Integrated Approach for RLA of Reformer Tubes by NDT (ARTiS)

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Abstract:

The primary reformers are widely adopted in fertilizers, petrochemicals and oil refining industries. They produce hydrogen with endothermic reaction at elevated temperature above 800°C in pressurized condition. The challenge for the metallurgy is to combat creep and thermal damages for long term durability. Advancement in alloy development has allowed robust design of reformer tubes which are typically designed for 100,000 hours of operation but can still perform for higher lifespan with extended interpretation of NDT results. The tube replacement strategy is generally dependent on NDT inspection results that includes estimate of cumulative creep strain through precise ID or OD measurements, tube bowing condition, ultrasonic attenuation measurement for detection of mid-wall fissures and to some extent microstructural degradations. These inspection methods are used in isolation and judgments are taken predominantly based on past experience.

Normally adopted deciding factors are: increase of diameter up to 3-6% is considered limiting creep strain depending on material of constructions. This limit for micro alloyed tube varies as the degradation mechanism of niobium carbides is different. Similarly, ultrasonic attenuation measurements alone cannot provide early warning to creep fissure detection on micro-alloyed metallurgy because the precipitation of carbides and primary grain boundary carbide coarsening mechanisms can widely affect the ultrasound attenuation characteristics. On the contrary decrease in ultrasound attenuation would be interpreted as normal, despite localized over-heating around 1000°C due to any reason that would tend to dissolve the required secondary precipitates.

This paper discusses how the interpretation can be correlated with respect to tube metallurgy and inspection findings. A model is suggested with comprehensive approach for tube retirement plan based on combination of NDT inspection and metallographic techniques. The paper discusses the methodology for more precise judgment of tube condition with individual rating for replacement planning by correlating Automated Ultrasonic Scanning (AUS) results, outer diameter measurement results, tube bowing quantification and microstructural characterization.

Introduction

Reformer tubes are used for cracking hydrocarbon with steam to liberate Hydrogen and CO_2. Normally, hydrogen generation is an endothermic reaction that requires a temperature range between 840-880° C with catalyst. It is known that temperature overshoot lowersthe tube life. Hence, reformer heater tubes often constitute most focused inspection activities during the turnarounds. This enables timely management decisions on budget allocation towards replacement of tubes and catalysts. Apart from materials cost, the replacement activities need more downtime, resource management and involvement of multiple agencies.

The heater tubes are made of chromium and nickel rich alloysthat have been developed over the years for better life expectancy. Conventional HK40 alloy has been replaced by improved versions containing niobium addition and other micro alloyingelements. The developments are mainly purported to bring down the capital cost and the downtime. The tube service life in excess of 10 years has been experienced on many of the reformers when they have been operated under controlled parameters-bylowertube skin temperature.

The increased demand for production with minimal investment on original production schema (debottlenecking) can generally be achieved with higher flow rates. Higher the flow rate, shorter the reaction time within the tube length for cracking in the tubes necessitates increased furnace temperature.

Often the optimization of increased production compromising effective tube life can yield to profit although there is a risk of unnecessary downtime because of tube failure. The risk can be minimized by resorting to meticulous inspection of heater tubes during the scheduled turnarounds. The clear guideline on tube remaining life judgment is dependent on inspection activities involved and the interpretation of results.

Remnant life assessment (RLA)

The tube life of 100,000 hours may be considered safe under normal operating conditions. The life expectancy is nearly based on heuristic considerations to facilitate safe replacement of the tube at an appropriate time. There are chances of premature failures despite maintaining proper service conditions.On the contrary there are chances of having extended life as well. The RLAapproach is a pragmatic tool to improvise the life expectancy.

In order to change from time based to condition based philosophy, it requires confidence in the methods and techniques deployed to determine tube integrity. Extracting tubes, close to their end of design life and subjecting them to metallurgical investigation is a fairly well accepted practice. While there are novel NDT techniques now available, the changes in tube microstructures and their anisotropy do pose certain difficulties in the interpretation of the results.

Some of the predominant damage mechanisms causing tube failures are enunciated hereunder.

