CHAPTER 1

INTRODUCTION

1.1 Background of Study

During internship period at Petrochemical Plant in Terengganu, author had an opportunity to face a real case study, which is regarding the Heat Exchanger Tube leakage. During planned shutdown in November 2010, it is found that one of the heat exchanger tube bundles available in the plant was leak. The affected heat exchanger is a type of shell-and tube heat exchangers used to cool down ethylene gas after it being compressed by the compressor. The ethylene gas is the main gas used in the plant as it will be processed to become Low Density Polyethylene (LDPE).

Shell-and tube heat exchangers are built of round tubes mounted in large cylindrical shells with the tube axis parallel to that of the shell. They are widely used as oil coolers, power condensers, preheaters in power plants, steam generators in nuclear power plant, in process applications, and in chemical industry. [1]

Heat exchanger tube leak is one of the problems in petrochemical plant that keep reoccurring although appropriate action had been taken before. Immediate investigation and study need to be taken to prevent the same problem occurred again in the future. Failure analysis is performed to further investigate this problem.

Failure analysis is an engineering approach to determining how and why equipment or a component has failed. Some general causes for failure are structural loading, wear, corrosion, and latent defects. The goal of a failure analysis is to understand the root cause of the failure so as to prevent similar failures in the future. [2] Failure analysis entails first using deductive logic to find the mechanical and human causes of the failure and than using inductive logic to find the latent causes. It should also lead to the changes needed to prevent the recurrence of failure. [3]

1.2 Problem Statement

Heat exchanger is one of important equipment used in industry nowadays, especially in petrochemical plant. It is functioned to cool down or rise up the temperature of medium which flow through it by using two different medium. During internship period at Petrochemical Plant in Terengganu, author had an opportunity to face a real case study, which is regarding the Heat Exchanger Tube leakage. During shut down in November 2010, it is found that one of the heat exchanger tube bundles available in the plant was leak.

The affected heat exchanger used to cool down ethylene gas after it being compressed by the compressor. The ethylene gas is the main gas used in the plant as it will be processed to become Low Density Polyethylene (LDPE). Heat exchanger tube leak is one of the problems in petrochemical plant that keep reoccurring although appropriate action had been taken before. Therefore, further study on why this problem keeps reoccurring need to be perform. The best way to investigate the problem is by performing failure analysis.

1.3 Objective

The objectives of this project are:

i. To perform failure analysis on the heat exchanger tubes leak case.
ii. To suggest appropriate actions in order to reduce risk of the same problem for keeps reoccurring in the future.

1.4 Scope of study

This project is a practical and research based which emphasized on the plant safety and equipment reliability issues as the top priority with consideration of investment cost. During internship at petrochemical plant in Terengganu, author realized that plant safety and equipment reliability was the most important issues faced by the company.

In this project, author will focus on the failure analysis methodology and possible actions to be taken in order to reduce risk of heat exchanger to fail again in the future. Heat exchanger leakage problem and root causes of the problem will be investigated.

Understanding the working principle and process undergoes by the heat exchanger is important before finding the root causes of this problem. Appropriate tools also required for the investigation purposes. All relevant data and findings related to the leak heat exchanger's tubes need to be collected and further study will be done on it.

1.4.1 Feasibility of the Project within the Scope and Time Frame

It is an obligatory for Mechanical Engineering students to complete final year project within two semesters. The project commences with research work in first semester (FYP 1) followed by continuous research work and data analysis in second semester (FYP 2). It will be assumed that the project is feasible within the scope and time frame regardless of no issues with regard to equipment and tools function.

CHAPTER 2

LITERATURE REVIEW / THEORY

2.1 Critical Review

No.	Author/ Title/ Findings
1.	D.r.h Jones, 2001, *"Failure Analysis Case Studies II: Type I Pitting of Copper Tubes from a Water Distribution System"*, Elsevier Science Ltd, page 307-315 Findings: Objective(s): The objective of this project is to investigate the failure copper tubes from cold water distribution system carrying potable water in a shopping centre. Methodology: i) Visual examination is performed to investigate the surface (external) and the internal condition of the copper tubes. ii) Chemical Analysis of Internal scale and corrosion product: Sample of tubes were examined in a scanning electron microscope (SEM) equipped with an energy dispersive spectroscopy of X-Ray (EDS) facility. iii) Metallorgraphy: Samples from the ubes examined were prepared for metallorgraphic analysis using standard grinding and polishing techniques. Etching carried out in acidified ferric chloride. iv) Chemical Analysis: An analysis of the chemical composition of the tubes was carried out using a wet chemical analysis method.

	Result: i) From analyzed data it can be seen that pits penetrating into the tube wall. ii) Large silicon and calcium peaks, and smaller aluminum peak due to presence of greenish-white scale in the scale. iii) Minor chloride peak detected. Usually this ion associated with pitting corrosion, but quantity of chloride is small in this case. iv) Typical microstructure observed in all cases consisted of large equi-axed grains, indicating the tubes in annealed condition. v) High phosphorus content proves that the tubes were made from phosphorus de-oxidised copper. Relevancy to this project: The objective of this journal is almost similar to the objective of the research to be done. Besides, the methodology used is common failure analysis methodology which also can be implemented in other failure analysis case.
2.	D.r.h Jones, 2001, *“Failure Analysis Case Studies II: Failure Analysis of Carbonate Reboiler Heat Exchanger”*, Elsevier Science Ltd, page 313-322. Findings: Objective(s): The objective of this project is to perform investigation on failed heat exchanger. Methodology: i) Visual Examination performed to investigate the surface (external) and the internal condition of the heat exchanger. ii) Dye penetrant testing (DPT) was carried on shell-side surface, welded-

side face, and longitudinal sections of the cut blocks of the tube sheet (with tubes).

iii) Dimensional measurement is performed in order to determine the extent of expansion of the tubes into the tube sheet.

iv) Metallorgraphic examination.

v) Corrosion Testing involved electrochemical potential measurements, galvanic current measurement, anodic polarization test, crevice corrosion test using multiple crevice assembly.

Results:

i) The failure of two heat exchangers involved damage to the tube sheet in the region close to the shell face and localized thinning of stainless steel tubes which coincided with the damaged region on the tube sheet.

ii) Metallorgraphic examination of both tube sheet and tube materials, including weld regions showed normal microstructures.

iii) Dye penetrant examination indicated non-uniform tube-to-tube sheet gaps.

iv) Electrochemical and crevice corrosion tests, carried out as part of the failure investigation, indicated that the material is susceptible to crevice corrosion attack in the process solution.

v) Corrosion failure of a carbon steel component due to decreasing vanadium concentration in the potassium carbonate solution has reported elsewhere.

	Relevancy to this project: The objective of this journal is almost similar to the objective of the research to be done. Besides, methodology used is common failure analysis methodology which also can be implemented in other failure analysis case.
3.	Usman, Nusair, 2007, *“Failure Analysis of heat exchanger tubes”*, journal, page 1-11. Findings: Objective(s): The objective of this project is to perform investigation on failed heat exchanger. Methodology: i) Visual examination: All received tubes were observed using the help of a hand magnifier and stereomicroscope. ii) Chemical Analysis iii) Fractography and metallorgraphic study using optical and SEM. iv) Simulated experimentation. Results: i) The chemical composition of all the tubes was according to ASTM A213 grade T-11. ii) The cracks across the tube axis had features typical of thermal fatigue. This might be due to repeated temperature swings causing stresses in the tube wall. The temperature variation maybe due to poor water circulation during the plant operation. iii) Cyclic heating and cooling caused thermal fatigue which resulted in circumferential cracks;

	iv) Exposure to higher than permissible temperature caused bulging with longitudinal cracking. Relevancy to this project: The objective of this journal is almost similar to the objective of the research to be done. Besides, methodology used is common failure analysis methodology which also can be implemented in other failure analysis case.
4.	Allahkaram, Zakersafee, Haghgoo, 2010, *“Failure Analysis of heat exchanger tubes of four gas cooler”*, journal, page 1-7. Findings: Objective(s): The objective of this project is to perform failure analysis on failed heat exchanger. Methodology: i) Visual Inspection was performed to investigate heat exchanger condition, internally and externally. ii) Chemical analysis: The alloy composition was confirmed by optical emission spectroscopy method (Quantometry analysis). iii) XRD Analysis: Deposits scrapped from the tubes and shell in the gas cooler was analysed using X-ray diffraction method (XRD). iv) SEM and EDX analysis used to analysed the corroded area. v) Corrosion testing: Since degradation on heat exchanger tubes was confirmed to the regions where crevice corrosion had occurred, hence the corrosion behavior of alloy 625 was investigated using the multiple crevice assembly, electrochemical potential measurement and anodic polarization.

	vi) Crevice Corrosion test using multiple crevice assembly: The multiple crevice washers were bolted to both sides of each specimen using Teflon bolts and nuts. vii) Electrochemical potential measurement: For investigating the potential changes of alloy 625, the specimens were exposed to seawater for 60 days and the open circuit potential (OCP) was monitored until steady state potential (SSP) was reached. viii) Anodic polarization test Results and Discussions: i) OCP behavior of alloy 625 shows a more nobel behavior after 60 days of exposure to the seawater but it is susceptible to crevice corrosion in location, where crevices are present. ii) Under very tight crevice conditions, Inconel 625 can be severely attacked. Formation of deposits between tubes and baffle provide tight crevices, which can entrap small amount of solutions that lead to enhanced corrosion of alloy 625 these regions under stagnant condition iii) Therefore, periodic cleaning of the heat exchanger from deposits is very necessary in order to prevent precipitations. Relevancy to this project: The objective of this journal is almost similar to the objective of the research to be done. Besides, methodology used is common failure analysis methodology which also can be implemented in other failure analysis cases.

