Controlling the stresses of the primary reformer

Risk associated with the primary reformer is highly dependent on its operation. In this article we look at common problems associated with catalyst tubes, pigtails, operating close to material limits etc. and discuss latest practices and new materials to prevent these issues and allow plants to run at maximum output without unplanned outages.

Steam reformers used in hydrogen, ammonia and methanol plants are complex, energy intensive and expensive. By nature their design is often aggressive, due to the need for harsh operating conditions and specialty materials. A failure in the primary reformer typically has large financial implications, often running into millions of dollars, as significant downtime is incurred alongside the costs of tubes, engineering and catalyst.

The basics

In a conventional steam reforming process (Fig. 1) hydrogen and mixture of CO/CO₂ are produced by reacting methane with steam over a nickel catalyst at high temperatures. The catalyst is contained in the reformer tubes, which are located in a box type fired furnace (Fig. 2) that provides the large endothermic heat of reaction.

The basic reactions of the steam reforming of methane are expressed by the following chemical equations.

**Desired reactions:**

\[ \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \]  
\[ \text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \]  
\[ \text{CH}_4 + \text{CO}_2 \rightarrow 2\text{CO} + 2\text{H}_2 \]

**Unwanted reactions:**

\[ 2\text{CO} \rightarrow \text{C} + \text{CO}_2 \]  
\[ \text{CH}_4 \rightarrow \text{C} + 2\text{H}_2 \]  
\[ \text{CO} + \text{H}_2 \rightarrow \text{C} + \text{H}_2\text{O} \]

Reaction (1) is known as steam methane reforming, while reaction (2) is referred to as the water gas shift reaction. Both reactions are reversible and approach equilibrium. In addition to the desired reactions (1) and (2), other side reactions (3, 4, and 5) are under certain conditions also possible. Selection of suitable catalyst and appropriate operating conditions will promote reactions (1) and (2) and suppress reactions 4 to 5. Reaction (3) takes place in steam reformers where CO₂ available downstream of the CO₂ removal section, is recycled back to the reformer in order to increase CO formation in the syngas (methanol, oxo syngas production).

The conversion is favoured by a high steam to carbon ratio (in excess of the stoichiometric quantity), high outlet temperature, low pressure and high catalyst activity. There are restrictions and limitations for maximum conversion:
- A steam to carbon ratio that is too high will make the process less energy efficient, large quantities of excess steam have to be condensed and high volumetric steam flow will increase the equipment cost. Low steam to carbon ratio will improve the energy efficiency, but can form carbon in the catalyst pores and other undesirable byproducts.
- An operating temperature that is too high poses problems of heat transfer and lowers the mechanical strength of the reformer tube material (metal temperatures up to 960°C under pressure of about 35 bar). Low operating temperature reduces the conversion, but sometimes this offers an attractive possibility for conversion completion under optimum conditions downstream the primary reformer;
- An operating pressure that is too low increases the cost of equipment and makes the reforming process inefficient, as it is always necessary to compress the produced syngas at higher pressures for further processing (purification and synthesis). There are mechanical limits for higher reforming pressures, but in general higher reforming pressure reduces the overall operating and investment cost.
- Catalyst with too high activity could at first improve the conversion rate, but because of its sensitivity, it may easily lose activity due to feedstock impurities, or because of maloperation. Small size catalyst in a given total reformer tube volume will present a higher surface to catalyst volume ratio and thus a better approach to equilibrium, but also gives a higher pressure drop. Loss of activity may lead to reformer tube overheating, as reduced conversion means less heat absorption for the endothermic reforming reaction.

**Primary reformer configurations**

Several configurations of reforming furnaces are in use today, characterised mainly by the disposition and position of the burners. The most common types are top-fired, side-fired and terraced wall-fired reformers. Bottom-fired reformers are not very common in modern syngas plants. Fig. 3 shows the overall geometry of these reformer furnaces.

The top-fired reformer uses multiple rows of reformer tubes with burners located in the arch on each side of the tubes. The heat to the reformer tubes is supplied by the radiating products of combustion. The main advantage of this configuration is the few burners relative to the reformer tubes, the higher radiant efficiency, the presence of the high heat flux zone in the “cold” inlet of the feedstock and the very large reformer tube number which can be accommodated in one radiant box. The main disadvantages are the limitation in the heat input control and the hot operating level at the top.

The side-fired reformer has multiple radiant wall burners along both side walls and one row of reformer tubes in the middle of the box. The heat to the reformer tubes is emitted from the radiant walls. The main advantage is the uniform heat distribution and the very good heat input control. Disadvantages are the large number of burners required, the lower radiant efficiency and the size limitation of the fired box (single box for 100 to 150 reformer tubes).

The terraced wall type, developed by Foster Wheeler may be regarded as an intermediate between the side-fired and bottom-fired reformers. The reformer has inclined walls with several terraces on which upward firing burners are installed. This unique burner positioning makes it possible to adjust the heat flux in each zone.

Bottom-fired furnaces have a rather constant heat flux profile along the reformer tube with high metal temperatures on the outlet side.

In a conventional reforming process only 40% of furnace duty is absorbed by the endothermic heat of reaction. About 35% is recovered in the form of waste heat export steam, by utilising part of the
latent heat of the syngas for CO₂ removal and by preheating feed stock-combustion air or boiler feed water in the convection section of the reformer, where flue gas is cooled from 900 to 950°C to about 125 to 150°C. In the region of 20 to 25% of the heat applied is lost in the stack, in cooling water and in heat losses.

Overview of reformer tubes

The most critical item in a fired reformer are the reformer tubes in which the catalyst is placed. Reformer tubes constitute up to the 30% of the total reformer cost. For mechanical and process reasons, a typical reformer tube is 10.0 to 14.0 m long, with ID of 75 to 140 mm and wall thickness between 8 and 15 mm. Reformer tubes are usually centrifugally cast and machined in the internal borehole. The tubes are typically made in 3-4 sections consisting of individual castings.

The size of the primary reformer has increased step by step over the last decades due to increasing ammonia plant capacities. Whilst a primary reformer for a 400 t/d ammonia plant designed in the 1960s had less than 200 reformer tubes, a reformer for a 3,300 t/d ammonia plant designed nowadays is equipped with more than 400 reformer tubes arranged in eight rows. Although ammonia plant capacities have increased considerably the number of installed reformer tubes, i.e., the installed heat exchange area, has been reduced continuously for a given capacity. A modern reformer for an ammonia plant capacity of 1,000 t/d has less than 900 m² heat exchange area. The same reformer designed more than 30 years ago had a heat exchange area of more than 1,300 m². Together with the optimisation of the reformer tube pitch, i.e., the tube-to-tube distance and the tube row distance, a very compact reformer design is available today.

