CONTRIBUTING FACTORS TO THE UNUSUAL CREEP GROWTH OF
FURNACE TUBING IN ETHYLENE PYROLYSIS SERVICE

D. E. Hendrix
ARCO Chemical Co.
P.O. Box 777
Channelview, TX 77530

Malcolm Clark
Lummus Crest Inc.
1515 Broad Street
Bloomfield, New Jersey, 07003

ABSTRACT
Unusual axial creep growth has been experienced in newly installed, centrifugally cast, radiant section outlet tubes cracking NGL feedstocks. Computer simulation studies using a finite element analysis approach were conducted to explore factors contributing to this creep growth. These studies rationalize the field and laboratory observations on representative elongated tubes. Both operational and environmental parameters were investigated and show that carburization, axial loading and production run length are the major contributing factors.

INTRODUCTION
Predicting tube life in olefins cracking service is difficult due to the many uncontrollable variables involved including carburization rates and thermal cycles. Traditionally, olefins radiant section tubes have been designed using 100,000 hour stress-rupture calculations. Thermal cycling and carburization initially were not significant design considerations. This 100,000 hour life historically has seldom been realized as premature failure from stress rupture, thermal fatigue or cracking at carburized areas has almost always occurred. Today, tube design philosophy is shifting towards a greater emphasis on optimizing resistance to damage from thermal cycling and minimizing carburization.

ARCO Chemical Co., a division of Atlantic Richfield Co., has experienced repetitive service failures of HK-40 and HP-40+1% Nb outlet tubes, particularly in natural gas liquids (NGL) service. The primary cause for Failure has historically been from cracking at carburized areas, with most failures occurring when heaters cycle to ambient temperature or during decock cycles. An anticipated life of two to three years has been predicted for tubes in this service.
Heater upsets can further reduce the predicted tube life.

Unusually rapid axial growth has also occurred to outlet tubes in heaters cracking NGL feedstocks. Laboratory analyses of these tubes has indicated severe ID wall carburization.

Elongation measurements taken on representative tubes indicate a longitudinal growth for outlet tubes in NGL service of approximately 2.5% per year. Available creep data for the HP-40+1% Nb alloy and laboratory analyses of failed tube sections indicate that retirement due to creep damage can be expected after approximately three years in NGL service, or at approximately 10% total elongation.

Current short-term solutions to the problems associated with tubes interfering with the furnace floor from the growth have involved cutting off a short length and reinstalling the return bend. This fix has enabled the furnace to continue operating. However, the tube growth is undesirable as it results in significant maintenance expenses and production losses. Initial examination of specific operating conditions failed to reveal an apparent reason for the significant tube growth. An industry survey also indicated that the tube growth experienced was apparently unique.

In an attempt to explore factors possibly contributing to this growth, computer simulation studies using a finite-element approach were conducted. Both operational and environmental parameters were investigated and showed that carburization, axial loading and production run length were major contributing factors. The results also rationalize the field and laboratory observations on representative elongated tubes.

The conclusions from this study, although based on the experience of a specific plant, are believed to be applicable to all ethylene plants since the basic parameters are common to all designs.

BACKGROUND

In the fourth quarter of 1979, discussions began with Lummus Crest Corp. regarding partial replacement of radiant section tubes in ARGO Chemical olefins heaters. The tubes selected were of controlled Si content HP-40+1% Nb metallurgy. The basic HP-40 alloy designates a 25 wt.% chromium, 35 wt.% nickel material with 0.40% nominal carbon. This alloy has been the industries’ primary choice for pyrolysis service when the intended operating temperatures are expected to exceed those recommended for the HK-40 alloy, an alloy nominally containing 25 wt. % chromium and 20 wt. % nickel.

An HP alloy was selected to replace the original HK-40 tubes as end-of-run tube metal temperatures were expected to increase with a planned change in operation. Besides resistance to high temperature oxidation, resistance to stress rupture has historically been the primary criterion for selecting materials for olefins cracking service. The HP-40+1%Nb alloy was chosen specifically due to improved stress-rupture properties over the basic HP-40 alloy and equal or better mechanical properties compared to other modified HP alloys.

