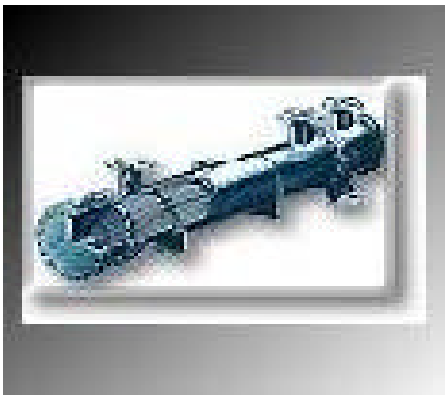
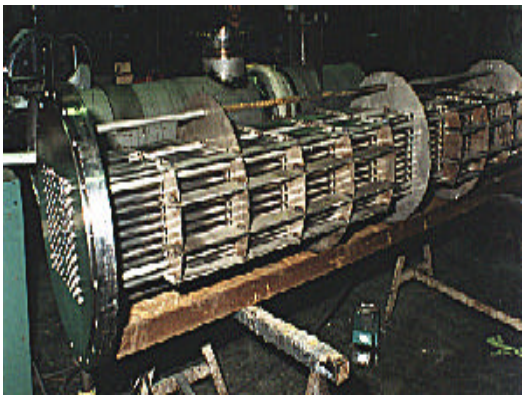
FAILURE ANALYSIS OF HEAT EXCHNGERS

AN APPROACH AND CASE STUDIES

AT RELIANCE INDUSTRIES LIMITED, HAZIRA





Prepared By

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CES (INSPECTION AND CORROSION)

CASE 1. Failure of 2nd Stage Reactor Effluent Cooler (E741) in Cracker Plant due to Acidic attack

CASE 2. Failure of Rotary Air Inlet Heater (EC5701BX) Tubes in PVC Plant due to Corrosion/Oxidation

CASE 3. Failure of Solvent Dehydration Column Reboiler (E2-602) in PTA- 2 plant due to Crevice corrosion.

CASE 4. Failure of TA Drier Gas Heater (E2-504) in PTA- 2 plant due to Acetic Acid corrosion of SS-316L.

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CASE 6. Failure of Admirality-brass cooler tube of Gas Turbine 6 in CPP plant due to Dezicifiaction & mechanical damages along with fabrication aspects

CASE 7. Failure of lube oil cooler tubes of Diesel Generator Set in PTA plant due to Dezicifiaction

CASE 8. Failure of lube oil cooler tubes of York Compressor (EA6517AX) in VCM plant due to Dezicifiaction

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CASE 24. Failure of Tube of VCM Column Condenser (EA6504B) in VCM Plant due to internal pitting.

CASE 25. Failure of Tube of 2nd Quench Bottoms Heater (EED6410) in VCM Plant due to internal corrosion.

CASE 26. Failure of Tube of Quench Vapor Condenser (EC6402B) in VCM Plant due to internal corrosion.

FAILURE ANALYSIS AN APPROACH

Objective of Failure analysis

The purpose of the failure investigation and analysis is to determine the cause of the failure and based on determination, corrective action should be made to prevent reoccurrence of the similar failure.

Steps of Failure analysis

Failure analysis conducted in steps to reach the root cause of the failure. Although the sequence is subject to variation, depending upon the nature of a specific failure, the principal steps that comprise the investigation and analysis of a failure are:

- ***Collection of background data and selection of sample***
  The information should describe the circumstances of failure, operation or other pertinent details.

- ***Preliminary examination of the failed part (visual examination and record keeping)***
  Much information concerning a failure can be obtained from a careful visual examination. Dimensional changes reflect swelling or thinning. The pattern, extent, or nature of corrosion or cracking is often an important clue to the cause of failure. Visual examination will indicate the direction of further work; the detailed investigation should be planned at this stage.

- ***Nondestructive testing***
  Nondestructive tests like Dye penetrant test can be used to confirm any fabrication defects.

- ***Mechanical testing (including hardness)***
  Hardness tests can be used to check whether heat treatment was correct or uniform or if hardening occurred from cold working, overheating, carburization, or phase changes in service.

- ***Selection, identification, preservation, and/or cleaning of all specimens***
  The proper selection, preservation and cleaning of fracture surfaces are vital to prevent important evidence from being destroyed or obscured. Surfaces of fractures may suffer mechanical or chemical damage.

- ***Macroscopic examination and analysis (fracture surfaces, secondary cracks, and other surface phenomena)***
  The detailed examination of failed sample at magnifications ranging from 1 to 100X may be done with unaided eye, a hand lens or a low power optical microscope. The amount of information that can be obtained from examination of the fracture surface at low power magnification is surprisingly extensive.

- ***Microscopic examination and analysis***
  For metallurgical investigation, microstructural details provide much information about thermal history, operating temperatures, chemical environment, manner of attack and cracking.

- ***Chemical analysis***
  Information on corrosive agents is usually obtained by analysis of corrosion products or metal surfaces.

- ***Analysis of all the evidence, formulation of conclusions, and writing the report (including recommendation)***
  At a certain stage in every investigation, the evidence revealed by examinations and tests mentioned above is analyzed and collated, and preliminary conclusions are formulated. Obviously, many investigations will not involve a series of clear-cut stages. If the probable cause of failure is apparent early in the examination, The pattern and extent of subsequent investigation will be directed towards confirmation of the probable cause and the elimination of other possibilities. Other investigations will follow a logical series of steps and findings each step will determine the manner in which the investigation proceeds. However, the cause or cause of failure cannot always be determined with certainty. In this case, the investigation should determine the most probable cause or cause of failure.
  After establishing cause or most probable cause of failure, the failure analysis report should be written clearly, concisely and logically. Report should include description of failure, observations, tests carried out on the samples, most probable cause of failure, Analysis of the findings, and recommendation for prevention of similar failure.

HEAT EXCHANGERS

Introduction

For the vast majority of heat transfer equipment applications, the transfer of heat takes place between two fluid streams. The heat exchanger is simply a device which directs the flow paths in such a way that the two streams are brought into thermal contact through a conducting wall while being kept physically separate. This thermally conductive wall is the tube in shell-and-tube type heat exchangers. The relatively thin-walled tube, selected primarily for heat transfer efficiency, becomes the critical component in condensers and other heat exchangers.

Names and functions of Heat exchangers

Heat exchangers are used whenever it is desirable or necessary to heat or cool a fluid. Individual heat transfer equipment are named after the function which they perform.

1. **Cooler :**
   A cooler cools the process fluid, using water or air, with no change of phase.
2. **Chiller**
   A chiller uses a refrigerant to cool process fluid to a temperature below that obtainable by water.
3. **Condenser :**
   A condenser condenses a vapor or mixture of vapour using water or air.
4. **Exchanger :**
   An exchanger performs two functions in that it heats a cold process fluid by recovering heat from a hot fluid which it cools. None of the transferred heat is lost is lost.
5. **Steam Heater :**
   A steam heater uses steam to heat either water or process fluid.
6. **Steam Generator/Waste Heat Boiler :**
   A steam generator produces steam from water using hot process fluid (that requires cooling) or hot gases produced in chemical reaction.
7. **Reboiler :**
   A Reboiler uses steam or any hot fluid to heat process fluid (hydrocarbon) for distillation column.

Types of Heat Exchangers

Heat exchangers can be classified according to mechanical constructional feature, mode of the heat transfer, flow configurations etc., detailed classification of the heat exchanger is out of the scope this book. Following are the most common type of heat exchangers.

1. Shell and Tube Heat Exchangers

These are most widely used types of heat exchangers. In general, a shell and tube exchanger consists of a shell, a tube bundle, a channel head, floating head cover and shell cover. Commonly used shell and tube type exchangers are as follows:

a) Floating head exchanger,
b) Fixed tube sheet exchanger,
c) U- tube Exchanger,
d) Kettle Shell

2. Double Pipe Heat Exchanger

These usually consists of concentric pipes. One fluid flows in the inner pipe and other fluid flows in the annulus between the pipes in a counter current flow configuration.

3. Finned tube Heat Exchanger

To increase the heat transfer surface area, fins are used on the outside/inside of the round or flattened tubes. The tubes are connected at each end by a header.

4. Plate type Heat Exchanger

This is constructed by a series of corrugated parallel plates held firmly together between frames. The two fluids travel in counter-current directions, and the heat transfer takes place through plate.

5. Spiral Plate Heat Exchanger

It consists of two flat plates welded together along their long edges and then bent into a spiral coil. Thus it forms two separate channels through which hot and cold fluids flow in counter current directions.

Common Corrosion Failure in Heat Exchangers (An overview)

Failures in heat exchangers are commonly associated with methods of manufacturing pipe and tubing, handling methods during fabrication, testing methods in the shop and in the field, and the total environment to which the unit is exposed after fabrication – including condition during shipment, storage, start-up, normal operation and shutdown.

Heat exchangers are exposed to various Corrosive services which leads to failure of the exchanger components. This section will cover common Corrosion problems in heat exchanger. Followings are the basic mechanisms of corrosion

Uniform Corrosion

Though Uniform corrosion is an idealized form of corrosion and cause less damage than the other forms of corrosion. This leads to uniform thinning of the base metal. This can be estimated depending upon material used and service.

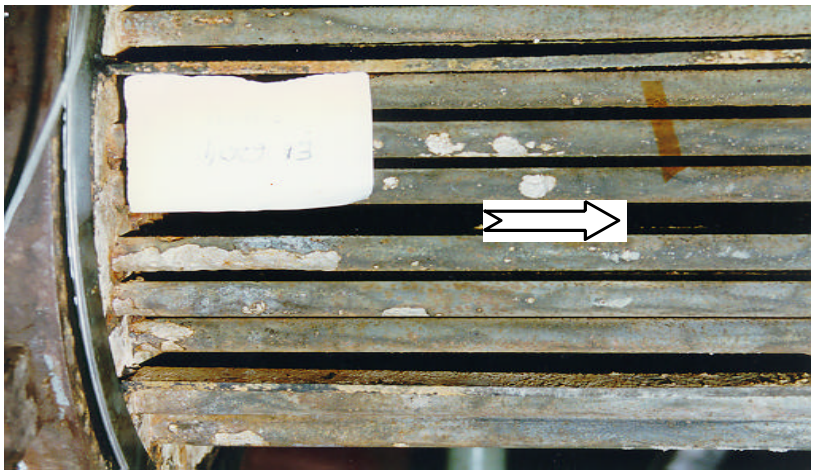

Fig. 1 Showing Uniform corrosion of the heat exchanger tubes.