2.2 Selection of Heat Exchangers

The basic criteria for heat exchanger selection from various available types are:

i. The heat exchanger must satisfy the process specifications; it must continue to the next scheduled shut down of the plant for maintenance.
ii. The heat exchanger must withstand the service conditions of the plant environment. It must also resist corrosion by the process and service stream as well as the environment. The heat exchanger should also resist fouling.
iii. The heat exchanger must be maintainable, which usually implies choosing a configuration that permits cleaning and the replacement of any components that may be especially vulnerable to corrosion, erosion, or vibration. This requirement will dictate the positioning of the exchanger and the space requirement around it.
iv. The heat exchanger should be cost effective. The installed operating and maintenance costs, including the loss of production due to exchanger unavailability, must be calculated and the exchanger should cost as little as possible. [1,9]

2.3 Common Failure Faced by Heat Exchanger in Industry

Heat exchangers are commonly used to transfer heat from steam, water, or gases, to gases, or liquids. Some of the criteria for selecting materials used for heat exchangers are corrosion resistance, strength, heat conduction, and cost. Corrosion resistance is frequently a difficult criterion to meet. Damage to heat exchangers is frequently difficult to avoid. The tubes in a heat exchanger transfer heat from the fluid on the inside of the tube to fluid on the shell side (or vice versa). Some heat exchanger designs use fins to provide greater thermal conductivity. To meet corrosion requirements, tubing must be resistant to general corrosion, pitting, stress-corrosion cracking (SCC), selective leaching or dealloying, and oxygen cell attack in service.

Some common causes of failures in heat exchangers are listed below:

i. Pipe and tubing imperfections
ii. Welding
iii. Fabrication
iv. Improper design
v. Improper materials
vi. Improper operating conditions
vii. Pitting
viii. Stress-corrosion cracking (SCC)
ix. Corrosion fatigue
x. General corrosion
xi. Crevice corrosion
xii. Design errors
xiii. Selective leaching or dealloying
xiv. Erosion corrosion

[2, 10]

2.4 Effects of Fouling

Lower heat transfer and increased pressure drop resulted from fouling decrease the effectiveness of a heat exchanger. [1]

2.4.1 Categories of Fouling

Fouling can be classified in a number of different ways. These may include the type of heat transfer service (boiling, condensation), the type of fluid stream (liquid, gas), or the kind of application (refrigeration, power generation). Because of the diversity of process conditions, most fouling situations are virtually unique. Accordingly, fouling is classified into the following categories: particulate, crystallization, corrosion, biofouling, and chemical reaction.

Below are the descriptions about the fouling categories:

- **Particulate Fouling**

  The accumulation of solid particles suspended in the process stream onto the heat transfer surface results in particulate fouling. In boilers, this may occur when unburnt fuel or ashes are carried over by the combustion gases. Air-cooled condensers are often fouled because of dust deposition. Particles are virtually present in any condenser cooling water.

- **Crystallization Fouling**

  A common way in which heat exchangers become fouled is trough the process of crystallization. Crystallization arises primarily from the presence of dissolved inorganic salts in the process stream, which exhibits supersaturation during heating or cooling. Cooling water systems are often prone to crystal deposition because of the presence of salts such as calcium and magnesium carbonates, silicates and phosphates. These are inverse solubility salts that precipitate as the cooling water passes through the condenser (as the water temperature increase). The problem becomes more serious if the salt concentration is high. For example the accumulation in cooling tower water system with an evaporative cooling tower. The deposites may result in a dense, well-bonded layer referred to as a scale, or a porous, soft layer described as a soft scale, sludge, or powdery deposit.

- **Biofouling**

  Deposition and/or growth of material of a biological origin on a heat transfer surface results in biofouling. Such material may include microorganisms and their products, and the resulting fouling is known as microbial fouling. In other instances, organisms such as seaweed, water weeds, and barnacles form deposites known as microbial fouling. Both types of biofouling may occur simultaneously. Marine or power plant condensers using seawater are prone to biofouling.

- **Chemical Reaction Fouling**

  Fouling deposits are formed as a result of chemical reaction(s) within the process stream. Unlike corrosion fouling, the heat transfer surface does not participate in the reaction, although it may act as catalyst. Polymerization, cracking, and coking of hydrocarbons are prime examples. [1]

2.4.2 Techniques to Control Fouling

There are a number of strategies to control fouling. Additives that act as fouling inhibitors can be used while the heat exchanger is in operation. If it is not possible to stop fouling, it becomes a practical matter to remove it.

This section will provide a discussion of some of these techniques:

- **Surface Cleaning Techniques**

  If prior arrangement is made, cleaning can be done on-line. At other times, off-line cleaning must be used. Cleaning methods can be classified as continuous or periodic cleaning.

  i) <u>Continuous Cleaning</u>

     Two of the most common techniques are the sponge-ball and brush systems. The sponge-ball system recirculates rubber balls through a separate loop feeding into the upstream end of the heat exchanger. The system requires extensive installation and is therefore limited to large facilities. The brush system has capture cages at the ends of each tube. It requires a flow-reversal valve, which may be expensive.

ii) Periodic Cleaning

Fouling deposits may be removed by mechanical or chemical means. The mechanical methods of cleaning include high-pressure water jets, steam, brushes, and water guns. High-pressure water works well for most deposits, but, frequently, a thin layer of the deposit is not removed, resulting in greater affinity for fouling when the bundle is return to service. High temperature steam is useful for the removal of hydrocarbon deposits. Brushes or lances are scrapping devices attached to long rods and sometimes include a water or steam jet for flushing and removing the deposit. Chemical cleaning is designed to dissolve deposits by a chemical reaction with the cleaning fluid. The advantage of chemical cleaning is that a hard-to-reach area can be cleaned. However, the solvent selected for chemical cleaning should not corrode the surface.

- **Additives**

Chemical additives are commonly used to minimize fouling. The effect of additives is best understood for water. For various types of fouling is described as below:

i) Crystallization Fouling

Minerals from the water are removed by softening. The solubility of the fouling components is increased by using chemicals such as acids and polyphosphates. Crystal modification by chemical additives is used to make deposits easier to remove.

ii) Particulate Fouling

Particles are removed mechanically by filtration. Flocculants are used to aid filtration. Dispersants are used to maintain particles in suspension.

iii) <u>Biological Fouling</u>

Chemical removal using continuous or periodic injection of chlorine and other biocides is most common.

iv) <u>Corrosion Fouling</u>

Additives are used to produce protective films on metal surface. [1]

2.5 Failure Analysis

Failure analysis is an engineering approach to determining how and why equipment or a component has failed. Some general causes for failure are structural loading, wear, corrosion, and latent defects. The goal of a failure analysis is to understand the root cause of the failure so as to prevent similar failures in the future.

In addition to verifying the failure mode it is important to determine the factors that explain the "how and why" of the failure event. Identifying the root cause of the failure event allows us to explain the "how and why" of failure. [3]

2.5.1 Test and Nondestructive Examination

Judicious use of nondestructive examinations and tests during inspections can reveal hidden flaws, indicate the degree (and sometimes the rate) of deterioration occurring with use, and provide a check and the quality of maintenance.

- **Visual Inspection (VT)**

  The first inspection to make is visual. The unaided human eye can tell whether:

  i. Additional cleaning is needed before a more detailed inspection can be made
  ii. Rough corrosion, erosion, distortion, bulging, buckling, or misalignment is occurring.
  iii. Severe cracking or other surface defects have developed.
  iv. Tools are needed to aid in more detailed visual inspection.
  v. Additional types of inspection and more sophisticated tools are necessary for a more detailed inspection.

For tubular equipment, this is predicted on the observer's having considerable experience in looking at exchangers and making judgment. Thorough visual inspection requires clean surfaces. Suspicious regions, coated or encrusted with process fluid residues and foulants, may require hydrocleaning. With proper precautions against excessive erosion, sand, grit, or hydroblasting may also adequately expose the surfaces.

Good practice, before completely inspecting a disassembly removable-bundle exchanger, is to hydroclean the bundle inside the tubes and on its exterior and to use hysdrocleaning or hydroblasting to clean the inside of the shell, channel head, and other parts. The tube side of straight-tube equipment can also be effectively cleaned by mechanical methods such as drilling, brushing, forcing cleaning plugs through the pipes with air or water, or combinations of these techniques.

It is not possible to clean the shell side of a fixed-tubesheet unit except chemically. Therefore, the possibilities for visually inspecting inside fixed-tubesheet exchanger shells are limited.

- **Radiographic Examination (RT)**

  Radiographic examinations give pictures of the inside of parts. They are made either by using x-ray generating equipment or a radioactive isotope, most frequently of iridium.

  i) Spot Radiography

     Under the ASME Codes rules, spot radiography consists of a manufacturer's radiographing one spot, chosen by the AI, for every 50 ft of butt welding performed by a given welder. Its purpose is to verify the welder's ability to produce sound welds. It assigns an 85 percent joint efficiency to the weld.

  ii) Full Radiography

     The purpose of radiographically examining the full length of all the butt welds of the pressure envelope is to show that they conform to the required quality standard. Welds that meet the code's acceptance standards for full radiography are assigned a joint efficiency of 100 percent.

  iii) Partial Radiography

     The ASME Code's nameplate stamping requirements indicate when the full length of the welds of part of a pressure vessel is fully radiographed. The 100 percent joint efficiency is applied only to the fully radiographed weld of the part. For exchangers in critical services, it is prudent to require full radiography of the welds of those parts that can be radiographed.

- **Ultrasonic Examination (UT)**

  Ultrasonic examination is excellent for disclosing flaws and measuring the thickness in seamless and longitudinally welded pipe and tubing. The techniques and practices have evolved rapidly.

  The principle maintenance uses are to determine the thicknesses of various parts of an exchanger to determine remaining thickness and examining welds that cannot be radiographed. For these purposes the surface contact method is preferable since it eliminates the need to immerse the part to be measured in water.

  The *Internal Rotary Inspection System* (IRIS), developed to measure tube-wall thickness and reveal the depth of pits in tubes, is not suitable for these purposes. The IRIS has a probe that carries its own source of water into the tube. It can examine 100 percent of the tube surface without distortion even where the tube penetrates baffles or supports.

  The principle disadvantage of IRIS is that it is a relatively slow process when compared with eddy-current examination-about 2.44m (~8ft)/min compared with 18.3 to 27.45m (~60 to 90ft)/min. This slow speed enhances the signal clarity, giving the system much greater accuracy that other methods.

- **Liquid Penetrant Examination (PT)**

  Liquid penetrant examination reveals surface discontinuities such as cracks and porosity. Indications of these discontinuities are assumed to be evidence that flaw extends below the surface. In contrast to magnetic particle examining, which can disclose discontinuities for a moderate depth beneath the surface, liquid penetrant examining will not expose any flaws beneath an unbroken, continuous surface. Flaws revealed by liquid penetrant examination must be ground or chipped out until sound metal is reached, rewelded and reexamined.