Stress to rupture of reformer tubes

The high operating temperature and pressure to which the primary reformer tubes are exposed mean that the reformer tubes are close to the metallurgical limits and therefore operate in what is commonly known as the, “creep regime”. This means that reformer tubes will suffer gradual plastic deformation, resulting in micro voids, which develop into large cracks with time in service. Eventually the cracks will propagate throughout the thickness of the reformer tube such that process gas can leak from the reformer tube into the flue gas side of the reformer. This is illustrated in Fig. 5, which highlights the progression of creep through a reformer tube with time.

Once cracks have reached the inner wall the reformer tube can be considered to have failed. Although this will normally take many years it can, in very specific process circumstances, happen in a matter of minutes. As can be seen from Fig. 6, stress to rupture is dependent on the tube wall temperature with modern micro-alloys offering significant benefits over older materials. As a result the tube wall thickness has been reduced considerably whilst keeping the same design tube life time as before (100,000 hour).

Fig. 5: Progression of creep through a reformer tube

Source: IKR Richter
Development of reformer tube materials

The materials used for reformer tubes in recent decades are illustrated in Fig. 7. The first centrifugally cast reformer tubes were made of HK 40, a material containing 25% chromium and 20% nickel. Today microalloyed steels are used that contain 25% chromium, 35% nickel, niobium and traces of other elements like zirconium and titanium. As alloy strengths have increased, tube wall thicknesses have decreased, thus reducing the thermal stress, and process volumes have increased, whilst keeping the same design tube life time as before.

A 14 mm thick reformer tube made of microalloyed steel would have a wall thickness of approximately 17 mm if made out of HP modified and more than 30 mm if made out of HK 40. Clearly such thick reformer tubes do not represent an optimal design, and therefore reformers utilising older tube metallurgies will have a larger number of narrow diameter tubes. The reformer tube inlet pressure, the inside diameter of the tubes and the reformer tube inlet pressure, the inside diameter of the tubes and the design temperature, can be increased with an unacceptably large wall thickness. Reformer tube inlet pressures have increased from around 20 barg up to more than 40 barg and the inner diameter of the reformer tubes has increased in steps from 97.2 mm to 127 mm over the last decades.

The strength improvement between HK 40 and later alloys is due to the increased amount of secondary carbides, which are finely distributed throughout the parent material. They prevent the movement of dislocations through the material and hence reduce the extent of creep damage. In HK 40 only the chromium forms carbides whilst for the later alloys, niobium forms secondary carbides.

Titanium, zirconium, tungsten and caesium are all strong carbide formers and form finer carbides that last longer, therefore providing higher strengths that are retained for longer. These higher strengths allow for a reduction in reformer tube wall thickness when utilising modern alloys. By changing to an improved reformer tube material it may permit, for example, a reduction of the overall reformer tube count could be reduced or an increase to the inside reformer tube diameter.

The generally accepted methodology for designing reformer tubes is to utilise the Larson-Miller plot with the appropriate data for the metallurgy to be used. This plot can be used to determine whether the assumed reformer tube dimensions and operating conditions will deliver the required reformer tube life time. The reformer tube dimensions or operating conditions can then be varied to achieve the required design life time.

Most reformer designers or reformer tube vendors design the reformer tubes to provide 100,000 hours (or circa 11 years) of continuous operation based on the assumed design conditions. However, this steady state approach does not take into account start-ups and shutdowns, designers tend to use 75-85% of the mean stress to rupture values allowing for start-up and shutdown transients. Deviations from these assumed design conditions will clearly affect the achievable reformer tube life time.

New alloy materials for reformer outlet systems

Outlet systems are an important part of steam methane reformers. Although these elements are typically located outside of the reformer firebox, they operate at severe conditions up to the metallurgical limits and while significant research efforts have been made over the last 30 years in improving alloys used for steam reformer catalyst tubes, no major efforts were devoted to improving outlet system materials.

Outlet manifold materials differ depending on reformer designer preferences. Typically, low temperature systems with design temperatures below 829°C use either 800 HT or cast equivalent 20Cr-32Ni, while designs targeted for higher temperatures use cast materials 20Cr-32Ni almost exclusively.

20Cr-32Ni alloy material supplied by the Schmidt+Clemens Group is named Centralloy® G4859. This alloy is a low carbon alloy designed to maintain good ductility after ageing and a good creep resistance in the range of 800°C to 1,000°C. Niobium is used as carbide forming element (20Cr-32Ni-Nb). A substantial benefit of the cast alloy with Nb is that the creep strength is about 50% higher than the wrought alloy (800 HT) with Al and Ti.

New Schmidt+Clemens materials have recently become available for outlet header components as alternatives to standard material GX10NiCrNb32-20.
Steam methane reformers

1.5 balance 0.5 0.1 0.13 0.1 32 20 20 25 32 1 1.5 0.5 balance 1 0.5 1 1 37 balance maximum operating temperature of 1,000°C.

Composition optimisation has enhanced quantities of elements like titanium and alloy 20Cr-32Ni-Nb.

Significantly improve creep resistance and ductility seen for alloy G4859 in the range of 700-900°C might be related to the stability of brittle intermetallic phases like G-phase, leading to a localised embrittlement of the alloy material.

**Creep tests**

Creep resistance is one of the major requirements for these type of materials. Creep strengthening is accomplished by the formation of carbides in the microstructure. Material creep resistance is typically shown in Larson-Miller curves (parametric stress rupture strength). Minimum parametric stress to rupture values for a life time of 100,000 hr is represented in Fig. 10.

**Characterisation and results**

During the development of these new materials, Schmidt+Clemens carried out extensive characterisation of tensile properties and creep performance. Additionally, significant efforts were made on material microstructural characterisation and accelerated ageing tests in order to study the driving forces regarding material ductility exhaustion.

**Tensile tests**

Room temperature (RT) and high temperature tensile tests were performed on these three materials. 0.2% yield strength, ultimate tensile strength and elongation to rupture properties were measured.

Results for 0.2% yield strength (Fig. 8) showed that the addition of micro alloying elements has improved material yield strength in comparison with alloy G4859.

When comparing the ultimate tensile strength (UTS) for these materials, no relevant differences could be seen between G4859 and G4859 Micro, while H101 Micro UTS values seem to be slightly inferior.

Elongation to rupture values results (Fig. 9) indicated a superior ductility of G4859 at low temperatures, while H101 Micro has a better ductility at higher temperatures. G4859 Micro alloy has a slightly lower ductility. The relevant reduction on ductility seen for alloy G4859 in the range 700-900°C might be related to the stability of brittle intermetallic phases like G-phase, leading to a localised embrittlement of the alloy material.