Damage mechanisms:

Creep rupture: Creep damage is defined as time dependent degradation of material. The damage in the reformer tubes starts from $1/3^{rd}$ of wall thickness, appearing in the form of round voids randomly distributed on dendritic boundaries. Their preferred orientation is on boundaries perpendicular to the maximum principal tensile stress i.e. hoop’s stresses from internal pressure. As the creep damage advances, the boundaries show an alignment of creep voids, but without links between them. At later stage, microstructure would show aligned voids and micro-cracks (or fissures) produced by their linkage. Some fissures may extend to the internal surface andthe useful life of the tube is considered nearly extinct. At final stage, cracks reach to outer half of the wall thickness and tube would fail. Creep damage generally results in multiple longitudinal cracks, often along with bulging. Operation of tubes at temperatures beyond the design limits can lead to early creep damage.

Localized overheating: Mis-alignment of burners and their clogging, disturbance in flue gas path can lead to direct flame impingement to the tubes. As a result, tubes tend to damage locally by overheating. The irreversible metallurgical degradation takes place by way of loss of creep strength. Such localized overheating occurs normally at the burner facing areas.Normally, at top portion when top-fired burner schema is used or anywhere along the tube length when side fired burners are present.

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 particlesmaking them more friable. The fine ‘ash’ like particles settle down and choke the gas path such that a localized channel would get form and passage of gas gets completely resisted. Wherever the internal gases are frizzed, the endothermic reaction stops and as a result tube metal temperature increases. The degradation of catalyst thereby leads to localized temperature overshoot.

Metallurgical degradation: The carbide coarsening mechanism is temperature and time dependent phenomena[1]. 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 800^0-900^0C 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 900^0-1000^0C 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.

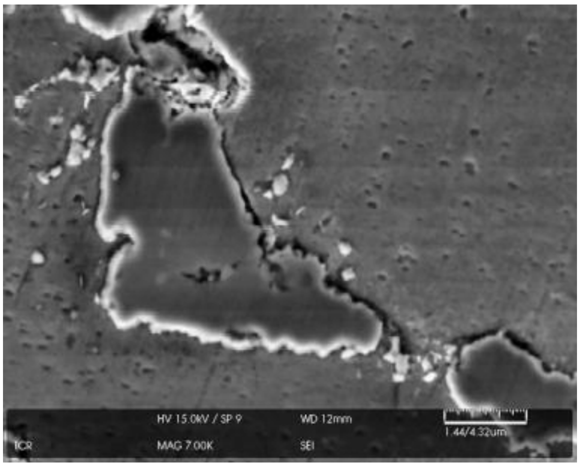


Figure 1SEM image of HP-Modified grade alloy, showing carbide growth with blocky nature of primary carbides

Thermal fatigue damage: Repeated start up and shutdown in quicker succession would cause thermal fluctuation in to the furnace and its components. There are guidelines given in API 572 define susceptibility of thermal fatigue of most components when the gradient exceeds 93°C.However, the load fluctuation because of production requirements would certainly bring about changes in the thermal and thermo-mechanical stress distribution in the reformer tubes. Even the minute changesunder the elevated temperature conditions would enhance the tube susceptibility towards thermal fatigue damage.

External tube oxidation: This oxide scale is an effective barrier against diffusion of carbon and oxygen from the gas phase into the metal matrix. It also blocks the catalytically active alloying elements, like Fe, inside the alloy from reaching the surface. 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 (Figure 2), 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. This results in gradual loss of thickness and lowering of external surface roughness of tube. The higher the surface roughness better is the heat transfer characteristics. To compensate the total heat transfer over a period, the temperature of furnace requires to be increased which also results in higher tube skin temperature.

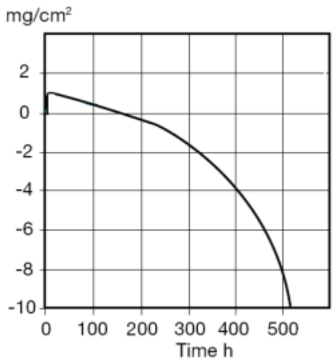


Figure 2 Oxidation damage of 25C-35Ni alloy[2].

