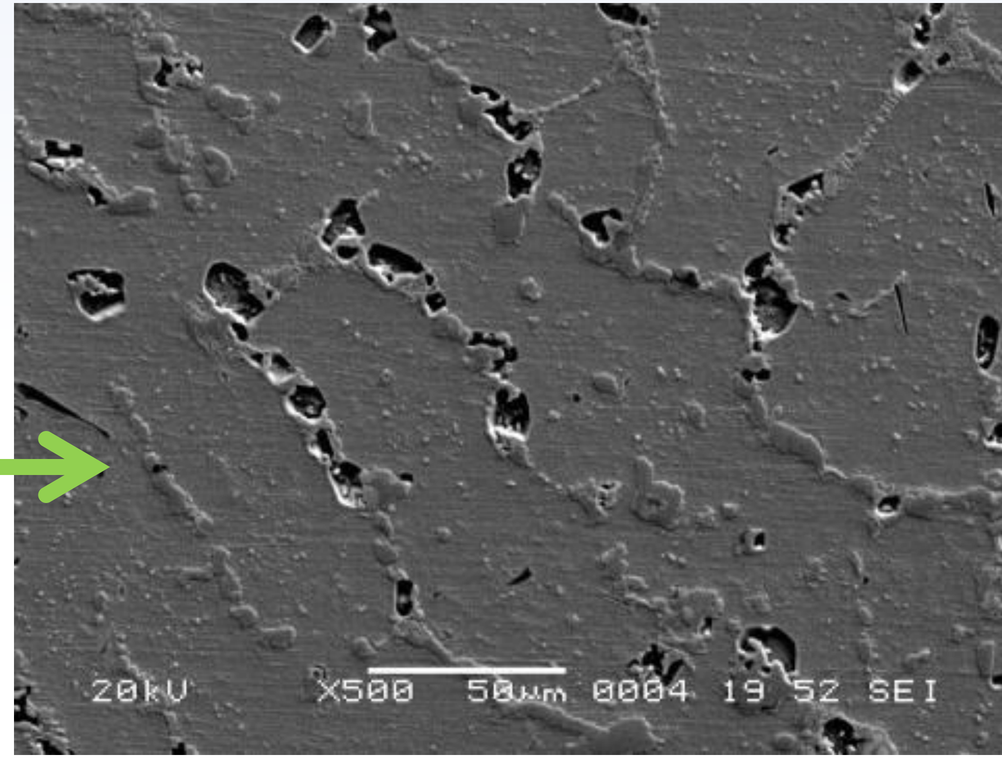
Creep failures:

Occur as a result of continuous exposure of high temperature and stress.

Results in:

Unacceptable dimensional changes and/or creep rupture because of mid-wall creep-crack growth.

Creep failure



Bowing of reformer tube

- Thermal expansion and contraction in succession (cycling)
- Improper heat distribution
- Improper / damaged supporting system

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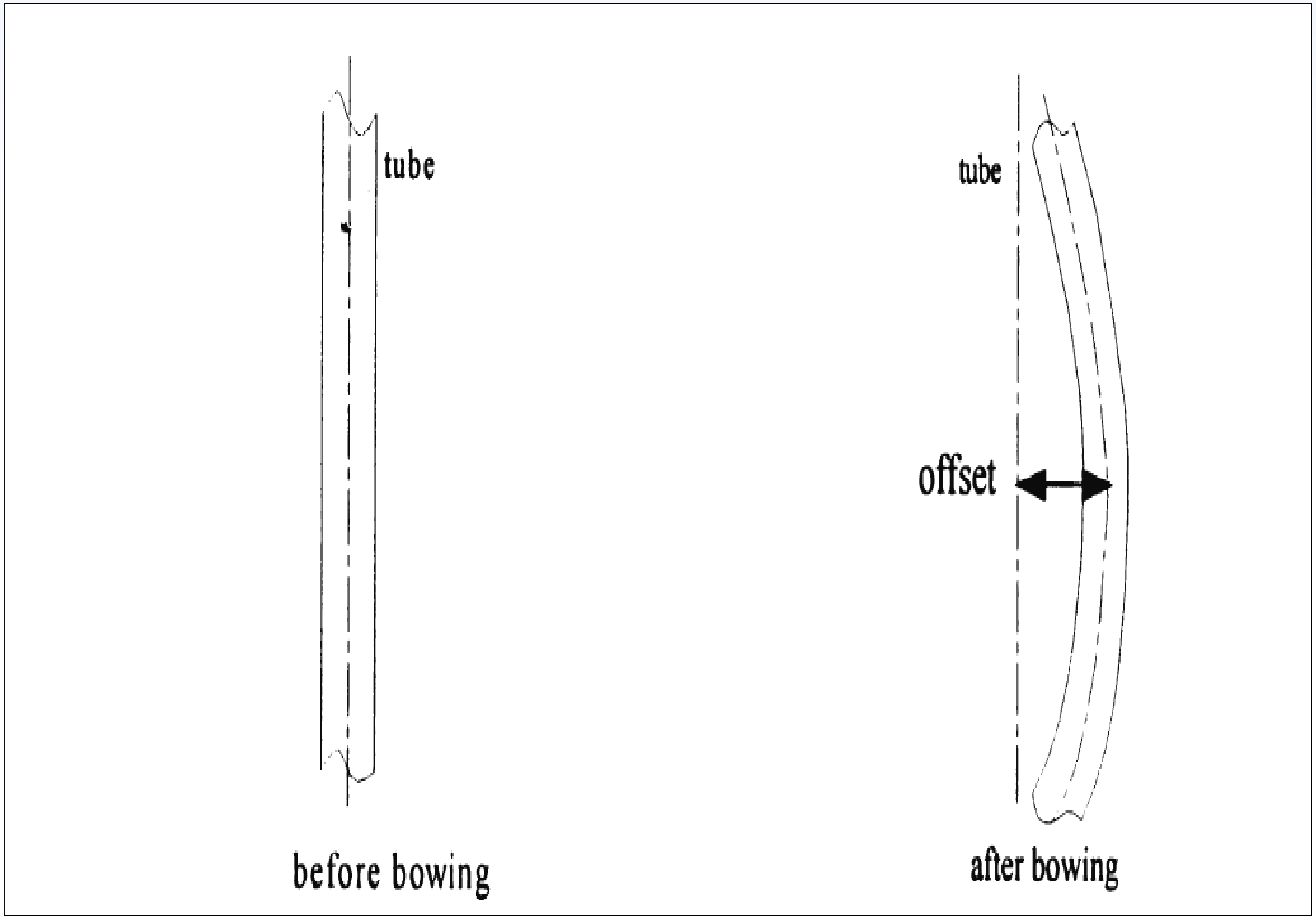
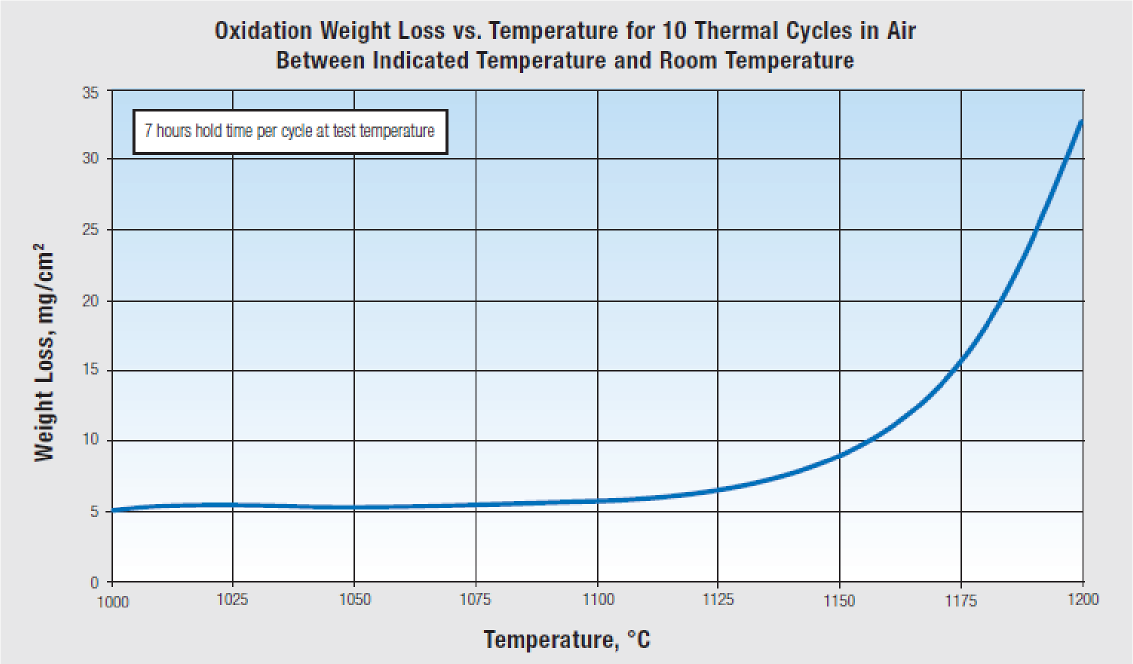
Bowing of reformer tube