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<table>
<thead>
<tr>
<th>Composition, wt-%</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Nb</th>
<th>Ti/Zr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralloy® G4859</td>
<td>0.1</td>
<td>1</td>
<td>1.5</td>
<td>20</td>
<td>32</td>
<td>1</td>
<td>-</td>
<td>balance</td>
</tr>
<tr>
<td>Centralloy® G4859 Micro</td>
<td>0.1</td>
<td>1</td>
<td>1.5</td>
<td>20</td>
<td>32</td>
<td>1</td>
<td>additions</td>
<td>balance</td>
</tr>
<tr>
<td>Centralloy® H101 Micro</td>
<td>0.13</td>
<td>0.5</td>
<td>0.5</td>
<td>25</td>
<td>37</td>
<td>0.5</td>
<td>additions</td>
<td>balance</td>
</tr>
</tbody>
</table>

Source: Schmidt+Clemens

or ASTM CT 15C (20Cr-32Ni-Nb). These materials named as Centralloy® G4859 Micro and Centralloy® H101 Micro can significantly improve creep resistance and ductility after ageing over the standard alloy 20Cr-32Ni-Nb.

The main advantage for plant operators are wall thickness reduction of outlet header components, with benefits in weight reduction, and increased resistance to thermal shock. Alternatively, maintaining original wall thickness, lifetime of such components can be substantially increased keeping the same design and operating conditions.

The nominal composition of these materials is represented in Table 1.

**Centralloy® G4859 Micro**

A logical improvement of 20Cr-32Ni-Nb is the development of a micro alloy version – Centralloy® G4859 Micro. Addition of small quantities of elements like titanium and composition optimisation has enhanced significantly material performance. Like standard material G4859, this alloy has a maximum operating temperature of 1,000°C.

Centralloy® G4859 Micro has been available in the market since 2011. Currently more than 102 outlet manifold arms and 2950 outlet reducers have been installed in service, together with more than 40 T-pieces and transition cones. Performance of these components in operation has been regarded as excellent.

**Centralloy® H 101 Micro**

Low carbon versions of HP-Nb (25Cr-35Ni-Nb) were originally designed for operation under severe corrosion conditions only requiring a moderate ductility. These conditions are typical in steam cracker applications. Nevertheless, these materials were described in the literature as a potential replacement of 20Cr-32Ni-Nb materials, especially in designs requiring higher operational temperatures.

Unfortunately, lower ductility after aging performance compared with 20Cr-32Ni-Nb has been regarded as the main drawback. Therefore, material replacement in outlet manifold components was not advisable.

Schmidt+Clemens has designed a micro alloyed version of this low carbon material, with an optimised chemical composition, capable of enhancing creep resistance and ductility after ageing over existing 20Cr-32Ni-Nb materials. Furthermore, higher chromium and nickel contents would allow outlet components to be designed for higher temperatures up to 1,050°C.

The first reference in reformer outlet components was supplied in 2016.

**Typical composition of Schmidt+Clemens low carbon alloy materials for outlet components**

![Fig. 8: 0.2% yield strength comparison](image)

![Fig. 9: Elongation to rupture comparison](image)

![Fig. 10: Minimum creep resistance comparison](image)
Both microalloyed materials have a superior creep resistance compared with G4859. Small additions of strongly carbide forming elements lead to the formation of stronger and more evenly distributed secondary carbides in the austenitic matrix.

**Ductility after aging**

Ductility after aging is a major requirement for these types of materials. Material samples are aged in a furnace (controlled temperature and time of ageing), and later aged samples are tensile tested at room temperature to measure elongation to rupture. Ageing conditions and test results are shown in Fig. 11.

Considering all three materials, superior ductility after ageing performance is achieved with alloys H101 Micro and G4859 Micro in comparison with alloy G4859. Such superior behaviour might be explained by the formation of more thermodynamically stable primary carbides and due to delay/suppression of intermetallic phase formation.

**FE modelling of outlet manifolds**

Finite element analysis (FEA) provides the opportunity to test real components simulating the continuous operation in the furnace. FEA can be carried out on outlet header systems, but the model accuracy strongly depends on the quality of the creep model, boundary conditions, geometrical models and correct meshing.

Creep modelling is clearly the most complicated issue. Manufacturers like Schmidt+Clemens provide stress to rupture data. Therefore, having a good creep behaviour modelling is imperative in providing good FEA results.

Analysis results indicate that new materials are improving time to rupture compared with standard 20Cr-32Ni-Nb materials. Nevertheless, inadequate operation or maintenance of outlet header components can lead to overstressed zones that can lead to early component ruptures in operation, even if the entire header is securely designed according corresponding standards.

**Simulation study results**

Two simulation steps were considered for all three materials. The first step considered a static structural simulation of just one second, to evaluate stress/strain distribution on the outlet header. The second step considered a one-year simulation of the part under creep regime. Wall thickness of the component was estimated using ASME B31.3 calculations for alloy material G4859 considering a design time of 100,000 hours.

Some surprising results were obtained from the static structural simulation. Even considering that reformer tube counterweight system was compensating all weight stresses over the material, significant part deflection was observed on header tube arms due to the thermal expansion of the transfer line.

All material results showed that the outlet header tube support location has a strong impact on the stress distribution in the component. Supported areas and T-piece/arm tube zones had the highest stresses in these models. Therefore, these parts are the most susceptible to failure due to creep damage.

Life time predictions can be applied into the model considering the Larson-Miller curves for each material. Most stressed portions of the outlet header are determining the lifetime of the component in operation.

According to the simulation, material G4859 will have a time to rupture of 133,000 hours in such an area. On the other hand, more creep resistant material like G4859 Micro (255,000 hours) and H101 Micro (220,000 hours) will have a significantly higher time to rupture in operation.

Lack of maintenance or inadequate alignment of header components (like arm supports) might add additional stresses on the part and, consequently, reduce dramatically the lifetime of the outer header.

Results of these simulation efforts show that material selection is the most critical part in ensuring that the outlet system is able to achieve the required design time.

In addition, components of the entire header system like tube supports, can also have a significant impact in the outlet header performance/life if they are not working adequately.