Role of NDT in detection of tube damage

The role of NDT in detection of different damages explained above is narrated in Table 1.

Table 1:

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	Early detection of creep fissures and aligned creep voids.

	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

Theory on fissure detection by Ultrasonic Inspection

The ultrasonic inspection of reformer tubes is done in T-R (Transmit-Receive) mode where ultrasound energy is transmitted from one sensor, passed through middle of the wall section and received at other sensor (Figure 3). The energy transmitted is the sum of energy received and the energy lost in beam scatter. The phenomenon of ultrasonic beam scatter is illustrated in Figure 4. The microstructures as seen in scanning electron microscope is shown in Figure 5 shows secondary carbide precipitates and partially transformed primary carbides from their eutectic morphology to compact blocks.

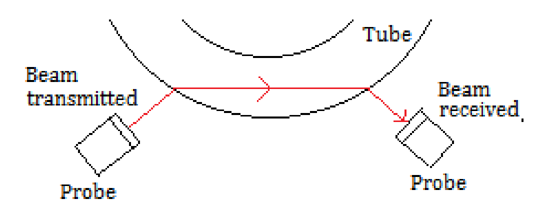


Figure 3 Principle of Attenuation Measurement: Ultrasound test in TR mode with specific angle of incidences such that beam travel is from mid-wall.

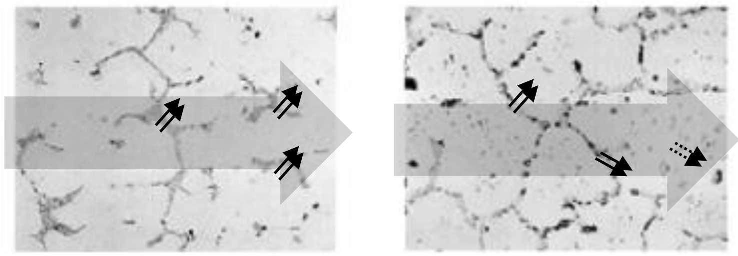


Figure 4 Potential regions for ultrasound attenuation
Dendrite boundary
Secondary carbides
Creep voids

In as cast material, scattering within the material occurs primarily at dendrite boundaries containing primary carbide chains. After being exposed to elevated temperature in operation, the alloy tends to precipitate secondary carbides. At later stage, nearing design life, the alloy exhibits creep damage seen as formation of voids and interlinked voids (fissures) at mid-wall. The ultrasound energy is significantly lost when the beam passes through voids or fissures, which indirectly reveal creep damage.

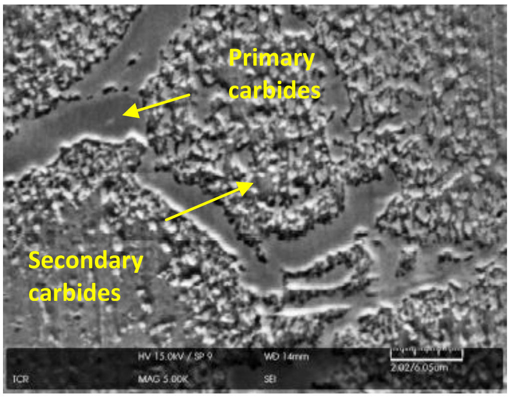
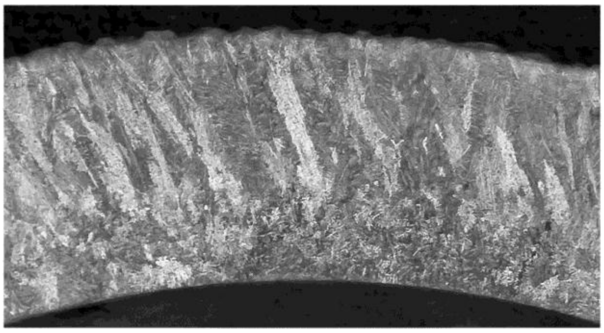


Figure 5*Service exposed HP-Modified, Scanning electron micrograph showing potential regions for ultrasound attenuation (5000X)*

However, sound attenuation also occurs at secondary precipitated carbides much before the creep voids are formed. The initial scatter pattern of ultrasound beam also changes with change in eutectic morphology of primary carbides to form compact blocks. The additive effect of beam scatter is presented in unit of dB when the echo is maintained at 80% full screen height that becomes the measure of energy lost. The increased dB therefore can reflect presence of creep voids or carbide coarsening in microstructure or both.