This can be prevented by one or more of the following methods

- Cathodic protection
- Inhibitors
- Protective coating.

Galvanic Corrosion

When dissimilar metals or alloys differing in their galvanic or corrosion potential are employed and if they are electrically shorted they induce this type of corrosion. The corrosion rate of the alloy with lower corrosion potential will be accelerated by that of higher corrosion potential. This type of corrosions were generally seen on lube oil cooler, and on the chiller condenser of the compressor where generally tubes of cooper base alloys and tube sheet of carbon steel were used. In such case grooving noticed on the tube sheet. This type of corrosion can be identified by visual inspection of the corroded surface.

Typical features of the galvanically corroded metal are

- Grooving of the interface
- The active metal is corroded
- Noble metal deposit from the stream.

This type of corrosion can be avoided by

- Choose alloys closer in galvanic series
- Coat the active metal surface

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- Protect the corroding metal with a sacrificial anode, which is anodic to corroding metal.

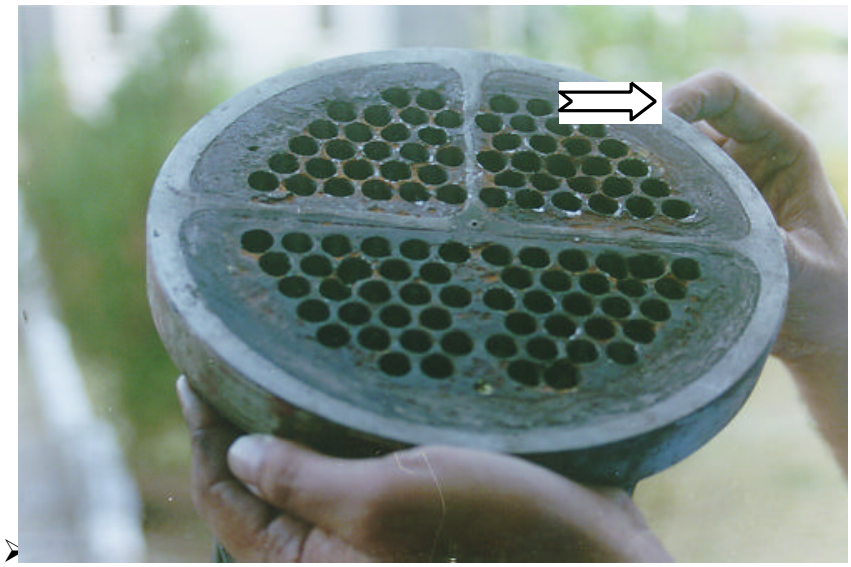


Fig. 2 Showing galvanic corrosion of tube sheet.

Crevice Corrosion

This type of corrosion occurs if differential aeration exists due to crevice, metal joining (lap Joints, flanges etc.) or deposit. Interestingly the location starving for oxygen is forced to become anodic and getting corroded, and the region having free access to oxygen becomes cathode.

This type of the corrosion can be prevented by

- Avoid flanges, lap joints, riveting and go for welding joints.
- Prevent stagnancy of the fluid in the vessel
- Frequent removal of the deposits, by using back wash in the case of heat exchangers.
- Use of solid non-absorbent gaskets.

Pitting Corrosion

Alloys in the presence of certain ions (such as halides) are prone to pitting . The rate of growth of pits can be as high as one million times as compared to uniform corrosion in similar environment.

Fig 4 Showing under deposit pitting of heat exchanger tube

Fig. 5 Showing pitting corrosion of tube to tube sheet strength weld and tube sheet.

Typical features of the pitting corrosion are

- Pinholes
- Normally grow in the direction of gravity
- The alloy environment combination

This type of corrosion can be avoided by

- Eliminate the specific ions responsible for pitting (say halide in the case of SS)
- Choose alloy resistant to pitting. In stainless steels High MO promotes pitting resistance.

<u>Selective leaching</u>

When noble and active element form an alloy, e.g. Brass, it result in selective removal of the latter. As a consequence the alloy looses its strength and fails prematurely. Cu-Zn alloys are well known where in dezincification occurs if Zn content exceeds beyond 15 wt%. Similarly we have denicklification, desiliconation, decobaltification.

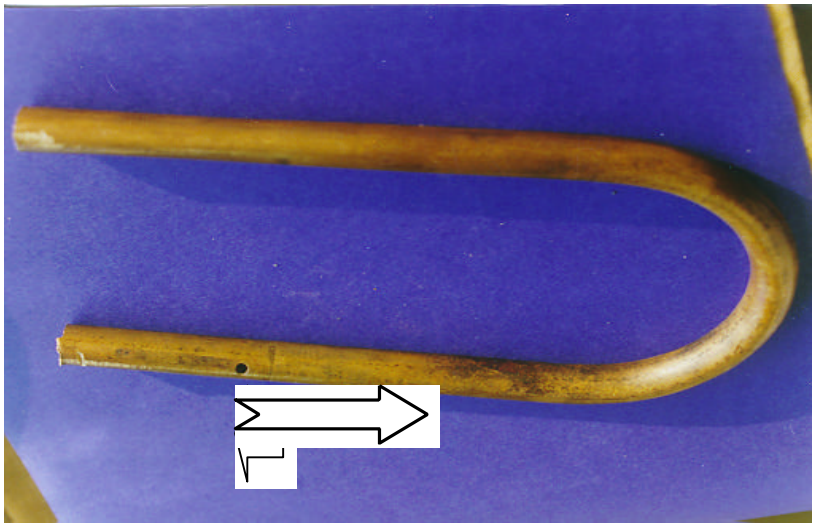


Fig 6 Showing plug type dezincification of heat exchanger tube.

Typical features of the Dezincification are

- Change in color (from yellow to brown in the case of brasses)
- They give rise to plug and layered type of attack.
- There can be a change in density in some cases.

This type of corrosion can be avoided by

- Addition of any one of the elements namely Sn, As, Sb, and P in the alloy. (like Sn in the case of admiralty Brass.
- Al addition reduces overall corrosion and to some extent dezincification.

Intergranular Corrosion

This type of corrosion occurs as a result of selective attack of the grain boundaries when either grain boundary becomes highly active or phases prone to selective attack are formed. This type of corrosion takes place in stainless steel when it subjected to temperature between 400-900^{0}C. Welding, a common practice in fabrication, causes such an IGC attack.

Typical features of the Intergranular Corrosion are

- Attack of alloy away from the weld ment called heat affected zone.
- Clear ditch type of attack along the grain boundary.

This type of corrosion can be avoided by

- Choose low carbon and extra low carbon stainless steels (such as SS304L, SS316L)
- Choose Ti or Ta and Nb stabilized stainless steels (SS321, SS341)
- Provide a solutionizing treatment to dissolve the carbides (heating up to 1050oC holding for 30min followed by air cooling).

Erosion Corrosion

When there is a relative movement of the corrosive environment with respect to the alloy it can lead to erosion corrosion. Typical feature of erosion corrosion is Grooves in the direction of liquid flow. This type of corrosion can be avoided by

- Reducing the velocity of the medium
- Choosing hard metal
- Provide hard coatings.

Stress Corrosion Cracking

SCC is the brittle cracking of a metal due to the result of combined effects from localized corrosion and tensile stress. However SCC is specific to environment and it takes place if the stress exceeds a threshold level. The alloys are susceptible to SCC only when specific ions are present akin to pitting corrosion. There are many examples in which specific metals and environments in combination cause such problems. A few examples include:

- ✓ Brass - SCC in solutions with ammonia
- ✓ Steel - SCC in caustic (high pH), amine solutions
- ✓ Stainless steels and aluminum alloys - SCC in solutions containing chlorides.
- ✓ Ti-alloys - SCC in nitric acid or methanol.

Typical features of the Stress Corrosion Cracking are

- Failure occurs by brittle mode
- Branched cracks with a transgranular/Intergranular propagation

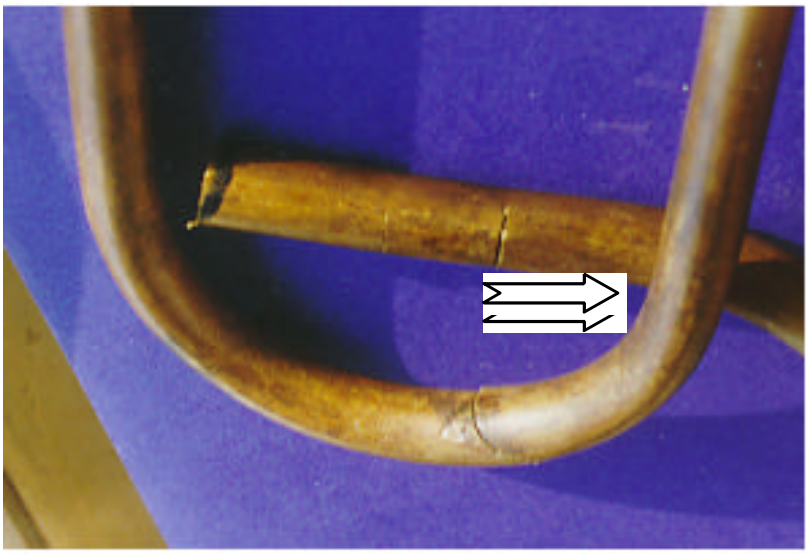


Fig 7 Showing Stress corrosion crack of heat exchanger tube.

Stress corrosion cracking can be prevented by

- Lower either applied or residual tensile stresses.
- Modification of the environment to eliminate specific SCC agent(s).
- Change alloy or increase alloy content (i.e. Stainless steels and nickel base alloys).
- Cathodic protection to change corrosion potential out of SCC range.
- Add chemical inhibitor.

SUMMARY OF HEAT EXCHANGERS FAILURE AT RIL HAZIRA SITE

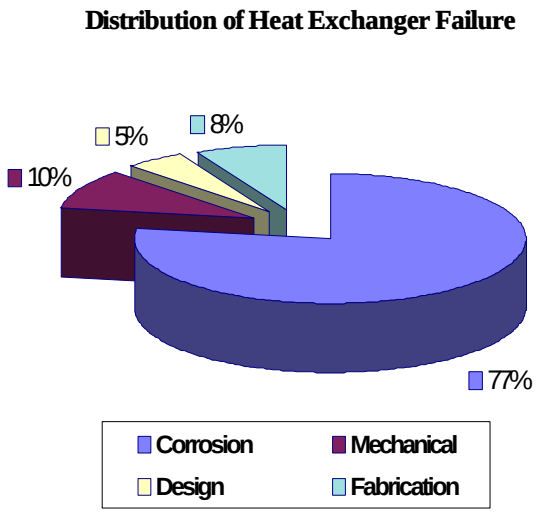
As discussed in previous chapter, heat exchangers can be failed due to manufacturing defect and/or corrosion during service.

