Investigation of an Unusual Reformer Tube Failure

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1.0 SUMMARY

This paper reviews the experiences of a methanol plant operator with an unusual reformer tube failure problem. The paper describes the problem itself, works through the investigation into the failures and reports the conclusions from the investigation. The paper also covers the remedial actions taken, both in the short term to maintain production before a retube could be carried out and longer term to prevent the same failure mechanism from damaging the new tubes.

2.0 INTRODUCTION

The Trinidad and Tobago Methanol Company (TTMC) has operated its first methanol plant, a design by Toyo Engineering Corporation (TEC) using Synetix's process technology, since 1984.

The first reformer tube failure occurred in the twelfth year of operation which itself would not normally be viewed as unusual, except that:-

(1) It occurred less than two months after a Turnaround in which a full NDT inspection of all the tubes was conducted, and which delivered a clean bill of health for another two years of operation. (Three tubes actually ruptured.)

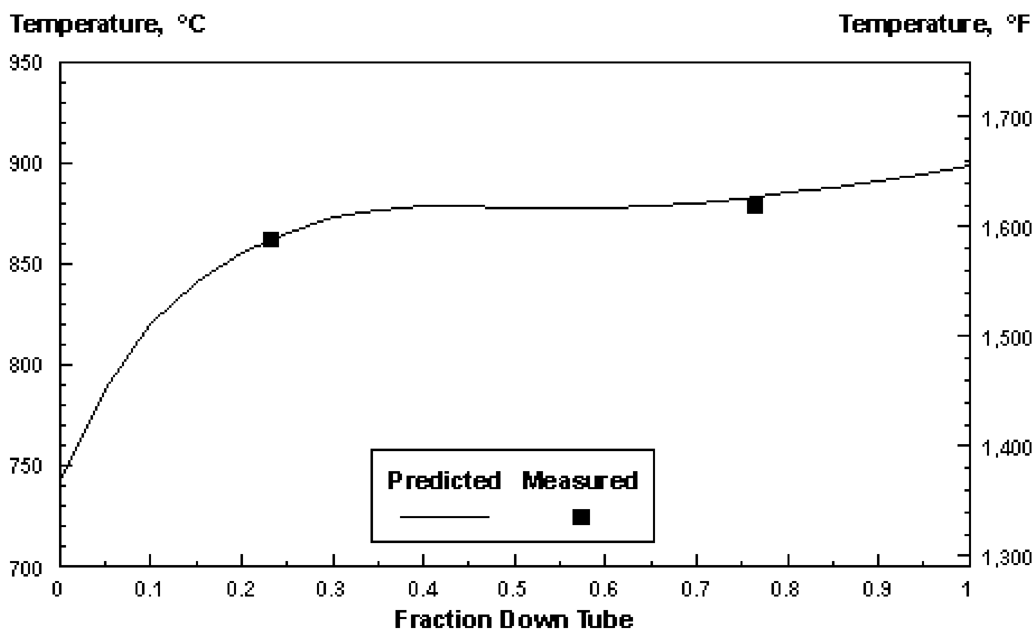
(2) It occurred in the region of the tubes near the bottom, remote from the region of highest heat flux and tube skin temperature, approximately one-third of the length from the arch of the furnace.

(3) For much of its life the reformer had been operated well within its design parameters. In particular tube temperatures were on average about 30°C below the design temperature of 996°C. These effects, taken from start-up, would have resulted in an expected life approaching 20 years.

The failures were therefore considered premature and necessitated investigative efforts that were conducted with considerable assistance from Synetix 1 and TEC, and with co-operative support from Lyondell Chemicals and Caribbean Methanol Company Limited.

Synetix undertook a full reformer survey using the procedures outlined in Reference 1. The results of this survey confirmed that the reformer operation should not in fact result in tube damage. The measured tube wall temperatures along with the predicted temperatures are given in Figure 1.

Figure 1 : Reformer Tube Temperatures



As indicated the unusual feature of the failures was the fact that they occurred at the bottom of the tubes, between the fluegas extraction tunnels. Tube failures in this region of top-fired reformers are becoming more common, and this is discussed in more detail in Reference 2. Briefly, this can be attributed to the adoption of shaped (4-Hole, for example) reforming catalysts. These catalysts reduce the tube wall temperatures along the whole length of the tube due to the increased activity and heat transfer performance. However, the point of maximum temperature is moved from the top section of the tube with ring catalysts to the bottom section of the tube with the shaped catalysts. Furthermore, it is difficult to accurately measure the tube wall temperatures in this region of the furnace and the actual tube temperatures may be higher than expected.

3.0 BACKGROUND

3.1 Reformer Description

The reformer is a down fired box type with 400 tubes, arranged in ten rows of forty tubes. Each row of tubes is further divided in half, each with its own collection header at the bottom, to which the tubes are directly connected. Each of the headers connects, through a T-piece, to a transfer line underneath the furnace which runs along the centre line at the right angles to the run of the rows.

The reformer tubes are of HP modified furnace tube material (Manaurite 36X) with 113mm OD and 13.4mm MSW. Design tube skin temperature is 996 ^{0} C for a 100,000 hour life.

3.2 Reformer History

Operations in the initial years were circumscribed by poor reliability of the supply of commercial electrical power in conjunction with the inability of the plant to properly respond to power interruptions occurring with high frequency. The result was 37 plant trips within the first 18 months of operation, each trip resulting in a thermal cycle of the reformer, together with process instability that are attendant to such situations.

In a 1986 project (called the Electrical Reliability Improvement Project), the plant was made more tolerant of fluctuation in the power supply and ensured that the reformer could be maintained on-line with a loss of power. These goals achieved, reformer cycling reduced to an annual average of about 3 per year in the succeeding period. Unfortunately, however, the harsh operation of the earlier period had done irreversible damage to the outlet collector headers of the reformer tubes. Correction of this deficiency was effected over Turnarounds in 1990, 1993 and 1995, by replacing partial sections of the headers adjacent to the transfer line.

The early years operating experience sensitised both operations and maintenance personnel on reformer metallurgical limits to the point where the design tube temperature became an operating parameter. This was supported by regular (once per 12 hr. shift) tube temperature surveys and a large panel display of the common outlet process gas temperature (i.e. the transfer line outlet), which was treated almost with the reverence of the synthesis catalyst temperature.

3.3 Inspection History

Operation's monitoring of tube skin temperatures is cross-checked through weekly independent surveys by the Inspection Engineer.

At each turnaround from the fifth year of operation (or approx. half of design life) full inspection of all 400 tubes was conducted. This included:

(a) Eddy current examination and/or continuous creep measurement.
(b) X-rays of critical weldments, particularly the collectors to transfer line T-pieces
(c) Liquid penetrant tests on weldments susceptible to failure, particularly tube to collector welds and inlet pigtails to tubes.

In addition to the above, the opportunity was available in 1990 to obtain a sample from one tube (D21) for metallurgical testing. This found no appreciable evidence of creep and supported the NDT work.

This inspection regime caused tremendous confidence to be built in both the operating and maintenance philosophy. With regard to the catalyst tubes, there was no instance of a "call" on any tube and the population appeared to be "ageing gracefully" with an expectation in 1995 of at least another four (4) years of life for a total realised life of fifteen years. This reformer has no outlet pigtails so the opportunity for on-line crimping does not exist. Each tube failure results in a total outage and therefore the economics of timing of a complete retube vary from Reformers that facilitate crimping. In fact, the total cost of a re-tube can typically be paid for by the contributions of between 5 - 8 outages, product price being the key variable. The results further suggested that the impact of the early years operation was much less severe on the catalyst tubes themselves than on other elements of the reformer. The reason for this is outside the scope of this paper.

A brief word on the eddy current technique is in order at this point. The two popular methods of automated furnace tube inspections use different approaches, ultrasonics and eddy current, on a similar crawler carrier that climbs the tube. The ultrasonic method is the older with much of its experience on HK 40 alloys. The eddy current technique is more recent, available only for the last decade and as a result of its development, having more information on HP modified material. The results of both methods require substantial interpretation and are not well correlated with each other. The plant operator therefore needs to select a technique and use the results for comparative purposes over several turnarounds.

