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STRESS CORROSION CRACKING OF TUBE OF A VACCUM RESIDUE STEAM GENERATOR: A CASE STUDY

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ABSTRACT

Causes of failure of a vacuum residue steam generator tubes were investigated using visual,microscopic and chemical methods. It was found that the main cause of such failure was due to stress corrosion cracking. Suggestions were made to control causes of such failure.

RESUMEN

Se investigó las causas de la falla de los tubos de un generador de vapor al vacío utilizando inspección visual y microscópica y métodos químicos. Se encontró que la causa principal de tales fallas fue debida a corrosión por tensiones. Se hacen sugerencias para controlar las causas de tal falla.

INTRODUCTION

Stress corrosion cracking (SCC) of steels in corrosive media (1) can occur when such steels have tensile stresses. These tensile stresses may range from as low as 10% of the yield stress to as high as 70% the yield stress for the SCC to occur. For each alloy-environment combination,there is an effective of threshold stress. These tensile stresses may be due to any cause : applied, residual, thermal or welding.

Corrosion products can cause stress of up to 10000 psi in constricted regions. The presence of chlorides with dissolved oxygen or any other oxidizing agents in a given aqueous environment can cause SCC to austenitic stainless steels. Absence of such oxidizing agents or oxigen will inhibit stress corrosion cracking. SCC is accelerated with temperature like most chemical reactions.

Metallurgical factors such as alloy chemical composition, grain orientation, presence of dislocations, etc. are important factors for the SCC to occur. The mechanism by which SCC occurs is not well understood. In general, corrosion can initiate the formation of cracks which can act as a stress raiser, i.e. a high stress concentration will develop at the tip of the notch and this stress increases tremendously as the radius of the notch decreases. Pardue et al. (2) using audio-amplification methods showed that a mechnical step (i.e. pings) can occur and were heard during crack propagation.

Methods for controlling SCC are one or more of the following : lowering the stress below the threshold value if one exists, eliminating the critical environment by degasification, pH adjustment or any other means, changing to another alloy if possible noting that carbon steels are better than stainless steels in this respect, applying cathodic protection, and adding inhibitors if possible such as phosphates or any other inorganic or organic corrosion inhibitors.

HISTORY OF THE PROBLEM

A number of tube failures occurred in two steam generators after a short period of service. Most of the failures were in the hot zones and towards the outside of the bundles. All the removed tubes showed transverse fracture which was located adjacent to the expanded section of the tubes as shown in figure (1). The right hand end of the tube is the section that was expanded into the tube sheet hole by a process of roller expansion over the first 2 inch of the tube length. The outer surface of this section is fairly bright. The fracture is adjacent to this section. The remainder of the tube shown in the figure extends into the main body of the generator.

Material specification for the tubes is ASTM A179 which is a cold drawn condenser tube material having the composition : 0.12% carbon, 0.35% manganese, 0.05% sulfur and 0.05% phosphorous.

This kettle type steam generator is one of seven similar units using different plant products (e.g. vacuum residue, waxy distallation,etc.) for producing steam to be used for the different plant processes (e.g. vacuum distillation, steam tracing of piping network, heating coils in storage tanks, etc.). The plant which is a newly operated bitumen plant is located inside a petroleum refinery complex in Gulf Corporation Council.

The steam generator under investigation was manufactured from carbon steel. The tube side fluid was vacuum residue containing 5.2% sulfur and some H_2S at high temperature. The agressive nature of this fluid resulted in a failure of two steam generators working with this fluid. The failure was due to leakage of the tube side fluid (vacuum residue or Bitumen) to the shell side fluid as shown by water and steam analysis of these generators. Unplanned shutdown of the whole plant took place to investigate and rectify the cause of failure. Samples of the cracked tubes were pulled out for investigation and were renewed using tubes of the same material (ASTM A179).

Failure analysis showed that the reason of leakage was stress corrosion cracking SCC of the tubes which have been overexpanded during manufacture and enhanced by the improper water treatment (high pH). Appendix shows the conditions and design data for the steam generator and its fluids.

EXPERIMENTAL

The outer and inner surfaces of the tubes were examined at different positions using low power optical microscope. An overall view of the failed tubes were taken by a camera with a color film. (Figures a, b, c, d and e) Samples were taken from different areas of the tube, prepared metallographically and examined under the optical microscope. Wall thickness of the tube was measured in a number of areas using micrometer.

RESULTS

1. THE OUTER SURFACE:

The outer suface (excluding the expanded portion of the tube) was covered with a fairly smooth black scale. However, there were localised regions of corrosion which were visible at low magnifications (Figure 2). On removal of this scale it was found that the surface was fairly deeply pitted (Figure 2) on the expanded side of the fracture, but no pitting was visible on the expanded section of the tube. Instead there was found to be a large number of longitudinal creacks on the surface of the expanded part of the tube (Figure 3).