In March 1982, the first replacement tubes were installed. Since that time a majority of the remaining heaters have been refitted with the HP-40+1%Nb tube metallurgy. In December 1982, the initially installed tubes had experienced permanent longitudinal growth from creep to the point where they were touching the heater floor during operation. Tubes cracking liquid feedstocks were not experiencing growth of this magnitude. An immediate fix was accomplished by shortening the tubes approximately 8 inches.

An initial metallurgical analysis of samples removed from the elongated tubes indicated no observable creep damage resulting from the growth. Based on expected adequate remaining creep life, the affected tubes were left in service. Subsequent to that time, tubes in several other heaters cracking primarily NGL’s have also required shortening, resulting in maintenance
costs, production losses, and inefficient heater utilization.

As the elongation of the newly installed tubes was perceived to be excessive and questions were raised as to how this would affect original tube life estimates, an investigation was initiated to determine the reason for the excessive tube growth. Work centered on two parallel paths:

1. Collecting and correlating operating information on heaters cracking NGL’s vs. heaters cracking liquids and, 2. Laboratory field investigation of all available elongated tube samples.

Investigation of the various operating parameters of heaters primarily cracking NGL’s vs. heaters cracking primarily liquids revealed several differences between the two. In NGL heaters, run lengths were shorter, the coke buildup was more rapid and dense, and start of run and end of run temperatures were higher. A photograph of an inlet tube sample showing the substantial coke buildup experienced in cracking NGL feedstocks is shown in Figure 1.

Fitting to fitting tube length elongation measurements had been recorded on tubes cracking both NGL’s and liquids during maintenance work. Analysis of the elongation data and feedstock type indicated a direct relationship between NGL feedstocks and tube growth. Data indicating this relationship including tube growth on a per operating day basis is shown in Table 1. A more graphic representation of this data is shown in Figure 2 and indicates that the apparent relationship between tube growth and feedstock type is not unique to a specific metallurgy.

Laboratory and field analyses of elongated tubes were conducted to provide additional information on metallurgical/mechanical changes experienced as a result of this growth. Photographs of representative tube samples analyzed are shown in Figures 3 and 4. Microstructural analyses of samples removed from elongated tubes indicated that all samples had experienced severe carburization. In one sample, carbon pickup in excess of the nominal as-cast carbon content had occurred through the entire wall. Two representative photo micrographs showing the carbon content of an HP-40 tube sample at the ID and OD surfaces can be seen in Figures 5 and 6, respectively.

An entire tube from the first heater retubed and shortened became available for analysis during a recent unit turnaround. This particular tube had lengthened to a point where it would have been scheduled for a second shortening if it had not been removed. Magnetic response measurements indicated it to be heavily carburized on the entire length with the carburization being somewhat spotty. Weld to weld measurements taken on the tube as compared with measurements taken on as received uninstalled tubes indicated that the growth was fairly uniform along the tube length, permitting extrapolation of growth data for retirement purposes (Figure 7). Microstructural analysis of a sample removed from this tube revealed that after 3% growth of the total tube length, creep in the form of void formation at carbide matrix interfaces was visible. As a result of the investigation it appeared that tube growth, cracking of NGL feedstocks, and carburization were related in some manner.

**COMPUTER ANALYSIS**

In order to establish the relative influence that different operational environmental parameters may have on the performance of HP-40 + 1% Nb heater coils, a computer study was carried out using a finite element computer program which analyzes creep and accumulated stress damage. The program is based on the program “TUBE” developed by Battelle under an industrial group sponsorship for analysis of steam reformer tubes. “TUBE” has been modified to accommodate up to twenty subcycles which are then automatically recycled as many times as specified. The creep subroutine of this program has further been modified to accept creep rate property data in
the form of a parametric curve which is predetermined from laboratory creep data.