**Pigtails material selection**

Pigtails are piping systems for the connection of the catalyst tubes to the manifolds in both the inlet and outlet of the reformer are prone to different mechanical and thermal stresses and possible failures (Fig. 12). Inlet pigtails are less critical as they work at lower temperatures (550-600°C), but still require careful material selection. Outlet pigtails, on the other hand, which carry the reformed gas from the catalyst tubes to the collection manifold, must be able to...
Steam methane reformers

Risk to the safety of personnel. Hydrogen leaks with risk of explosion and into the crack itself, it is important to have strength rupture, and consequently burst material from cracking due to low creep resistance is the cal fatigue to the tubes and the bended shape they have, creep resistance is the most important property. To prevent the material from cracking due to low creep strength rupture, and consequently burst into the crack itself, it is important to have a resistant material. Ruptures can lead to hydrogen leaks with risk of explosion and risk to the safety of personnel.

The properties of stainless steels are different when there is “diffusion” of gases into the protective oxide layer (Fig. 13). In these corrosive environments good resistance to creep and structure stability is required. The grain size of pigtails also has a huge influence on the mechanical behaviour of these materials.

Industry requirement for these particular materials regarding grain size is commonly found in standards and specifications as “average grain size 5 or coarser” according to ASTM E112. This specification does not, however restrict the grain size distribution. It is known that the upper and lower tail of the statistical distribution has a large influence on mechanical behaviour of materials.

There is therefore a general need for precise grain size characterisation and grain size control, which has a strong influence on creep strength. Restricted grain size is also required in the bent portion of U-bends. Cold bending followed by annealing may cause the grain size to fall outside the preferred grain size window.

Research into grain size and grain size control is ongoing at Sandvik, who can provide narrow grain size windows upon request. A commonly used pigtail material is Sandvik Sanicro 31HT, an austenitic nickel-chromium alloy characterised by:
- high creep strength;
- very good resistance to oxidation;
- good resistance to combustion gases;
- very good resistance to carburisation;
- good resistance to nitrogen absorption;
- good structural stability at high temperatures;
- good weldability.

Sandvik Sanicro™ 31HT can be used at temperatures up to about 1,100°C. In order to have the best ductility, it should be used above 700°C.

Referring to industry standards and the most common specifications, an average grain size of 5 or coarser is required which can be mainly derived from ASTM B 407.

The methodology is described in ASTM E112, however, this specification does not contain any requirement regarding the grain size distribution. Consequently, the manufacturing process of pigtails must be adjusted in a manner that the properties and hence the behaviour of these tubes lead to an increasing service lifetime.

Reformer revamping

Many critical components of the steam reformer unit, such as the catalyst tubes, pigtails, intermediate tube sheets and shield coils are inevitably forced to operate very close to their material design limits and there is a time frame, before a point of failure, when symptoms or warning signs can be identified in time and with good reliability, avoiding unplanned outages and potential risk to plant personnel.

In many cases, conditions that were already critical can be exacerbated when improvement modifications or revamping activities are carried out, particularly when the plant owner does not request a licensor assessment, which is fundamental to minimise risks and avoid any subsequent surprises on plant consumption figures.

The following two cases demonstrate the importance of carrying out a detailed data analysis of the whole reformer to identify where abnormal conditions or upset operating parameters are located.

Revamp case 1

In this first case, Casale was awarded an EP project for an ammonia plant revamp to reduce energy consumption and increase plant ammonia production capacity from 1,700 to 1,900 t/d.

The methodology is described in ASTM E112, however, this specification does not contain any requirement regarding the grain size distribution. Consequently, the manufacturing process of pigtails must be adjusted in a manner that the properties and hence the behaviour of these tubes lead to an increasing service lifetime.

The manufacturing process is of even greater importance when it comes to the bending of pigtails. Based on the fact that there are many different furnace designs, pigtails come in different shapes, they may be straight but may also have bends. A high amount of strain is induced during the bending process and it is important to have appropriate control of the deformation, minimise ovality and avoid scars or superficial defects. Depending on the degree of cold work induced during the bending process, this will cause the material to change its microstructure which will then have an impact on the performance during service lifetime. In order to improve pigtail performance it is recommended to perform a final annealing heat treatment.
A detailed assessment of the plant revealed many limitations in the primary reformer convection section (Fig. 14) as it had already been revamped many times. The reformer is an induced draft top fired type with an omega convection section configuration and an external auxiliary boiler.

In the past, the client decided to replace the mixed feed coil and process air coils with new ones with the aim to reduce the fuel consumption to the reformer arch and tunnel burners which was progressively increasing. It was decided to proceed providing an increased surface on both coils of about 50%.

Following this modification, the temperature of the flue gas stream coming from the reformer hot leg dropped so much that the steam superheating burners had to be operated at their maximum heat release in order to reach the desired steam superheated temperature. However, this practice can create issues with the steam superheater coil.

Analysis
After data collection, an overall detailed analysis of the primary reformer was performed, and the original reformer design was verified.

It was found that both the mixed feed coils and the process air coil, before replacement, were significantly underperforming and were unable to achieve the desired process stream outlet temperature despite the flue gas temperature from the tunnel section being higher than required.

Based on Casale’s experience, this primary reformer section is very critical and subject to mechanical degradation, accelerated by operating conditions, which normally lead to minor or major underperformance of the coils. This phenomenon is made worse by the practice to compensate for the temperature drop by increasing the tunnel combustion heat release.

The second point to be analysed was related to the new geometry of the coils which, it turned out, affected performance of the cold steam super heating coil. This solution in effect moved a problem from one section to another: the cold steam super heating coil section.

The coil was found be operating well below the expected performance and below the expected performance considering operation aging. This was demonstrated by the hard firing of the steam superheating burners.

Solution
The plant was revamped with the aim to preserve the existing mixed feed and process air coil geometries considering the project targets and at the same time solving the balance issues of the convection section.

The overall steam consumption required for the reforming reaction and internal plant use was decreased and optimised. In this way, it was possible to reduce the required duty of the BFW preheater coil, whose surface was partly replaced by a new coil, with the purpose to “cold” preheat the process air so that the surface of the existing “hot” process air coil could be reduced (Fig. 15).

These modifications allowed more heat to be released in the hot leg available downstream for steam, while reducing the steam flow making the coil surface adequate despite the plant capacity increase.

In the end, the original normal operability of the steam superheating burner section was restored and the whole convection section was rebalanced. As a consequence of reducing the heat release from the superheating burners, the operating conditions of the superheater coil is milder, and stress is reduced.

Since it was also found that the cold steam superheating coil together with intermediate tube sheets had lost most of their residual life, a new design was provided that fitted the geometry of the existing one but with upgraded materials of construction.

Revamp case 2
In this second case, Casale was requested to assess the operation of a steam reformer unit for a 1,500 t/d methanol plant. The steam reformer had been revamped many
times in the past, mainly in the convection section, without any modifications to the radiant chamber. Some years later the catalyst tubes at the end of their life were replaced by new ones manufactured with the latest generation microalloy material. During the same turnaround, it was decided to change all primary reformer original low-NOx burners with the new generation ultra-low NOx burners.