Schematic of tube bowing. Acceptable up to 1.5XOD as long as not wedging

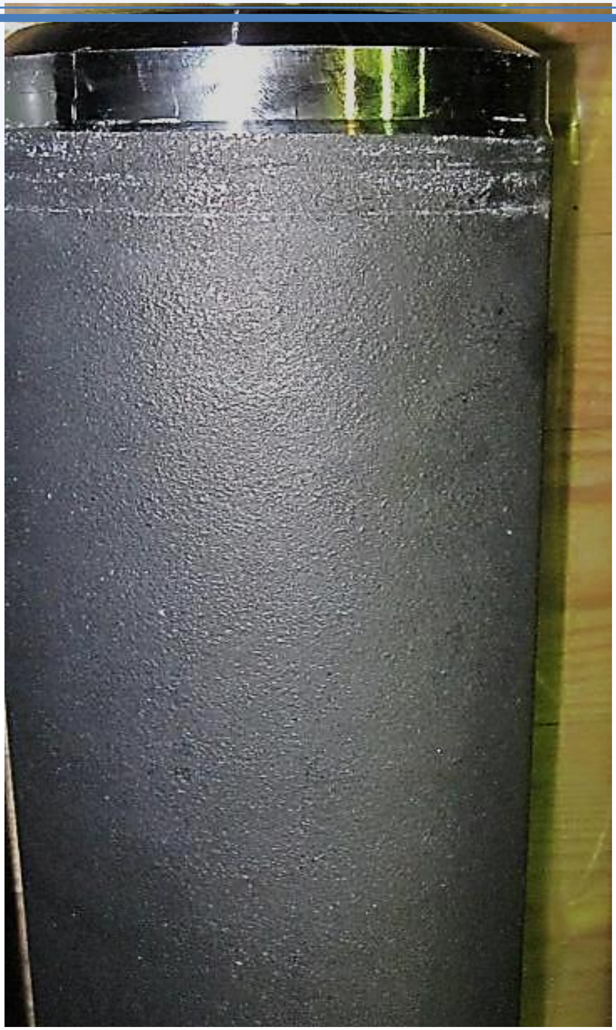
Baldness in reformer tubes (Oxidation)

- 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.



G4852 Micro

Baldness in reformer tubes *Fuel / air ratio*



Comparison between two reformer tubes for showing baldness
Result: Loss of effective tube metal thickness

Thermal shock

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

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Localized overheating

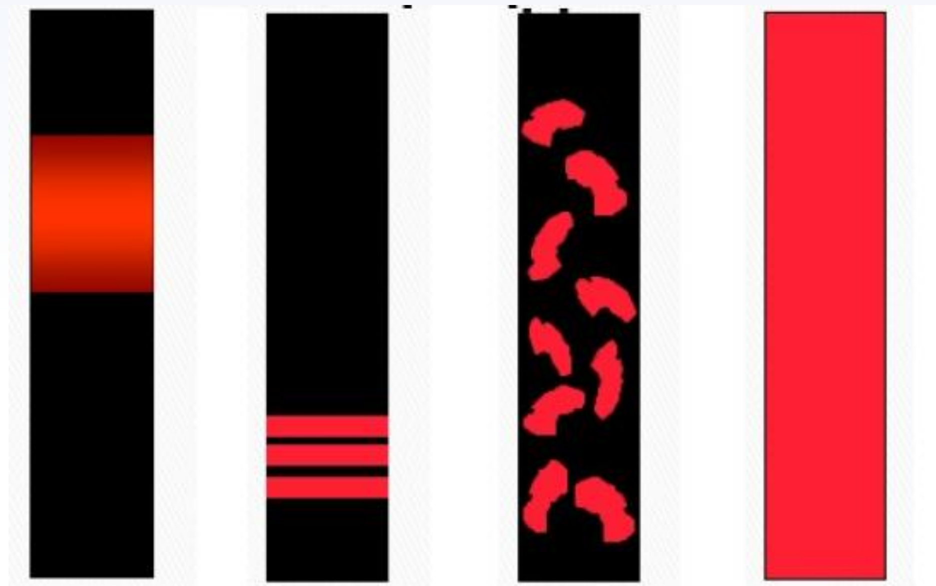
➢ *Direct flame impingement*:

- 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.

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 / layered; and choke the gas path such that a localized channel would get form and passage of gas gets completely resisted.



Hot band | Tiger tailing | Giraffe necking | Hot condition

Courtesy: Johnson Matthey

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 800-990°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 990-1100°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

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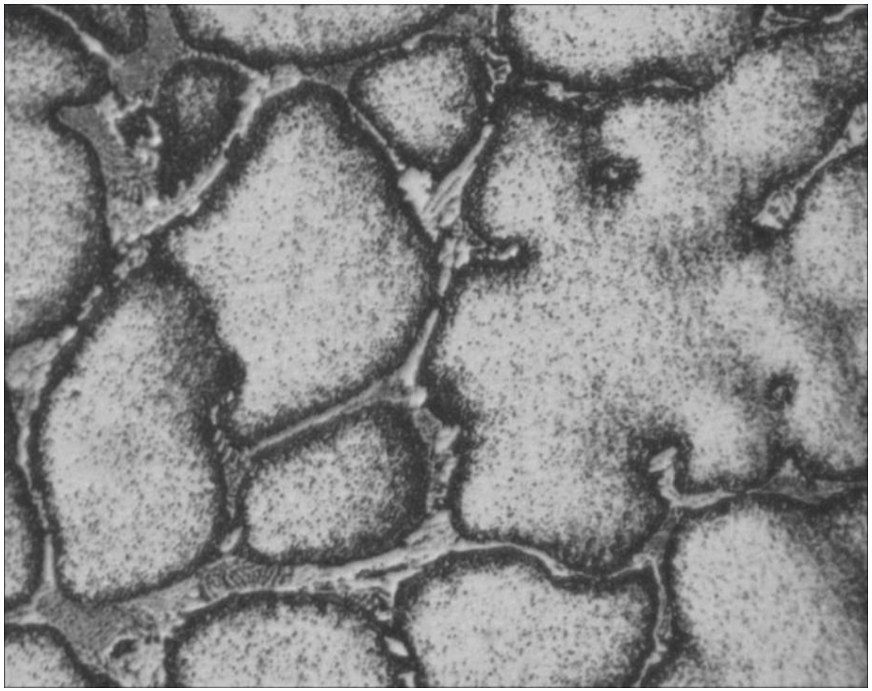
Metallurgical degradation