In a pyrolysis tube, the primary stresses are imposed by the pressure, and by the axial weight and gas velocity thrust stresses. However, the maximum stress imposed on any element of the tube is a result of the thermal flux creating a thermal profile through the wall of the tube. At the start of operation, these stresses can be 10- to-20 MPA on the outer and inner surfaces of the tube. Since the temperature is higher on the outside element, these stresses at the onset are compressive on the outer surface and tensile on the inner surface. As the tube is held at operating conditions, these stresses relax with time in accordance with the creep characteristics of the material at the temperature of each element. These stresses tend towards the primary pressure and axial load stresses as a result of this stress relaxation. Two conditions influence the rate of approach to these base loads. First, the process deposits coke on the inner surface of the tube resulting in a necessary increase in tube wall temperature to counteract the insulating effect of the coke. This changes the rate of stress relaxation. Secondly, a time is reached where sufficient coke has been deposited that the coil cannot function as designed. Either the tube temperature becomes too high or the pressure drop is excessive. The coke must be removed by a steam/air decoking procedure.

Decoking is an exothermic reaction, in contrast to the endothermic process reaction, and operates at a much lower heat flux than the pyrolysis process. This establishes a new thermal profile and a new set of thermal stresses on the tube. This new thermal profile tends to reverse the stress direction in the wall of the tube from the relaxed stress condition. During the decoking period the outer surface element stress becomes tensile while the inner surface element stress becomes compressive. Thus, during decoking, part of the stress which has been removed from the tube wall by creep relaxation during operation is restored resulting in a new high stress starting point for the next operating run. This is illustrated in Figure 8.

The creep strain developed in the tube is the summation of strain relaxation and pressure and weight strains. Stress-rupture life is the summation of all the portion of stress-rupture life consumed at the stress and temperature represented at each increment of time. Since stresses encountered in low pressure ethylene pyrolysis service are relatively low, it was necessary to examine existing creep data at the lower stress range and at tube metal temperatures normally encountered in pyrolysis heaters. A source of such data is provided by Falkenbridge Ltd. in a paper presented at CORROSION 83. This data was supplemented by Wisconsin Centrifugal, Inc. Creep-rupture data was taken from these same sources and compared with data developed by the Chemical and Petroleum Panel of MPC.

One of the factors to be assessed was the influence of carburization on creep and stress rupture. A set of test data was obtained on HP-40 + 1% Nb carburized to a 2.5% carbon level, and creep correlations were developed with this data. They were compared with data from V. Guttmann of the JRC Petten Establishment in The Netherlands on the creep influence of carburized HK-40. The comparison of results indicated a good agreement on creep rate and rupture life as influenced by carburization.

In the computer program, the physical properties of the carburized material are assumed to be the same as the as-cast material. This is probably an incorrect assumption; however, at the time, no better data was available. Furthermore, the program accepts only one material at a time, thus the influence of varying the carbon profile across the tube wall was not determined.

In addition to the internal pressure stress on a pyrolysis tube, there are other loads which must be considered. These include the weight stress of the tube material, the weight of coke which accumulates, and the kinetic forces applied by the mass of high velocity gases which react on
the return bends and outlet elbows. As a result of the thermal movements and guide restraints, moments resulting in longitudinal stresses are also imposed on the tubes which are more difficult to quantify.

It is estimated that in addition to the primary longitudinal pressure stress, longitudinal loads of from 3 to 4 MPa can result from these various weight and kinetic effects. Field creep measurements of typical HP-Nb tubed pyrolysis heaters indicate that this axial stress is of the order of 4 MPa.

RESULTS

Several runs on the computer were made to determine the influence of operating and environmental conditions on the creep behavior of pyrolysis tubes. As a result of these analyses, it is evident that the major influence on longitudinal creep extension are carburization, axial load, and decoking length and temperature. The factors which have greatest influence on projected tube stress-rupture life are carburization, run length, decoking time and temperature, and the rate of heat up. These factors are shown in Table 2. In each run compared, the only operating condition varied is the one shown.