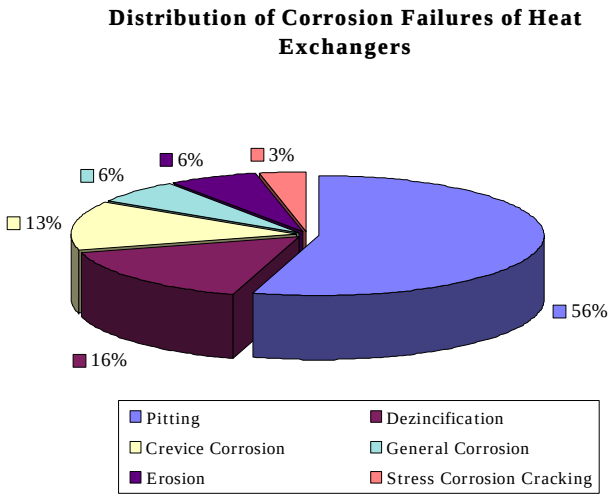
At RIL Hazira site total 40 major failures of heat exchanger have been observed for which Failure analysis report have been prepared. Most of the exchangers were failed due to in-service corrosion. Apart from in-service failure few exchangers in VCM plant failed during plant start-up after shut down due to moisture ingress in acidic deposits.

Following are the statistics of the heat exchanger failures:

- In-service corrosion failure (like pitting, SCC) **72.5%**
- In-service mechanical failure (like fatigue and erosion) **10 %**
- Due to fabrication defect **7.5 %**
- Due to improper design **5 %**

Following chart shows the distribution of failures.





The Corrosion Failures can be further categorized according to the type of corrosion like Pitting, Crevice corrosion, Stress corrosion cracking. Above chart gives distribution of Corrosion Failures of Heat Exchangers.

Statistics of failures heat exchangers indicates pitting corrosion (under deposit pitting or internal pitting) was the predominant cause of heat exchanger failure.

Failure due to dezincification of Brass tubes were also have remarkable number. This type of corrosion was noticed in lube oils coolers having Brass tubes. MOC of all the failed lube oil cooler tube upgraded to Cu-Ni, since than failure due to dezincification in same were not reported. The reason primarily happened to be due to inferior material selection of these tubes, which was later on upgraded as required to meet the process needs.

Case-1 Failure of 2nd Stage Reactor Effluent Cooler (E741) in Cracker Plant due to Acidic attack

FAR No	FAR/M/99/35	**FAR Date**	20 July 1999
Date of Failure	07 July 1999		

Failure Description :
Suspecting leakage from the tubes of E-741, the cooler was opened up for inspection/ hydro testing. 23 tubes were found leaking profusely and 6 tubes were leaking from tube to tube-sheet expansion/ welding joints. All leaky tubes were plugged & welded when one minor

Observation
Suspecting leakage from the tubes, cooler was opened up for inspection/ hydro testing. 23 tubes were found leaking profusely and 6 tubes were leaking from tube to tube-sheet expansion/ welding joints. All leaky tubes were plugged & welded when one minor leakage from tube to tube sheet joint was seen in final hydro-testing.

Cooler was once again leaked within 40 hours of operation. Tube bundle was pulled for inspection and detailed observations were made as follows:

Minor Reddish/Black deposits were seen at the tubes OD surface, mainly at inlet side.
Severe corrosion damage / erosion marks noticed at outer surface of the tubes, resulted in to thinning down and puncture of the same. Damage was predominant in the outlet pass section of the tube bundle.

Yellowish hard layer of cooling water scaling was observed at the tube ID surface.
Tube edges were found eaten away, at places, indicating poor quality of tube to tube-sheet strength welding.

Cooling water deposits observed at both the tube sheets. On cleaning, condition of the tube-sheets was found satisfactory, when no appreciable corrosion damage was noticed.
Minor corrosion/erosion effect was seen at the baffles.

History :
Cooler was commissioned in March-1997. Leakage was experienced first time after commissioning
Reasons :
Severe acidic corrosion at the OD side (i.e. process side) of the tubes.
Analysis :
Sample of the leaky tube was cut into halves across the longitudinal section & internal side of the tube was examined. Sample inspection revealed severe corrosion damage marks at the OD surface of the tubes, resulted in to local thinning down, at places(mainly at the first 3 baffles from the inlet side). Shallow pitting was observed at the ID side of the tube, however, the same appears to be the after effect of the main leakage from OD side.
Acidic flow marks were also seen at the OD of the tube nearby the leaky portions of the tube.
Hardness of the failed tube sample checked and found to be around 63 to 65 HRB, which meets the requirements of ASTM A 179.

Discussion :

The measurement of ID/OD of tube as well as from longitudinally cut leaky tube sample, implies severe corrosion damage / erosion and thinning down of the tube from external side. Close inspection of the punctured zone of the tube revealed deep grooving marks initiated at the external surface of the tube.

However, internal surface of the tube did not indicate appreciable corrosion signs of pitting or general corrosion.

The type of damage noticed at the external surface of the tube, it is evident that the damage has been occurred primarily by corrosion and aggravated by erosion. The protective oxide film got damaged due to erosion. Subsequent film could not be formed due to liberation of nascent hydrogen during acid attack. This phenomenon led to very high corrosion rates which subsequently led to puncture of the tube. The low pH and presence of sulfates confirm the acidic nature of the deposit.

Although pH of deposit collected from the ID side of the tube was also low (4.3-4.5) and the nature of deposit was also acidic, but no significant corrosion has been observed probably due to the after effect of the leakage and ingress of the acidic material from the OD side and got mixed up in the short exposure at tube ID with cooling water deposit at tube side.

Recommendations :

1. Detailed process study to be carried out by TLS with respect to the deposits and its acidic nature noticed.
2. Periodic and frequent cleaning of tube bundle, once a year .
3. Sampling arrangement to be made in the upstream of cooler, at process side

Case-2 Failure of Rotary Air Inlet Heater (EC5701BX) Tubes in PVC Plant due to Corrosion/Oxidation

FAR No	FAR/M/99/35	**FAR Date**	01 September 1999
Date of Failure	08 August 1999		

Failure Description :
Leak in B2 coil of line-2 dryer system was suspected for last few weeks. This job was planned during K57-11 shutdown to avoid any production loss on account of coil replacement. The suspected leaky heating coil was dismantled and taken out. On hydro-testing of the same, 1 no. failures of similar nature were noticed in line -1 heating coils.

Observation

- The suspected leaky heating coil was dismantled and taken out. On hydro-testing of the same, 1 no. tube was found leaking. The punctured area of the coil was identified & was cut & forwarded to I&C for investigations.
- Blackish deposits were noticed on the entire heating coil OD surface, except around the punctured zone, where green colored deposits were noticed.
- Most of the fins were found to be brittle, oxidized & also broken at several places.
- Close observation of the leaky zone revealed corrosion originated from OD side and the tube section found considerably (by 50%) thinned down (Original thickness- 0.89 mm).
- The puncture had taken place at the line of fins.

History

This is the first time the failure of heating coil has occurred in line –2 heating coil.

Reason

Corrosion/thinning of tubes due to hydrolysis of chloride present in the PVC powder deposited on external surface of coils.

2. Due to damaged (embrittlement/oxidation) fins, this may lead to uneven heat transfer causing local overheating, oxidation, chloride attack of copper fins & weakening of tube.
3. The considerable water hammering effect on thinned down coils might have caused final puncturing and leakage of tubes in the line of fins.

Analysis

1. MOC of the heating coil tube checked in the lab was conforming to actual specification, i.e. 90Cu-10Ni.
2. Micro structural examination of failed section has revealed inter-granular attack from OD side of the tubes.
3. PVC is hydrolyzed on reaction with moisture at temperature slightly more than the ambient resulting in formation of Hydrochloric acid. Copper alloys are attacked by HCL (greenish salt present) in presence of oxygen. The accumulation of cupric ions make the reaction autocatalytic. The contamination of the fins by PVC & moisture can take place if the suction filters of FD fan are damaged during operation or when the coils are exposed to atmosphere during shutdowns/breakdowns of drier. The gradual reduction in thickness of tubes is due to corrosion by HCL thus formed.
4. Another contributing factor in the present case is probably water hammering. The hammering takes place if the Condensate is not completely removed by steam traps or draining. The final failure of the tube probably takes place due to above combined factors that is thinning of tubes due to HCL formation & subsequent water hammering.

Recommendations:

1. The contamination of external surface of coils caused by PVC powder during replacements or operation should be avoided by cleaning of coils as and when they are taken out. (By air blowing)
2. Changing of suction filters for effective filtration of PVC

Case 3 Failure of Solvent Dehydration Column Reboiler (E2-602) in PTA- 2 plant due to Crevice corrosion.

FAR No	FAR/M/99/18	**FAR Date**	06 December 1999
Date of Failure	25 November 1999		

Failure Description :
Leakage through top dome gasket of E2-602 while the equipment was in operation.

Observation
Gasket found damaged in leakage area. Seating surface of the top dome in leakage area found corroded & pitted. The depth of pitting / grooving was found to be as deep as 2-3 mm. The corrosion effect was visible up to 1meter length along the seating face.
The condition of dome inner surface was found to free from any significant corrosion. The condition of tube tube-sheet and tubes were found to be good.

History
The equipment was in operation since the plant was commissioned in Nov. 1997 without any failure.

Reasons
The damage in the gasket seating surface is crevice corrosion might have occurred due to presence of highly corrosive concentrated acidic cell (90 % acetic acid concentration).

Analysis
The gasket surface was made by weld overlay over CS base flange having thickness of 5.0mm. The over laying was done first by E-309L as barrier layer (2.0 mm) and than Haynes 25 overlay (3.0 mm) over 309L.

2. Haynes 25 was used for both corrosion as well as wear resistance. However, 309L will corrode in this type of service condition.
3. Dilution of welding / overlay may take place by inferior base metal if thickness of the layer is less.
4. As 309L layer was very thin (only 2.0 mm), dilution on the layer by CS base metal took place, and consequently affected the following Haynes 25 overlay, ultimately affecting the corrosion property of Haynes 25. However, insitue MOC checking could not be done due to temperature (70-80 Deg C) of the surface.
5. The corrosive liquid which could enter through the gasket and come in contact with the seating face corroded the surface badly.