A more detailed examination of the outer surface was carried out on a cross section of the tube. Figure 6 shows the outer surface in the expanded portion of the tube; the surface is quite smooth and free of pits. On the other side of the fracture face this surface showed deep pits with cracks beginning to spread from some of them; one such crack is shown in Figure 4.

On a part of the outer surface remote from the fracture there was found to be a region of localised deformation and associated cracks (Figure 5).

2. THE INNER SURFACE:

The general appearance of the inner surface was one of fairly loose corrosion products which were bright rust coloured at, what was considered to be, the bottom of the tube. At high magnifications (Figure 6) it can be seen that there is general corrosion and this is also appparent on the cross section of the tube shownin Figure 6. In addition, deep score marks were also evident over the first 4" or so of the tube (measured from the expanded end of the tube). Some of these marks are shown in Figure 6 and the result of this scoring on the deformation of the grain structure can be seen in Figure 5.

3. THE FRACTURE SURFACE:

The whole of the fracture surface was coated by a uniform black scale, (in all appearances the same as the scale on the outside of the tube). The fracture was approximately transverse with a small discontinuity on the surface. Examination of this surface microscopically showed that intergranular attack had taken place and this was seen under the optical microscope (Figure 4). The fracture path follows the grain boundaries and inter granular attack can also be seen adjacent to the fracture. The intergranular regions close to the fracture surface appear to be filled with oxides. It can also be seen from this photograph that the general microstructure of the steel consists of large ferrite areas interspersed with regions of spheroidal cementite.

4. REDUCTION IN WALL THICKNESS:

The wall thickness of the tube was measured at a number of places along the tube and at any one section at different circumferential positions. It was found that the wall thickness in the vicinity of the fracture varied from 0.110" to 0.130" and away from the fracture from 0.118" to 0.126". The lower figures appear to coincide with the tube.

DISCUSSION

It is considered that the cause of failure of the tube is stress corrosion cracking; the following factors are thought to be most significant :

(a) Material specification : Steels containing 0.1% carbon are most susceptible to stress corrosion cracking under certain conditions. The steel used for manufacturing the tubes contains 0.12% carbon.

(b) Temperture : Stress corrosion cracking is more likely at high temperatures. Most of the tube failures have occurred in the upper section of the bundles.

(c) Stress : The level of internal stress at the junction between the expanded and non-expanded section of the tube is probably sufficient to initiate the stress corrosion cracking.

(d) The pH of the water : High pH values in the water will promote stress corrosion cracking, anything above 8 may be considered to be high.

(e) Alkalinity : Some concentration of alkali may occur in the small space between the tube sheet and the unexpanded tube. This may add to the corrosion problem.

(f) Break in passive film : Local corrosion may occur at a break in a passive film. The section of the tube which has not been expanded is covered with a uniform oxide layer, but the expanded section is not uniformly coated, there is, therefore,a break in the passive film in the vicinity of the fracture. This may aid stress corrosion cracking.

It can be seen that all the factors that promote stress corrosion cracking are present in this application; rapid failures are to be expected.

The route to failure is proposed as follows :

Appreciable internal stress is introduced into the tube during the expansion process, evidence for this is :

(i) Score marks on the inside surface (Fig. 6)
(ii) Grain deformation on the inner surface
(iii) Cracking on the outer surface

In addition to this stress there will probably be applied stresses due to thermal expansion and contraction of the tube. The buckling of the outer tubes may also contribute to the total stress. The corrosive medium, (high temperature water of high pH) produces pitting in the outer surface of the tube and where the stress is high cracking will occur. The combination of corrosion and stress in the region where the final fracture occured is sufficient to produce very rapid fracture of the tube. Indirect evidence that the material is sensitive to stress corrosion can be seen in Figure 5, where some sort of deformation has occurred on the outside of the tube away from the fracture. Here corrosion and subsequent cracking has taken place over the very localised area. Although extensive corrosion has taken place from the inside of the tube, shown in the corrosion products and loss of wall thinckness, the conditions are not favourable for stress corrosion cracking to initiate at this surface.

CONCLUSIONS

Failure occured by stress corrosion cracking SCC. The crack started at the outside of the tube and spread between the grains very rapidly. The conditions leading to this failure are high temperatures, presence of internal and applied stresses, high pH values of the water, and low carbon content of the steel. Some internal corrosion of the tube has occured but this has almost certainly not contributed to the failure.

RECOMMENDATIONS

1. The pH value of the water must be reduced or shifted to a new position. It is probably not practicable to assemble the tubes without expansion rolling. However, it should be possible to expand for the full thickness of the tube sheet. In this way the critical internal stress region will not be within the sheet hole where concentration of corrosion products may take place.