At the time of electing to use the eddy current technique, TTMC was drawn to it by :

(a) its potential to better detect the formation creep related micro-voids, the mechanism of ageing in HP modification materials.
(b) its slightly greater precision in quantifying damage.
(b) its non-reliance of water as a signal couplant, ensuring it had minimum impact on other activity.

Very recently (not part of the investigation of this paper) TTMC performed a 100% parallel inspection with both techniques. The results not only validated the initial decision but proved to be disappointing in that the ultra-sonic technique was not able to detect longitudinal tube wall fissuring that was detected by liquid penetrant inspection and could be identified (though with a little effort) by the naked eye.

TTMC is aware of another operator who conducted a similar trial on HP modified tubes with similar conclusion, and a third operator who tested HK 40 tubes with results that were exactly opposite. There is obviously much opportunity for better understanding about the two techniques and in particular the limitations of each in detecting certain failure mechanisms. The adage of "the buyer beware" can become one of "the user be cautious" in this instance.

A third technique simply automates diametral creep measurements and provides a continuous indication. TTMC has found this to be a useful adjunct to the other technique.

3.4 Catalyst History

The original catalyst was Synetix 's ring type as follows:

14.6 kg	Type 46 - 1	-	Top
25.0 kg	Type 25 - 3	-	Middle
35.0 kg	Type 23 - 1	-	Bottom

The use of the alkalised Type 46-1 catalyst at the top was to address a problem of liquids and high hydrocarbon entrainment in the natural gas supply. This was a peculiarity of the time that no longer exists. This scheme was continued and proved successful for the debottlenecked plant in the post-1990 period.

In 1993 at a normal change cycle, Synetix recommended their higher activity 4-hole catalyst. The benefits expected were mainly to be in lowered catalyst tube temperatures, at no penalty in reformed gas methane slip. The charge of catalyst was therefore change to:

27.2 kg Type 25 - 4	-	Top
48.0 kg Type 23 - 4	-	Bottom

The one process difference immediately noted upon re-start after the change was the comparatively higher temperature (approximately 15 ^{0} C) initially required to attain the same methane slip as achieved previously. At the time this was disconcerting as one also expected to have to increase outlet temperatures by about 20 ^{0} C over the life of the catalyst. Synetix 's advice was that the new charge of 4-hole catalyst required a higher outlet temperature to achieve the same methane slip due to changes in other operating parameters such as reformed gas pressure and steam ratio. It was also advised that the more active 4-hole catalyst requires less of a temperature increase from start of run to end of run conditions. Up to the time of the subject incident (August 1995) this information was borne out by TTMC's experience. The subsequent operating period is not valid for comparative purposes as reformer operating conditions were deliberately limited after August 1995 so as to favour mechanical reliability of the furnace.

4.0 DESCRIPTION OF THE FAILURES

The first part of the investigation was a survey of the tube diameters throughout the furnace to asses the condition of the tubes, and to provide data for the investigation into the failure mechanism. This survey was undertaken in two stages, with the first stage being a survey of the tube diameter along the length of several tubes throughout the furnace. These measurements were converted into the percentage increase in tube diameter over the manufactured diameter, i.e., the percentage creep. The creep measurements for a typical tube are presented in Figure 2.

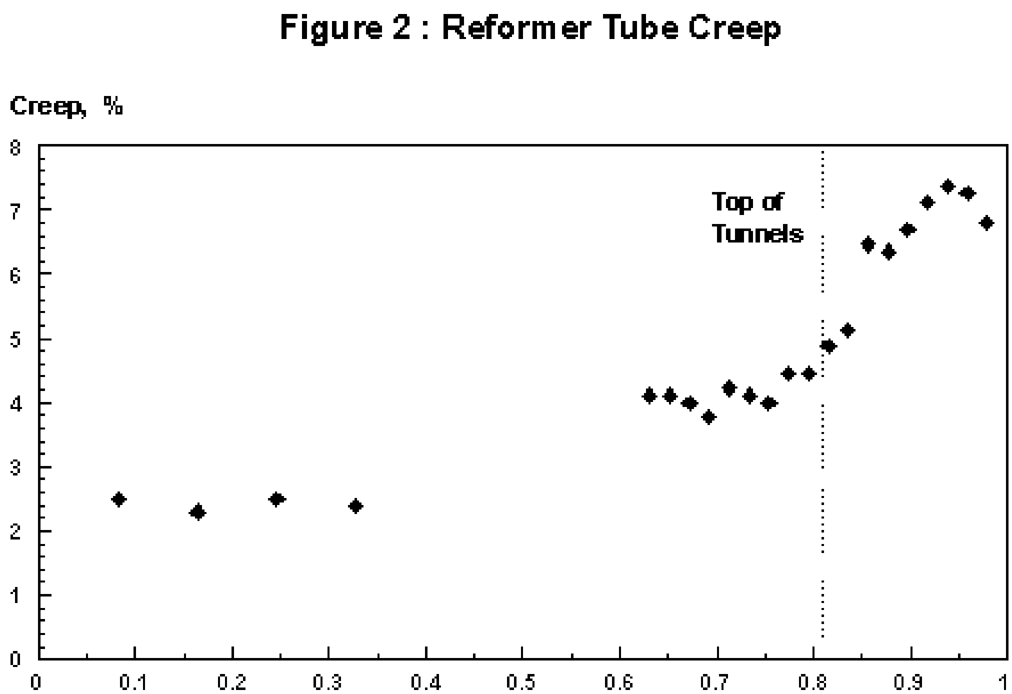
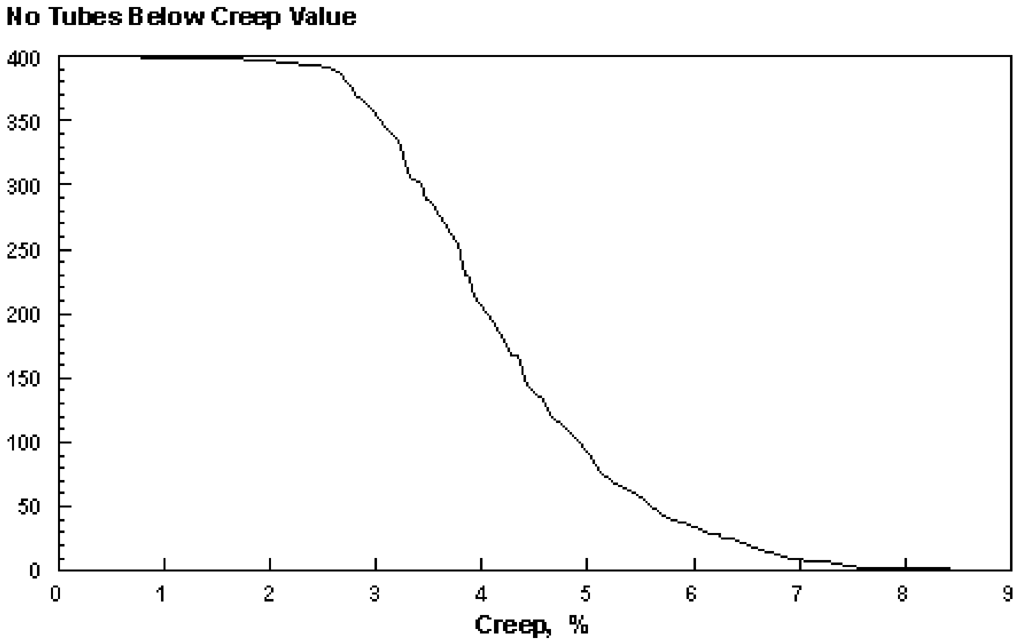


Figure 2 confirms that the damage to the tubes was confined to the bottom 2.4m (8ft) of the tube. An initial observation suggested that the damage was related to the presence of the fluegas extraction tunnels, with the position of the tunnels being shown in Figure 2. Therefore, the second stage of the survey involved the measurement of the tube diameter of the bottom section of all of the tubes within the furnace taken at 0.6m (2ft), 1.2m (4ft), and 1.8m (6ft) from the floor of the furnace. The results of this survey are presented as a distribution curve in Figure 3. From these data it can be seen that significant numbers of tubes had sustained extreme levels of damage, measured as creep levels in excess of 6%. The data also show that at least 50% of the tubes had exceeded 4% creep, which indicated the need for a retube within a short period of time.