Recommendations
1. The damaged surface was repaired locally by grinding and welding (by Haynes 25) and flushing the surface.
2. The affected surface should be offered for inspection during next shutdown to assess the condition of the corroded surface.
3. Proper weld ove

Case 4 – Failure of TA Drier Gas Heater (E2-504) in PTA- 2 plant due to Acetic Acid corrosion of SS-316L.

FAR No	FAR/M/99/19	FAR Date	06 December 1999
Date of Failure	25 November 1999		

Failure Description
Suspected tube puncture as liquid was coming into C2-503 suction.

Observation
The exchanger is a double tube one. The following observations were noted.

- The leakage was from upper portion of the bottom U-tube near the head. On removal of the tube one hole of 2-3 mm dia and 2/3 more pin holes were observed.
- Severe localized pitting was visible near the affected area from inside.
- Thickness survey of the whole tube revealed 3-4 mm thickness reduction locally near the punctured location. No significant thickness reduction was observed at other locations of the tube.

History
Similar failure occurred in PTA-1 also last year. The location of failure was nearly same.

Reasons
The failure of the tube is probably due to acetic acid corrosion of SS316L material.

Analysis

- The corrosion was found to be mainly concentrated at the outlet zone of the exchanger where the temperature is maximum i.e. 105-110 deg C. At other section of the tube no significant corrosion or thickness reduction was observed.
- Higher temperature at the outlet zone may be causing the corrosion problem in the presence of acetic acid.
- Process upset like increase in concentration of acetic acid and temperature (than designed) may cause pitting / corrosion.

Recommendations :

1. The corroded area was repaired locally by grinding, welding and putting patch plate over the surface. Hydrotest was then carried out.
2. All other tube are required to be offered for inspection during next shutdown to assess the condition of other tube
3.
4.

Case-5 Failure of Refrigerant Package (GC5715) in PVC plant due to due to localized crevice attack adjacent to the internal spiral rib/fin in tube ID

FAR No	FAR/M/98/18	**FAR Date**	18 November1998
Date of Failure	12 September1998		

Failure Description
On suspecting leakage, the condenser and evaporator were taken under shutdown for necessary inspection and corrective action.

Observations
- Majority of the tubes found choked with cooling water side debris (stone, plastic, wooden piece etc.)
- Thorough cleaning of the tubes was carried out prior to pneumatic test.
- On 13/09/98, the condenser and evaporator were pneumatically tested, on the shell side, at 22.0 psig and 2 nos. tubes were found leaking in the condenser (i.e. total 11 no. leaky tubes found so far). No tube leakage was found in the evaporator.

The two leaky tubes were pulled out for analysis. The following are observed in visual examination:
- OD surface of tube found to have fine, loose layer of rust.
- Location of leak was found to be 2.1m and 2.5m away from the inlet side.
- No corrosion from external side was observed.
- Sample piece including leaky portion of the tube (200mm long) was split longitudinally to examine the internal surface of the tubes. The following significant observations were noted:
- ID surface was found free from any loose deposit, however, yellowish intermittent corrosive deposits were observed on the inner surface.
- The leaky zone was located adjacent to one of the internally spiral fins.
- The size of pit around the leaky zone was 4.5mm X 3mm.

History
In past, 9 nos. leaky tubes (already plugged) have been reported since commissioning of the YORK Compressor, GC-5715(RFS-5R) in 1992.

Reasons
Probable reason of tube leakage appears to be due to localized crevice attack adjacent to the internal spiral rib/ fin.

Analysis
- Cooling water side foreign deposits on the ID surface forms a de-aerated cell. The difference in oxygen content under the deposit and surrounding area established an differential cell (electrolytic cell) under the deposit. The end result was nodules of a corrosion product and pits. These pits eventually became localized holes in the tube wall in due course of time.
- The destructive analysis of the failed tube sample piece was performed by external party. Following are the results:
- The chemical analysis and hardness of the failed tube matches with the specification of 90-10 copper-nickel(UNS no. C70600).

- The microstructure consists of partially elongated single phase grains which is typical of this metallurgy.

Recommendations

1. Strainer to be installed at the inlet of condenser to prevent cooling water side debris entering the tubes, so as to minimize the fouling of tubes. To be recommended by PVC / CES Mech. Dept.
2. To prevent the recurring failure, it is essential that no deposit is accumulated inside the tubes.
3. Frequent/periodic cleaning / back washing of condensers may help in improving the situation top eliminate the problem substantially.

Cleaning Schedule

Sr. no.	Tag no.	Present schedule (as per plant) (in months)	Recommended schedule (in months)
1	RFS-1R	12	6
2	RFS-2R	6	3
3	RFS-3R	4	2
4	RFS-5R	2	1

The above measures shall be implemented in all remaining York refrigeration systems

4. Meanwhile, as suggested by M/s York International Corporation, the possibility, feasibility and effectiveness of Eddy Current Testing of the tubes of the condenser is being explored in consultation with M/s KRIBHCO, Surat. On successful outcome of this study , the Eddy Current Testing of the tubes may be conducted to assess the condition of tubes in the condenser.

Similar type of Corrosion failures was seen earlier in GC5712

Reference FARs - FAR/M/98/10 Date-20 August 1998

Case-6 Failure of Admiralty-brass cooler tube of Gas Turbine 6 in CPP plant due to Dezicifiaction & mechanical damages along with fabrication aspects

FAR No	FAR/M/99/102	**FAR Date**	25 July 1999
Date of Failure	13 July 1999		

Failure Description
Leakage of East side Lube oil cooler of GT#6.

Observations
- 2 of the peripheral tubes were found to be damaged at the location of last baffle plates (13 No. i.e., -closest to 'U' bend).
- Last baffle plate found to be slightly bent /wavered at its outer edges.
- Fins at the locations of baffles of few peripheral tubes were found to be slightly damaged and at the locations of bending the portions appeared to be in tension.

History
Since there have been recurring failures especially from the last week of June to July-" 99, a thorough review of the working conditions of all M/s BHEL make coolers was reviewed and the following were put forward.

In the recent months, recurring failures have been observed in coolers of GT4,5 & 6.

The right side coolers of these GTs (including GT-3) have been replaced with Cupro-Nickel against the existing admiralty brass coolers.

Reasons
Dezicifiaction & mechanical damages along with fabrication aspects.

Analysis
- In the past we have observed that tubes have failed on account of plug type Dezincification. In case of GT -3 LO coolers. In the recent failures also, samples collected from GT-4 and GT-6 have shown similar type of indications of dezincification.
- It was confirmed from plant also that the velocity of the water in tubes is in the range of 0.6 to 0.8m/s against the required minimum of 0.9 to 1.5m/s.
- The deposits have been collected from tube ID side of GT-5, GT-6 and GT-4 have shown pH in the range of 4.5 to 5.2 and Chlorides as high as 600ppm against the required specified value of 200ppm maximum in case of cooling water. This large variation is probably due to accumulation of deposits from time to time.
- Chemical analysis of tube samples of GT-6 and GT-4 coolers revealed that inhibiting element Arsenic was of insignificant quantity , in both the cases, to meet with the specified quality of Admiralty Brasses. This material (non inhibited admiralty brass) is presumably inferior to admiralty brass for resistance to Dezincification. Hence the faster failure.
- In some of the tubes of west side cooler of GT 4, circumferential cracks initiating from ID side were observed, probably during the fabrication of the finning or the tube insertion, indicating the poor quality of fabrication. Severe stress during drawing/finning /& bending has

lead to substantial localized thinning making those zones to faster Dezincification and cracking, as seen in the microstructure.

- Micro-examination of the GT 6 cooler also revealed dezincification along with transgranular cracks. These cracks were present just beneath the dezincified spots in the tube.

Discussion

From the above observations and analysis it is evident that the failures of lube oil coolers are not due to single mechanism. Evidence of multiple failure mechanisms have been observed. The following factors have contributed to the final failure of tubes:

Low Water Velocity

Water velocity of 0.9 m/s is minimum required cooling water velocity. Low velocity leads to accumulation of deposits. Deposit in the tube ID surface cause increase in the tube metal temperatures which can further lead to dezincification and subsequent failure.

Improper Material

It appears that chemical analysis of the tube sample exhibited the absence of inhibiting element Arsenic, which is inferior to the admiralty brass and probably made it prone to dezincification.

Mechanical Damage

The tubes have been found damaged near U -bend side in these coolers. The fins were also found damaged near last baffle plate. The U bend radius was not perfectly matching with the respective baffle holes, their by tubes were forcibly adjusted into these misalign baffle holes during the tubes insertion into the skeleton assembly of the tube bundle ,causing severe stresses in this location.

FRC Excursions

Since the no of recurring failures have been increased in recent months, cooling water analysis reports were reviewed for last one year. It was observed that in one year several excursions of free residual chlorine have occurred . Free residual chlorine level up to 1 ppm (against a range of 0.2 to 0.5ppm) have been observed on some occasions. Free residual chlorine increases the corrosion of copper alloys and increases the risk of dezincification and stress corrosion cracking also.

Thus the above factors contributed to the failures of lube oil cooler tubes by such phenomenon

Recommendations :

1. Header pressure of the cooling water may be increased to achieved the required water velocity to prevent accumulation of water side deposits.
2. To prevent mechanical damage to the tube fins, the finned length of tube should be reduced and the thickness

Similar type of Corrosion failures were seen earlier also in GT-3, 4, 5 and GT-6 coolers.

Reference FARs - CPP/M/96/27 Date-24 February1997, I&C/CPP/97/02 Date- 14 February 1997, FAR/M/98/76 Date-23 November 1998

Case-7 Failure of lube oil cooler tubes of Diesel Generator Set in PTA plant due to Dezicifiaction

FAR No	FAR/M/98/32	**FAR Date**	23 January 1999
Date of Failure	24 November1998		

Failure Description
DG set lube oil cooler E1-DG1 leaked.

Observations
- While hydro- testing the cooler, profuse leak was observed in two tubes before pressurizing. On subsequent pressurizing, 12 tubes were found to be leaky.
- On removal of tube bundle for cleaning no significant deposit/corrosion was observed on the tubes from outside. Deposit was observed inside the tubes.
- Thick brownish deposit was observed in the domes from inside. Sacrificial anode provided at the dome was found to be completely consumed.
- As no drawing of the cooler was available, the MOC of the tube could not be identified. However, the tubes were found to be non magnetic and appeared to be of Copper based (like Admiralty brass) which is common for lube oil coolers.
- Since the leaky tubes were all in the inner side of the bundle, no leaky tube could be collected for detailed analysis. One non-leaky tube was cut from outer periphery of the bundle. A portion of the tube was sectioned longitudinally when minor reddish spots were observed on the inner surface of the tube.

History
The cooler was in service since January 1997.