- **Magnetic Particle Examination (MT)**

  MT consists of dusting the area to be examined with colored iron dust and the creating a magnetic field in the parts. The iron dust arranges itself uniformly along the lines of magnetic flux. When there is a discontinuity, the defect distorts the magnetic field.

  Because magnetic particle examination is limited to materials that can be magnetized, it is useless for most austenitic stainless steels and nonferrous materials. It gives erratic results on porous materials. It can detect subsurface defect; however, it does not indicate the depth to which they extend. The depth to which it can penetrate depends on the strength of the magnetic field. The usual limits are approximately 6.5 to 12.5mm.

- **Pressure Testing**

  The purposes of Pressure Testing are to:

  i. Stress the exchanger parts under internal pressure to some value below the yield stress so as to verify that the structure can withstand the applied internal pressure.
  ii. Disclose leaks that penetrate the wall of pressure envelope, whether at the tube-to-tubesheet joints, main-seam welds, and nozzle-to-shell and –channel welds, or flanged, gasket joints.

Testing is done with test pressure on one side and atmospheric pressure on the other and then again with test pressure applied simultaneously to both sides. The most frequent pressure-testing in inspection is simply to scan very closely for any leaks from the pressurized side to the atmosphere. This may be facilitated by adding fluorescent dye to the test water and scan under black light. [5]

2.5.2 Root Cause Analysis

Proper root cause analysis identifies the basic source or origin of the problem. Root cause analysis is a step by step approach that leads to the identification of a fault's first or root cause. There are specific successions of events that lead to a failure. A root cause analysis investigation follows the cause and effect path from the final failure back to the root cause. [3] There are three general classes of failure causes or roots:

i) Physical roots

This is the physical mechanism that caused failure. It may be fatigue, overload, wear, corrosion, or any combination of these. The importance of understanding the physical root or roots cannot be overstated. Failure analysis must start with accurately determining the physical roots, for without that knowledge, the actual human and latent roots cannot be detected and corrected. [3]

ii) Human roots

The human roots are those human errors that result in the mechanisms that caused the physical failures. A good nonindustrial example of a human root of a problem would be an automobile driver's use of a cell phone and the effect of this on accident rates. [3]

iii) Latent roots (system weaknesses)

These are the corporate policies or actions that allow “inappropriate human action.” [3]

2.5.3 Preventing Reoccurrence of the Failure

It is not always necessary to prevent the first, or root cause, from happening. It is merely necessary to break the chain of events at any point and the final failure will not occur. Frequently the root cause analysis identifies an initial design problem. Then a redesign is commonly enacted. Where the root cause analysis leads back to a failure of procedures it is necessary to either address the procedural weakness or to develop an approach to prevent the damage caused by the procedural failure. [2]

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1 Problem Identification

The project will begin with identification of the problem. In this project, the main problem is; one of the heat exchanger tube bundles (E-105) available in a petrochemical plant got leakage and this lead to plant shut down on 8 November 2010. The problem is keep reoccurring since Turn Around in 2005. The project methodology will explain in detail on failure analysis methodology of old tube bundle and new tube bundle.

The heat exchanger's material specification, design, operating and service environment are as follow: [6]

Table 3.1: LD1-11-E105 2nd Stage Primary Heat Exchanger [6]

No	Description	Shell	Tube Side
1	Materials	SA 516 Gr 60	SA 179
2	Process Fluid	Cooling Water	Ethylene Gas
3	Design/ Operation Pressure (barg)	9/5	113/100
4	Design Temperature	170	200
5	Operating Temperature	33/43	95/45
6	Nominal Thickness (mm)	12	19.05 OD x 2.1
7	Corrosion Allowance (mm)	3	-

Petlin Inspection report on April 2005 reported that upon removal of the heat exchanger from the shell, it is observed that heat exchanger (E-105) are heavily fouled with brownish deposit covering most of the tube external and blackish deposit/slime collected at the tubing and baffle plate intersection/crevice. Sign of corrosion, pinhole leak and coating degradation/blister were also observed. [6]

During the shutdown, the tube bundle was removed for inspection. The detail activities description can be refer in **Appendix 1.**

Pictures below show the condition of old tube bundles of heat exchanger E-105 after being removed from the shell:

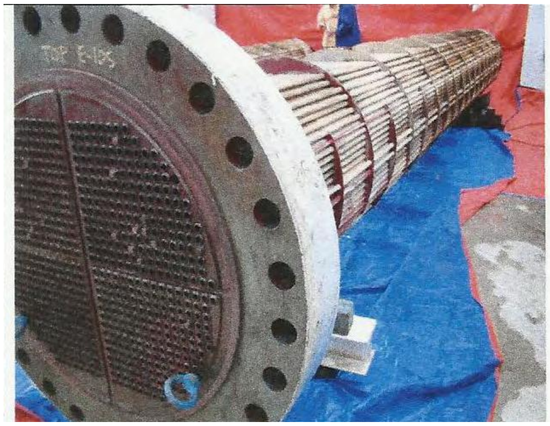


Figure 3.1: E-105 after being removed from the shell [6]

Figure 3.2: Thick brownish/slimy deposit/fouling observed next to tubing and baffle plate intersection [6]

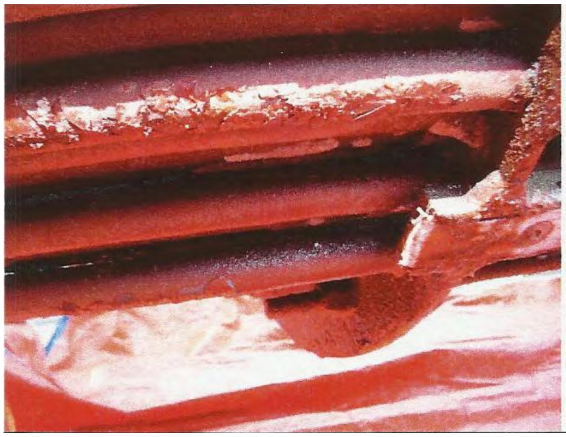


Figure 3.3: Coating damage and blister observed on E-105 tubing [6]

Figure 3.4: Close-up of E-105 localized corrosion/pitting and groove/mechanical damage near baffle plate to tube intersection [6]

3.2 Pressure Testing

The purposes of Pressure Testing are to: [3]

i. Stress the exchanger parts under internal pressure to some value below the yield stress so as to verify that the structure can withstand the applied internal pressure.
ii. Disclose leaks that penetrate the wall of pressure envelope, whether at the tube-to-tubesheet joints, main-seam welds, and nozzle-to-shell and –channel welds, or flanged, gasket joints.

Testing is done with test pressure on one side and atmospheric pressure on the other and then again with test pressure applied simultaneously to both sides. The most frequent pressure-testing in inspection is simply to scan very closely for any leaks from the pressurized side to the atmosphere. This may be facilitated by adding fluorescent dye to the test water and scan under black light. [5] For this heat exchanger, the Design Pressure is 9.0 barg while the Testing Pressure is 13.5 barg. [15]

3.3 Failure Analysis Methodology

3.3.1 Visual Testing and Macro-examination

The first inspection to make is visual. The unaided human eye can tell whether: [5]

i. Additional cleaning is needed before a more detailed inspection can be made.
ii. Rough corrosion, erosion, distortion, bulging, buckling, or misalignment is occurring.
iii. Severe cracking or other surface defects have developed.
iv. Tools are needed to aid in more detailed visual inspection.
v. Additional types of inspection and more sophisticated tools are necessary for a more detailed inspection.

Cut out samples from the heat exchanger for analysis. E-105 is cut into straight section.

3.3.2 Tubing and Coating Thickness Measurement

The standard procedures are as follow: [6]

i. Tubing wall measured using vernier caliper.
ii. The tubing coating thickness on undamaged area was measured using digital coating thickness gauge.

3.3.3 Cooling water Analysis

A 500ml sample of cooling water was collected and analysed to check for these following parameter: [6]

i. PH value
ii. Total Hardness
iii. Total Suspended Solid (TSS)
iv. Total Dissolved Solid (TDS)
v. Chloride
vi. Sulfate
vii. Iron

3.3.4 Chemical Composition Analysis

A piece of E105 heat exchanger tube was analysed using ark spark spectrometer to check its chemical composition. The tubing metal composition is compared to the SA179 material specification. The chemical reaction result is then recorded. [6, 10]

3.3.5 Tensile Test

Tensile test was carried out on E105 in accordance to ASTM A370 to check whether the plate material conformed to the requirement in SA 179. The tensile test result is then recorded. [6, 10]

3.3.6 Micro-hardness Measurement

Micro-hardness measurement was taken by using a load of 200kgf at position of every 1mm from the side of the pit.

3.3.7 Metallorgraphy Analysis

Metallorgraphy analysis for the heat exchanger was prepared using standard grinding and polishing procedures. The sample was etched using *aqua regia* solution (45ml HCl, 15ml HNO_3 and 20ml Methanol), swabbed with cotton for 5 to 10 minutes. [6]

3.3.8 Scanning Electron Microscopy (SEM) and Microanalysis

Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray (EDX) microanalysis was carried out on the corroded surface in the pit hole of E105 to check for the chemical element present. [6]

3.3.9 Deposit Analysis using EDX

Energy Dispersive X-Ray (EDX) microanalysis was carried out on two samples namely, Black and White Deposit collected from site to check for the chemical elements present and make up. [6]