2. Some assessment of present roller expansion practice may be worthwhile to determine whether or not variables in fabrication procedures may by introducing more internal stress into some tube than others.

3. Consider using alternative steels such as ASTMA 199. These are chromiun, molybdenum condenser tube steels which may give much better service. There are eight possible steels quoted and which should be chosen depends very much on operating conditions. The choice could only be made after some controlled experimentation.

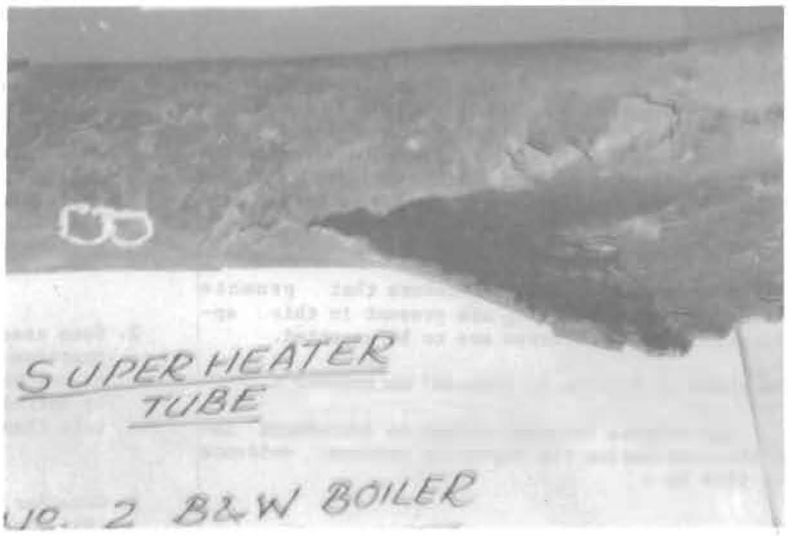
4. It is to be expected that other tube failures may occur at later stages in the lower temperature regions so that careful monitoring should continue.

ACTIONS TAKEN:

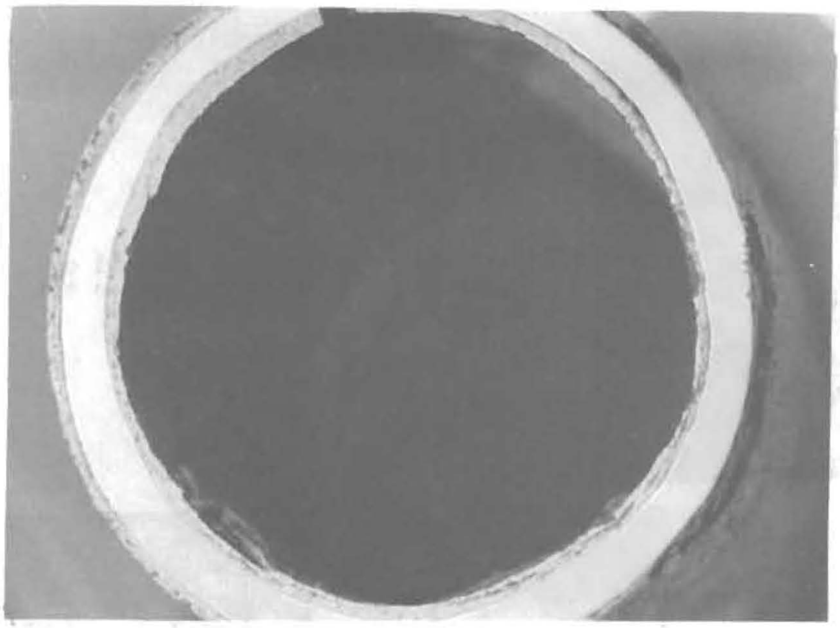
pH controlled to be "8"
New tube bundle purchased to include a higher corrosion resisting material.
New Tubes Material : ASTM - A 199 Gr. T9
Expansion of tubes was made to the full length inside the tubesheet.
Also tube ends have been seal welded.

a) THE FAILED TUBE - OVERALL VIEW

b) THE RUPTURED OF THE TUBE



c) THE CRACK PROPAGATION AREA



d) THE TUBE THINNING

e) SCALES ON THE OUTER SURFACES

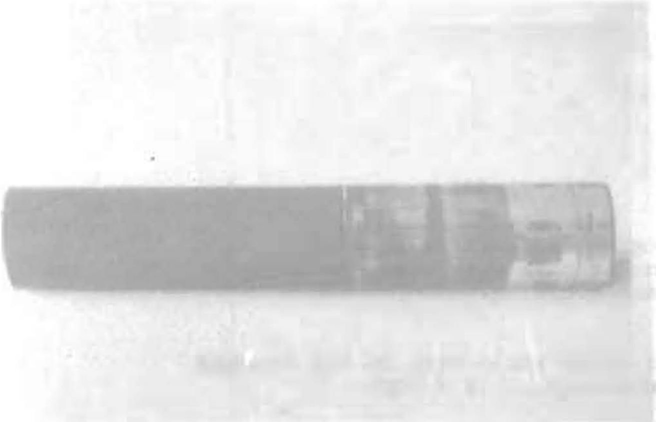


Figure (1)

General view of tube showing expanded section, fracture and uniform cracking on the outer surface of tube in contact with water.