The reformer is a very big (16 tube rows) balanced draft top-fired type with a horizontal convection section.

Analysis
After data collection, an overall detailed analysis of the primary reformer was performed and the original reformer design verified. The plant process scheme is based on pure steam reforming technology, which makes the furnace operating conditions very critical since it requires a reforming process outlet temperature of about 900°C. From a preliminary analysis of the recorded tube skin temperatures, a temperature deviation was found ranging from 30°C for the inner tube rows to 50 °C for the outer tube rows.

Due to the use of ultra-low NOx burners it was necessary to analyse the flue gas distribution inside the radiant chamber in greater detail, since this technology limits pollutant emissions by forcing the burner to operate with inefficient combustion, staging the fuel into many zones (two or more). As a result, the flame shape is worsened in term of dimensions, affecting both the radiant chamber efficiency and the catalyst tube skin temperature profile.

From the computational fluid dynamics analysis, it was clear that the tunnel extraction system was not adequate to mitigate the poor distribution in the radiant chamber, while the combustion air distribution was adversely affected by the ultra-low NOx burners which require a much lower pressure drop on the air side than conventional low NOx burners.

Fig. 16 shows the pressure distribution on the combustion air ducts.

During the site survey, it was found that the entire system was balanced by regulating the firing of each burner throttling the relevant combustion air damper and fuel gas valve.

Of course, this practice relied exclusively on the plant operators and is commonly applied to steam reformer units to mitigate radiant chamber maldistribution and provide a uniform catalyst tube skin operating temperature. However, although this approach is acceptable to reduce stresses of the catalyst tubes, it can lead to burners being operated with process parameters far from the operability and stability range.

From a mechanical point of view, the outlet pigtailed proved to be the most critical components of the system. Despite the catalyst tubes operating at very high temperatures, the new micro-alloy material together with the low design pressure of the tubes, provided sufficient safety margin on the tube thickness which can be converted to an extended tube life. The outlet pigtailed, on the other hand, were manufactured of Alloy 800 HT and were operating very close to the material design limit. In this case, the reformer outlet temperature variation had to be strictly contained within a reasonable range.

Solution
Some rectifications were proposed in order to solve the issues on the combustion system with the aim to preserve and extend the life of critical items. On the air side, a dedicated calibrated orifice plate was designed and provided just before the burner damper to ensure the required pressure drop for distribution and the necessary air split ratio between the inner and outer burners.

It should be noted that the modification itself does not have an impact on the overall duct pressure drop since the local damper
The effect of these measure were:
- to reduce the temperature spread recorded on the skin temperatures and on the outlet pigtails by about 40%;
- to operate the burners within a safe and operable range;
- to have a straightening effect on the flames to reduce the risk of tube impingement.

Reformer tube failure mechanisms

There are two key operating conditions that must be considered in reformer tube design, the reformer tube operating temperature and the tube-side operating pressure.

Large temperature excursions reduce the residual reformer tube life time because higher temperatures increase the rate of loss of secondary carbides which reduce the strength of the parent reformer tube material. As a rule of thumb, a 20°C rise in tube wall temperature will halve the expected reformer tube life time. For example, an excursion of 200°C for six hours will reduce the expected reformer tube life time by approximately nine months. Operation at higher pressure than the design pressure, for example due to higher than expected pressure drop downstream of the primary reformer, will increase the differential pressure across the reformer tubes and therefore reduce the reformer tube life time. Transients such as start-ups and shutdowns will lead to the generation of thermal stresses within the reformer tubes. These stresses are cumulative and so will reduce the ultimate reformer tube life time. The faster the increase or decrease in reformer tube temperatures, the greater the stresses and therefore the greater the reduction in the ultimate reformer tube life time. A rapid shut-down can reduce the life time of the reformer tubes by four to six months in comparison to a controlled shutdown. The most common failure mechanism of reformer tube is nearly always due to the creep of the reformer tube material; however, others do exist.

A typical creep failure is longitudinal with the crack extending axially from the original failure point in both directions as illustrated in Fig. 18. There are a number of different causes of reformer tube failure depending on the location of the section of reformer tube and the problems that can affect the reformer tubes in these different locations. The root cause of reformer tube failure can be broken into two discrete groups based on whether the section of reformer tube has been overheated due to a general or a local effect, i.e. generalised overheating or localised overheating.

Generalised overheating is defined as a large area of the reformer tube being overheated (typically greater than 2 m of reformer tube which affects many tubes). Generalised overheating can be caused in a number of ways, for instance:
- The normal overheating process that occurs within a primary reformer due to the operating temperature required by the steam reforming process;
- Overheating during transients such as start-ups and shut-downs where the fuel rate has not been sufficiently reduced;
- Low catalyst activity due to poisoning or carbon formation, reducing the rate of hydrocarbon reforming and hence the rate of heat absorption;
- Fouling of foreign material at the outer and inner surface of the reformer tubes

Localised overheating is defined as a small area (typically 1-2 m in length and can be isolated to 5-10 reformer tubes) of the reformer tube being overheated. Again, there are a number of different ways that this can occur due to:
- Flame impingement due to poor alignment of the burners or where the burners ports are blocked;
- Catalyst bridging which leads to void formation and hence a reduction in the rate of reforming with the associated increase in tube wall temperature;
- Point problems such as the tunnel port effect;
- Failure at welds or within the parent reformer tube material due to poor manufacturing techniques. With advances in the metallurgy of weld materials this effect has made this less common; however, there are still a large number of reformers that still utilise older weld materials and are vulnerable;
- Fouling of foreign material at the outer and inner surface of the reformer tubes.

Pinched tubes

Isolated hot spots and tube ruptures can occasionally develop on radiant tubes during operation. Rather than shutting down the furnace to replace these isolated tubes, the tubes are externally pinched by hot crimping both inlet and outlet pigtails. Some leaks at the crimped locations. A second crimping before the pigtail gets cold at 90°C to the first crimping can be done if there is space in the straight leg of both inlet and outlet pigtails. Some users use a second crimping as a backup against failure of first crimped locations. If a leak persists there is no alternative but to shut down the reformer furnace for repair or replacement.

Thermal shock

Thermal shock is very damaging to tube life, it can even cause catastrophic effects to the whole reformer. After a thermal shock event it is important to perform an inspection, check for damage and have a good plan in place to deal with all inspection findings. Ideally the inspection results
can be compared to a previous inspection. Any damage that occurred during the excursion should be evaluated carefully, due to the rapid damage all indications are of importance. After a thermal shock it is much more difficult to predict how the damaged areas will react when they are brought back online.