Figure 3: Creep Distribution

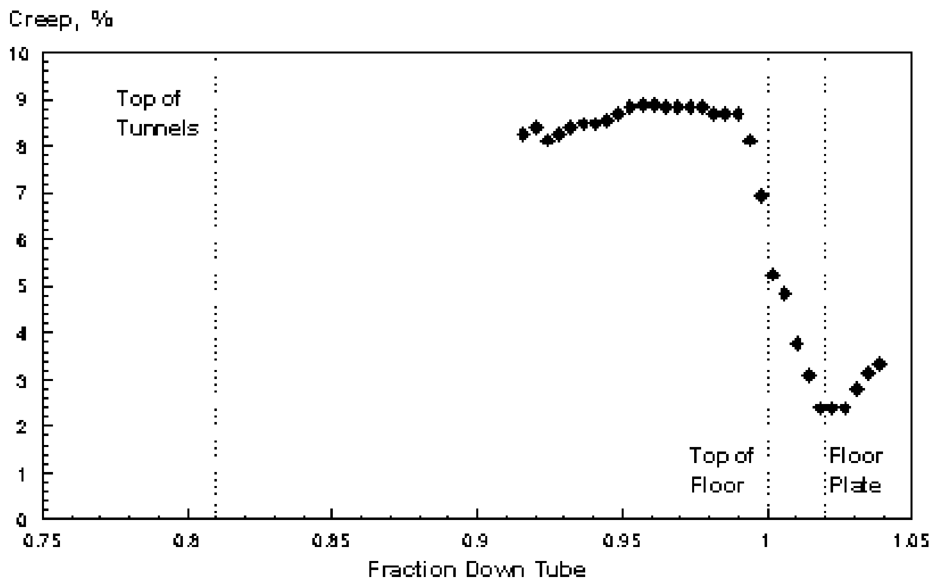


One of the first anomalies with the tube damage and failures in this furnace becomes apparent when Figures 1 and 2 are compared. In normal operation creep is predominantly dependent upon the tube operating temperature and the creep damage should follow the same profile as the tube temperature. Therefore, continuous operation at the temperature profile given in Figure 1 should not result in a creep damage profile as found in Figure 2.

Reference 2 discusses a heat transfer effect whereby the tube temperatures at the bottom of a top-fired reformer are higher than expected. This effect has been reviewed for this furnace, but has been found to result in only a 30°C (55°F) increase in tube temperature, rather than the required increase of 70°C (130°F) to be of significance. Additionally, the area of high creep extends above the levels of the tunnel ports which further eliminates this as the dominant mechanism in this furnace.

A 1.5m (5ft) section of tube which had been cut from the bottom of a tube was analysed by Synetix. This section of tube extended upwards from the weldolet on the collection header into the tunnel region of the furnace box. The first data item collected from this tube was the diameter variation along the length of the tube. This is reported in terms of creep in Figure 4. Labels showing the relative position of the tube to the furnace have been placed on the graph to allow location of the measurements.

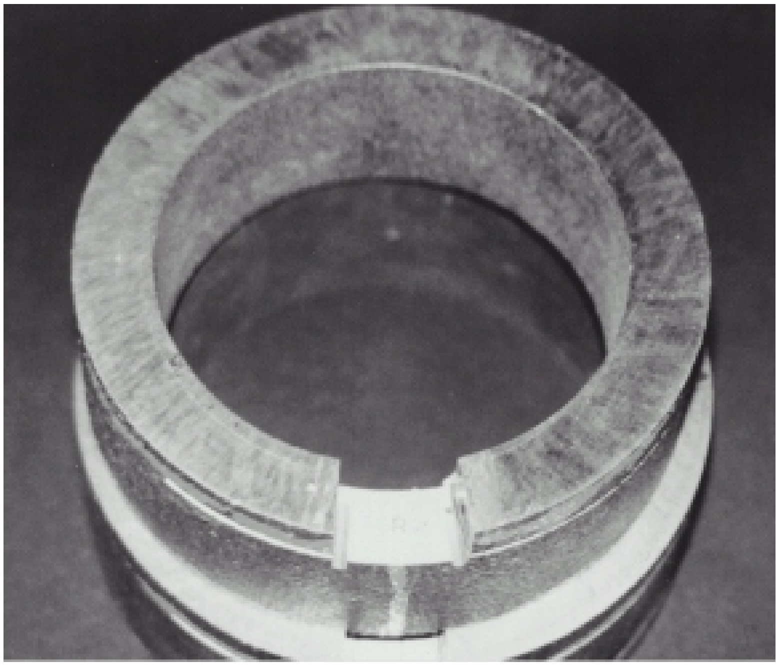
Figure 4 : Creep Measured in Sampled Tube



This tube exhibits the same high levels of creep within the tunnel region of the furnace as the data presented in Figure 3. One of the most important features of this graph is the presence of creep in the portion of the tube which is outside of the radiant section of the furnace. This part of the tube operates at the process gas exit temperature, a temperature (840-860°C) which is much lower than the tube design temperature and should therefore never be subject to creep damage during normal operation. Furthermore, the tube temperature will be almost constant from the upper surface of the floor through to the exit headers since the tube temperature is controlled by the process gas exit temperature. Based on a constant tube temperature, the creep exhibited by the tube from the top of the floor downwards should be roughly constant.

The tube was then sectioned and subjected to metallurgical examination, including microscopy and hot tensile yield tests. The smallest and largest rings sectioned from the tube have been photographed together in Figure 5.

Figure 5 Damaged Tube Compared to Normal Tube



This photograph illustrates the substantial increase in tube diameters at the bottom section of this furnace. Microscopic investigation of the damaged tube revealed an unusual pattern of damage. Figure 6 shows a micrograph of the damage found in the tube. Figure 7 is a micrograph of classical creep fissure damage in a reformer tube for comparative purposes.

Fig 6 Micrograph of Damaged Tube

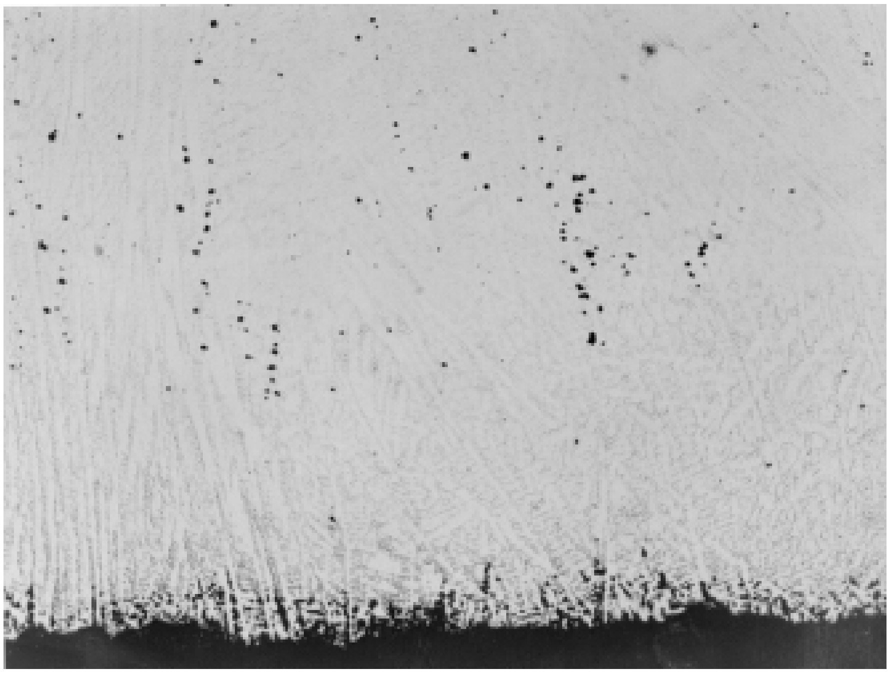


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Fig 7 Miocrograph of Typical Creep Fissure