Secondary carbides

Primary carbides



Formation of compact blocky carbides

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

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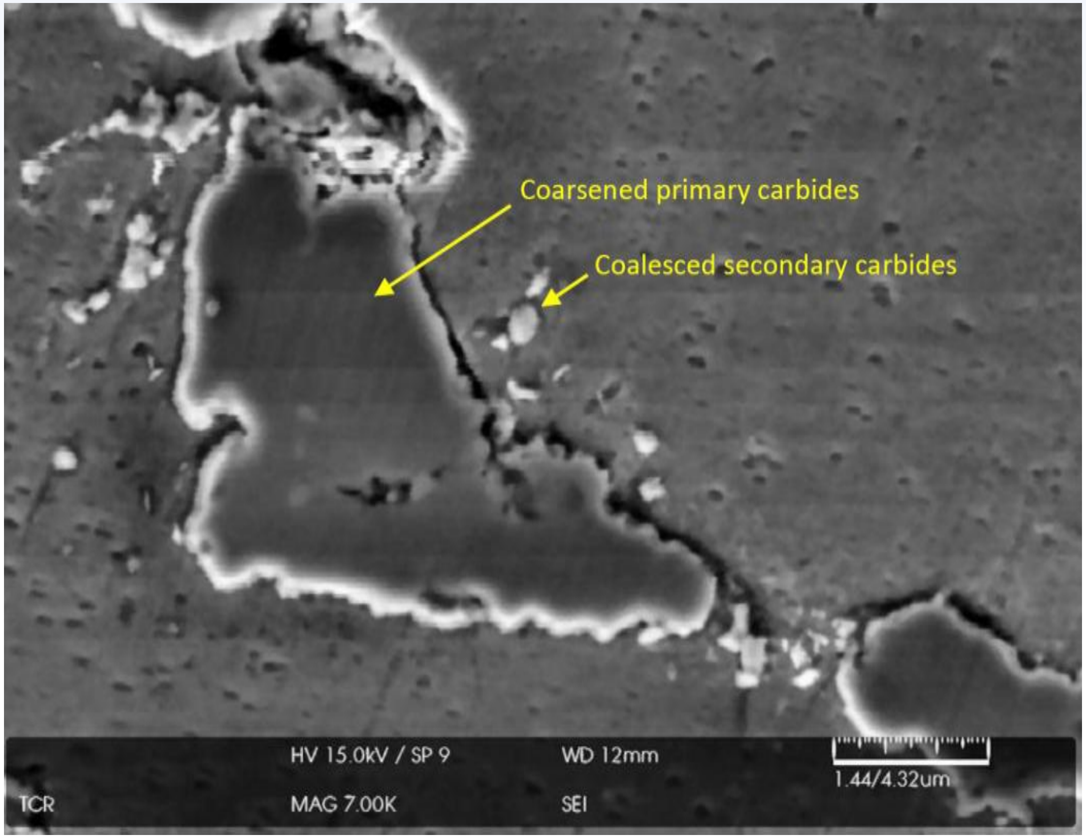
Metallurgical degradation



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.

RLA *NDT Approach*

Shutdown inspection: 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

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General criteria for tube replacement

- Tube failure
- Visual appearance / marking of localized heating
- Severe tube bowing condition
- Internal cracking detection: e.g. High UT attenuation followed by radiography confirmation
- Calculated creep strain based on outer diameter measurements, tubes exceeding 5% are generally prioritized

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Role of NDT to identify damages

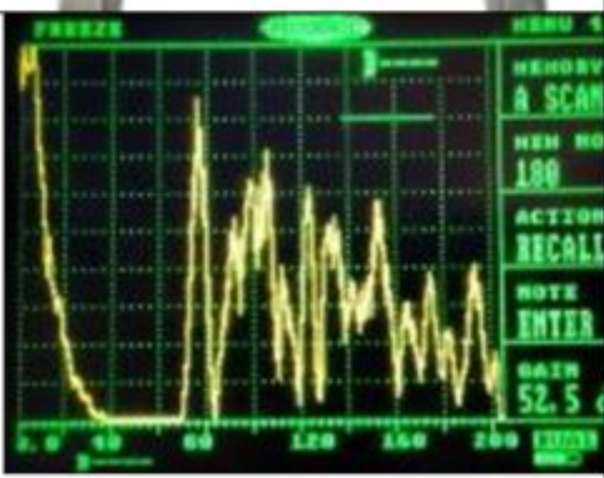
Damage mechanism	NDT method for detection	Information available
Creep damage	Diametric measurements	Often increased diameter by 3 to 6%.
	Ultrasonic scanning for attenuation measurements	Increased attenuation indicating presence of creep voids and / or creep fissures
	Eddy current testing	Detection of creep fissures at later stage.
	Metallography	Creep fissures and void at primary carbide chains, detected generally after 2^{nd} 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

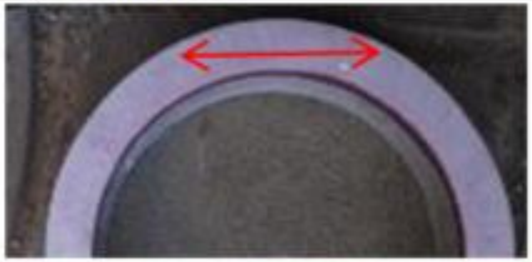
Detection of creep fissures: typical attenuation comparison