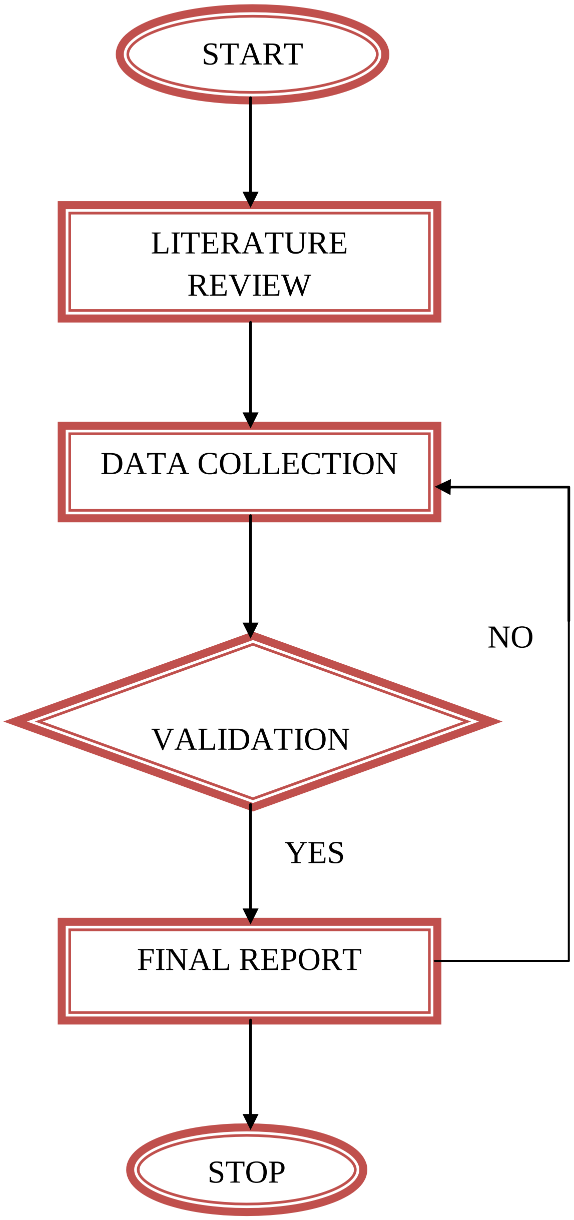
3.3.10 Deposit Analysis using XRD

X-Ray Diffraction (XRD) analysis was carried out on both the Black and White Deposit collected from site to check for the chemical compound present and make up. The analysis result will show whether the both deposits are amorphous material or crystalline material. [6]

3.4 Root Cause Analysis (RCA)

Failure analysis involved root cause analysis (RCA) which can be presented by several ways, for example; *Fish Bone Analysis and 5 why method.*

Project methodology will further describe by Figure 3.5 below:



- Preview / Analysis problem
- Fundamental studies from references and journals
- Literature review

- Identify suitable solving method for the project
- Identify suitable tools to be used for the project
- Gather all data related to the project

- Analyze all data collected
- Root cause analysis
- Recommend appropriate action to be taken based on data collected.

Figure 3.5: Project Methodology work flow

3.5 The Steps of Research

Research is a method taken in order to gain information regarding the major scope of the project. The sources of the research are from books, technical paper and journal. Below are the steps of research work:

- Find suitable sources of the research according to the scope of study.
- Gain information about Shell-and Tube Heat Exchanger, common equipment failure in industry, Failure Analysis methodology, Test and Non-destructive Examination.
- List down all the useful information.
- Analyze the information taken.
- Choose the best information which most related to the project.
- Identify the suitable methodology and tools for the project based on readings and standard available.
- Analyze the data collected from the project.
- Suggest appropriate actions to reduce the risk of heat exchanger failure in the future.

Milestone for the project can be found in **Appendix 2 and Appendix 3.**

3.6 List of Tools/Equipments Required

Tools and equipments required for the project are listed in Table 3.2 below:

Table 3.2: Tools/equipment required

NO	TOOLS/EQUIPMENT	FUNCTION/PROCEDURE
1	Hydraulic Bolt Tensioning (HBT)	To dismantle the heat exchanger cover
2	Distributed Control System (DCS)	To monitor heat exchanger performance in plant
3	Leak detection tools	To detect the heat exchanger tube leakage
4	Pressure Test equipment	To perform pressure test on the heat exchanger
5	Vernier Caliper	To measure the tubing wall thickness [6]
6	Digital Coating Thickness gauge	To measure tubing coating thickness on undamaged area around the tube. [6]
7	Arc Spark Spectrometer	To check the chemical composition of the tubes. [6]
8	Tensile Test Equipment	To perform tensile test. [6]
9	Micro-hardness measurement	By using load of 200kgf at position of every 1mm from the side of the pit. [6]
10	Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray (EDX)	To check the chemical elements present on the corroded surface in the pit hole. [6]
11	Digital Camera	To capture pictures of all findings for visual inspection.

CHAPTER 4

RESULT AND DISCUSSION

The results can be divided into two parts, which are results for old tube bundle and result for new tube bundle.

4.1 Old Tube Bundle

4.1.1 Visual Testing and Macro-examination

E-105 is cut into straight section. The results of observation are as follow: [6]

i) E-105 shows the sign of coating damage along the tubing surface. Probable reason for coating blisters could be inadequate surface preparation, dirty/dusty and trapped solvent or air bubbles.
ii) Compared to E-104 tubing, E-105 has more corrosion sites and the extent of corrosion pits is concentrative over a small area adjacent to the baffle plate to tubes intersection.
iii) Mechanical damage i.e. long narrow groove is observed at one of the sites as shown in figure below.
iv) Trough wall pitting is observed. Probable cause for high concentration of pitting at adjacent area of baffle plate to tubing intersection could be crevice corrosion and under deposit corrosion as this is the area where no flow to low flow condition prevails.

The result can be seen clearly in figures below:

Figure 4.1: As received E-105 with coating damage/blister on tubing external [6]

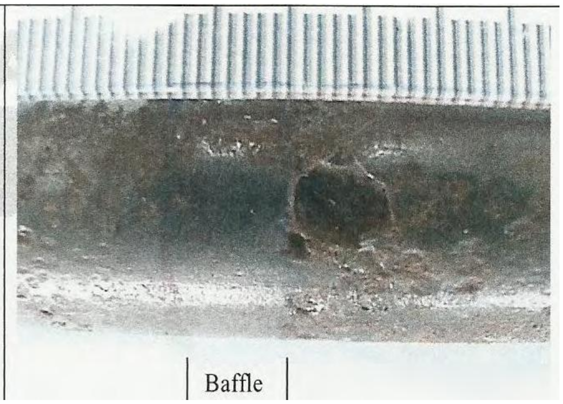


Figure 4.2: E-105 with trough wall pitting 5mm x 6mm located next to baffle plate and tubing intersection. Smaller size pits observed in adjacent area. [6]

4.1.2 Tubing and Coating Thickness Measurement

Result for tubing wall thickness measured using vernier caliper is recorded in table below:

Table 4.1: Tubing wall thickness measurement [6]

No	Description	E-105
1	Outer Diameter (mm)	19.08
2	Inner Diameter (mm)	13.94
3	Wall Thickness (mm)	2.57

It is observed that the wall tubing thickness measured is within the specified minimum of 2.1mm.

The tubing coating thickness on undamaged area around the tube was measured using digital coating thickness gauge. The result is as follow:

Table 4.2: Tubing coating thickness measurement [6]

No	Description	E-105
1	12 o’clock (µm)	65
2	3 o’clock (µm)	80
3	6 o’clock (µm)	266
4	9 o’clock (µm)	248

It is observed that the tubing coating thickness is not uniform around the diameter of the tube. It appears to range from 65µm to 266µm for E-15 against the requirement of 200µm. it is also observed that the coating blisters seemed to concentrated on the portion where the coating thickness is lowest. [6]

4.1.3 Cooling water Analysis

A 500ml sample of cooling water was collected and analysed. The results are recorded in table below:

Table 4.3: Cooling water analysis result [6]

Test Method	Parameter	Unit	Result	Suggested Typical Range
APHA 4500H	PH	-	8.21	8.0-8.9
APHA 2340C	Total Hardness	$MgCaCO_3/L$	136	120-200
APHA 2540D	Total Suspended Solid (TSS)	mg/L	12	< 15
APHA 2540C	Total Dissolved Solid (TDS)	mg/L	347	Depends on make-up & cycle
APHA 4500-CI B	Chloride (Cl-)	mg/L	141	< 50
HACH 8051	Sulfate (SO_4)	mg/L	53	< 50
AAS-Flame	Iron (Fe)	mg/L	0.05	< 3

The test result shows that the cooling water is within a reasonable typical range os an evaporative cooling water system. However, the chloride and sulfate ion content should be kept to a minimum as it contributes to pitting corrosion in carbon steel and stress corrosion cracking (SCC) in carbon steel. Additionally, Petlin should ensure that the water quality, treatment programme and flow are within the range and parameter specified to reduce/prevent deposition, fouling and corrosion. [6]

4.1.4 Chemical Composition Analysis

A piece of E105 heat exchanger tube was analysed using ark spark spectrometer to check its chemical composition. The tubing material composition is then compared to the SA179 material specification. The chemical composition result is tabulated as follows:

Table 4.4: Chemical composition analysis [6]

Chemical Element	**Composition %**	
	SA 179	**E-105**
Carbon	0.06-0.18	0.08
Manganese	0.27-0.63	0.39
Phosphorus	< 0.035	< 0.001
Sulfur	< 0.035	0.001
Silicon	Not specified	0.20

It is observed that the tubing materials are within the allowable range specified and thus meet the requirement of SA179 material as specified. [6]

4.1.5 Tensile Test

Tensile test was carried out on E-105 in accordance to ASTM A370 to check whether the plate material conformed to the requirement as specified in SA179. The tensile test result is as follow:

Table 4.5: Tensile test result [6]

Parameters	**E-105 Tube**	**SA179**
Tensile Strength, MPa	375	325
Yield Strength, MPa	289	180
Elongation in 50mm, min %	43	35

The E-105 tube material conformed to SA179 Specification for Seamless Cold Drawn Low Carbon Steel Heat Exchanger and Condenser Tubes. The sample mode failure is ductile. [6]

4.1.6 Micro-hardness Measurement

Micro-hardness measurement was taken by using a load of 200kgf at position of every 1mm from the side of the pit. There is no significant variation in hardness value for the tube. Result is then recorded in table 4.6 below. [6]

Table 4.6: Micro-hardness measurement at different location from the pit [6]

Distance from pit (mm)	**Micro-hardness result (VHN)**	
	Left side	**Right side**
1	108.4	104.8
2	108.4	112.2
3	104.8	106.5
4	103.0	110.2