DISCUSSION

Carburization is a major contributor to longitudinal creep growth and shortening of tube life. Figure 9 shows the influence of increasing carbon content through carburization. As the carbon content increases, the creep rate increases dramatically and is accompanied by a reduction in tube life. This is a result of the change in creep-rupture properties as the material carbonizes. Results of correlations made on creep- rupture tests of carburized material have shown that for an HP-Nb alloy carburized to 2.5% carbon at a stress level of 7 MPa, the creep rate at 900°C is forty times that of the as-cast alloy. At the same conditions, the time to rupture is reduced to 15% of the as-cast material. Different relationships are developed by the computer simulation program because of the interaction of stress relaxation and stress level during thermal cycling (Figure 10).

As the axial load is increased, the rate of creep increases. However, at a low axial stress the life of the tube depends on the circumferential stress and until an axial stress is reached which becomes the dominant stress, it has little effect on tube life. This is presented in Figure 11. Here the stress from internal pressure is such that an axial stress of 2.7 MPa must be reached before it becomes the governing rupture stress. Above this stress level, the axial stress governs the tube life and ultimate failure will probably take place in the circumferential direction. Increasing the length of run between decoking cycles results in fewer cycles per year. As shown in Figure 12, this results in a decrease in creep and an increase in life projection. This can more readily be understood by relating these factors to the number of cycles. Tube life and creep extension are a function of the number of cycles experienced. Figure 8 shows the cyclical nature of the operation. If the run length is extended, the tube spends more of its total time at the low stress portion of the cycle. Lower total stress results in longer life and less creep. Stress at the start of each cycle can be reduced by extending the time of heat up. During a gradual heat up, some stress relaxation takes place, the peak stress at start of run is lowered. This reduces the overall creep and increases the tube life by reducing the maximum stress level for each cycle (Figure 13), so during decoking, a reversal of stress occurs. Since creep strain is reversible, decoking reduces the accumulated creep. As the length of decoking time is extended, the creep decreases and the life increases (Figure 14). The number of cycles per year are decreased by the extended decoking time and an equivalent increase in projected tube life results. In this case, the peak stress of the run cycle is higher because of a longer stress reversal time, but this high stress portion of the cycle occurs less frequently in a year’s time so the stress damage rate is lower.
Increasing tube temperatures during decoking results in more stress relaxation in the stress reversal cycle. This in turn produces a higher starting stress on the production cycle, increasing creep and decreasing life projection. In contrast to increasing decoking time, increasing the decoking temperature does not reduce the number of cycles per year and so has the opposite effect on tube life.

The influence of carburization on the stress profile across the wall of a tube is a complex mechanism. As the metal carbides are formed, a unit volume change takes place which in itself creates a stress profile. The probable changes in thermal conductivity and thermal expansion cause a change in the thermal stress profile. These are somewhat countered by the significant change in the creep rate of the carburized material. However, their influence is beyond the scope of this investigation.

CONCLUSION

As a result of field and laboratory observations and the computer simulation runs, it is concluded that the primary cause of the unusual axial creep growth experienced is the rapid carburization which is occurring in the NGL feed pyrolysis heater tube. The carburization is associated with a rapid buildup of coke, requiring more frequent decoking (i.e., shorter run times). As the inside tube diameter is reduced by the coke layer, rising stream velocities and process pressure drops increase axial loading. All of the above factors cause an increase in the axial creep growth and a reduction in tube life.

Many of the parameters studied are procedures which are at the discretion of the operators. However, use of extended heat up rates, decoking cycle times and temperatures to control tube life and creep must be weighed against their effect on production on-stream time and overall plant capacity.

The pyrolysis heaters involved in the study exhibited good operational flexibility as evidenced by their ability to meet process requirements under a variety of production demands and feedstocks. The goal attained was to further our understanding of the mechanical behavior of heater tubes in the plant, enabling the operating and maintenance groups to minimize tube replacement and maintenance costs without prejudicing process requirements. The environmental and operating parameters examined are common to all ethylene furnace designs.