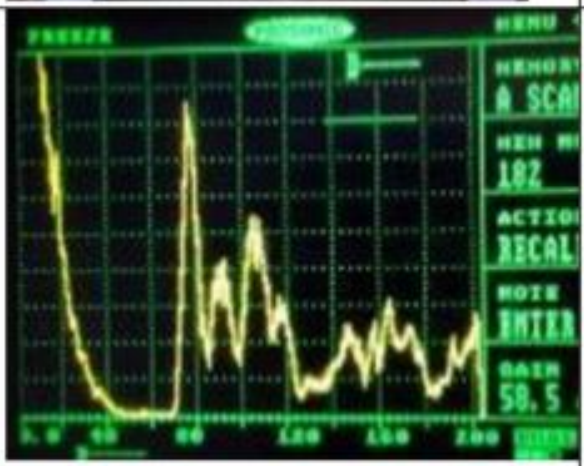
Echo response comparison

New material

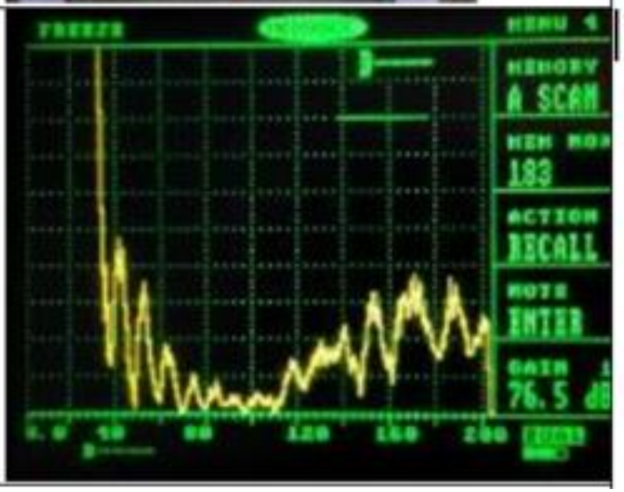


Aged material

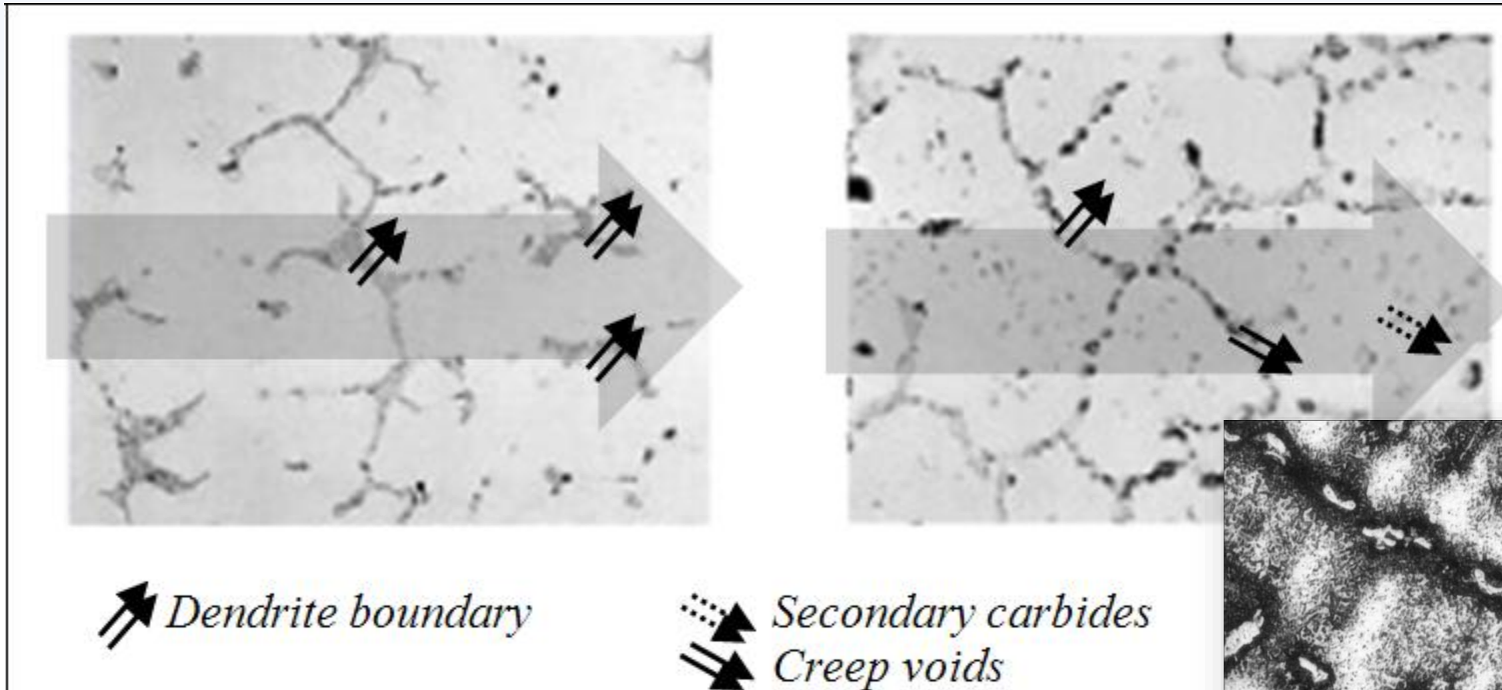




Material with midwall fissures



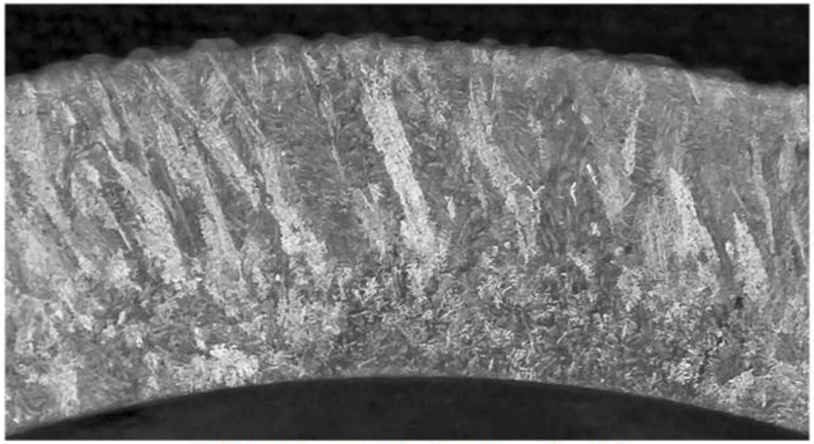
Creep detection by UT: *Effect of carbides*



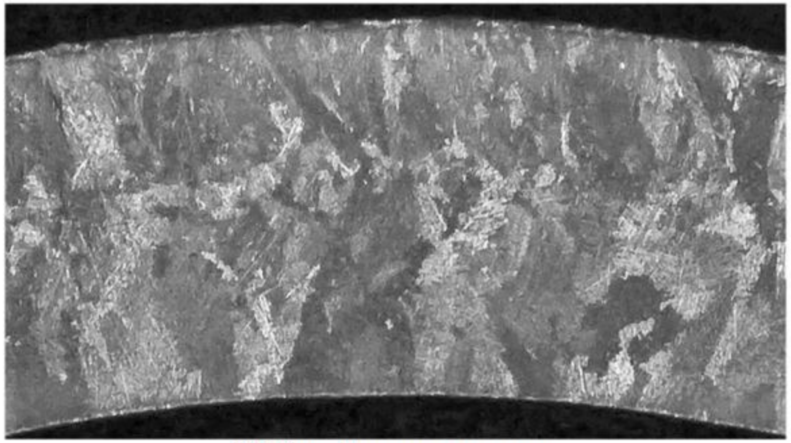
TR Mode ultrasound wave attenuates by:

- 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

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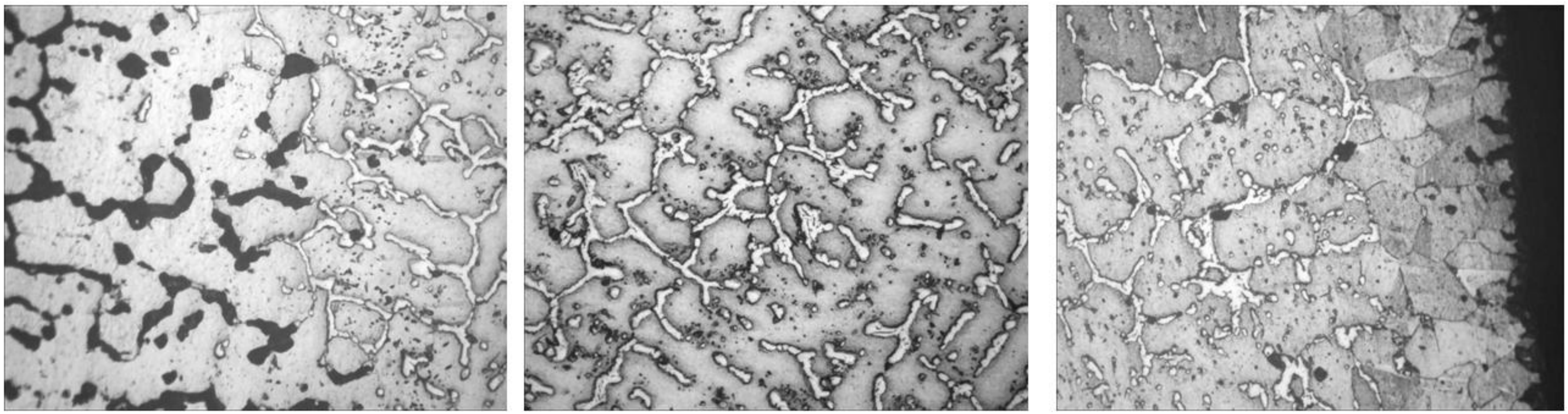
Microstructure and UT Pattern: *Tube MOC*