Reasons
Most probable reason appears to be dezincification of tubes.

Analysis
The red spots observed in the inner surface of the tube indicated initiation of selective leaching out of zinc leaving behind red spots of copper. In the past also similar failures of brass tubes in similar service in other plants (VCM & CPP) have been observed, where brass tubes failed mainly because of dezincification. Although thorough micro and macro examination of the leaky portion of the tube could not be carried out to confirm the dezincification because of non-availability of leaky tube. But the initial and prominent observations indicate that the tubes of the present cooler have failed because of "Plug Type Dezincification".
The MOC of the cooler tubes in VCM and CPP plants, where similar type of failure occurred, was upgraded to CU-Ni (70-30 %) to avoid such type of failure. And the results were found to be encouraging.

Recommendations
1. MOC of the present cooler tube may be upgraded to 70-30 Cupro-Nickel.
2. New sacrificial anode (made of Magnesium) may be installed to protect the CS domes from Galvanic corrosion.
3. Other similar type of coolers should be opened for cleaning and in

Case-8 Failure of lube oil cooler tubes of York Compressor (EA6517AX) in VCM plant due to Dezicifiaction

FAR No	VCM/M/96/06	**FAR Date**	31 December 1996
Date of Failure	09 December 1996		

Case-9 Erosion Corrosion of the tubes / inlet / projected edges on the bottom tube sheet of Glycol Bleed Flasher-II Reboiler (NE509) in MEG-2 Plant

FAR No	FAR/M/98/13	**FAR Date**	10 September 1998
Date of Failure	24 July 1998		

Failure Description
Tube leakage in NE509 was suspected due to pressure rise of NC506. Same was confirmed by stopping steam to NE509 & finding of process liquid in upstream of LPD steam trap.

Observation
Minor erosion effect was found on most of the tubes' inlet / projected edges only on the bottom tube sheet.
A layer of deposits of abrasive / gritty material was found at the internal surface of the tubes.

History
The equipment was opened up for inspection for the first time since commissioning.

Reasons
The damage appears to have been predominantly caused by erosion, when no appreciable corrosion effect on the other portion of the tubes or tube sheet was noticed

Analysis
- Though erosion effect was noticed on tubes, specially at the bottom edges & nearby area of tube ID, no appreciable corrosion effect on the other portion of the tube noticed.
- The high velocity impact of the gritty / abrasive particles, entering the tubes, eroded the tubes' inlet side along with edges. This further caused thinning of the tubes along the flow direction of the tubes and finally leaking the same, at places, predominantly towards the entry side.

Recommendations
FAR/M/98/13

Similar failure found earlier in the case of E-509, MEG -1 plant.
Refer FAR No. I&C/MEG/95/01 dated 14/11/95.

Case-10 Fatigue failure of liquid inlet line of Propylene Tower Aux. Reboiler (E-541A) in Cracker Plant

FAR No	FAR/M/99/30	**FAR Date**	08 May 1999
Date of Failure	21 April 1999		

Failure Description

Leak was noticed by operator from the liquid inlet of E-541 A., C3 liquid was oozing out of insulation.

Observation

- After removing insulation on affected line, a crack was observed in half coupling to pipe joint (size-1").
- A crack was found at the bottom weld toe towards east side covering 75% of the circumference. The DP test of the complete joint revealed that the no branching and further crack propagation was observed beyond the above mentioned zone. The crack was a "one-line appearance".

History

In past, no leakage was observed in CBD lines.

Reasons

The failure was caused due to fatigue at the toe of the socket weld joint.

Analysis

Detail study/observations of the failed piece revealed the followings:

- The edge of the nipple pipe (inserted into the coupling) was found non-uniform. Probably the root gap inside the coupling was not maintained during the original fabrication. The crack was found to have initiated at the toe below of this zone.
- Fresh and old beach marks (typical of the fatigue) were observed on the fractured surface (i.e. the cracked face) indicating that the failure was due to fatigue. The crack found to have initiated OD side and propagated inside.
- Excessive grinding of the weld toe (probably to remove the weld undercut, a defect during the original fabrication) reduced the effective thickness of the nipple pipe at this location and enhanced the increased stress to the joint and probably contributed the crack initiation. The crack ultimately propagated in the presence of inherent vibrations in the pipe which lead to the failure in due course of time.
- In absence of supports at the neck of the nipple joint & due to existing heavy vibrations in the pipe, severe stresses in the weld joints were generated. These stresses lead to the failure due to fatigue in due course of time. As beach marks found closely spaced at the initiation region and spaced further apart away from the region which indicate that the failure initiation started quite sometime back.
- Non-uniform gap provided in the socket joint resulted into the uneven thermal expansions & probably contributed to the fatigue at the toe of the weld joint.

Recommendations

1. Proper supports to be provided in all other joints to minimize the vibrations/stresses.
2. Gusset plates to be welded from pipe to header for similar lines for additional strength.
3. Excessive torque/twisting pressure should be avoided during manual o

Case-11 Thermowell flange to nozzle pipe welding cracked due to Fatigue in Cycle Gas Cooler No 1 (E4002A) in PP Plant

FAR No	PP/M/96/6	**FAR Date**	30 June1997
Date of Failure	16 October 1996		

Failure Description
Thermowell flange to nozzle pipe welding cracked, leading to hydrocarbon leakage.

Observation
50% of the circumferential weld was found cracked. Confirmed by DP check.

History
The line was commissioned in Sept.-96 and the weld joint failed within one month of the operation.

Reasons
Inferior quality of the weld joint. Fatigue due to vibrations & cyclic stresses on the weld joint.

Analysis
The visual inspection revealed the circumferential crack in the weld metal zone of the socket weld joint of flange (SA 105 S80) to the 1.5" pipe branch off 30" cycle gas inlet line to cycle gas cooler E-4002A. The crack possibly occurred either because of the lesser reinforcement of the weld or due to the deposition of the inferior weld metal. The exact reason could not be found out as the socket weld flange was cut and removed from the weld metal zone because of the limited available length of the nozzle pipe. The line vibration also possibly contributed in the initiation and propagation of the crack in the weak weld joint and hence resulted in the weld failure within one month time of operation of the line.

Recommendations
1. e under the stage wise inspection/NDT. The same is under operation for the last 7 months without an The socket weld flange was replaced with the weld neck flange
2. y further problem. Hence, no further corrective action is recommended.

Case–12 Gasket failure of STDP Detol Tower Reboiler (E213) of Aromatic Plant

FAR No	FAR/M/99/28	FAR Date	21 September 1999
Date of Failure	21 August 1999		

Failure Description

Heavy steam leak from channel cover flange bottom side. End channel cover gasket was replaced by specified steel jacketed graphite gasket. Leakage of steam was observed within 24 hours of operation. Subsequently the gasket was replaced by wire breaded CAF gasket. Thereafter, no leakage was observed.

History

- The equipment is in service since commissioning of plant in March-97.
- On 30/10/1998, steam leakage was noticed through channel flange to tube-sheet gasket. Grooving was noticed on the gasket face. Groove was locally weld repaired and machined. However channel and channel cover gasket face found free from grooving. Wire braided graphite-Asbestos (Super-54, 3 mm thick) was used in place of steel jacketed graphite gasket which is specified in drawing.
- On 23/06/1999, exchanger was opened up to attend leakage from tube to tube-sheet joints. Wire braided gasket was replaced by plain CAF gasket as specified steel jacketed graphite gaskets was not available

Reasons

1. Use of non-specified gasket.
2. Improper installation of gasket.
3. Temperature fluctuations.
4. Water hammering effect.

Analysis

As the exchanger was not offered for inspection, exact reason of failure could not be investigated. However, following points to be considered as reasons for failure.

- The failed gasket is plain CAF gasket and not the specified steel jacketed graphite gasket. Plain CAF gasket is not recommended in this service.
- After 24 hours of operation, steel jacketed graphite filler gasket was failed. This could be due to improper installation of gasket, uneven flange tightness and water hammering. Outlet of exchanger contains steam+water at 40 Kg/sq.cm.. If water hammering takes place at the bottom portion of the channel, there is possibility of failure of gasket due to vibration. Cyclic stresses resulting due to temperature fluctuations might have also contributed to leakage within short period of operation. In drawing gasket face width of channel cover is given as 58mm and gasket width is 20mm. As a trial basis, gasket having more width can be used after checking the design as the sealing area increases thereby reducing the chances of leakage.

Recommendations

1. Possibility of water hammering should be looked into in consultation with CTS and the same should be eliminated. .
2. As a trial basis, width of the gasket can be increased after checking the design.
3. Use of properly specified gaskets should

Similar type of Corrosion failures was seen earlier.

Reference FARs - FAR/M/98/20 Date-22 December 1998

Case-13 Failure of Blade holders of Fin-fan Coolers (EEC6402C2 and C4) of VCM plant

FAR No	VCM/M/97/3	**FAR Date**	02 May 1997
Date of Failure	16 April 1997		

Failure Description
Blade holders of Fin -fan coolers (C2 and C4) were severely cracked. The cracks were located at the sharp corners of the housing of fan holders.

History
Fin fan cooler C2 and C4 was supplied by M/s Paharpur cooling tower, installed during expansion of VCM plant. The same were commissioned in February'97.
Blade holders of the both the fans failed within a month.

Reasons
The failure may be attributed to improper design of the blade holders.

Analysis
The crack appeared to have been initiated from edge of the sharp corners (between horizontal plane and vertical collar) of blade holders. Chemical analysis revealed that the material was low alloy steel with Chromium around 0.8%. Hardness of the failed holder was found 82.7 to 83.6 HRB.
The sharp corners between horizontal plane (provided for clamping of the blades) and vertical collar, acted as stress raiser leading to concentration of stresses at the edge of corners. As most of the holders found cracked at the sharp edge-portion it appears that the holders are inadequately designed to sustained the stresses raised (during rotation)at the sharp edge. The total stress concentrated due to the above factor would have gone beyond a value more than load bearing capacity of the edge, leading ultimately to premature failure of the fan holders.

Recommendations :

Case-14 Longitudinal cracking of upstream and down stream reducers of SCO Reactor Effluent Filter (Z1123B) in Cracker Plant

FAR No	FAR/M/99/37	**FAR Date**	29 July 1999
Date of Failure	20 July 1999		

Failure Description
Z-1123 B upstream and down stream reducers developed leaks.

Observation
Longitudinal cracks were noticed in the parent metal of the reducer, at three different locations. DP test revealed that size of the cracks were bigger at ID side, compared to OD side cracks.

History
This is the first case of failure of reducers in upstream/down stream of Z -1123B.

Reasons
Defective material failed during service.