Results of the study indicate:

1. Creep of heater tubes can vary significantly between different operational/environmental parameters and must be accommodated in the mechanical design.

2. The creep and carburization resistance characteristics of tube materials must be carefully assessed when specifying tube metallurgy.

RECOMMENDATIONS

The strongest factors emerging from this study relate to carburization and accumulation of coke. Since it is generally considered that carburizing potential and coke deposition rate are closely related, current programs by tube manufacturers to improve carburization resistance and to develop coke suppressing characteristics in tube materials should be encouraged as a means of increasing tube life and improving on-stream factor.

REFERENCES


### Table 1 - Operational History of Heaters vs. Tube Growth Measurements

<table>
<thead>
<tr>
<th>Metallurgy Outlet Passes</th>
<th>Time Operating Days Service</th>
<th>Liquid Feed %</th>
<th>Gas Feed %</th>
<th>Tube Growth In./Total</th>
<th>Elongation %/Day</th>
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<tbody>
<tr>
<td>HP-40 1 Nb</td>
<td>259</td>
<td>0</td>
<td>87.6</td>
<td>8.75</td>
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<td>HP-40 1 Nb</td>
<td>205</td>
<td>17.4</td>
<td>68.5</td>
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<td>HK-40</td>
<td>372</td>
<td>40.4</td>
<td>41.4</td>
<td>5.88</td>
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<tr>
<td>HP-40 1 Nb</td>
<td>130</td>
<td>64.1</td>
<td>0</td>
<td>0.625</td>
<td>0.0048</td>
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### Table 2 - Operating Factor Influence

<table>
<thead>
<tr>
<th>Factor</th>
<th>Condition</th>
<th>Axial Rel. Creep</th>
<th>Rel. Life Projection (%)</th>
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<tr>
<td>Carburization</td>
<td>HP Nb as-received</td>
<td>1.00</td>
<td>100</td>
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<td></td>
<td>1.25C</td>
<td>4.70</td>
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<td></td>
<td>2.5C</td>
<td>16.5</td>
<td>54.5</td>
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<td>Axial Load</td>
<td>110 psi (0.758 MPa)</td>
<td>1.00</td>
<td>100</td>
</tr>
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<td></td>
<td>230 psi (1.58 MPa)</td>
<td>1.88</td>
<td>100</td>
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<td></td>
<td>400 psi (2.76 MPa)</td>
<td>3.68</td>
<td>98.7</td>
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<td></td>
<td>600 psi (4.14 MPa)</td>
<td>5.86</td>
<td>74.0</td>
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<td>Run Length</td>
<td>42 days</td>
<td>1.00</td>
<td>100</td>
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<td></td>
<td>20 days</td>
<td>1.56</td>
<td>59.0</td>
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<tr>
<td>Heat Up Rate</td>
<td>Rapid</td>
<td>1.00</td>
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<td></td>
<td>6 hours</td>
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<tr>
<td>Decoke Length</td>
<td>2 days</td>
<td>1.00</td>
<td>100</td>
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<tr>
<td></td>
<td>6 days</td>
<td>0.58</td>
<td>186</td>
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<td>Decoke Temperature</td>
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<td></td>
<td>982°C</td>
<td>1.40</td>
<td>45.5</td>
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Figure 1 - Photograph of an inlet tube showing coke deposits.

Figure 2 - Tube Growth vs. Feedstock

Figure 3 - Representative tube samples received for analysis.
Figure 4 - Close-up of a failed tube sample showing a circumferential crack.

Figure 5 - Photomicrograph of a carburized tube showing I.D. carbon pickup.

Figure 6 - Photomicrograph of the tube sample in Figure 5 at the O.D.

Figure 7 - Twenty-three month service outlet tube elongation (weld-to-weld).

Figure 8 - Thermal stress/strain profile of typical tube vs. operational cycles.
Figure 9 - Carburization.

Figure 11 - Axial load.

Figure 10 - Carburization

Figure 12 - Run length.
Figure 13 - Heat up rate.

Figure 14 - Decoke time.