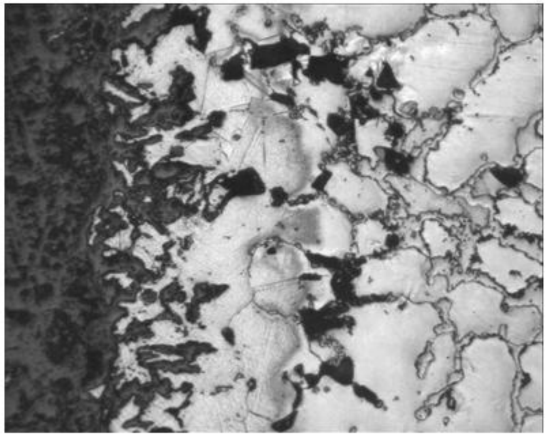
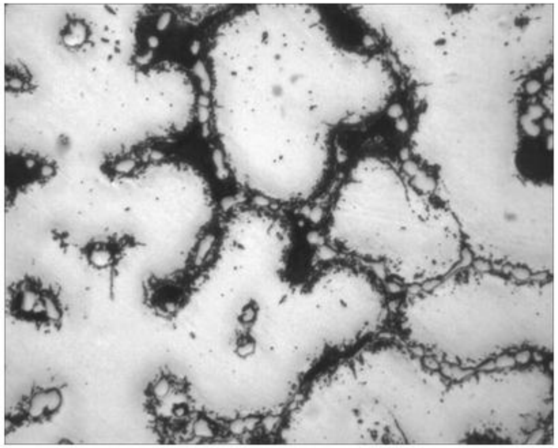
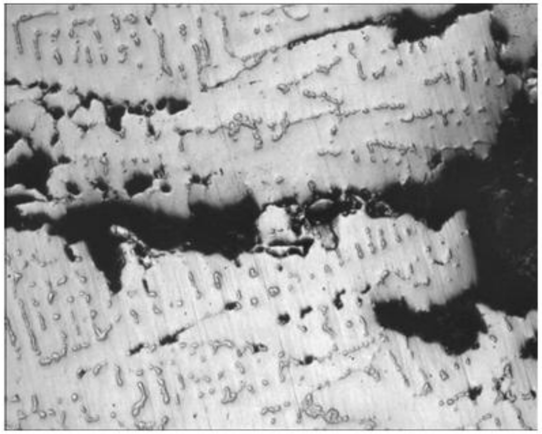


Alloy:KHR35CT, 100X, service exposed material (125000h),

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

Microstructure and UT Pattern : *Tube MOC*

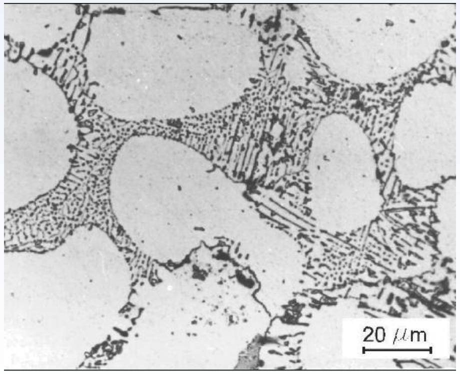




Alloy HK40, Service exposed 29 years,

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.

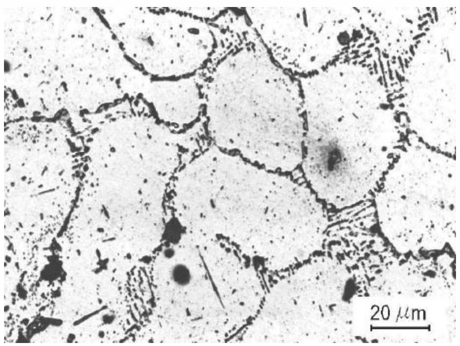
Sound attenuation measured is 56 to 62 dB

Microstructure and UT Pattern: along length of tube



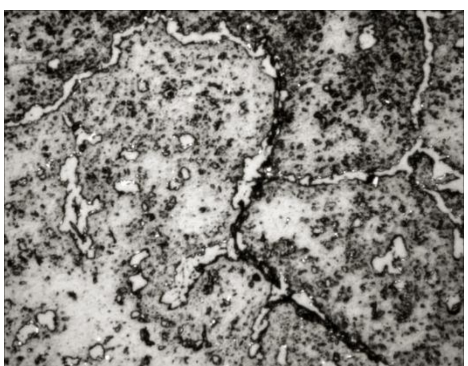
The microstructure of unused IN519 tubes is shown in Figure left, having dendritic columnar austenite grains oriented perpendicularly to tube walls.

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

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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

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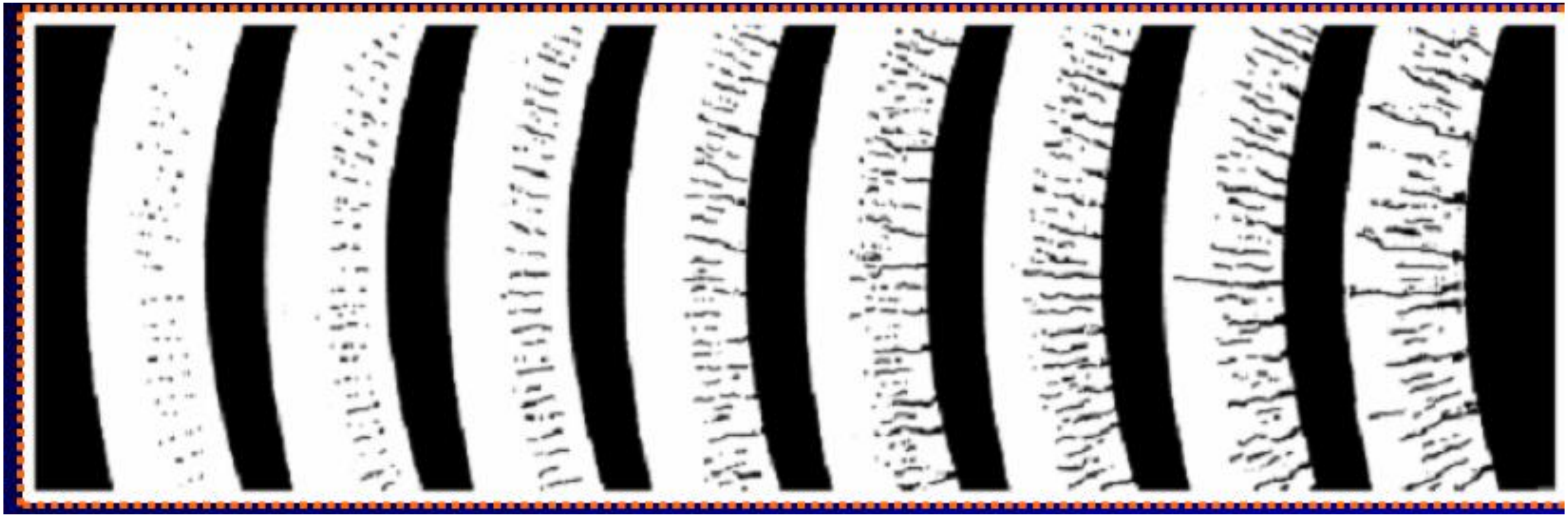
Progressive creep cracking (Reformer tubes)

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



ARTiS: NDE 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

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+ Destructive test result database
+ 200,000 metallography database

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.