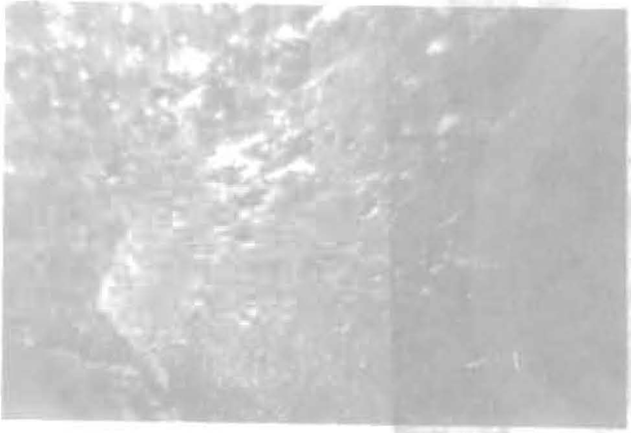


Figure (2)

Pittings revealed after removal of scale on outer surface close to the fracture.

Figure (3)

Cross-section through the outer surface of expanded portion of the tube showing pittings and cracking ... (X = 200)

Figure (4)

Cross-section of fracture showing intergranular path with some branching into adjacent grains.

Note: the oxide scale with in the cracked boundaries... (X = 500)

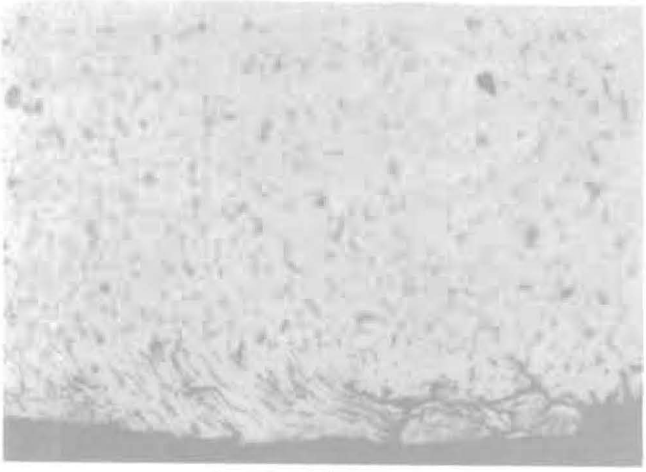


Figure (5)

Deformed region of the outer surface remote from the fracture showing some cracking .... (X = 200)

Figure (6)

Scoring on the inner surface.

APPENDIX

Thermal Design Data of the Steam Generator :

Shell side :

water velocity = 1.674 ft/s
Flow rate of water = 18.565 lb/hr
Inlet temperature = 212 °F
Shell operating pressure= 60 psig
Fouling factor = 0.001 hr ft^2/Btu
Outlet temperature. = 308 °F
Outlet fluid = 17680 lb/hr steam + 885 lb/hr water
Average pH of feed water = 10 (It reached 11.8 in some instances).

Tube side :

Flow rate of vacuum residue = 108,896 lb/hr
Fouling factor = 0.01 hr ft^2 °F/Btu
Inlet temperature = 650°F
Specific gravity = API = 7.8
Specific heat = 0.627 Btu/lb °F
Outlet temperature = 390°F
Operating pressure = 120.7 psig

Characteristics of vacuum residue (Bitumen) :

Sp. gr. (at 60°F) = 1.016
Viscosity (at 140°F) = 45,000
Viscosity (at 210°F) = 1,500
Sulfur content = 5.2%
Pour point, °F = 120

The steam generator is of the horizontal kettle type with overall dimensions of 58" x 67" x 197" with 2 shells and with net heat transfer area of 556 ft . It has 1768 tubes 3/4" o.d. gauge 12 (B.W.G.) and 16 in length. The mean temperature difference (MTD) is 182°F. Total heat exchanged = 17.75 x 10° Btu/hr. The design heat transfer coefficient for clean pipes is 9.09 Btu/hr °F ft^2.

REFERENCES

[1] FONTANA, M.G. and GREEN, N.D.: "*Corrosion Engineering*", McGraw-Hill Book Company, 1983.

[2] PARDUE, W.M.; BECK, F.H. and FONTANA, M.G.: Am. Soc. Metals Trans. Quart., 54, pp 539-548(1961).

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