The ultrasound attenuation is also dependent on macrostructural condition. The cast tubes possess mixture of columnar and equiaxed structures as shown in Figure 6. The columnar structure scatters ultrasound more than the equiaxed structure of material. The variance in cooling rate during manufacturing of reformer tubes may result in change of columnar to equiaxed grains depth. It may vary from piece to piece and no generalized statement can be made unless macrostructural examination is conducted.



Columnar at OD, Equiaxed at ID

Fully columnar structure

Figure 6Macrostructures of the reformer tube showing cast pattern

The ultrasonic "attenuation measurement" inspection technique therefore has these limitations based on the surface condition of tubes, ratio of columnar to v/s equi-axed grains, carbide size etc. Hence, an integrated approach of use of NDT methods like UT, VT (visual inspection and dimensional measurement) along with microstructural examination can help in evolving go/no go decisions. Database of ultrasonic attenuation measurement with vis-à-vis degraded microstructural features, coupled with judicious interpretation of NDT would enhance the reliability techniques to RLA.

Automated Reformer Tube Inspection System (ARTiS)

ARTiS is abbreviated for 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 widely accepted by the industry with enhancements. While scanning, to the full height of tube, it provides ultrasonic dB level of attenuation, diameter of tube and bowing at predetermined interval of distance. The outcome of inspection becomes more systematic and traceable throughout the tube height. ARTiS avoids the need of scaffolding and saves inspection time, achieving reduced shutdown of plant. Typical comparison between ultrasonic inspection by manual method and by ARTiS is given in Table 2.

Table 2: Comparison between manual and automated tube inspection

Parameter	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	Quantitative measure

	measurement, additional time	during UT scan
Safety consideration	Higher risk (elevated work area)	Lower risk (platform area)
Reporting	Manual data entry	Software based with statistical data analysis

Relation between microstructural characteristics and ultrasonic attenuation

From failure investigation studies, as referred hereunder, correlation of ultrasonic attenuation measurements at, near and away from the failure area with corresponding microstructures is presented. The study covers generally observed cases of creep rupture and short term overheated tube failures.

Creep ruptured failure:

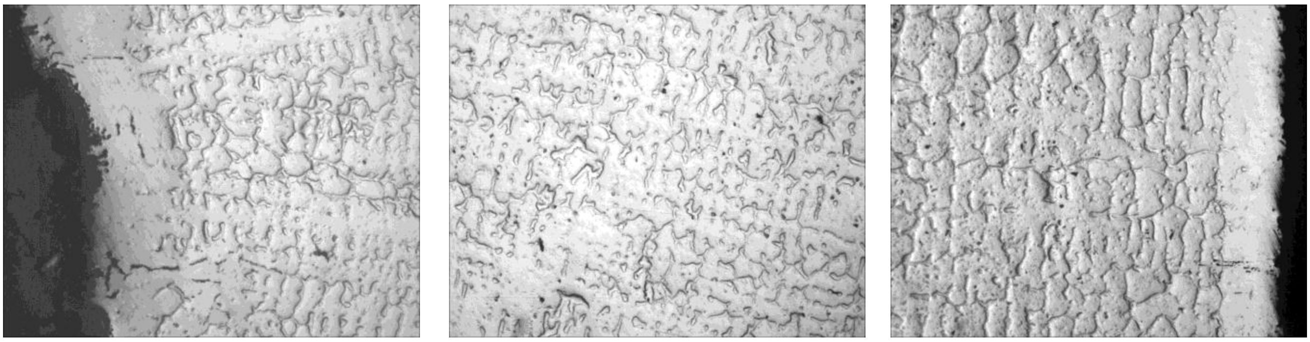


Figure 7 Alloy:KHR35CT, 100X, service exposed material (125000h) from top portion of tube, microstructures from OD (left), core and ID (right) show primary carbides at dendritic grain boundaries. ID and OD edges show partial decarburized condition.Sound attenuation measured is 54 to 58 dB