Analysis
Material incompatibility is also another likely reason for failure in service but the material of construction for upstream and downstream lines is also the same (i.e. Monel) and service is spent caustic. These lines have not shown any failure till date.
Monel (UNS 04400) is resistant to general corrosion by caustic, however stress corrosion cracking can occur at higher concentrations and temperatures (at 10% NaOH at 300°C) whereas in present case the caustic concentration is around 2% and the design temperature is 150 °C. Hence the chances of SCC is very remote. Moreover no indications of any SCC have been observed in the upstream/downstream pipes. Hence the most probable reason of failure appears to be original material defect which propagated in due course of time and gave rise to leaks.

Recommendations
1. It is suggested to provide the sample of the failed reducer/s to "I&C-CES" for detailed failure study.

Case-15 Steam leakage from inlet nozzle reinforcement pad of Boiler Feed Pre-heater (E207B) in MEG Plant

FAR No	MEG/M/96/5	**FAR Date**	26 July 1996
Date of Failure	26 June 1996		

Failure Description
Steam leakage from inlet nozzle reinforcement pad (N1,6" 30#,Sch-40, 15k steam).

Observation
Steam leakage was found from tell-tale hole of reinforcement pad of inlet nozzle.

History :
1. The exchanger did not have any reported leakage from nozzles, so far.
2. Gasket faces of both the tube sheets & of the channel cover were found repeatedly affected by erosion & wire drawing resulting into deep grooving & leakages from gasket faces.
3. Some of the tube sheet seal welds were also found leaking during hydrotest in past.
4. All the above abnormalities was repaired by machining & welding at L&T Hazira in Feb-Mar,1995.

Reasons :
1. Original fabrication defect in welding (porosity, slag inclusion at root) at the neck of the nozzle-to-shell/reinforcement pad which got opened up to a through & through leaky passage, during operation.
2. Erosion at the corner / neck of the nozzle to shell joint due to high velocity of steam.

Analysis :
Probably the internal weld between the shell, the nozzle and the reinforcement pad was not properly made and was having original defect which in due course of time was eroded and given way, resulting into a through & through leak.

Recommendations :
Immediate action:-
- As an immediate measure, the tell-tale hole should be sealed
- By threaded plug, so that the same can be taken out as & who
- En the permanent repair is done.

Permanent measure:-
1. The shell should be offer for internal in

Case-16 Fatigue cracking of Stripping Bottoms Cooler (EB5603N) Spiral Heat exchanger of PVC plant due to Improper clearance between the studs & spiral at manufacturing stage.

FAR No	PVC/M/97/10	**FAR Date**	25 June 1997
Date of Failure	24 April 1997		

Failure Description
Leakage found in HE-3GN. Cooling water observed in slurry line & PVC slurry observed in cooling water return line, During this time column CL-1G was out of line & HE-3GN was idle.
Observation
The exchanger was removed from foundation & kept vertically in opened-top-cover condition for pressure test. Spiral side (Slurry side) was pressurized pneumatically up to 1.25Kg/cm2 & filled up with cooling water at other-side. Leakage was noticed on the outer most spiral (Outer plate of spiral), at the same location repaired in Jan-97

History :
The spiral heat exchanger is manufactured by Alfa Laval, Pune vied PO No. RA01/RV/003 dtd. 13-09-94 & was commissioned in April-96. Immediately after commissioning, leakage was noticed through cover gasket. On opening the cover it was noticed that spiral portion of the exchanger was deformed & locally bulged at few places affecting the inter-pass clearance between spiral. The spacer studs were found poorly tacked to the spiral, leading to dislodging of some of the studs. In Jan-97, leakage was noticed through the crack along the bulged outer spiral (Outer plate), same was rectified by Alfa Laval representative in consultation with I&C. The repair done on the spiral coil plate was of temporary nature. In view of the criticality & nature of failure I&C recommended to send the unit to M/s Alfa Laval for detail repair involving complete removal of bulged coil & to review the design of the exchanger.

Reasons :
Improper clearance between the studs & spiral at manufacturing stage led to bulging of spiral outer-most-plate at locations causing weak zone, causing fatigue line at this zone, weakening the same longitudinally, resulting into final cracking of the same in cyclic stressed condition.

Analysis :
Clearance/gap between spirals are maintained by the studs provided, which are most important factor to take care of the periodic enlargement/contraction of the spiral during service. As noticed, many studs were found dislodged/got bend, causing excessive/improper clearance between spiral leading to inadequate supporting of the spiral plate at locations. At maximum unsupported area, the spiral plate bulged under pressure in running condition. Due to excursion/fluctuations in pressure, the bulged area have been subjected to repeated cyclic-stresses resulting into crack initiations on the bulged spiral plate due to fatigue. The initiated crack would have propagated further during operation & led to the ultimate failure.

Recommendations :
1. al, from thickness of plate point of view. Necessary stud welding technique or related NDT method to ensure their reliability in operating condition should also be studied in depth.
2. Design of the exchanger should be reviewed by M/s Alfa Lav
3. I

Case-17 Chloride Stress Corrosion Cracking of tubes of Cleaned Pellet Convey. Air Cooler (E8069B) in Polypropylene Plant.

FAR No	FAR/M/98/28	**FAR Date**	09 November 1998
Date of Failure	28 September 1998		

Failure Description
The numerous tube leakage of the Pellet Coveying Air Cooler E-8069B.

Observation
- Both the Dome covers were opened up. On pneumatic testing 51 tubes (out of total 604 Nos.) were found leaking and the same were plugged. The Heat exchanger was put into the service because of the plant requirements on 28/9/98.
- The heat exchanger E-8069B was then pneumatically tested on shell side at 1.5 kg/cm2 while further 245 nos. tubes were found leaking.
- On removing the tube bundle from the shell no significant deposit and corrosion / pitting observed on outermost peripheral tubes OD surface.
- One leaky tube was pulled out for detailed testing and investigation. On visual inspection of the tube, numerous multiple branch type cracks were observed in the tube length of 200 mm from the hot air inlet end of the tube. The tube OD surface was also found pitted in the above length at various places. Some of the cracks appeared to have initiated from the pit.
- The piece of the removed tube was sent for metallography while the observed cracks were found to be multiple branch type, transgranular and starting from OD and extending towards ID.
- The chemical analysis of the deposits from the OD side (near the cracks) of the removed tube indicated the chloride presence of 7000 PPM (analysis report attached).
- The tubes and tube sheet are made of SS-321. Chemical analysis of the failed tube piece confirmed the same.

History
The heat exchanger is in the service since the commissioning of the plant in September 1996. Till date no other failure was reported.

Reasons
Chloride Stress Corrosion Cracking initiating from OD side of the tube & progressing transgranular.

Analysis
The cracks in the tubes as revealed are of transgranular type with multiple branching, which have started from OD side (Cooling water side) and extending towards ID side. The cracks are observed in 200 mm length of the tube from the Hot air inlet side only. The remaining length of the tube is in good condition. The Hot air inlet temp is approx. 170 degree centigrade hence the tube surface temp is also higher on the air inlet side compared to the other side. The analysis of the deposits on the cracked tube OD surface revealed the chloride content of 7000 PPM.

Recommendations :
1. In view of the severe chloride SCC, it is recommended to replace the MOC of the tubes to seamless duplex type stainless steel (type S31803).

Case-18 Tube leakage in VCM Recov Condenser (EA5521A) of PVC Plant due to Pitting Corrosion

FAR No	FAR/M/99/29	FAR Date	09 June 1999
Date of Failure	01 June 1999		

Failure Description
Suspecting tube leakage in RVCM condenser. The same was taken under shut down and offered for inspection.

Observations
Observations reveal the presence of considerable process deposits (wet Polymer) inside the tubes. Some tubes were found completely choked with deposits.
One no. tube was pulled out and was subjected to critical examination after splitting throughout the length, when the following points were noticed :

- The tube was found choked with process deposit. The deposit was found to be of two types - loose deposit away from tube inner surface and hard adherent deposit sticking to tube inner surface.
- Several isolated deep pits were observed on the inner surface of the tube.

History :
1. In every shut down, whenever the exchanger was visually examined, each time considerable amount of process deposits were noticed in tube ID side.
2. In July'98 shut down when the condenser was hydrotested, 14 no. tubes out of total 559 no. were found leaking for the first time. Same were plugged and final hydrotested

Reasons :
1. Pitting and / or Stress Corrosion cracking (SCC) of tubes.

Analysis :
From the observations of inner as well as outer surfaces of the tube, it can be implied that the pitting is the predominant degeneration mechanism. Since no indications of any cracks were observed, the probability of the failure by stress corrosion cracking is very low. The following points should be noted :

- The tubes are made of stainless steel as per SA 213 TP 304L. Stainless steels are prone to pitting corrosion in presence of chlorides. Pitting in SS304/304L type stainless steels can occur even at 100-200 ppm of Chloride content. The analysis of bulk deposit taken from inside the tube showed a chloride content of 290 ppm, which is very conducive to pitting corrosion. The accumulated chloride at the tube surface (i.e. on the skin) during the past has increased to 14.4% or 14400ppm which is having deleterious effect on the SS.
- The tube side service is VCM along with some air and water. Selection of stainless steel as tube material for the service is not questionable because stainless steels are, generally, resistant to VCM. However, VCM, in presence of water and oxygen, hydrolyses to form HCl. The chlorides found in deposit were of inorganic water soluble type, which implies that these chlorides were formed by reaction of hydrochloric acid thus formed.
- Once pits are initiated, they continue to grow by a self-sustaining, or auto-catalytic process. The corrosion processes within a pit produce conditions that are both simulating and necessary for the continuing activity of the pit. The propagation of corrosion in pits or under deposits involves dissolution of metal and the maintenance of a high degree of acidity at the

bottom of the pit or under the deposit. Highly acidic nature (pH-3.7%) of the deposit close to the inner surface of the tube confirms this phenomenon.

- Thus, it can be concluded that the pitting corrosion initiated by under deposit attack led to tube failure over a period of time.

The above conditions also remain a highly potential zone for SCC of SS tubes

Recommendations :

1. The problem of tube deposits should be resolved in consultation CTS either by

1) frequent cleaning or 2) by increasing the tube side flow rate or 3) by design modification.

2. EA5521A & B exchangers should be cleaned and offered for inspection at every a

Case-19 Failure of Aux. Dil Steam Stripper (E280A) Tube due to under deposit corrosion attack in acidic environment at Cracker Plant

FAR No	FAR/M/99/33	**FAR Date**	02 July 1999
Date of Failure	24 June 1999		

Failure Description
Profuse leakage from the tubes.