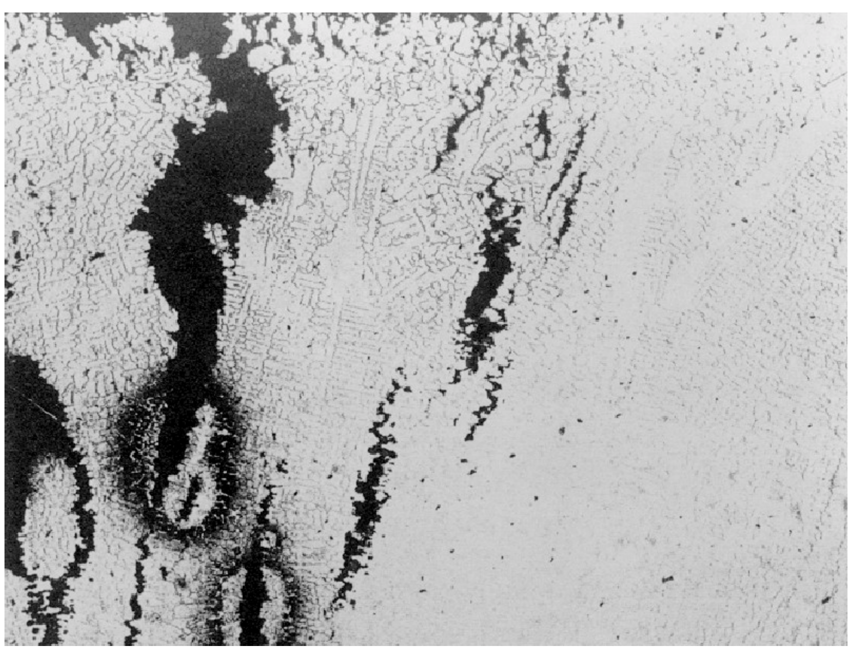


Figure 6 shows the damage in the sample tube to be present as a series of isolated voids throughout the depth of the tube wall. Typically in creep that is governed by maximum temperature gradient (i.e. in the upper section of the tube length) these stresses are maximised at the inner surface and creep voids reflect this with a pattern that is predominant between the inner wall and outer radius position (see Figure 7). The extent of voids through the wall of the tube suggests that steady state, fully relaxed stresses are playing a significant role in life consumption. Therefore tube life in this reformer may be controlled not by the position along the tube at which through-wall temperature gradient is at a maximum but that a which the mid-wall temperature is maximum.

Several micrographs showed a ring type effect, which suggests that the damage occurred as a series of short term stress events. Under normal operation at elevated temperature which results in tube creep, the voids migrate and elongate to form creep fissures. In Figure 6 fissures have not formed, therefore it can be concluded that the stress and temperature which the tube has been subjected to in normal operation are too low for creep at a significantly high rate to occur. This is supported by the fact that in the upper half of the furnace the average creep level was 1.1% with a high of 2.5%, except for 5 tubes. A further factor with the tube damage is that the voids are not aligned in any particular direction. Normal creep damage is unidirectional since the hoop stress is the dominant stress in the tube. Therefore, normal creep results in creep fissures in a single direction.

It was stated that the damage seems to have occurred as isolated events. The presence of voids within the metal without any indication of gross creep damage suggests that the tube may have been stressed in excess of the yield stress of the tube for a short period of time.

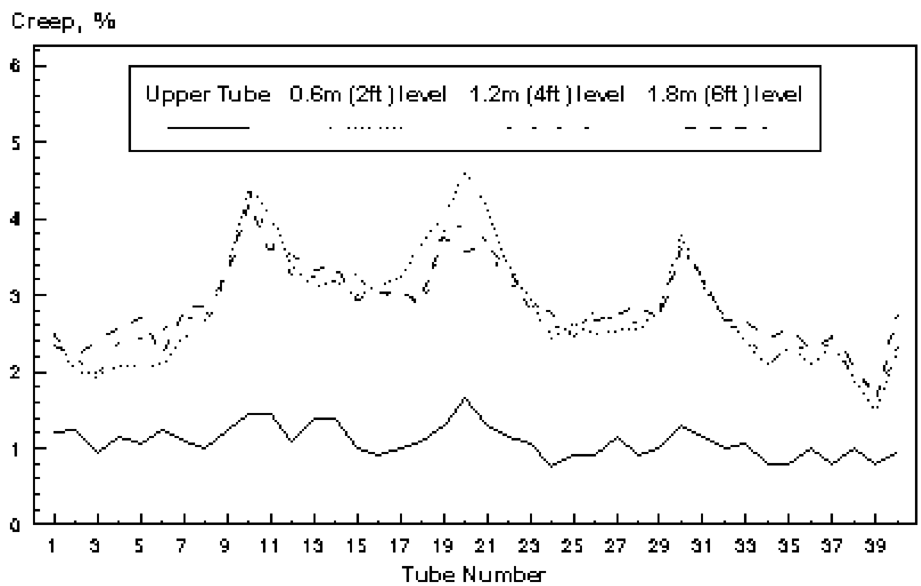
In order to asses the state of the metal after 11 years in service hot yield tests were performed on samples of the tube and compared to the as manufactured yield stress. The tests showed that the tube metal had a yield stress 40% lower than as cast material. Given the amount of voids found in the metal this is understandable. The tube manufacturer confirmed that the history of the tubes associated with the voidage found would explain the severely reduced strength of the metal.

5.0 STATISTICAL ANALYSIS

The evidence above suggested a causation mechanism that is different from that expected from the normal conditions in the upper region of the radiant box of the reformer. Statistical analysis of the creep data provided confirmation of this hypothesis. Four data sets were used representing the creep data from the 400 tubes at levels of 0.6m, 1.2m and 1.8m (2 ft, 4 ft and 6 ft) from the floor, and the maximum creep readings from the region of the tubes outside of the tunnels.

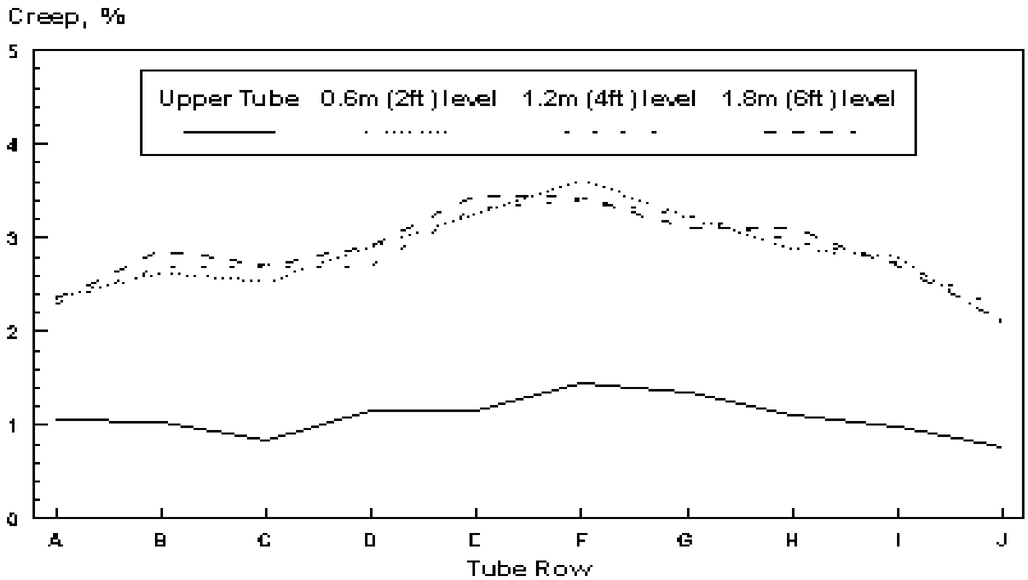
Mean creep (by tube number) was first compared as presented in Figure 8. It shows that differences along the rows are dominated by the position of the tube. This points to the higher radiative heat input experienced by the end-tubes and tubes at the quartile locations (10-11, 20-21 and 30-31) where tube spacing is approximately twice the spacing between other tubes. That the effect is evidenced in the upper region supports a purely radiation impact rather than one associated with a pattern in the flow of flue gas down the reformer and into the tunnels. One is therefore drawn to the belief that a radiative effect, different from and not necessarily driven by the effect in the upper region, is one dominant factor at the bottom of the tubes. Figure 8 also dramatically demonstrates the point made earlier on the difference between the creep experience at the top and bottom of the tubes.