4.1.7 Metallorgraphy Analysis

Figures 4.3 below show that the pit size was larger at external surface compared with internal surface of the tubes. This means that the corrosion originated from the external surface and penetrated into the tube wall. Both pits surfaces were covered with oxides/layer of corrosion deposit. [6]

i) As-polished Sample

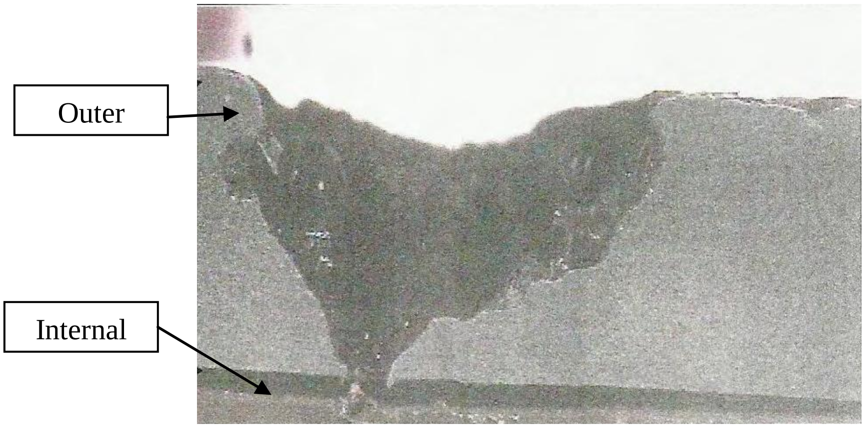


Figure 4.3: Cross-section view of E-105 through wall pit [6]

ii) After etched

Typical microstructure is observed in E-105 tube sample consisted of large equi-axed grains; indicating that tubes were in the annealed condition and not over stressed. No grain growth, grain deformation or microcracks is observed on both tubes, and corrosion attack is along the grain boundaries. [6]

Figure 4.4 below show the microstructure of E-105 tube sample:

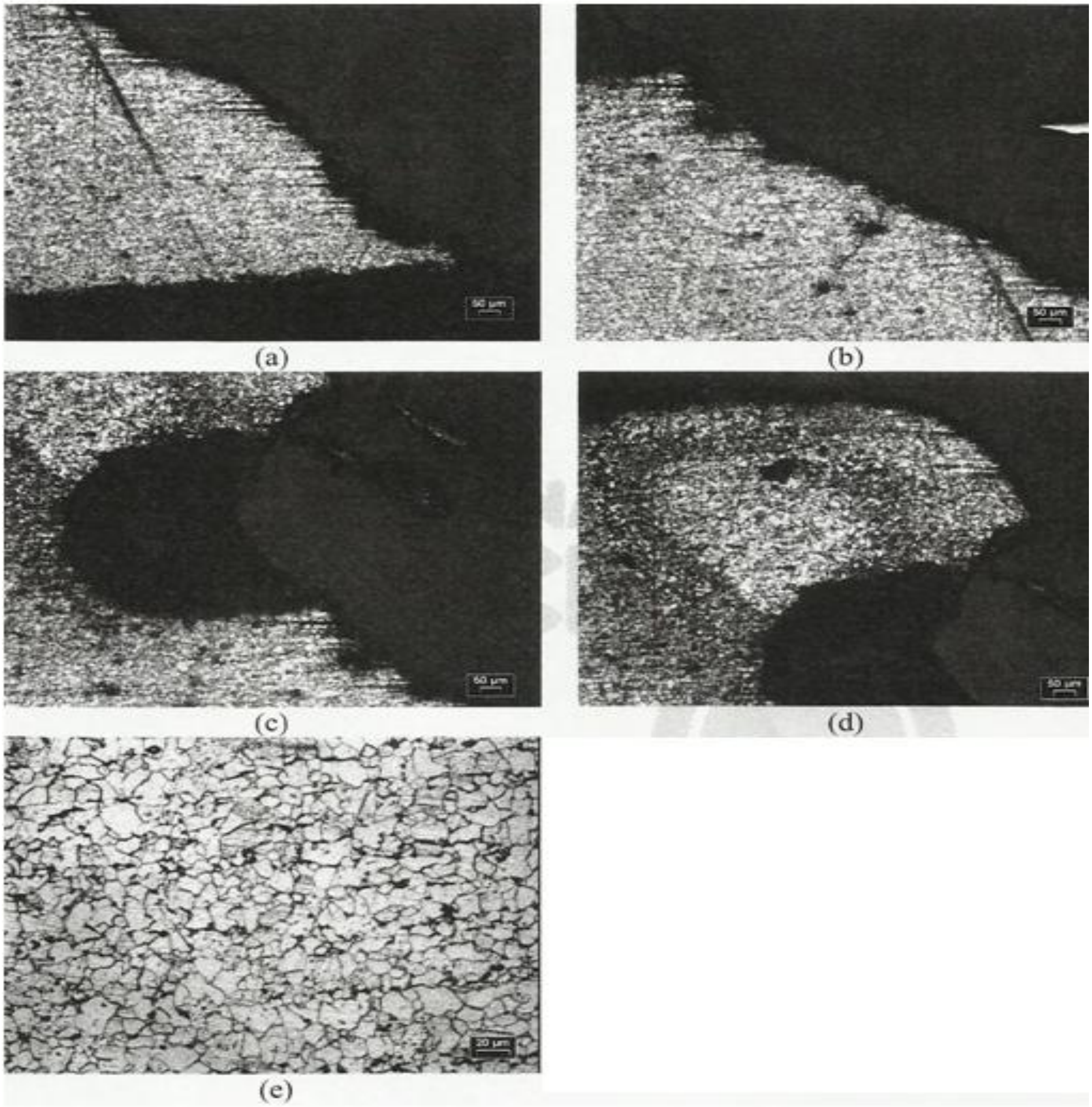


Figure 4.4: Microstructure photo of tube E-105 taken from pit internal to external surface (d) and close-up view (e). [6]

4.1.8 Scanning Electron Microscopy (SEM) and Microanalysis

It is observed that a large proportion of the corrosion product consists mainly of iron oxides. Trace element of chloride was again detected which means that an acidic corrosion cell was present/active. [6]

Figure 4.5 and 4.6 below shows the EDX result on corrosion product found in E-105 pit hole.

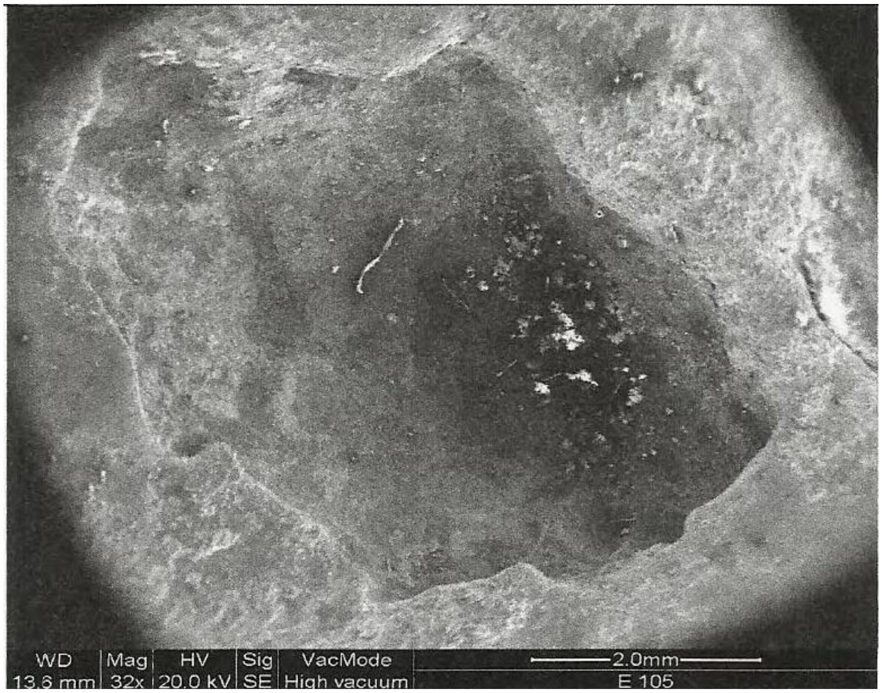
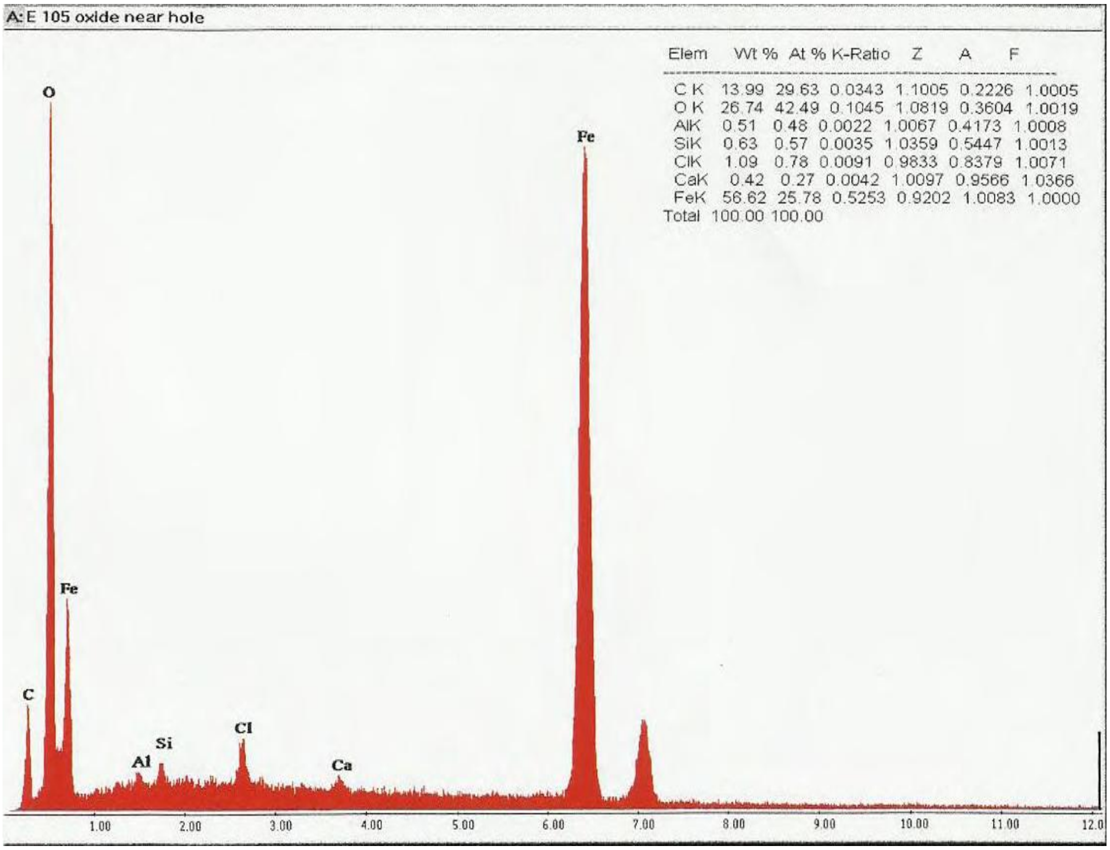