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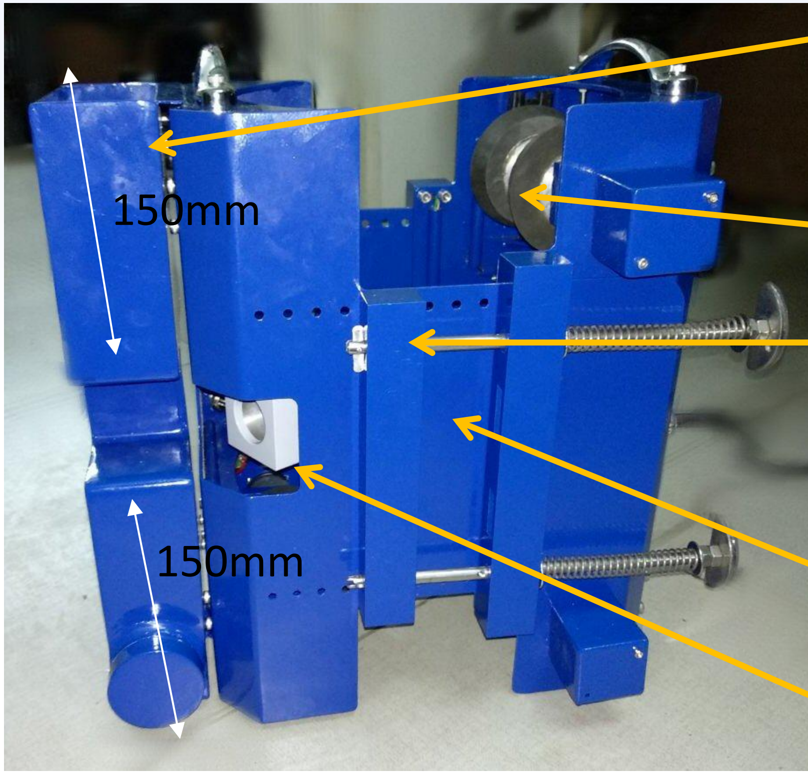
Crawler components



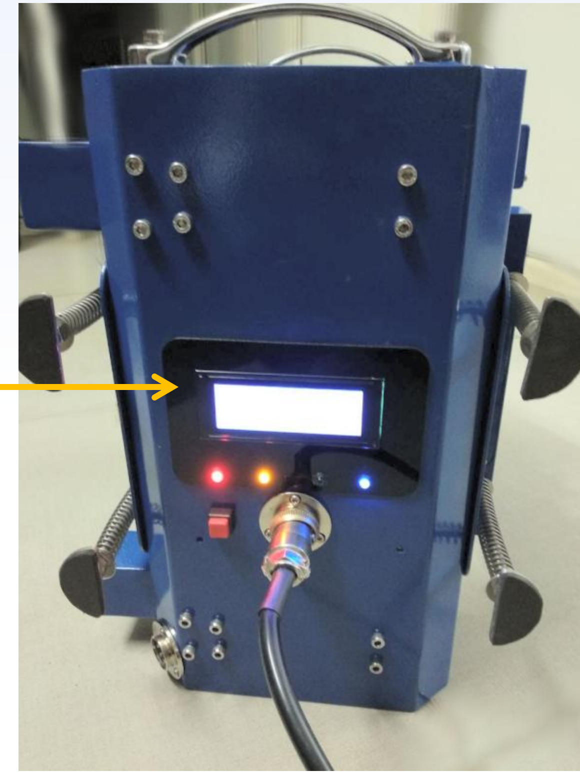
Water tank with pump

Drive

OD measurement

Adjustable arm

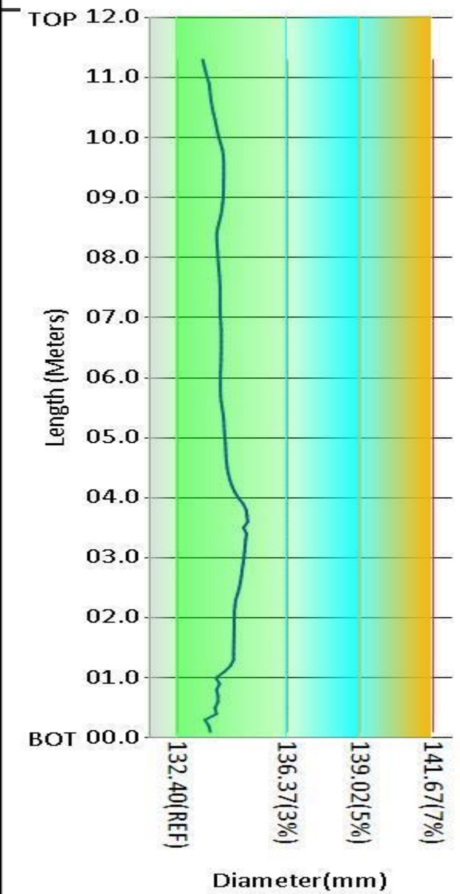
UT Probes



https://youtu.be/MRNmhSO4Xx8?si=0Ea4SSLJxTSECUf_

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	[illegible]	[illegible]	[illegible]	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



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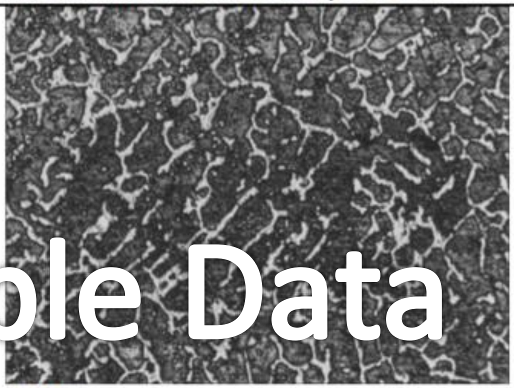
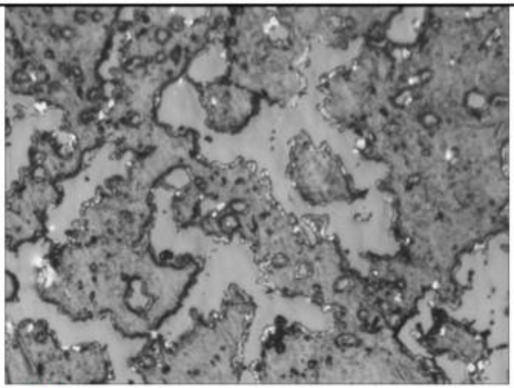
Automated Reformer Tube Inspection System (ARTiS)