Figure 8 : Mean Creep Distribution by Tube Number



The creep data as presented in Figure 8 did not permit any inference on differences at the different levels at the bottom. Significance testing (using 'T' and Mann-Whitney Tests) established that the 0.6m and 1.2m (2 ft and 4 ft) data sets were similar populations (with a 95% probability). However, the 1.8m (6 ft) data set was significantly different from the lower two sets. An explanation for this result is found in considering that the tube region between the tunnels is impacted by radiation from the upper regions of the reformer. This impact however is reduced as the tubes move deeper within the tunnels and are shielded by the tunnels themselves. The evidence of similarly in the two populations of data for the 0.6m and 1.2m (2 ft and 4 ft) levels suggest a uniformity of effect that is not consistent with a driving force that varies along the tube length (i.e. temperature). It therefore supported the belief that effect is not associated with normal operations. Consideration of the data by row rather than tube number yields no inconsistency with the foregoing analysis (Figure 9).

Figure 9 : Mean Creep Distribution by Tube Row



Analysis of the means and standard deviation provided further direction (see Table 1)., Analysis of these two parameters for creep data in the upper region (taken by Tube Number) showed a moderate correlation of 52% between them.

Table 1 - Analysis of Means and Standard Deviation

Creep location	Mean	Standard Deviation		Correlation between Mean and S.D. R^2
		Actual	**Computed**	
Upper region	1.11	0.62	--	52%
1.8m (6 ft) Level	2.88	1.1	1.79	28%
0.6m (2 ft) Level	2.83	1.31	1.75	52%

Assuming this to be typical of the tube population, computed standard deviations can be obtained from the actual means at the 0.6m and 1.8m (2 ft and 6 ft) Levels. The result shows that the actual standard deviation at the 1.8m (6 ft) level varies much more from the computed value (1.098 Vs 1.785) than at the 0.6m (2 ft) level. Further, the correlation between mean and standard deviation is much weaker (28%) at the 1.8m (6 ft) level whereas at the 0.6m (2ft) level it is similar to the upper region.

The interpretation put to this result is that although the cause of creep progression may be different, the tube in the region close to the floor is experiencing predominantly a single driving factor. On the other hand, the region closer to the top of the tunnel is being affected by more than one factor. We have already identified the role of radiation from the upper region of the furnace as a possible contributor. Given the generally low levels of creep in that region, however, it's contribution is unlikely to be significant. Two other factors were therefore studied in detail, the impact of tunnel burners on the tunnel brick work temperature and the effect of reformer trips. A third possibility, the impact of the use of shaped reforming catalyst, was also considered however several pieces of evidence eliminated this from consideration. These included:-

(i)The substantial reduction in creep levels as the tube passed through the floor (see Figure 4) on the reformer outlet.
(ii)The fact that process gas temperatures experienced on the reformer outlet were not higher than the range previously experienced.
(iii)The pattern of mean creep levels decreasing from the 1.8m (6 ft) level to the 1.2m and 0.6m (4 ft and 2 ft) levels were not consistent with the expected increase in average tube temperature were the process flow increasing in temperature to a significant extent.

One notes however, recent work by Lyondell Chemicals which identified normal operating temperatures in this region that are higher than predicted by the Synetix reformer simulation model. This work is discussed in detail in Reference 2.

6.0 EFFECT OF TUNNEL BURNERS

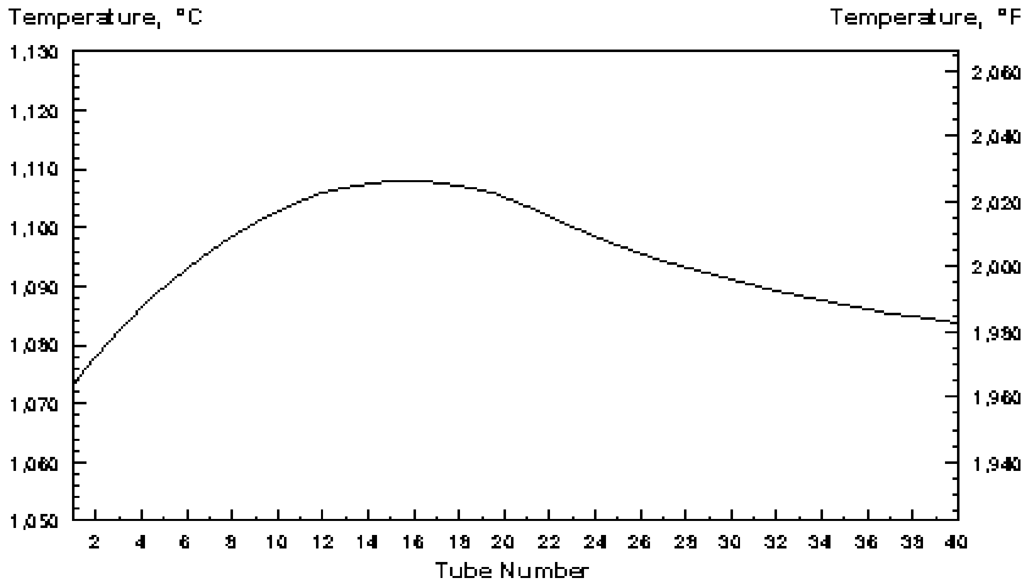
A single burner is located at the tube No. 1 end of each tunnel, and is roughly at the same level as the 1.2m (4 ft) creep readings on the tubes. Waste gas from the topping column is the fuel source with provision for augmentation with natural gas. The plant's experience is that natural gas is never required.

At normal waste gas flow rates it was estimated that the maximum flue gas temperature within the tunnel would increase by approximately 50 ^{0}C. The impact of this is a negligible increase in heat flow of 1 KW/m ^{2} through the brickwork but between 26 and 57 KW/m ^{2} through the tunnel ports (Reference 2) which increases the tube temperature by approximately 31^0 C. At worse this puts the tube temperature just at its design limit, with the majority of tubes below this temperature and is therefore not sufficient to explain the level creep experienced.

Increasing the heat release by a factor of ten is estimated to result in flue gas temperatures just in excess of 1100 ^{0}C and a tube temperature increase of 45 ^{0}C. This level of increase could be significant and would result in a flue gas profile as shown in

Figure 10. This profile tends to provide evidence to implicate the tunnel burners. This, however, is weakened by the reality of high creep levels in the tube positions 1 - 5 and further in that the pattern of Figure 8 (i.e. elevated at the centre) is reflected in Figure 9, which considers the creep data by Rows.

Figure 10: Fluegas Temperatures With Tunnel Burners



It would seem more likely then that the pattern of Figures 8 and 9 are both consistent with an off-line mechanism of differential cooling which would cause the outer ends of Rows and the end Rows (Row A & B and I & J) to cool quicker than the centre region of the furnace. The pattern of creep along the tube rows as shown in Figure 8 suggests that the tunnel burner firing may have a limited second order impact upon the observed creep levels.