Figure 4.5: SEM photo from top surface E-105 pit hole [6]



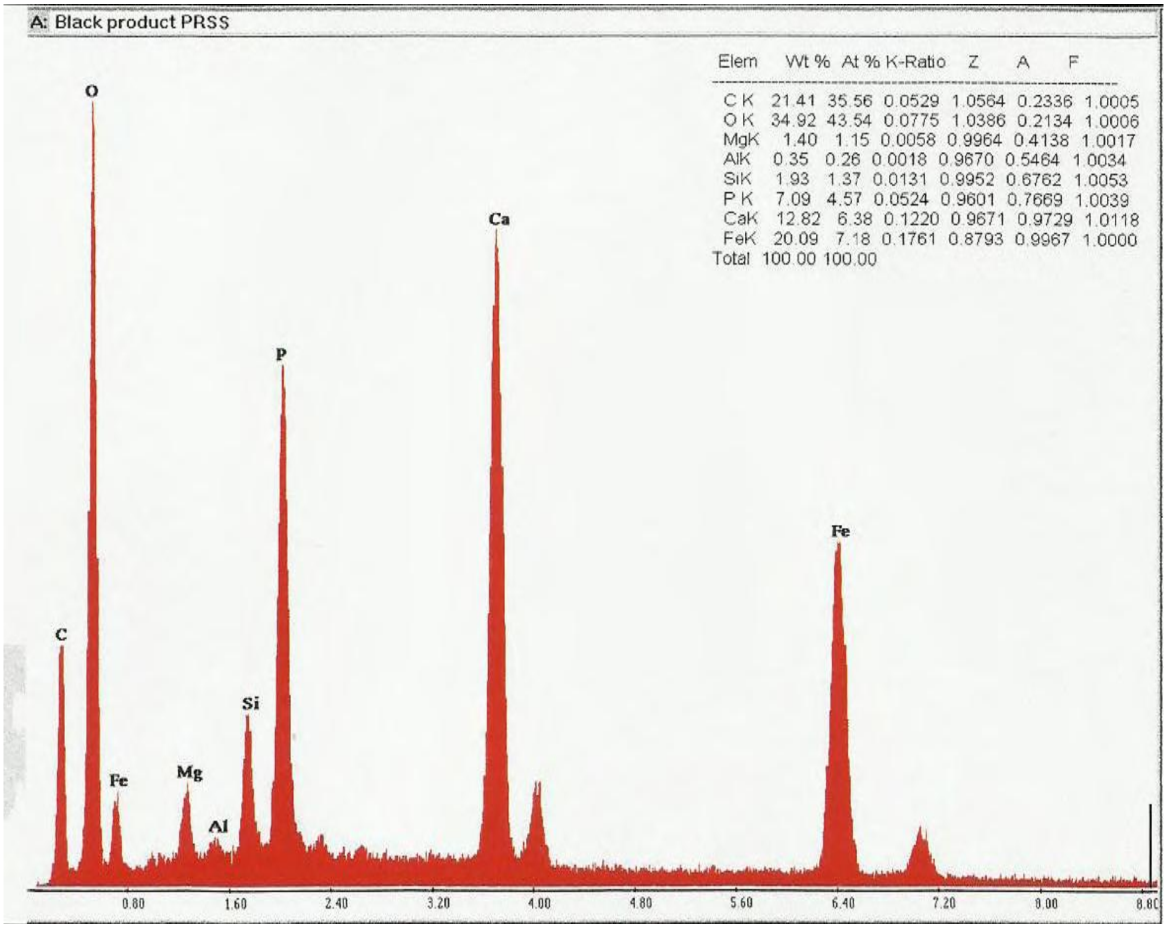
Elem	Wt %	At %	K-Ratio	Z	A	F
C K	13.99	29.63	0.0343	1.1005	0.2226	1.0005
O K	26.74	42.49	0.1045	1.0819	0.3604	1.0019
AlK	0.51	0.48	0.0022	1.0067	0.4173	1.0008
SiK	0.63	0.57	0.0035	1.0359	0.5447	1.0013
ClK	1.09	0.78	0.0091	0.9833	0.8379	1.0071
CaK	0.42	0.27	0.0042	1.0097	0.9566	1.0366
FeK	56.62	25.78	0.5253	0.9202	1.0083	1.0000
Total	100.00	100.00				

Figure 4.6: EDX analysis on corrosion product of E-105 tube [6]

4.1.9 Deposit Analysis using EDX

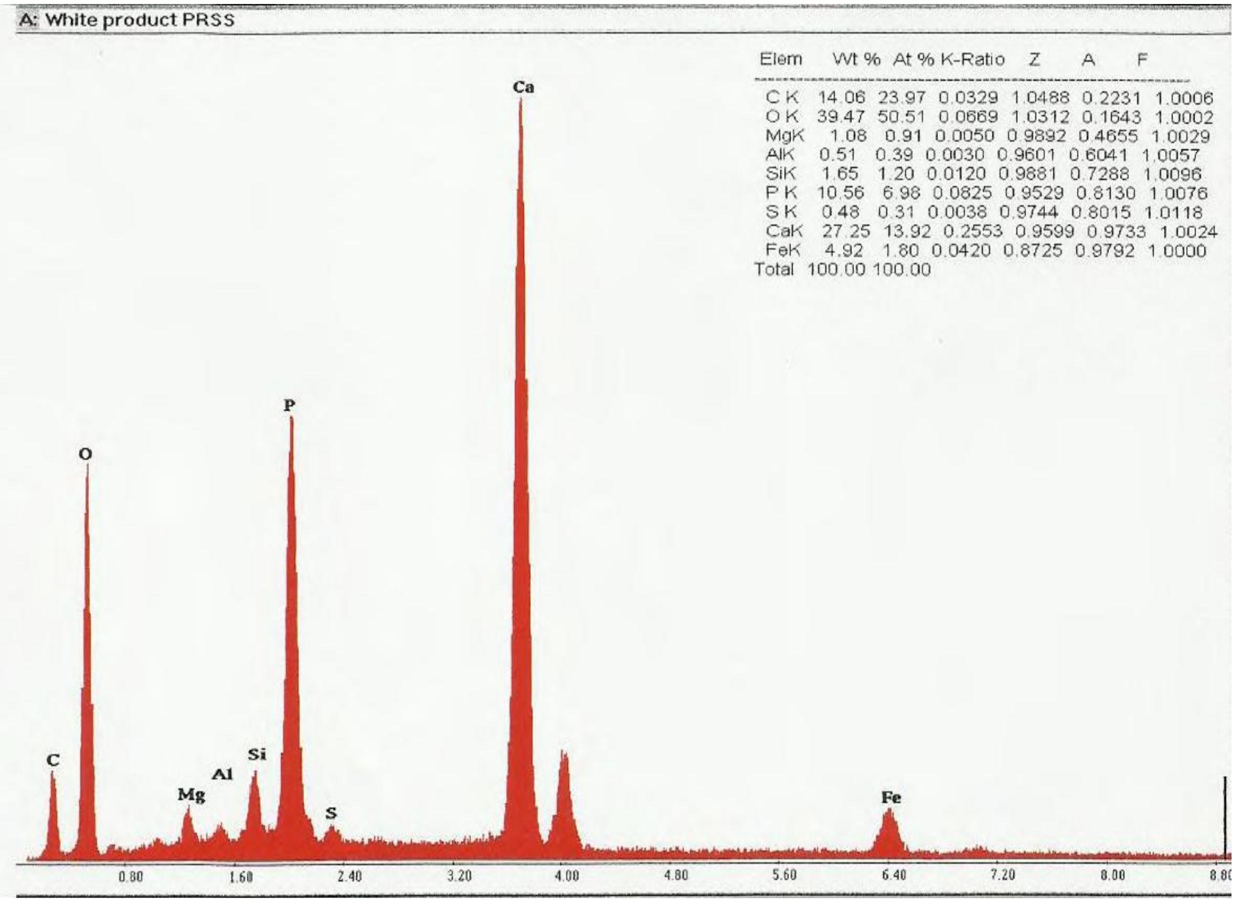
It is observed that a large proportion of the black deposits consist of calcium carbonate, phosphate, iron oxides and trace elements of silica, magnesium and aluminum. This is reflective of corrosion product from the metal itself and deposition product from the cooling water treatment.

As for the white deposit, it is observed that a large proportion of the deposit consist of calcium carbonate, phosphate and trace elements of iron oxides, silica, magnesium and aluminum. This is reflective of corrosion product from the metal itself and deposition product from the cooling water treatment. A trace amount of sulfur is also founded suggesting that MIC could be present/active. Figure 4.7 and Figure 4.8 show the EDX Analysis on black deposit and white deposit respectively. [6]



```
Elem     Wt %  At % K-Ratio    Z       A       F
-----------------------------------------------------------
 C K   21.41  35.56  0.0529  1.0564  0.2336  1.0005
 O K   34.92  43.54  0.0775  1.0386  0.2134  1.0006
 MgK    1.40   1.15  0.0058  0.9964  0.4138  1.0017
 AlK    0.35   0.26  0.0018  0.9670  0.5464  1.0034
 SiK    1.93   1.37  0.0131  0.9952  0.6762  1.0053
 P K    7.09   4.57  0.0524  0.9601  0.7669  1.0039
 CaK   12.82   6.38  0.1220  0.9671  0.9729  1.0118
 FeK   20.09   7.18  0.1761  0.8793  0.9967  1.0000
Total 100.00 100.00
```

Figure 4.7: EDX analysis on black deposit [6]



Elem	Wt %	At %	K-Ratio	Z	A	F
C K	14.06	23.97	0.0329	1.0488	0.2231	1.0006
O K	39.47	50.51	0.0669	1.0312	0.1643	1.0002
MgK	1.08	0.91	0.0050	0.9892	0.4655	1.0029
AlK	0.51	0.39	0.0030	0.9601	0.6041	1.0057
SiK	1.65	1.20	0.0120	0.9881	0.7288	1.0096
P K	10.56	6.98	0.0825	0.9529	0.8130	1.0076
S K	0.48	0.31	0.0038	0.9744	0.8015	1.0118
CaK	27.25	13.92	0.2553	0.9599	0.9733	1.0024
FeK	4.92	1.80	0.0420	0.8725	0.9792	1.0000
Total	100.00	100.00				