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

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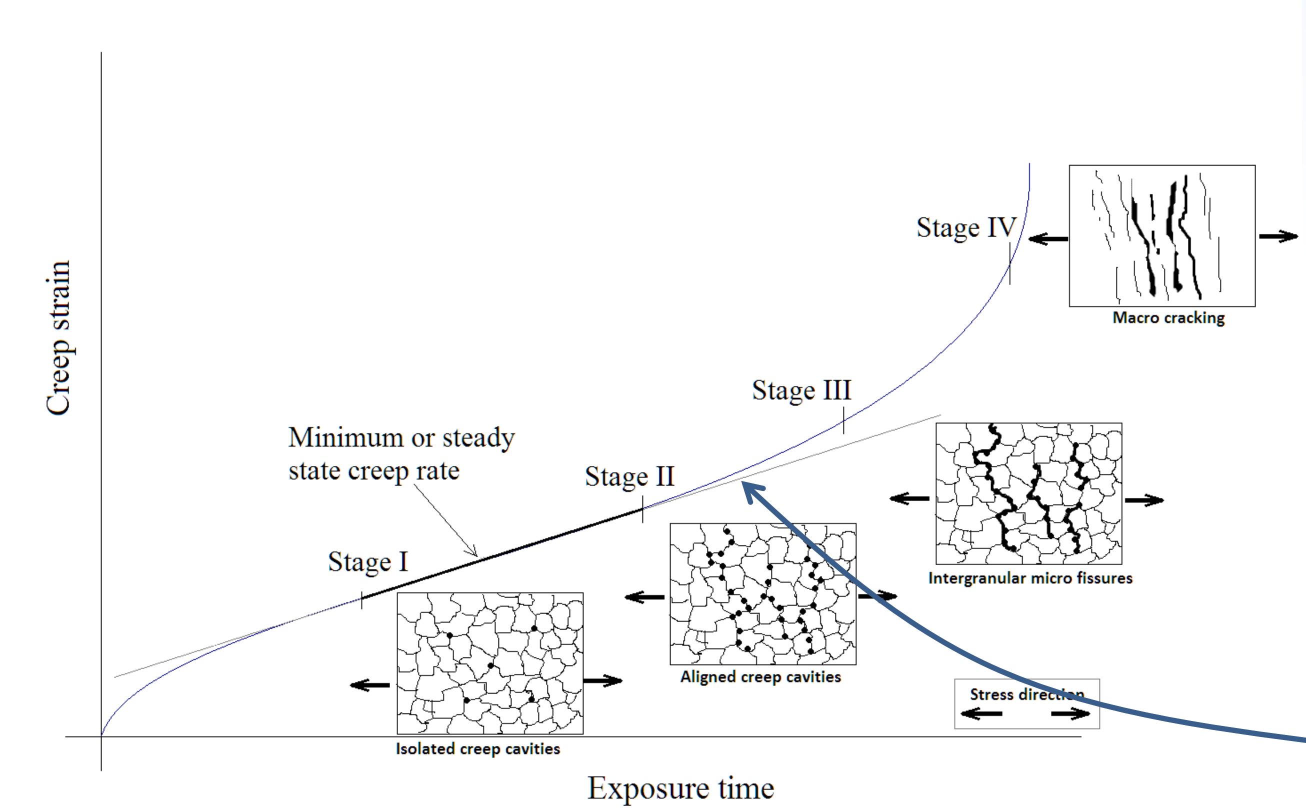
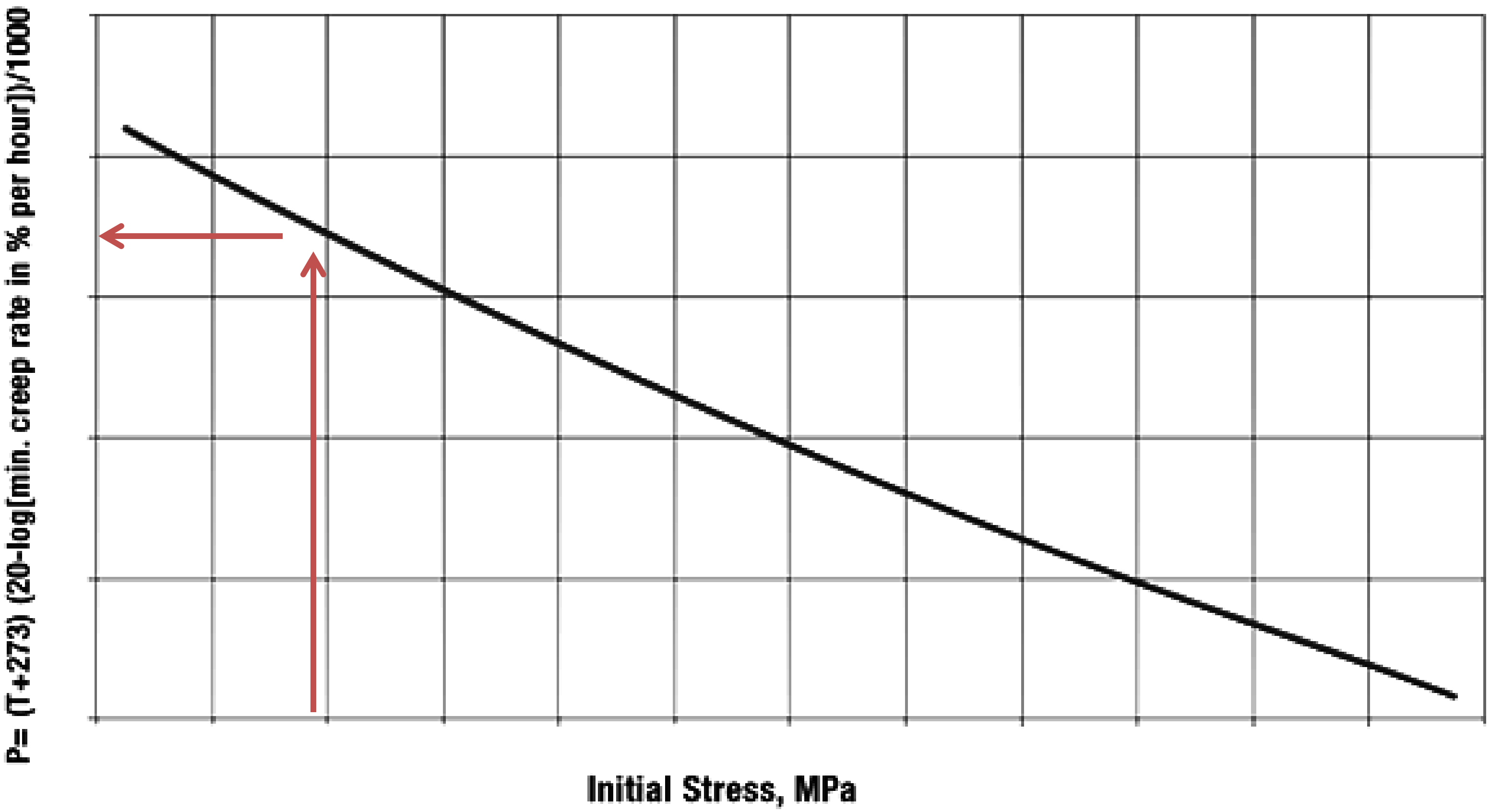
Life assessment (ARTiS)