**Overfiring protection case study**

In early 2015, when Profertil was performing a hot restart of their ammonia plant, an uncontrolled and rapid increase in flue gas temperature was noticed in the primary reformer. After natural gas feed was introduced to the primary reformer, it was observed that a rupture of several catalyst tubes had occurred and the plant was tripped immediately. Profertil requested Haldor Topsoe A/S to take the lead technical advisor role in a thorough root cause analysis, performed to identify the reason(s) for the tube rupture incident.

The results of this thorough root cause investigation led to a solution that assures such incidents will not happen again. The incident with ruptured tubes not only impaired plant capacity utilisation until the re-tubing of the furnace, but more importantly, the leaked gas from the ruptured tube could have resulted in unsafe conditions. Therefore, the possibility of avoiding this type of incident is of paramount significance to all plants operating with any type of tubular reformers. Following this incident, an automated overfiring protection (OPF) management system that provides four elements of protection against overfiring of primary reformer tubes was developed.

The OPF management system addresses both ‘local’ and ‘global’ causes of primary reformer catalyst tube overheating.

OPF does not allow fuel header pressure increase during start-up and enforces a symmetric burner ignition pattern. During start-up, these two protection elements not only help to avoid catalyst tube overheating but also ensures better heat distribution inside the furnace.

Moreover, double protection elements of duty and bridge wall temperature limitation ensure parity in duty input and duty uptake by adjusting fuel flow to the burners based on maximum estimated duty for the primary reformer at a particular capacity.

OPF is suitable and highly relevant for all types of tubular reformer designs.

**Monitoring tube wall temperature**

Reformer tubes are highly valuable assets. A large reformer contains hundreds of tubes, at an average tube cost of approximately $15k to $30k each, and unplanned outages can result in significant costs of $350k to $1m a day, so increasing tube life and reducing tube failures is essential asset management. That means having an effective method of temperature measurement.

The monitoring of tube wall temperatures (TWT) can help optimise catalyst tube life and ensure longevity, energy efficiency and productivity. With better temperature control, operators can increase profit by increasing output and lowering operating cost, resulting in better utilised feedstock, catalyst and fuel. A 2% improvement in output has the potential to save approximately $1 million a year.

Issues with the burner, flue gas distribution and the catalyst can all directly affect TWT and lead to premature tube failure. To prevent this, most operators tend to be overly cautious with TWTs. However, excessively cautious firing reduces the reaction rate and thus leads to lower production and/or higher energy consumption – a 10 °C drop in temperature can result in 1% decrease in productivity. Even taking a cautious approach, tube failures can still occur due to hot spots on tubes and hot areas within the convection box. Mechanical stress on the hot tubes increases exponentially, in worst cases causing tube ruptures.

Even though producers may be running at a reduced rate, they are still not guaranteed to have a balanced, reliable reformer. Reformer tube failure and process flow problems come about when temperatures are too high. Even operating at temperatures only 20°C above the design temperature can cut a tube’s lifetime in half. Maintaining optimum temperatures is therefore critical.

A thermal gradient through the tube wall is more significant at the bottom or close to the bottom of the tube, causing differential creep strain, which is a primary cause of damage. A fifth of all incidents involve tube cracking. Operators are required to have an in-depth understanding of reformer behavior and must also be able to analyse data and make rapid decisions when faced with catastrophic failure.

The burners, which fire directly inside the fire box from the top, sides or both, are also very important to tube efficiency, as the flames must not impinge on the tubes or wall. Proper alignment of the burner is very important to avoid flame impingement, gas flow restriction, burner issues, external tube scaling and afterburning (tube leaks).

Significant operator experience is necessary to fully understand basic reformer construction, process flow, heat transfer principles, background radiation, and emissivity along with the cooling effects that occur when the peep door is opened. Regularly opening a peep door can increase stress on the tubes and potentially cool those directly in front of the door by a variance of 30°C. With that in mind, operators need data on the TWT that is accurate, repeatable and reliable.

By continually monitoring readings, the operator will get an early warning of increasing tube wall temperatures, which can then be used to counteract potential catastrophic failure. Continuous monitoring, likewise, will allow the operator to safely and confidently increase temperatures, with a view to increasing production.

**TWT measurement methods**

In order to meet the demands for greater production, efficiency and safety, continuous 24/7 monitoring is required. Several different temperature measurement methods are available, two examples are given below:

- **Handheld spot pyrometers** enable users to take routine spot measurements to optimise steam reformers by maintaining operation closer to design temperatures and, in many situations, the pyrometers can provide adequate accuracy. However, with pyrometers, the operators are only able to view a local spot on the tubes and may miss hot spots in other locations.

- **Fixed thermal imaging provides more accurate and repeatable results than handheld pyrometers as they are less liable to human error and enable optimisation of the TWT to ensure a long tube life. Thermal imaging cameras are inserted into the reformer, with the end of the imager ¼” from the inside reformer wall refractory. Imaging is water- and air-cooled to ensure accuracy in the hot atmosphere of the reformer. This method improves efficiency and minimises the risk of catastrophic failure.**
Accurate temperature measurement must take emissivity into account. Within the reformer environment, several objects can reflect off the surface. Handheld pyrometers and visual inspection can wrongly interpret the reflections as real data, causing errors in temperature measurement. Thermal imaging cameras that are mounted strategically within the reformer do not allow this to happen, such as AMETEK Land’s Near Infrared Borescope (NIR-B) 3XR – which is certified for hazardous areas. The fixed thermal imager delivers a high-resolution image, with accurate real-time measurements of both the tube skin and refractory surface (Figs 19 and 20).

The image, combined with the 90° angle field of view, allows for multiple parallel tubes to be measured simultaneously. This can dramatically enhance efficiency and safety, as well as provide better asset management and furnace optimisation.

One of the major benefits of using fixed thermal imagers like the NIR-B 3XR is their rapid response time. Using the AMETEK Land Image Processing Software (LIPS) provided with NIR-B 3XR, for example, the software will sound an alarm the moment the tube wall reaches the maximum temperature in any region, identifying the problem region and allowing the operator to take corrective measures to fix the issue.

**Case study**

Air Liquide, the world leader in gases, technologies and services for industry and health, understands the critical importance of managing TWT and required a solution to deliver highly accurate and more complete measurement of the equipment and process, compared to spot temperature measurements, whilst operating in a hazardous environment.

AMETEK Land recommended its Near Infrared Borescope (NIR-B) 3XR, which provides a high-resolution thermal image with real-time high accuracy temperature measurements of both the tube wall and refractory wall surface, allowing for background compensation.