An incident of such high heat release could only occur in a process upset. A review of operating history identified only one likely event. No other information was found to confirm inclusion or exclusion of this mechanism from consideration. Therefore, though correlation to the evidence is weak, consideration was nevertheless necessary.

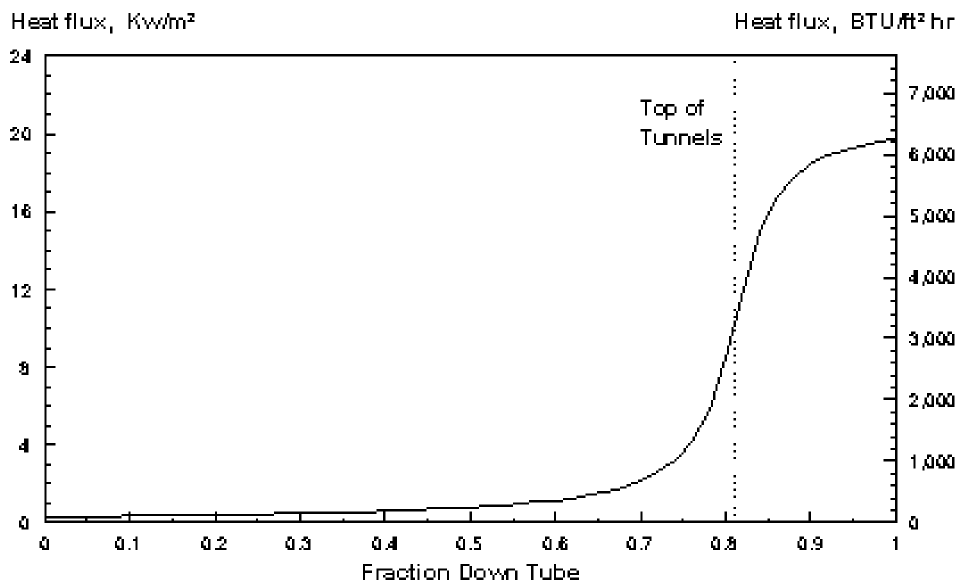
7.0 EFFECT OF REFORMER TRIPS

Based on the evidence above, the creep damage did not occur during normal operation. The evidence for this is substantial. The main facts which support this hypothesis are the low operating temperature compared to design, the creep pattern not following the tube temperature profile, creep having been found outside of the furnace, the volumetric nature of the creep and the lack of creep fissures in heavily damaged metal.

Therefore, the investigation had to address the operation of the furnace during trip and restart conditions. This furnace is a fairly modern furnace and is therefore insulated with ceramic fibre modules rather than brickwork. However, the tunnels and furnace floor are fabricated from brickwork. Due to the use of bricks for the tunnels and floor, the bottom of the furnace has a much larger thermal capacity than the rest of the furnace box with the ceramic fibre lining. Therefore, from the period in time just after a furnace trip into the early stages of a hot restart the tunnels represent the dominant heat source within the furnace.

Figure 11 is a plot of the radiant heat flux received by the furnace tubes along the tube length in the period after a reformer trip. This plot confirms that the tunnels do in fact dominate the heat transfer within this period of reformer operation. If Figure 11 is compared with Figure 2, the creep profile, both graphs can be seen to have a similar profile. This finding infers that there is a potential correlation between the two.

Figure 11 : Heat Flux After Reformer Trip



It is known that starting up and shutting down a steam reforming furnace results in a finite amount of tube damage due to the transient stresses built up as the thermal gradient develops within the tubes. However, with modern reformer tubes manufactured from HP-mod Nb and microalloy materials this has become less of an issue than with the older HK40 material. The modern tube materials are more ductile than HK40 and therefore relax the start-up stresses very quickly. This reformer was tubed with HP-mod Nb alloy, therefore to achieve the observed damage a substantial thermal cycle would be required to attain the high stress levels, especially if yield was to be achieved.

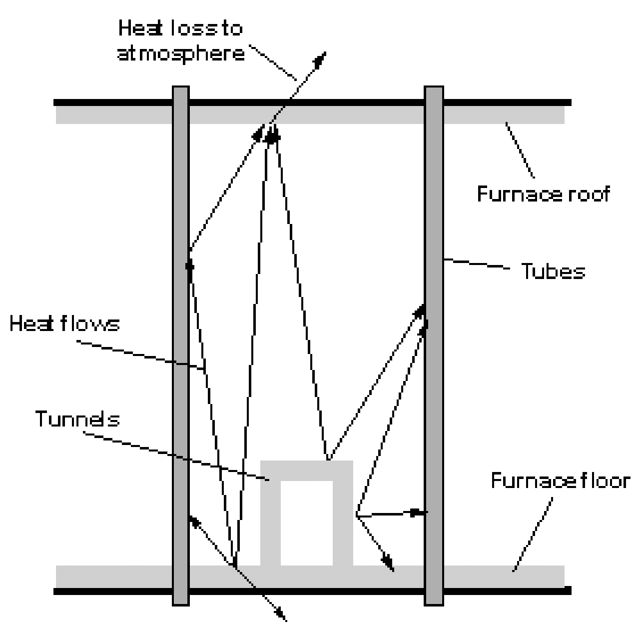
As discussed in Section 3.2 the plant had a poor electrical power reliability during the first years of operation. The plant was originally designed to shut down the reformer and auxiliary boiler totally upon power failure and leave the reformer boxed up. During a power failure trip the reformer was subject to a soak condition with no combustion air flow or steam flow through the tubes. This trip philosophy was designed into the plant on the basis that the furnace was ceramic fibre lined. It was thought that the ceramic fibre lining, having a low thermal capacity could not overheat the reformer tubes if the furnace was boxed in.

However, the effect of the tunnels as a large high temperature heat source during the reformer trip was not considered. Furthermore, the poor power supply reliability resulted in a large number of reformer trips involving reformer soaks during the initial years of operation. It was reported by operations staff that inspection of the furnace in the period just after a reformer trip revealed the upper 75% length of the tubes to be black, with the bottom 25% between the tunnels to be glowing orange. Based on the above, it could be concluded that the reformer tubes were being overheated during a trip, and this could be the reason for the accelerated tube damage. One however had to take account of the very low pressure-related stresses that were present during this period.

8.0 REFORMER TRANSIENT MODELLING

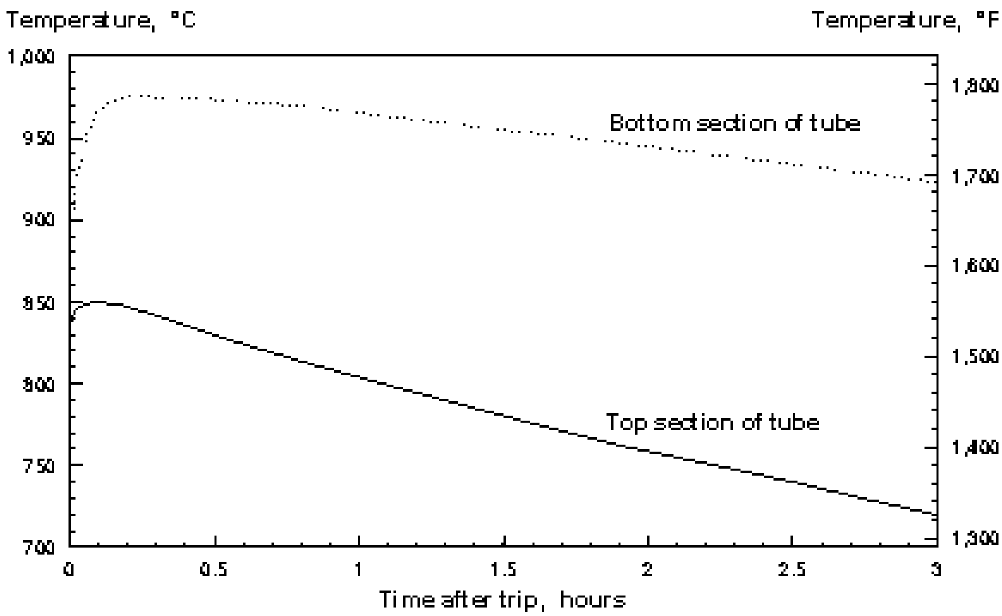
In order that this effect could be verified a detailed heat transfer model of the furnace was developed for this investigation. The purpose of the model was to calculate how the reformer temperatures varied with time after a plant trip. As a starting point the model used the temperatures measured during the reformer survey. The model then calculated the flow of radiant heat between all surfaces in the reformer such as the tubes, the tunnels and the refractory walls. Figure 12 illustrates some of the heat flows considered within this model.