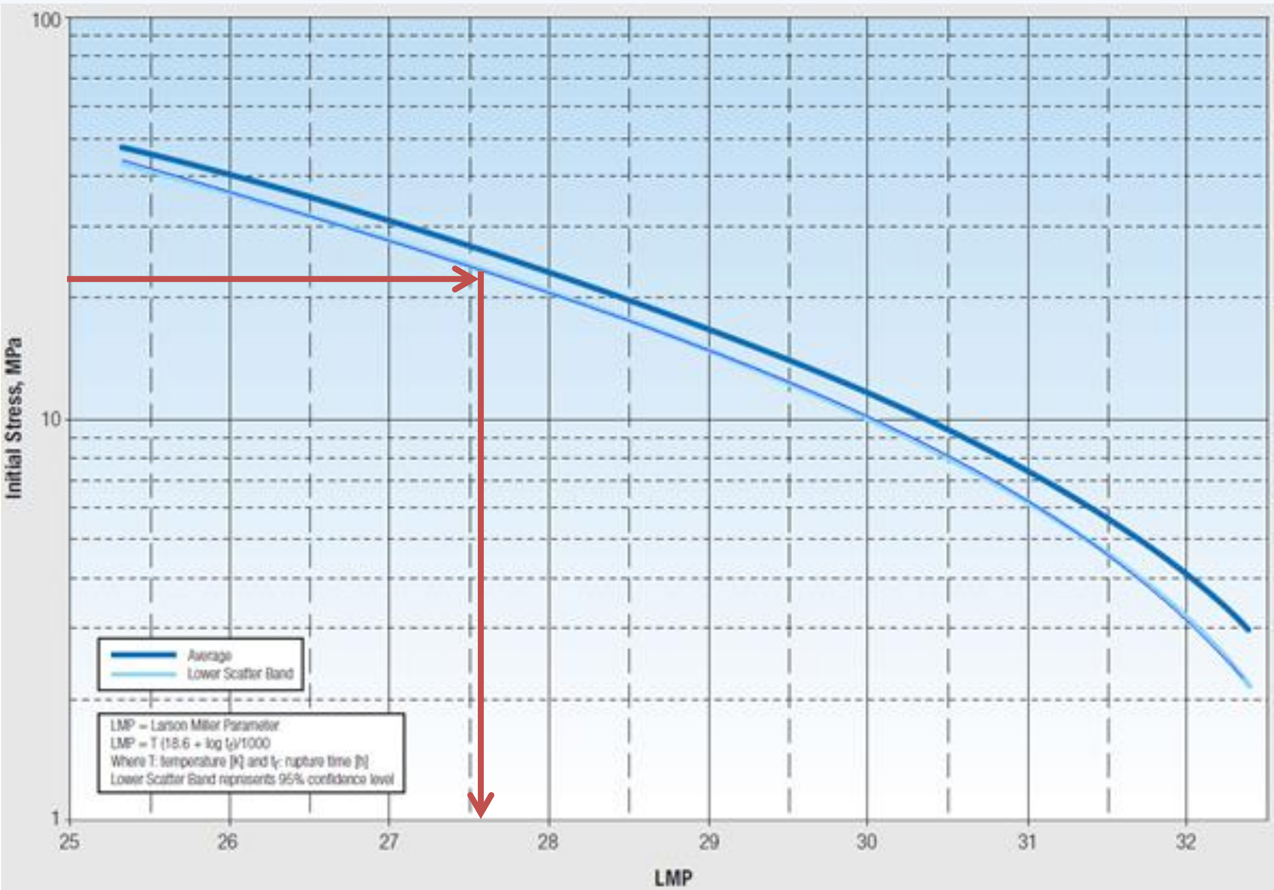


The creep strain to be used in calculations is necessarily a steady state creep rate.

Life assessment (ARTiS)



Life assessment (ARTiS)



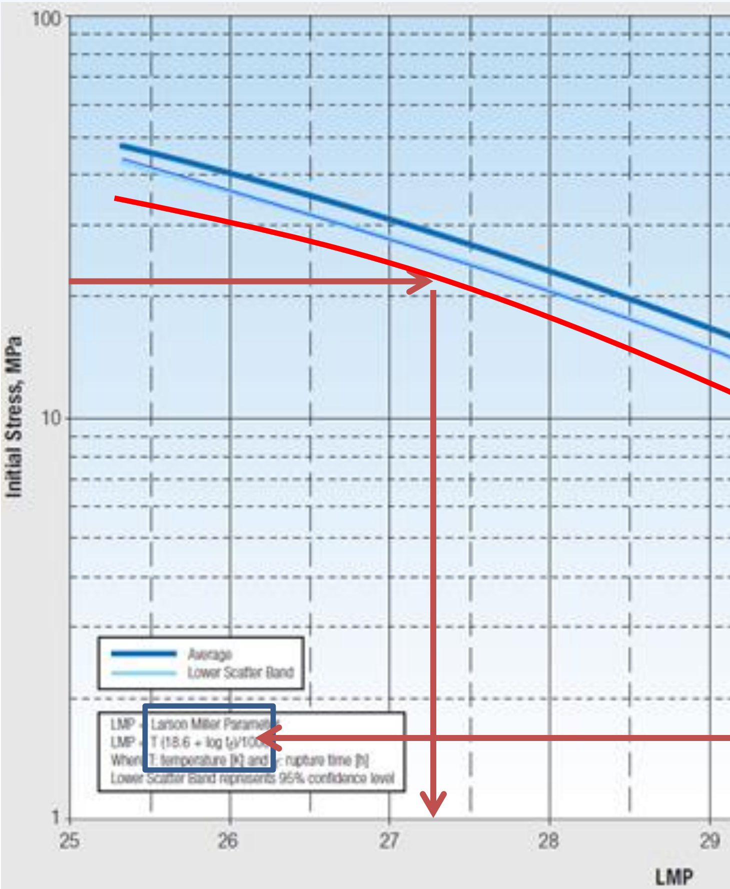
$$D_L = 10^{\{P / (T\text{-}EFF + 273)\}}$$

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.

Automated Reformer Tube Inspection System (ARTiS)



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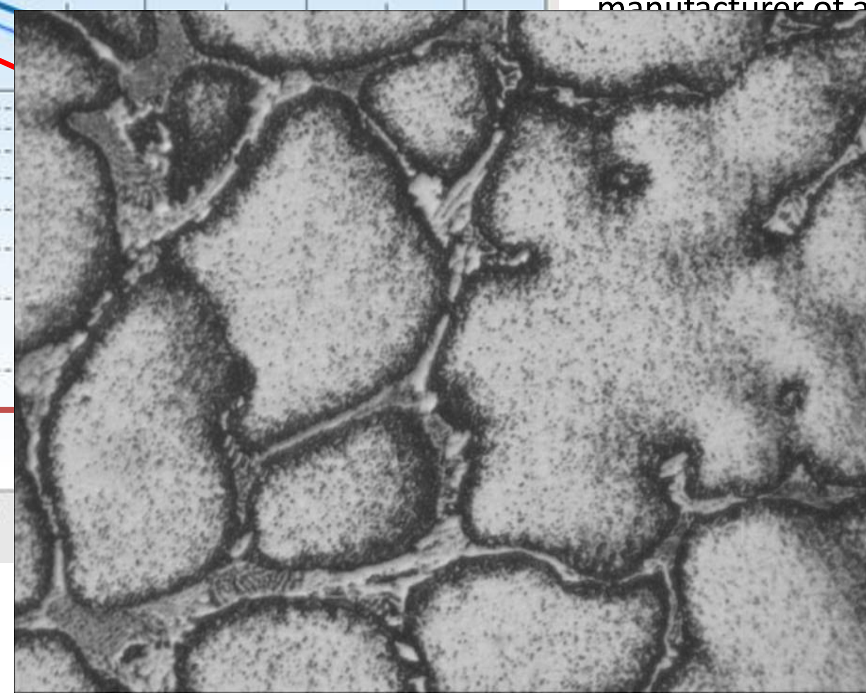
l with

w tubes.



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

Life assessment (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

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Life assessment (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

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Life assessment (ARTiS)

Damage Pattern

Conclusions

The non-destructive testing of reformer heater tubes has undue emphasis only on creep strain values.

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

Microstructural changes are necessarily to be categorized with respect to internal fissures and diameter correlation. This may be done through obtaining ultrasound attenuation values.

Conclusions

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.

ARTiS provides methodical approach for remaining life assessment based on API 579-1/ASME FFS-1.

TCR always on customer side,
not just a vendor.

Thank you