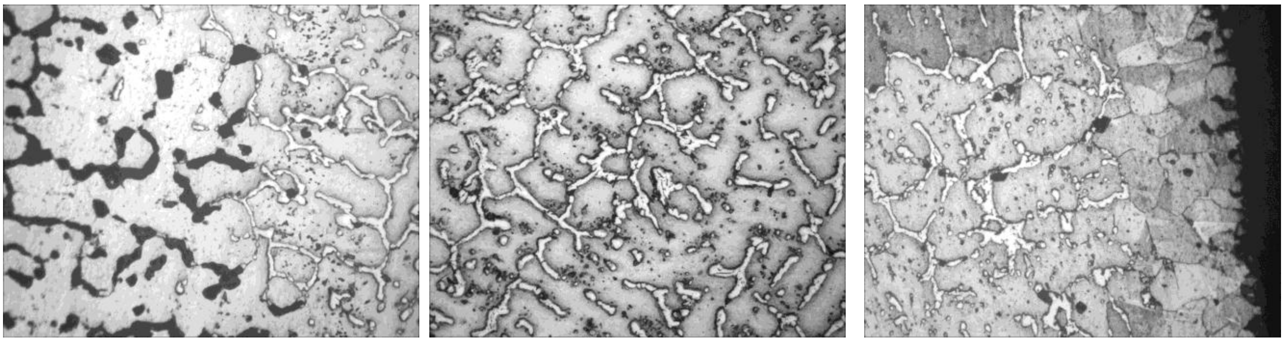


Figure 8Alloy:KHR35CT, 100X, service exposed material (125000h), from bottom 1 meter section at failure, 100X, microstructures from OD (left), core and ID (right) show primary carbides at dendritic grain boundaries. Creep voids are observed along primary carbide chain towards mostly on ID and OD edges. A few isolated creep cavites are observed at core along with tendency for carbide coarsening.Sound attenuation measured is 60 to 64 dB

Overheated failures for relatively short durations

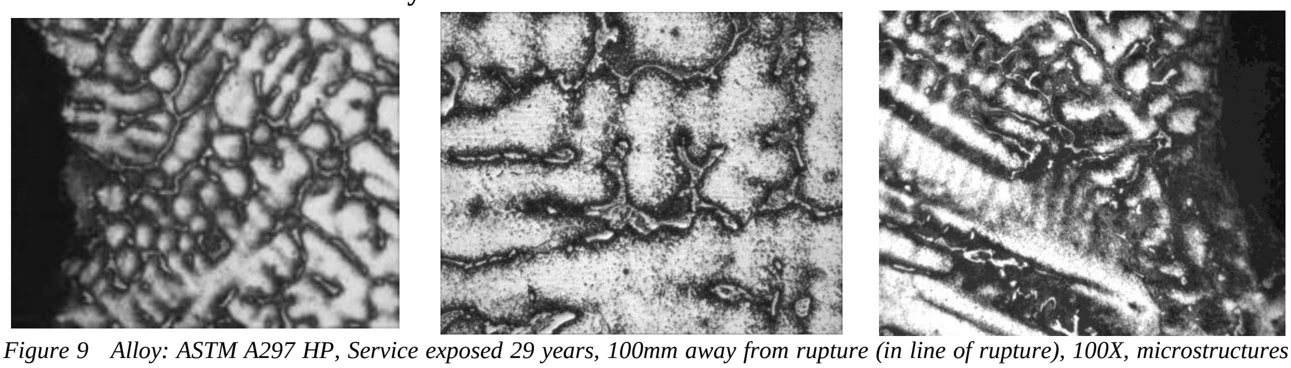


Figure 9 Alloy: ASTM A297 HP, Service exposed 29 years, 100mm away from rupture (in line of rupture), 100X, microstructures from OD (left), core and ID (right) show primary carbides at dendritic grain boundaries. OD and ID show intense tertiary creep cracking. Creep fissures are observed along primary carbide chain towards on core. The secondary carbides area nearly absent within the grains. Sound attenuation measured is 56 to 58 dB