Figure 12 : Heat Flows After Reformer Trip



The results of this model are given in Figure 13, which shows how the reformer tube temperatures vary with time after the reformer trip.

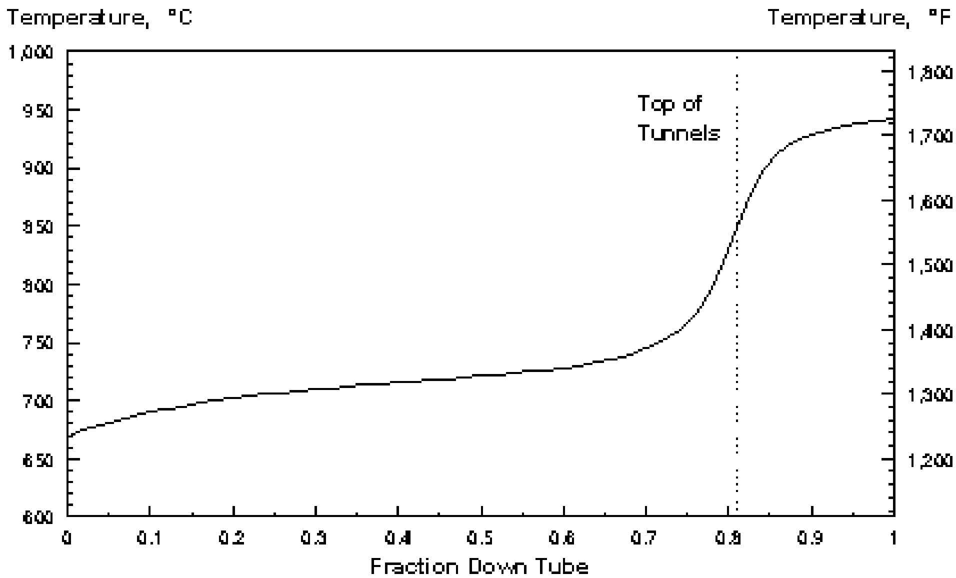
Figure 13: Tube Temperatures After Reformer Trip



The tube temperatures quoted in Figure 13 are the average temperatures of the length of tube between the tunnels (bottom) and the length of tube in the furnace above the tunnels (top). From this graph it can be seen that the tube temperature in the top of the furnace falls rapidly due to the low thermal capacity of the ceramic fibre blanket. However, the temperature of the tube within the tunnel region heats up to 975°C (1790°F) and remains hot for many hours after the trip whilst the upper tube cools.

At any given time after the trip, an approximate temperature profile down the length of the tubes can be determine by a combination of the temperatures in Figure 13 and the heat flux profile in Figure 11. An approximate tube temperature profile 3 hours after the trip is given in Figure 14, based on the average tube temperatures of 922°C (1692°F) at the bottom and 719°C (1326°F) at the top. From Figure 13 the observation that the tube temperatures are cold at the top and hot at the bottom, after a full reformer trip and box in, is confirmed.

Figure 14 : Tube Temperatures 3 hours After Reformer Trip



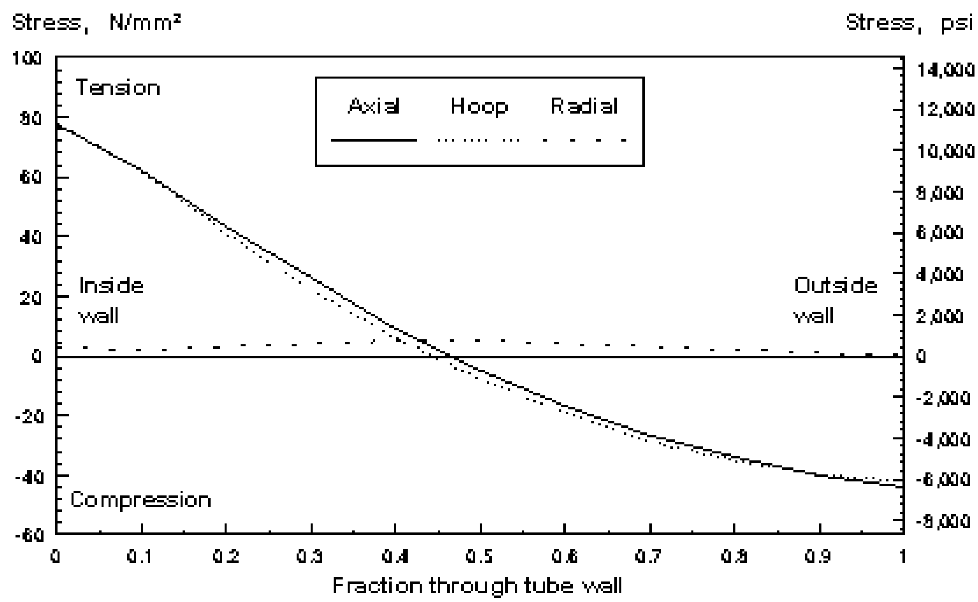
9.0 STRESS ANALYSIS.

The next stage of the modelling involved the calculation of the stresses occurring within the reformer tube after the trip. This revealed that the tubes were not over stressed during the period following a plant trip. Although the tubes were heated to high temperatures of at least 980°C (1800°F) during this period, there was little internal pressure and more importantly there were no thermal gradients through the tube wall. Subjecting the tubes to temperatures of this magnitude for several hours would in fact act as a stress relief heat treatment.

Consideration of the plant restart provided the final answer to how the tubes became damaged. During the period when there is no flow through the furnace or the tubes, a tube temperature profile similar to that given in Figure 14 develops. Taking Figure 14 as an example case where the reformer is restarted from the hot condition after 3 hours in the boxed in condition. The majority of the tube length is at a temperature of approximately 700°C (1290°F), with the bottom section of the tube above 900°C (1650°F). The transition between these two temperatures occurs over a length of only 1.2m (4ft) with a very steep temperature gradient. An early stage in the reformer hot restart involved admitting process steam to the tubes at a variable rate determined by the reformer temperature. As the steam flows down the tubes it will be heated by the tube metal and the catalyst until its temperature reaches 700°C (1290°F). This steam will then flow into the bottom section of the tubes which are at the much higher temperature, resulting in rapid cooling of the inner surface of the tube. As the inner surface of the tube cools it contracts, creating a tensile stress on the inner surface of the tube wall.

Based on the tube temperatures from the thermal model, a more detailed model of the lower section of the tube has been developed. In this model, the effect of the steam cooling on the tube wall temperatures can be explicitly calculated. The results from this model can then be used in a finite element stress analysis model to calculate the level of stress built up in the tube during the rapid cooling. The results from one of the restart models are presented in Figure 15.