Figure 4.8: EDX Analysis on white deposit [6]

4.1.10 Deposit Analysis using XRD

The XRD analysis result does not shows any peak for both deposits as indicated in Figure 4.9 and 4.10 respectively. This means that both deposits are of amorphous material/powder that does not contain any crystalline. [6]

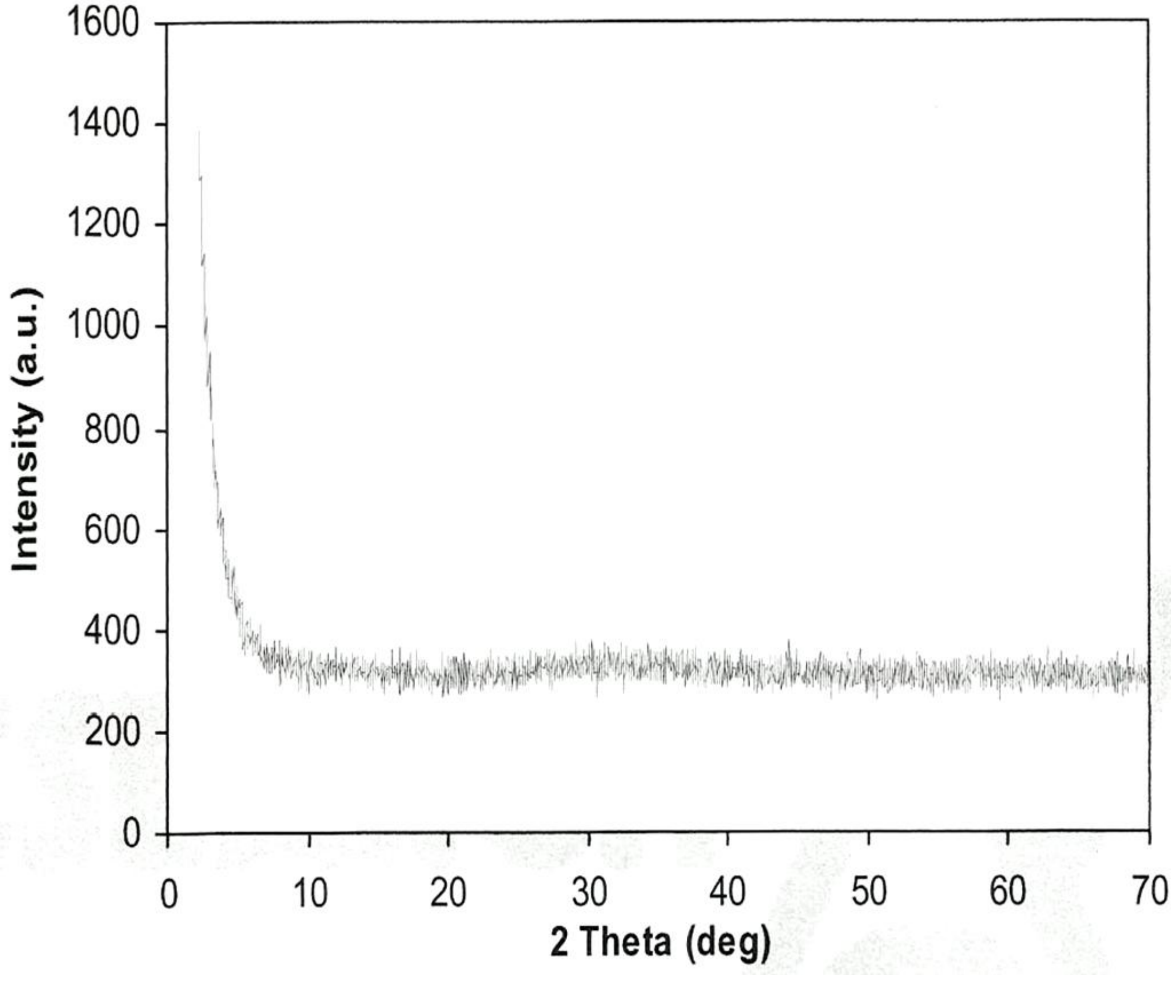


Figure 4.9: XRD on black deposit [6]

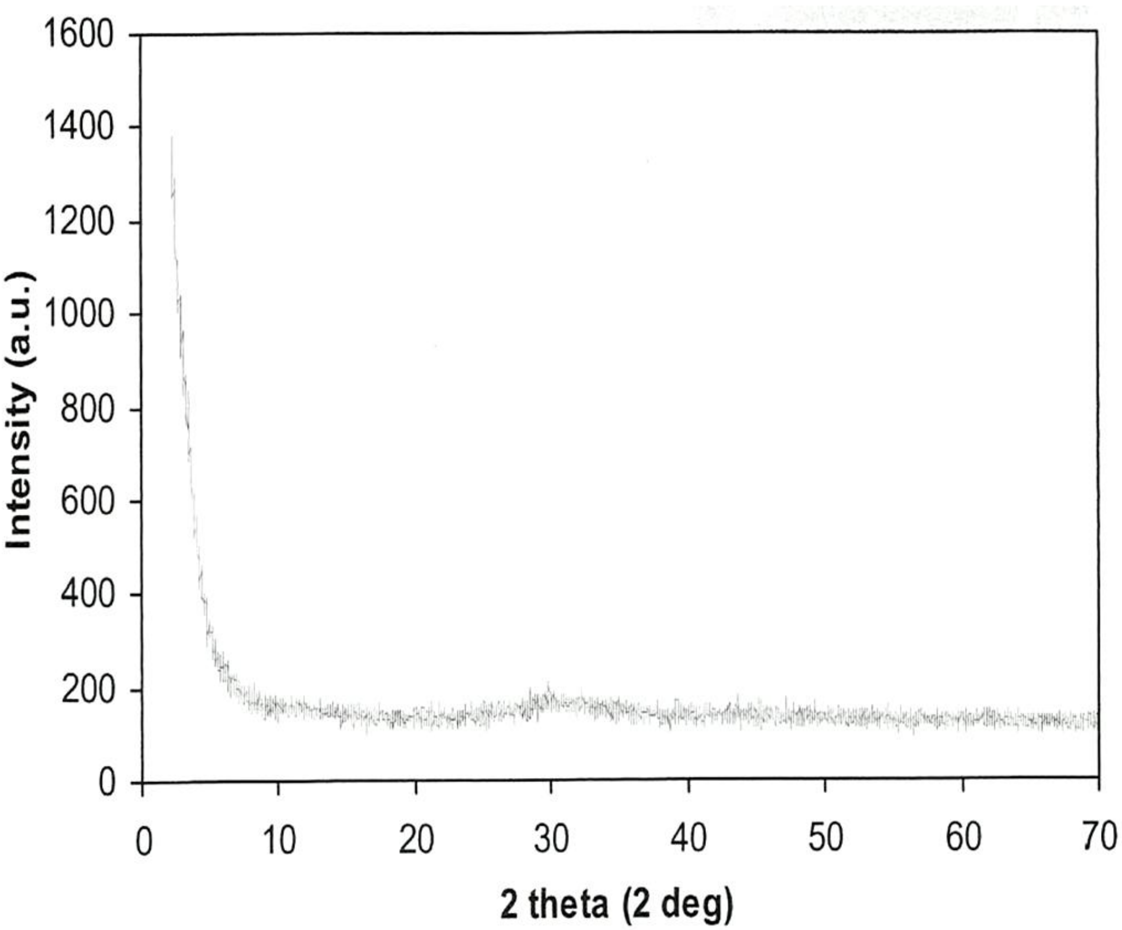


Figure 4.10: XRD on white deposit [6]

4.2 New Tube Bundle

4.2.1 Condition of New Tube Bundle, E105 during May 2009 Turn around (2 years, 10 months old)

Findings

After 2 years and 10 months in service, the tube bundle is in good condition. Not much issue on slight scale formation observed on top of the coating as far as heat transfer is concerned. [12]

i) Water side (Shell side):

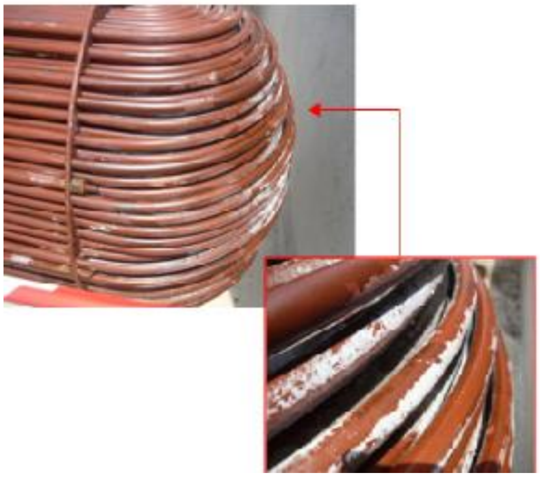


Figure 4.11: Layer of deposits scale found at tubes and mostly accumulate at U-bend area [12]

Figure 4.12: View of tube bundle noted in satisfactory condition. No sign of any abnormalities observed [12]

More old tube bundle E-105 pictures to can be found in **Appendix 4.**

Condition of New tube bundle, E105 after cleaning:

Water jetting done at external of the tube peeled off the coating in some areas. The removal of portion of the coating exposed the base metal which is prone for solid deposits that could lead to localized deposition/pitting corrosion. Therefore, action has taken to touched-up on the accessible areas but not on the inner layers. [12]

Figure 4.13: Peeled off coating in some areas due to water jetting [12]

Figure 4.14: Touched-up peeled off coating after the contractor did hydro-jetting due to some damaged peeled off the existing coating [12]

ii) Process side (Tube side)

Condition before cleaning:

At the tube side, found a thick layer of sticky residue. [12]