Observation
Tube bundle was visually inspected after pulling out from the shell and detailed observations were made as follows:

- Blackish hard deposit was noticed at the tubes OD surfaces, on the outer most rows of the tube bundle(top & bottom side).Minute brownish colored scaling/ deposit seen at the tubes ID surface.
- Severe corrosion damage/ pitting noticed predominantly at the tubes OD surface, on the outer most rows of the tube bundle, resulted in to puncture of the tubes at the several places.

History :

1. Reboiler was commissioned in March-1997.
2. Profuse leakage of the tubes was reported in July' 98, when 77 leaky tubes were plugged and 108 tubes were expanded to arrest leakage from tube to tube-sheet expansion joints.
3. Recently, 22 leaky and 2 corroded tubes were plugged. Total 101 (77+22 +2) U- tubes were plugged, so far.

Reasons :
Localized under deposit corrosion attack in acidic environment.

Analysis :

- Sample of the leaky tube was cut across the longitudinal section to facilitate inspection of tube internal surface. Visual inspection disclosed very minor pitting effect at the tubes ID side. However, severe corrosion damage/ deep pits seen predominantly at the OD side, resulting in to approximately 50% thinning down of the tubes.
- Evidence from the longitudinally cut leaky tube sample imply that severe corrosion damage/ pitting and thinning down of the tube from external side has taken place. Close inspection of the punctured zone of the tube revealed that under deposit pitting initiated at the external surface of the tube.
- Analysis results of the deposits collected from the top and bottom rows of the tube bundle revealed acidic nature, (pH =5.2 / 5.3) and presence of chlorides.
- In presence of (under deposit) corrosive environment, continuous corrosion process leads pitting damage more & more. Over a period of time, 'sound wall thickness' of tube becomes less than 'critical wall thickness' ultimately leading to puncture of the same.
- Minor pits also seen at the ID side of the tube. This pitting effect probably caused by corrosive/ acidic deposit entered through leaky hole of the tube, after plugging of the same.
- Severe corrosion attack seen only at outer most rows of the U tube bundle.
- Deposit from the process water (shell side) settles down at the tubes OD surface of the outer most rows of the U tube bundle. Pitting formation took place under acidic deposits at the outer surface of the tubes, which ultimately caused severe damage and puncture of tubes.

Recommendations :

1. Top most two rows of the u tube bundle should be plugged immediately, to avoid repeated tube leakage, in near future.
2. Tube bundle should be pulled out for thorough cleaning/ inspection at the regular interval (i.e. once a year)
3. Detail process study

Case-20 Localized caustic corrosion of SCO Feed/Vent Gas Exchanger (E1122A) plates in Cracker Plant

FAR No	FAR/M/99/36	**FAR Date**	29 July 1999
Date of Failure	31 May 1999		

Failure Description
E1122A Leakage because of which SCO product was getting contaminated.

Observation
- Visual inspection of the plates revealed localized corrosion in all the samples on spent caustic side of the exchanger.
- Cracks and punctures were observed at maximum deformed locations (at roots of corrugations).

History :
This is the first case of failure of E -1122A.

Reasons :
Localized caustic corrosion.

Analysis :
- The micro examination of the samples away from fracture revealed twinned, equi-axed grains indicating that the material was in annealed condition. No other microscopic defect was revealed. However near cracks/punctures, gradual thinning and grain elongation was observed implying that the localized corrosion was predominately acting in the cold worked / thinned downed regions.

Thus from the above results it is evident that the failure has occurred due to corrosion of titanium plates.

- Titanium alloys are generally very resistant to alkaline media. However in alkaline medium of (pH.> 12) and at a temperature of more than 80C can lead to hydrogen pick-up and subsequent embattlement of the titanium.
- Corrosion rates of less than 0.02mm/year are expected in boiling solutions of Sodium hydroxide(10%NaOH). The present heat exchanger has been designed keeping in view of the same. Moreover at 40% NaOH at 80C, the corrosion rates of titanium increase rapidly to 0.13 mm/year. In some oxidizing salt solutions such as 10% Na2SO4, the corrosion rate of titanium is drastically high up to 1.83mm/year even at 66C.
- In the present case the heat exchanger was apparently run in the partially choked condition before the same was opened for cleaning. Partial choking of heat exchangers lead to very high skin temperatures. The failed heat exchanger plates also suffered similar high temperature (probably upto130C).
- Partial choking caused low/no flow conditions leading to stagnant liquid and subsequent crevices. The concentrations of NaOH and Na2SO4, in the spent caustic liquid analyzed, are not very high. But crevices caused by the partial choking might have led to localized high concentration cells. As a result, metal potentials in the crevices became negative relative to metal surfaces exposed to bulk solution. This created electrochemical cells in which crevices became anodic and corroded, and the surrounding metal surface became cathodic.

Thus the crevice corrosion by Na2SO4 and NaOH lead to gradual thinning and subsequent puncture in the titanium plates in due course of time (during running the exchanger in partial choked condition).

Recommendations :

1. The heat exchanger should not run in full/partial choked condition.
2. The heat exchanger should be opened and offered for inspection after cleaning once in a year.
3. The reasons of choking and measures to avoid the same should be investigated by

Case-21 Under deposit pitting on Tubes of Recycle Sh Water Cooler (EA3101A) in PE Plant

FAR No	FAR/M/98/20	FAR Date	25 January 1999
Date of Failure	07 December 1998		

Failure Description
SH Content observed in Cooling water return line due the tubes leakages in the heat exchanger.

Observation
Shell side Hydro testing done at 12.0 kg/cm2 while 07 Nos tube were found leaking.

History :
- The original tube bundle installed in July 1992.
- Severe deposition was observed on cooling water side (on Tube OD surface) particularly on U-bends and near tube sheet in July 1993. Deep under deposit pitting was observed on tube OD surface.
- In Jan. '95 condition was found to be more severe on U-bend portion. To increase the cooling water flow velocity on U-bend and avoid the deposition, a vertical baffle was put at the dome internal.
- In Mar.'97, severe tube leakage was observed. The tube bundle was replaced with the new one manufactured by M/s V.M. Corporation.
- In Jan.'98, 1 leaky tube was plugged.
- In Aug.'98, 1 more leaky tube was plugged.
- In Dec.'98, 7 more leaky tubes were plugged (total nos. of the tubes plugged till date are 9 out of total 744 nos. tubes)

Reasons :
1. Insufficient cooling water flow to bottom exchanger.
2. Stagnant cooling water at U - Tube end of Exchanger tube bundle.
3. Poor Work man ship of U -Tube exchanger manufactured by Vendor.
4. Under deposit pitting on Tube OD side (cooling water side).

Analysis :
- The total nos. of the tubes plugged till date in the tube bundle of EA-3101A are 9 and all of them are located on the outer periphery of the tube bundle.

- The tube bundle is not removed till date after being put in the service in Mar.' 97. Hence the present condition of the tube OD surface vis-à-vis deposits and pitting is not known. In Jan.' 95, a vertical baffle plate was put at the dome internal to increase the water flow velocity near U-bend portion and avoid the deposition.

- However, based upon the experience with the old tube bundle, it is suspected that the deposits are still getting accumulated and causing the under deposit pitting resulting in the tube puncture. To confirm this, the inspection of the tube bundle and removal of the leaky tube is needed after taking out the same from the shell during the next available opportunity.

- The cyclohexane flows in series in the tube side of the Heat Exchangers EA3101A & S. The inlet temp of cyclohexane is 135 deg. C. and outlet temp is 45.1°C. (out of EA3101S). For #3à1 grade, the cyclohexane inlet temp is 160°C and correspondingly the outlet temp is 50°C

(out of EA3101S). Details are in the attached CTS report. The tube OD skin temperature (on cooling water side) is more in case of EA3101A (bottom exchanger) as compared to EA3101S (top exchanger) and hence there will be more deposition tendency in EA3101A The condition of EA3101A (bottom exchanger) is worse than EA3101S as can be seen that the total Nos of plugged tubes (till date) in case of EA3101A are 9 and in case of EA3101S are 5 nos.

- As per the design check by CTS on Aspen simulator, the shell side velocity limitations are expected at U-bend which has more area/spacing. The op. Velocity is 0.56 m/sec in case of bottom exchanger, which is less than 0.8 m/sec, as was expected after providing vertical baffle in 1995.

- CTS is presently carrying out the detailed design check through M/s IDEA and checking the possibility of operation of heat exchangers in parallel mode for cyclohexane or utilizing the heat of cyclohexane for preheating any other stream

- The reason for failure "Poor workmanship of the tube bundle manufacturer" can only be investigated after removal of the U-tube from the tube bundle.

Recommendations :

1. Removal of the tube bundle and failed tube from the bundle during the next available opportunity.
2. Provision for the back-washing facility
3. Chemical cleaning and re-Passivation
4. Designer/manufacturer may also be consulted for views on reasons of f

Similar Failure occurred in other exchanger (EA6131S) also.

Reference FAR no - FAR/M/98/21 Dated 25 January 1999.

Case-22 Under deposit pitting on Tube of Hiboil Product Cooler (EEA6310B) in VCM plant

FAR No	FAR/M/98/11	**FAR Date**	30 October 98
Date of Failure	23 October 98		

Failure Description
Leakage of EDC was noticed from the cooler tubes.

Observation
Visual inspection of the tubes OD surface :

- Tubes were found heavily deposited with cooling water muck along with rubber/wood pieces, mainly near the impingement plate.
- CW nuggets/ deposits also notices in most of the tubes near baffle zone.
- On cleaning of tube bundle externally, about 10% tubes were found Severely affected by under deposit corrosion damage and resulted in to 30 to 40% localized thinning.
- Other (than the above) tubes were also found pitted/ corroded, though at a lesser extent, which was not alarming in nature.

History
1. Cooler was commissioned in April'92. Modification done at (EDC) process side during VCM plant expansion project.
2. Tube leakage noticed first time in May'98, when one tube was plugged. Recently leakage seen from one more tube.

Reasons
Severe Under-deposit corrosion damage caused locally in the presence of heavy CW deposits/ nuggets on the tubes OD surface.

Analysis
- The corrosion damage as seen at the places wherever the nuggets of Cooling water deposits was formed.
- Localized stagnancy caused by heavy CW deposits/ nuggets at the tubes OD surface invited under deposit corrosion attack, which ultimately resulted in to puncture/ leakage of EDC from tube to shell side. Over a period of time, EDC leaking from corroded tube entrapped in CW deposits/ nuggets, which enhanced the corrosion rate and further aggravated the situation, ultimately resulting into severe corrosion damage of tubes.
- Probably the severe & advanced corrosion has taken place due to non-opening & cleaning of the shell side deposits for a long time, which helped in accumulation of hard deposits causing aggravated corrosion.