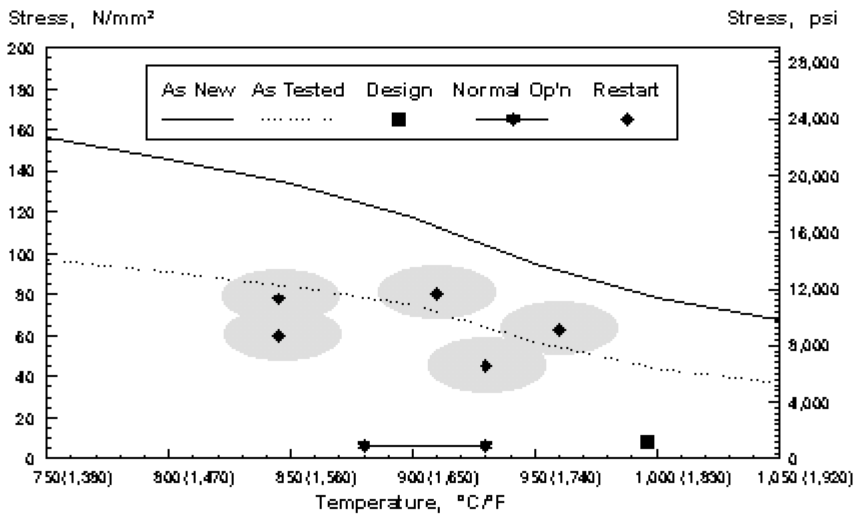
Figure 15 : Tube Stress During Reformer Restart



This shows the stress levels through the tube wall in the 3 orthogonal directions. The peak tensile stress is found on the inner surface of the tube, with the model assuming that all of the tube wall thickness is sound metal. An important feature of this graph is that the peak stress occurs in both the hoop and the axial directions, rather than in a single direction. This provides the mechanism required for volumetric creep rather than the normal unidirectional creep.

A series of restart cases were modelled in this manner for a range of tube temperatures and steam flows. The results are plotted in Figure 16, along with the design yield stress and the measured yield stress of the as used material. Figure 16 also includes the design point for continuous operation at a stress of 8 N/mm^2 (1160 psi) and the range of normal operating conditions. From Figure 16, it can be seen that various hot restart scenarios create a series of stresses in the tubes which are 5 to 10 times higher than the design stress, and encompass the current yield strength of the tube metal.

Figure 16 : Transient Stress Compared To Yield Stress



This applies particularly to the tube and refractory temperatures in both normal operation and during the trip and restart. This is not the case in a reformer and it is accepted that there are temperature variations due to varying heat input and tubeside flowrates. Therefore, the results should be seen not as point solutions, but as a range of stresses that would be seen at a range of temperatures. Figure 16 has a series of shaded areas for each of the results showing the typical range of values encountered throughout the furnace. Based on this work it is entirely reasonable that the hot restart case is producing stress levels in excess of the materials short term creep and yield strengths, in a limited number of tubes. This is particularly true for tubes 10 - 11, 20 - 21, and 30 - 31 at the gaps in the tube rows which do exhibit the highest levels of creep.

The assumption in the models that the whole tube wall thickness is sound, shows that with tubes in good condition high levels of stresses can be developed which are damaging to the tubes. Since the stress reduces through the tube wall only a small thickness of tube will be damaged during a thermal cycle. However, the damaged material is then substantially weakened and during the next thermal cycle will have a reduced strength, and the stress levels in the remaining tube will be higher. Therefore, as the tube experiences more thermal cycles, the damage accelerates, and moves through the tube wall as a series of damage rings, which accounts for the isolated voids found in the tubes. This is believed to be the reason why the metallurgical work carried out in 1990 could have yielded a favourable result and yet there is such a marked change five years later.

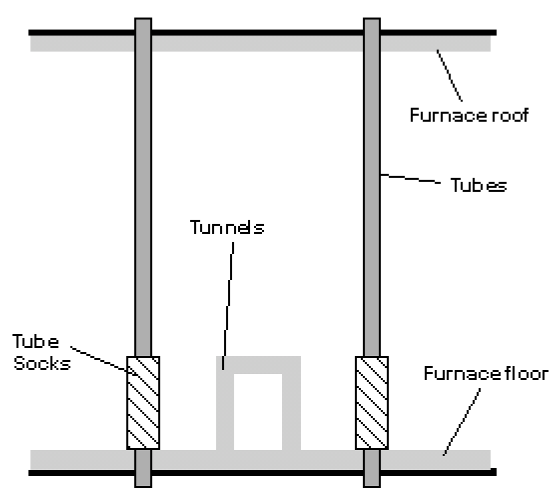
This same mechanism applies as the steam enters the upper portion of the tube, the same temperature gradients and stresses will develop as a result. However, the yield and creep strengths of the tube metal at the lower temperatures of some 700°C are some 50% higher than at the temperatures of the tube bottoms. Therefore, the tube bottoms alone suffer from severe damage due to the high temperatures of the metal when they are exposed to high stress levels. The creep results in Figure 2 indicate that creep is present in the upper portions of the tube, but the damage is limited and the tube has substantial remnant life.

Both Figure 2 and Figure 4 show that the creep damage to the tube reduces towards the floor of the furnace, with Figure 4 showing that it continues to fall as the tube passes through the thickness of the floor. The reason for this is that during a reformer trip, the tubes act as a path for heat losses out of the furnace and to atmosphere. Therefore, the section of tubes below the floor will be at a lower temperature than the tube between the tunnels. Upon restart, this section of tube will be subjected to a reduced quenching effect as the steam flows through the tube, hence the resultant stress levels and damage are lower.

10.0 PREVENTION OF FURTHER DAMAGE.

Based on the results of the creep survey many of the tubes in the reformer were at risk from creep failure within a short period of time. Therefore, the entire furnace required retubing and plans were put in place for a major reformer overhaul. However, before the retube could be carried out TTMC wished to minimise the risk of further failures. To achieve this ceramic fibre socks were installed on the outside of the reformer tubes within the tunnels. This is illustrated in Figure 17, and involved wrapping the lower 2.4m (8ft) of tube with ceramic fibre blanket and fixing it in place with high temperature wire.

Figure 17 : Insulated Socks on Reformer Tubes



The fluegas velocities are low in a top-fired reformer and the blanket is at little risk of erosion. The effect of the blanket is to reduce the tube wall temperature by some 25°C (45°F) and perhaps more directly opposite the tunnel ports. A reduction in tube wall temperature of this level will generally result in a doubling of tube life which would ensure that furnace could reach the overhaul with minimum tube failures. One disadvantage with the use of the ceramic fibre socks is the reduction in available heat transfer surface area and the reduced process heatload which is a direct result of this. The installation of the socks resulted in a reduction in reformer throughput of roughly 5% of the normal operating throughput.

In order to eliminate the tube failure mechanism from the reformer, the electrical reliability is now much higher than during initial plant operation as discussed in Section 3.2. Furthermore, if there is a power trip, the auxiliary boiler remains on line and can provide a continuous steam purge through the reformer tubes. A further direct recommendation of the study is the deliberate lowering of the reformer temperature such that the flue gas is under 800°C prior to a hot re-start. In addition the steam flow should be admitted at a very low rate after a trip where the reformer is boxed in. This then reduces the rate of cooling of the tube and allows the steam to be heated up more rapidly as it flows down the tube. The steam flow is then gradually increased as the reformer tube temperatures are cooled down.

11.0 CONCLUSIONS

The reformer tube failures reviewed in this paper are the result of thermal shock during the reformer restart. The major factor which created the conditions for this mechanism were the repeated reformer trips in which the furnace was completely boxed in. During this period the bottoms of the tubes became very hot, and with reintroduction of steam they were rapidly cooled. It is concluded that boxing in of a steam reforming furnace should not be the preferred normal trip action, even if the furnace is lined with ceramic fibre modules rather than brickwork. Where it is necessary then the operating procedure for a hot restart has to take cognisance of the possibility of thermal shock. Two other precautionary steps have been implemented - the installation of 60% limit stops on the tunnel burners gas valves, and inspection ports at the level of the tunnels so that more accurate tube temperatures can be obtained at the bottom of the tubes.

It is also shown that detailed modelling of the reformer furnace during normal operation, trip conditions and reformer restart is a valid mechanism for understanding the transient behaviour of the furnace, and the impact of this behaviour on the tubes.

12.0 REFERENCES

1. Primary reformer optimisation. PW Farnell & RJ Hughes. IMTOF 1997.

2. Heat transfer effects in the tunnel region of a top-fired reformer. PW Farnell. IMTOF 1997.