With the AMETEK Land solution in place, Air Liquide is now continuously measuring the temperature of reformer tube walls.

Gonzalo Navarro, Production Manager at Air Liquide Ibérica de Gases, explains: “Our main drivers in investing in AMETEK Land’s NIR-B 3XR were to extend tube and catalyst life, which we are achieving as a result. We are continuously learning about our reformer, which enables us to balance it correctly and follow online our main and critical asset.”

He adds: “Now, our teams can monitor the temperature of the tubes continuously, they are able to make more informed and confident decisions implying greater plant reliability”.

Air Liquide’s Research and Development team has since approved the NIR-B 3XR thermal imager for potential installation in additional steam methane reformers.

**Clariant TWT monitoring**

Clariant offers various technologies for monitoring the tube wall temperature. The simplest of these, the pyrometer, allows reliable single-point readings of the tube wall temperature by measuring through peepholes. As it is designed for ease of use, pyrometer measurements are limited to tubes which can be accessed through the peepholes. In addition, readings should be corrected for background radiation.
A more advanced solution is Clariant’s Thermal Scan, a high-resolution thermal imaging borescope which measures temperatures from 600 to 1,100°C at a short, accuracy-enhancing wavelength. The instrument presents a real-time, three-dimensional heat profile of all tube rows in the furnace, allowing easy detection of uneven heat distribution or hot spots. Plant operators benefit from a comprehensive temperature survey, which includes thermal images as well as recommendations for burner adjustments.

Alternatively, the Thermal Scan Plus Gold Cup has been developed for measurements using a golden reflector. This method provides superior precision due to its near-perfect reflectance. The data is used to calibrate the standard Thermal Scan, thus providing an extremely accurate temperature profile of the entire furnace (dT < ±/− 5°C). These instruments enable more effective troubleshooting, and help operators achieve maximum reformer performance and lifespan, without unnecessary and costly outages.

360° tube inspection

With today’s economy plants are pushing their reformers harder than ever to keep up with production needs, this can lead to many issues such as flame impingement, flue gas distribution, catalyst damage and pinching tubes online. All of these can lead to overheating of the reformer tubes around the complete circumference and in the past, the focus has always been on inspecting just the fired side of tubes. These issues are also affecting the non-fired sides of tubes and the industry has seen failures from overheating of these areas in the past.

A new method from Reformers Services is now available for detecting damage mechanisms affecting the complete 360° circumference of the reformer tube wall, as well as the full volume of the tube wall thickness simultaneously. The focus is the detection of damage mechanisms in the tube and the ability to size the damage on the equipment being inspected. The state-of-the-art technology proprietary crack detection system provides a full body examination of tubes and is able to detect the earliest stages of creep and bulging to the most severe stage of creep to prevent catastrophic failure. This inspection technology is fast and very repeatable using multiple lasers. On-site reporting software is integrated from the computer-controlled data acquisition system.

The new inspection technology consists of two reformer tube scanner types. The outer diameter reformer tube scanner, Tube Scan-360-OD, (Fig. 21) volumetrically inspects 360° circumferentially as it advances along the length of the tube producing real time data with two different technologies while identifying the damaged areas. Only 50 mm clearance is required between tubes. It provides 100% OD coverage of each reformer tube and 360° crack detection.

The internal diameter reformer tube scanner, Tube Scan-360-ID, (Fig. 22) also uses two different inspection methods running concurrently to provide a full 360° examination of the tubes. It provides 100% laser ID coverage and 100% crack detection coverage of each reformer tube.

Both reformer tube scanner types are equipped with a powerful proprietary eddy current technique for sensitive crack detection in reformer tubes up to 23 mm wall thickness. Measurements for both strain and crack detection are carried out simultaneously. Cracks can be detected in both the longitudinal and circumferential direction. Both scanner types offer repeatable accurate and fast inspection results, based on the collection of millions of data points during each tube inspection. All recorded data is used for remaining life assessment.

Fouling of reformer tubes

Fouling has been described as the major unresolved problem in heat transfer. Fouling is generally defined as the accumulation and formation of unwanted materials on the surfaces of processing equipment, which can seriously deteriorate the capacity of the surface to transfer heat under the temperature difference conditions for which it was designed.

In the production of the syngas, fuel combustion in the primary reformer can lead to dust deposits on the outer surface of the reformer tubes and prevent proper heat transfer which diminishes the overall performance of the primary reformer which is the main energy consumer in syngas production.

Major detrimental effects of fouling at the reformer tubes in any primary reformer include loss of heat transfer as indicated by charge outlet temperature decrease and the lower value of emissivity which consequently increase the energy consumption. Where the heat flux is high, as in primary reformers, fouling can lead to local hot spots resulting ultimately in mechanical failure of the heat transfer surface. Such effects lead in most cases to production losses, higher energy consumption and increased maintenance costs. Loss of heat transfer and subsequent charge outlet temperature decrease is a result of the low thermal conductivity of the fouling layer or layers which is generally lower than the thermal conductivity of the fluids or conduction wall. Reformer tubes continuously degrade due to the harsh environment of the furnace box from the moment they are commissioned. The upper limit of the reformer tube wall temperature is primarily governed by the reformer tube design temperature. If the temperature is too high, there is a high risk of premature creep damage and coke formation, resulting in the reformer tube failure and process flow restriction. The performance of the primary reformer is of crucial importance to plant efficiency and production because of the
reformer’s role as the single largest consumer of energy.

As a result of this lower thermal conductivity, the overall thermal resistance to heat transfer is increased and the effectiveness and thermal efficiency of the reformer tubes are reduced. The total thermal resistance to heat transfer is decreased during the first stages of fouling due to the surface roughness resulting from initial deposition. After that and with deposits building up, the thermal resistance returns to increase again. Fouling affects approximately 50 to 90% of reformer tubes, but multiple complex variables make it difficult to foresee. Scaling or corrosion from particulates can limit the performance of primary reformer tubes, as can unfavourable process conditions or malfunctioning upstream equipment.

Due to all mentioned and taking into consideration complexity of steam reforming operation it is therefore extremely valuable to conduct regular primary reformer assessments that result in solutions aimed at optimising parameters for peak primary reformer performance. Whether the catalyst is replaced or not, the reformer tubes should be physically measured for creep growth during the last production run to back up the results of the temperature monitoring in terms of whether any reformer tubes need replacement or a cleaning procedure. If the catalyst is being changed out, it is always recommended to conduct an internal inspection of the reformer tubes using a different technique to determine the diametrical growth of the reformer tubes with subsequent reformer tube cleaning technology of the outer or inner surface. If the catalyst is not being removed, again reformer tube cleaning technology can be utilised to improve the condition of the reformer tubes and enhance energy consumption with insuring higher reliability of the same. The cleaning technology can reduce stress which is even more pronounced in case of fouled reformer tubes with improvement of the process conditions in the terms of better throughput. Cleaned reformer tubes will not suffer due to higher temperature regime to reach the needed heat flux which is necessary for achieving proper level of steam reforming reaction, while the energy consumption will stay at the same level as is predicted in design case.