Recommendations
1. Severely corroded tubes should be plugged and tube bundle should be offered for inspection.
2. Cooler should be offered for inspection and testing after being in service for one month. Evaluating for re-tubing, if required.
3. Frequent back-wash of the

Case-23 Under deposit pitting on Tubes of VCM Bottom Cooler (EEA6512) in VCM plant

FAR No	FAR/M/98/12	FAR Date	21 November 1998
Date of Failure	07 November 1998		

Failure Description
Severe leakage experienced from the tubes.

Observation
Cooler was visually inspected after removal of covers. Details of the findings were as follows:
- Tubes were found slightly deposited by loose process muck and internal surface, (ID side) of the tubes were found free from appreciable corrosion damage.
- No corrosion damage was observed at the ID side of Dish-end covers. Gasket faces were also found in satisfactory condition.
- 7 tubes were found leaking, when cooler was subjected to hydro test at 8.75 Kg/cm2.

Tube bundle was not removed for cleaning/ inspection, to minimize production loss.

History
1. Cooler was replaced by new one during expansion of VCM plant in Dec'96.
2. Tubes were leaked in July'98 when the same were plugged and cooler was put back in to service.
3. Recently, 7 more tubes leaked and subsequently plugged in Nov. 98 on hydro test.

Reasons
Under-deposit corrosion damage in the presence of heavy CW deposits/ nuggets on the OD of tubes.

Analysis
- Tubes ID surface was inspected and same were found free from appreciable corrosion damage.
- OD of the tubes could not be inspected, because of the tube bundle was not pulled out for cleaning/ inspection. However, the previous exchanger (EA-6512 A & B replaced in Dec'96) had a history of severe corrosion damage and thinning down of the tubes affecting from the OD side, caused by excessive cooling water nuggets/ lump deposits. Similar corrosion is likely to cause thinning and subsequent puncture from OD side of the tubes.

Recommendations
1. Adequate back-wash, on shell side cooling water flow required to be scheduled, on 3 month basis.
2. Cooler should be opened up in every opportunity for cleaning/ inspection.
3. Procurement of the spare tube bundle should be planned to ensure the availa

Similar type of failures due to under deposit pitting were seen on other exchangers of VCM.
Reference FARs - FAR/M/99/16Date-04 February 1999, FAR/M/99/17 Date- 06 February 1999, FAR/M/99/20 Date-22 March 1999

Case-24 Failure of Tube of VCM Column Condenser (EA6504B) in VCM Plant due to internal pitting.

FAR No	FAR/M/99/23	FAR Date	08 June 1999

Date of Failure	12 May 1999

Failure Description
Leakage from the Tube.

Observation
- Greenish yellow colour loose powder-type deposits was found adhered to the tube ID surfaces as well as channel internal surfaces.
- Visible tube side surface was found free from corrosion/erosion. Pitting in minor nature was noticed on the internal surface of the end covers.
- After start up, leakage was noticed during filling up with water for hydro-testing & 13 nos. tubes found leaking, total to 18 Nos. of leaky tubes were plugged so far.

Due to the inaccessibility, the OD surface of the tubes could not be inspected.

History
- The exchanger suffered repeated leakage in numbers of occasions mostly during plant start up & plugging of tubes done accordingly.
- 31/03/93 - 1 no. leaky tube was plugged.
- 02/01/94 - 2 tubes were plugged.
- 07/07/94 - 1 no. leaky tube was plugged.
- 14/05/95 - 2 nos. leaky tubes were plugged.
- 28/05/95 -2 nos. Leaky tubes were plugged.
- 17/01/96 -2 nos. Leaky tubes were plugged.
- 25/09/96 -Condenser was replaced.
- 01/05/99 -3 nos. Leaky tubes were plugged

Reasons
1. High Moisture & acidity in VCM O/H systems. Localized condensation of vaporized HCl at ID of tube, (Mostly at bottom half) causing localized pits along the length of tubes. Some of them penetrated across the tube thickness. The problem appears to be more aggressive during upset condition of operation (moisture) resulting into high acidity in VCM.
2. Corrosion/erosion effect during process upset.
3. Shell side under deposit corrosion caused by cooling water.
4. Probably, the low velocity/relative stagnancy of the fluid inside the tubes have caused more deposition and sites of tubercles.

Analysis
- High Moisture & acidity in VCM O/H systems during the start-up activity may be present. Localized condensation of vaporized HCL at ID of tube, (Mostly at bottom half) causing localized pits along the length of tubes. Some of them penetrated across the tube thickness. The problem appears to be more aggressive during upset condition of operation (moisture) resulting into high acidity in VCM.
- Insufficient flow at the OD of the tube might have generated excessive generation of the cooling water deposit, under which the pits might have developed and caused the localized pitting leading punctures. Low velocity/relative stagnancy of the fluid inside the tubes may cause more deposition and sites of tubercles at OD of the tubes

Recommendations :
1. Spare tube bundle (with same MOC) may be considered for suitable / periodic replacement.

2. Frequent backwash facility may be adopted to flush out the adhered, low pH deposits to the tube ID surface, which are causing localized pits due to corrosion.

Case-25 Failure of Tube of 2nd Quench Bottoms Heater (EED6410) in VCM Plant due to internal corrosion.

FAR No	FAR/M/99/27	**FAR Date**	17 November 1999
Date of Failure	09 November 1999		

Failure Description
Leakage in top side shell & tubes.

Observation
The shell was found leaky and close inspection revealed a pinhole in the shell.

- Detailed thickness survey was carried out on surrounding zone of pinhole location. Minimum thickness was noticed 7.1mm as against nominal thickness of shell is 9.27mm, which is considered acceptable after taking 3mm Corrosion Allowance into account.
- Most of the tubes were found choked with hard coke deposits at ID. Difficulty encountered in removing the deposits by hydro jetting.
- On visual examination, the condition of tube ID surface (as far as visible) found to be satisfactory, when no appreciable corrosion effect was seen.
- Condition of the Tube sheet, End covers and Gasket faces were found to be satisfactory.
- Several loose spiral strips were noticed inside the tubes.

History

- Present failure is the first of its kind after the exchanger was commissioned in Oct ’96.
- Initially minor leakage was noticed from top side (11’O clock position) of shell between two bracket supports. As an immediate measure, the leaky portion of shell was furmanited in the past.
- After few days, again leakage was seen through furmanited clamp, then the exchanger was isolated and offered for detailed inspection.

Reasons
Leakage in the shell probably has occurred after-effect of tube leakages in that zone. Coke particles carried-over along with process vapor (EDC +VCM + HCl) are being deposited at Tube ID surface and subsequently resulting in severe choking of tubes, probably caused deep localized pits or SCC(stress corrosion cracking) at places of SS tubes.

Analysis
The root cause of the problem could not be ascertained as no leaky tube could be arranged for detail analysis/ study /investigation.

Recommendations :

1. Exchanger should be offered for detailed thickness survey, on periodic basis after removing the insulation.
2. Leaky tube should be passed on to CES (I&C) for detailed failure investigations, to ascertain the cause of leakage and comment on the remedia

Case-26 Failure of Tube of Quench Vapor Condenser (EC6402B) in VCM Plant due to internal corrosion.

FAR No	FAR/M/00/28	FAR Date	17 January 2000
Date of Failure	07 January 2000		

Failure Description
One leaky tube furmanited and during leak test one tube found leaking.

Observation
Suspecting the leakage from one of the tube of quench overhead condenser EC6402B, the same was offered for Visual inspection. The following were our observations :

- Inlet and outlet tube-sheets were found deposited with hard carbonaceous process deposits. However, deposit at inlet side was more as compared to that at the outlet side.
- Almost all tubes were found partially choked by these deposits (some tubes were completely choked).
- Initially all the tubes were individually leak tested by air at 5.0 Kg/cm2 and one tube was found leaking (location at 2nd row from top; 16th tube from East). The same was used for detail analysis and investigation.
- On cleaning, severe localized corrosion/thinning damage was seen at the tube internal side & outlet side, mainly near the inlet tube-sheet.

Detail observations of damaged tubes are as follows :

- Total 11 nos. tubes were found severely affected by corrosion damage, deep grooving/pits in tubes at ID side near inlet tube sheet
- Microscopic Study : The leaky sample was sectioned at the punctured location and polished to examine under microscope. The macro-study revealed the severe corroded surface causing localized thinning (as observed under microscope), indicating the Under-Deposit-Corrosion (pitting) as the predominant degradation mechanism

History :

1. The Quench Vapour Condenser (EC6402B) was commissioned in April-92.
2. Tube leakage was experienced first time during plant start up after completion of plant shutdown on 04-12-97 & total 9 nos. tubes were plugged.
3. One tube leakage was noticed on 6/1/2000, same was furmanited.

Reasons :
Under deposit corrosion due to the acidic deposit, giving rise to localized pits, eating away the tube material. This may be more corrosive while start-up or shutting down operation; Corrosive effect due the condensation of the acidic vapour.

Analysis :

- Coke particles produced during thermal cracking of EDC in Pyrolysis furnace are carried-over along with process effluents, which is quenched in Quench Scrubber and the scrubber overheads are being flown to the Quench Vapour condenser. The fine coke particles carried over by this vapour (EDC +VCM + HCl) are deposited at inlet side tube-sheet as well as at ID of the tubes near tube-sheet.
- The environment under the deposit becomes more and more corrosive over a period of time because of formation of galvanic cells. The zone below the pits become more and more anodic towards the rest of the environment and lead to severe localized corrosion. If the tubes are not effectively cleaned of deposits at regular intervals corrosion under the deposits leads to pitting and final leak of tubes occur. As it is obvious from the observations that almost all tubes were

found partially choked (with some tubes completely choked) pitting in ID side of tubes was also present . It is evident that the failure of tubes is due to under deposit pitting.

- The leaky sample was sectioned at the punctured location and polished to examine under microscope. The nature of thinning as observed under microscope also indicated the corrosion (under deposit pitting) as the predominant degradation mechanism.

Recommendations :

1. During every shutdown all the tubes must be cleaned off the corrosive process deposits and dried thoroughly prior to putting into service.
2. In view of the leakage experienced from the tubes and subsequently process deposit seen at the tubes ID

Similar type of failures due to under deposit pitting were seen earlier on same type of exchangers of VCM.

Reference FARs - FAR/M/97/16Date-23 October 1997, FAR/M/97/6 Date- 09 December 1997, FAR/M/97/8 Date-20 December 1997