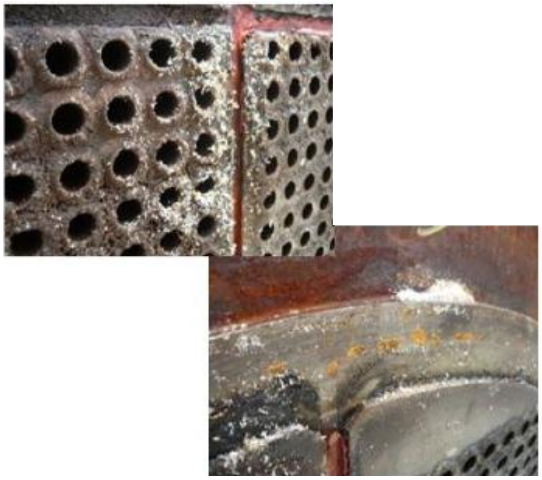


Figure 4.15: View of tubes sheet found with thick layer of product residue and white residue stick at tubes sheet [12]

4.2.2 Condition of New Tube Bundle, E105 on 8 November 2010 (4 years and 3 months old)

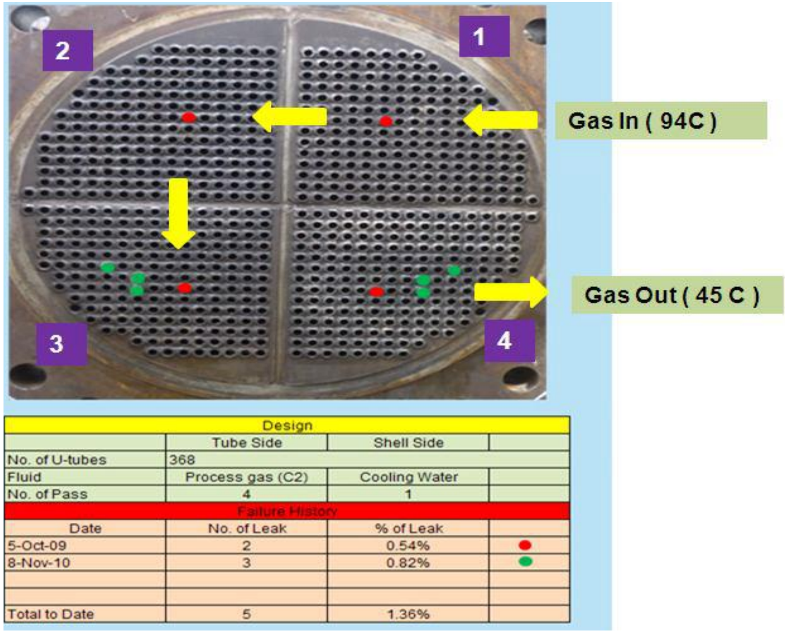
Findings:

i) New Tube Bundle:

It is found that, leaking tube is more at the bottom (3/4 pass). From the Root Cause Analysis (RCA) conducted, the most probable cause is “Localized pitting in area of the tube with peeled-off coating. Refer to Figure 4.16. [12]

ii) Old Tube Bundle:

The leak pattern is more concentrated at the upper portion (1/2 pass). Higher temperature at upper portion was found where deposition/pitting corrosion is accelerated. Refer to Figure 4.17. [12]



Design			
	Tube Side	Shell Side	
No. of U-tubes	368		
Fluid	Process gas (C2)	Cooling Water	
No. of Pass	4	1	
Failure History			
Date	No. of Leak	% of Leak	
5-Oct-09	2	0.54%	🟥
8-Nov-10	3	0.82%	🟩
Total to Date	5	1.36%	

Figure 4.16: New E-15 Leaking Mapping [12]

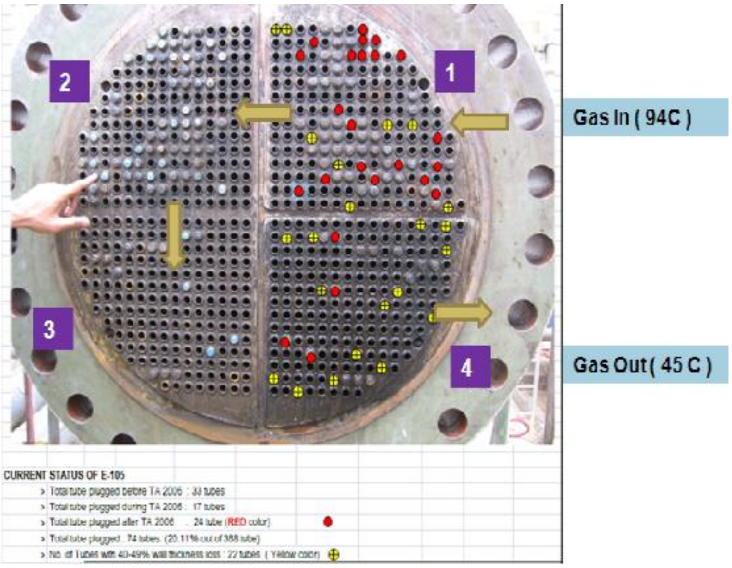


Figure 4.17: Old E105 Leaking Mapping [12]

iii) Process side (tube side):

- Sticky foam was noted at the bottom section of tube sheet.
- Visual inspection was done at tube sheet face. No abnormalities noted. Sticky blackish deposited was noted entire tube sheet surface.
- Magnetic test were carried out at deposited surface and the deposit attract to magnet. [12]

Figure 4.18: Sticky blackish deposited noted entire tube sheet surface [12]

Figure 4.19: Magnetic test carried out at deposited surface [12]

4.2.3 Performance of New Tube Bundle, E105

Performance of E-105 with new tube bundle until on 24 November 2010 was monitored by using X-changer Performance Monitoring system. By using this system, heat transfer rate, heat duty, shell side velocity and process temperature inlet/outlet can be monitored. [12]

Findings:

- Good heat transfer rate (indication of no fouling), steady process inlet and outlet temperature. [12]
- Part of action taken is to increase a bit cooling water supply to increase shell side velocity at about 1m/s

The new tube bundle, E105 performance details can be found in **Appendix 5.**

4.2.4 Root Cause Analysis (RCA) on New Tube Bundle, E105

Root Cause Analysis (RCA) has been done on the new tube bundle, E105. The RCA session has attend by several teams which are:

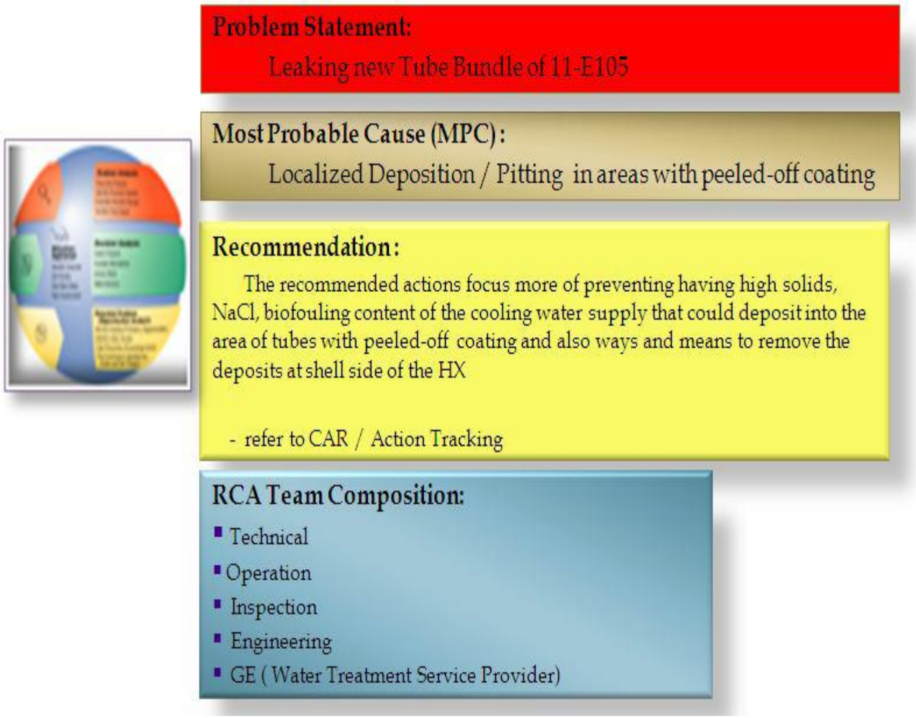
i) Technical Department

ii) Operation Department

iii) Inspection Department

iv) Engineering Department

v) GE (Water treatment provider in the plant)



Problem Statement:

Leaking new Tube Bundle of 11-E105

Most Probable Cause (MPC):

Localized Deposition / Pitting in areas with peeled-off coating

Recommendation:

The recommended actions focus more of preventing having high solids, NaCl, biofouling content of the cooling water supply that could deposit into the area of tubes with peeled-off coating and also ways and means to remove the deposits at shell side of the HX

- refer to CAR / Action Tracking

RCA Team Composition:

- Technical
- Operation
- Inspection
- Engineering
- GE (Water Treatment Service Provider)

Figure 4.20: Summary of RCA [12]

The RCA outcome is then become the guideline for action required to improve the performance of heat exchanger. Details on action required can be found in **Appendix 6.**

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Based on the testing done on the old tube bundle E105, there are several causes of failure which can be summarized as follow:

i) High TDS from cooling water caused by filter media break through from the side stream filter.
ii) Accumulation of solids leading to deposition/pitting at the U-bend portion of the heat exchanger. Drain port available but no drain line installed.
iii) Damage/peeled of coating due to mechanical method of cleaning.
iv) Low inter-baffle shell side velocity (0.60m/s)

Therefore, several improvements have been done to the new E-105 tube bundle installed in 2009, which are:

i) Changed of Sakaphen coating from SI57E to SI 57EN. The latter has a better thermal conductivity.
ii) Installed 16 pieces tube bundle Teflon shoe at the top and bottom of the tube bundle to ease the insertion of tube bundle and avoid scratching the shell.
iii) Installed drain line at shell side to have an intermittent draining and avoid build-up of deposits leading to deposition / pitting corrosion.
iv) Did flow mapping to ensure cooling water supply is sufficient to have at least 1 m/s inter-baffle velocity at shell side
v) Routine monitoring of Heat Exchanger Performance

5.2 Recommendations

Based on the Root Cause Analysis performed, there are several recommendations to improve the new tube bundle performance in the future, which are:

i) The recommendation actions focus more on preventing having high solids, NaCl, biofouling content of the cooling water supply that could deposit into the area tubes with peeled-off coating and also ways.
ii) Methods to remove the deposits at shell side of the heat exchanger.

The details on recommended actions can be found in **Appendix 6.**

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