Simple regular cleaning procedure of reformer tubes will have beneficiary effect to prevent creep damage and in the same time reduce the energy consumption which will have direct impact to financial savings.

Reformer tube cleaning

Poor design or operation of reformer tubes can lead to premature tube failure. This is very costly in terms of reformer tube replacement and lost production due to the downtime to replace failed reformer tubes. In the worst case, a complete reformer burn down, the cost can be as high as $18 million based on the lost production plus the cost of the catalyst and reformer tube replacement. If a failed tube is nipped (isolated on line), the production rate may need to be reduced if the front end of the plant is pressure drop limited; for example if 5% of the reformer tubes are out of service the plant rate will be reduced by approximately 2% decreasing the plant profitability by $650,000 per year for a 2,000 t/d (420 reformer tubes) ammonia plant.

To prevent this, a very simple cleaning procedure of the reformer tubes can be conducted by applying proprietary cleaning technology which will not only prolong the lifetime of the reformer tubes, but also result in financial savings due to the direct impact it will have on subsequent energy consumption.

To illustrate the benefits of the reformer tube cleaning technology IKR Richter Group provides two examples showing the impact of IKR reformer tube cleaning technology in an ammonia plant and a methanol plant. In both cases the financial impact of cleaning reformer tubes with different degrees of fouling, namely a fouling thickness layer of 1.0 mm, 1.75 mm and 2.0 mm, are shown.

An engineering methodology for understanding risk

Quest Integrity has a widely-used method for determination of remaining life in reformer tubes based on inspection data, entitled LifeQuest™ Reformer. This program is based on over 20 years of research and creep testing of common reformer tube alloys. In particular it is designed to capture the effect of material aging, which causes significant reduction in creep strength during service independently from the accumulation of creep damage. The major advantage of this approach is that it is strain-based, as opposed to temperature-based, and therefore it is not subject to errors in temperature measurement.

Within the program, the operating temperature is back-calculated from the strain. This allows the effects of changes in operating conditions to be analysed. In effect, the program can be used to develop integrity operating windows (IOWs) depending on requirements in the future. These IOWs may be based on corrected IR temperatures in conjunction with a temperature correction program such as CorrectIR™, or based on relative changes in uncorrected measurements provided the same tools and measurement techniques are used.

Historically the program has been primarily used in order to determine remaining life and fitness for service of reformer tubes. Recently however, the program has been utilised more and more in engineering decisions regarding the operation of the reformer. These decisions fall into two categories: (1) intended changes in the operation to influence production, or (2) non intended changes in operation, for example analysing the effect of tube hotspots caused by flame impingement or local catalyst deactivation.

A case study from category (1) is described in the following section.

Case study – intended changes in operation

This case study relates to a steam reformer operating in South East Asia, with 156 tubes in two rows of 78. The plant is currently hydrogen-constrained, and so there is significant advantage to be gained in increasing its hydrogen output. The reformer was commissioned in 2009 and first inspected internally using the Quest Integrity LOTIS™ tool in 2016. At that time, significant diametric expansion was found, however the damage was seen to be very localised. In particular, the damage was restricted to only a few tubes at either end of each row. The majority of the tubes showed very little damage. The strain distribution from 2016 is shown in Fig. 23.

With reference to the balance described in the introduction, this is obviously not an ideal scenario. The reliability in this case is controlled by the end tubes, which showed high damage, whereas the majority of the tubes were working beneath their limits, thereby limiting production.

The first decision which was made related to the end tubes. Remaining life assessment performed at the time of
inspection showed that there were a few tubes which were not fit for service through the next operating period. These tubes were predicted to exceed 80% calculated life during that time. It was therefore recommended that some tube replacements were made. However, due to turnaround time constraints, this was not possible. It was decided instead to continue to operate these tubes but with reduced operating conditions for the next period, i.e. it was necessary to calculate IOWs. As the critical tubes were grouped together at the ends of the tube rows, it was decided that this could be achieved through local adjustment of burners (in fact, just the burners at each end).

In order to calculate the allowable operating conditions for these tubes, LifeQuest™ Reformer, was utilised. The simulated operating temperature for the next operating period was varied until it was deemed that no tubes would exceed 80% life before the next major turnaround. The allowable limit corresponded to a reduction of 30°C compared to the previous time. As a consequence, the reformer was returned to service with a reduction of 30°C in the allowable tube metal temperature (TMT) limit on the end tubes only. The allowable TMT for the remainder of the furnace was very slightly increased to maintain production. Note that these changes were reviewed as part of a Management of Change (MOC) program.

Despite the significant damage in 2016, the unit ran without failure for two years until 2018, when it was shut down again for its scheduled turnaround. The LOTIS inspection was repeated and this time the incremental strain (i.e. strain between 2016 and 2018) was calculated. This is shown in Fig. 24. Note the end tubes had been replaced prior to the inspection.

Three findings are important here:

- No tubes showed significant damage, indicating that the risk of online failure was very low. All tubes subsequently passed a fitness-for-service remaining life assessment for the next two year period.
- The damage profile has been essentially inverted compared to the previous profile. This has ensured that the tubes with lower damage as of 2016 have been asked to work slightly harder in the following period (and vice versa). This was seen to be an effective method for maximising production with negligible added risk.
- All tubes showed some damage. This may seem a counter-intuitive statement. However, when it is considered that both life consumption and production are tied to temperature, it in fact is an excellent finding. The vast majority of reformer tubes inspected in furnaces globally show zero damage, indicating that they are fully capable of higher production (of course this is not always needed). The fact that in this case the entire furnace showed low, but not zero damage, indicated that the operating conditions between the last two inspections were optimised for production at no significant cost to reliability. In effect the furnace was well balanced and all tubes had contributed equally to hydrogen production.

Following the inspection, another engineering decision had to be made concerning the next operating period (2018-2020):

- continue operation as per the 2016-2018 period, or
- increase the allowable TMT by 18°C.

It was found that continued operation at the 2016-2018 limits resulted in four replacements being required in 2020. Increasing the allowable TMT was permissible in terms of fitness-for-service until 2020, however the result was that over 60 tube replacements would be required in 2020. This allowed the plant management to consider the economic impact of each scenario and tailor the operation of the furnace with good information.

References