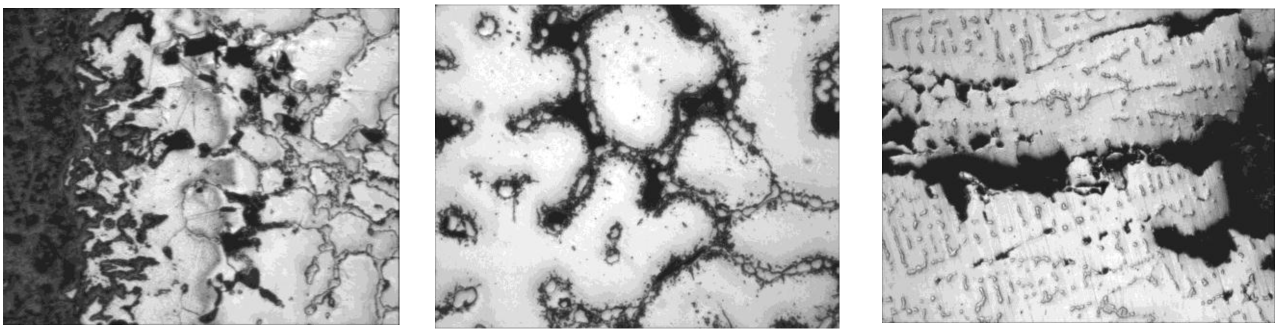


Figure 10 Alloy HK40, Service exposed 29 years, 100mm away from rupture (in line of rupture), 100X, microstructures from OD (left), core and ID (right) show primary carbides at dendritic grain boundaries. OD and ID show intense tertiary creep cracking. Creep fissures are observed along primary carbide chain towards on core. The secondary carbides area nearly absent within the grains. Sound attenuation measured is 56 to 62 dB

Suggested Model for tube life assessment based on integration of NDT

Role of diameter measurement: The increased diameter of tube can reflect creep strain. At increased diameter the same internal pressure would exert higher hoop's stresses and lead to further accelerated creep damage. The rate of creep damage can be estimated based on past inspection records, original (not nominal) tube diameter, measured tube skin temperature records and LMP calculations.

Role of tube skin temperature monitoring: The slight changes in burner alignments, distribution in fuel distribution, clogging of burners or degradation of catalysts can bring up the tube skin temperature. Regular monitoring and record of thermal imaging / pyrometer temperature records are important for consideration of tube life prediction. The average temperature of exposure together with present microstructural condition can be used to correlate stress v/s service time and LMP for life prediction.

Thermal fatigue: A record of number of start-up and shutdowns during the entire service life of reformer furnace can be accounted for transverse nature of cracking in tube. The higher the number more is the probability of thermal fatigue initiation and failure. Generally, 2 to 4 cold start ups and shutdowns in a year can reduce tube life by 50%.

Oxidation damage: The high chromium content in alloys combats oxidation. However, depending on occasional temperature overshoots and/or flue gas composition, the material tends to form oxide layers, spalling and promote partial decarburization from external surface. The damage may be indirectly assessed in combination of outer diameter measurement and reduction of tube thickness. Reduction in thickness and its trend would reflect rate of oxidation in long run, which may be utilized for increased precision on RLA judgment based on stress calculations.

Based on past experience, the test result summary and available published literatures, report can be produced to show overall condition of the tube. An ageing index is proposed hereunder on consideration of various NDT results. The table describes parameters for indexing.

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			

** Value is indicative, dependant on instrument settings, surface roughness of tube, test equipment and coupling conditions.*

Conclusion

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

Significant or complete loss of ultrasound energy however is 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 guide judgment. There is no proper consideration given to tube bowing, surface roughness or catalyst degradation for the life prediction of tubes.

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