Failure Mode Effect Analysis (FMEA) on Heat Recovery Steam Generator (HRSG): Water Tube Boiler

by

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Dissertation submitted in partial fulfillment of the requirement for the

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CERTIFICATION OF APPROVAL

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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

MAY 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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AL-AFNAAN BIN MASHAL

Abstract

This study is on Failure Mode Effect Analysis (FMEA) on Heat Recovery Steam Generators (HRSG) at UTP Gas District Cooling (GDC) plant. HRSG is a heat exchanger which converts water to steam at elevated temperature for power generation or process purposes. Operating at high temperature and pressure, the HRSG is subjected to several types of failures. The focus of this analysis are on sub equipment such as evaporator tubes, economizer tubes, boiler feed water (BFW) pump and steam drum. By using FMEA, failures associated with each sub system/component were identified and corresponding remedial methods to counteract the failures were recorded and tabulated in an FMEA table. The critical equipment of the HRSG was discovered through developing Risk Priority Number (RPN) and the critical equipment that was identified is evaporator tube. Proposed FMEA methodology can assist the maintenance engineers to analyze the HRSG's failure and reliability.

Acknowledgement

First and foremost I express my thanks and gratitude to Allah S.W.T The Most Merciful and Most Kind for providing this learning opportunity for me to gather knowledge and strength to complete this project. I would like to express my gratitude to my supervisor, AP Ir Dr. Mohd Amin Bin Abd Majid for guiding me tirelessly throughout my entire project duration. Finally I would like to thank my family and friends for giving me relentless support and all the help that I need.

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CHAPTER 1

INTRODUCTION

1.1 Background Study

In this globalization era, industrial activity has grown to an immeasurable size. Technological advances have brought out new and more complex designs of mechanical engineering systems. The need to maintain such complex system designs require a systematic framework and model in order to keep the industrial facilities up and running and serve the needs of whatever it is the system requires them to do. Take Malaysia for example, known as one of the fastest growing developing country over the past fifty years, both in economy and technology. However, a country endowed with today's modern technology requires great attention in maintaining its industrial activities up and running.

One such design is the industrial boilers in heat recovery steam generators (HRSG), a complex design of a system which utilizes the generation of steam to provide a work output on certain machines. According to V. Ganapathy (2003), problems such as corrosion are a main concern in keeping and maintaining the boilers and steam generators in its peak conditions.

In HRSG, boilers use thermal energy to change water into vapors or steam to produce power. There are many types of boilers, but most boilers used in the industries are either fire tube boilers or water tube boilers. The differences between the two are several, such as the position of the water and hot gases. In a fire tube boiler, hot gases are inside the tube and water is at outside the tube, while water tube boiler has water inside the tube and gases on the outside. Fire tube boilers produce lower rate of steam compared to water tube boilers. The focus for this will be on HRSG with water tube boilers.

Every functioning design should aim to obtain the highest output and production out of their respective systems as efficiently as possible. The reliability of a system should be at its optimum level at all times and each components of the design must have a long life time in order to cater to the demands of the system.

However, in reality, every functioning design would soon succumb to wear and other types of undesirable faultiness. This will lead to the inefficiency of the system and components. When such event occurs, this will lead to undesirable output and unsatisfied customers and also leads to higher cost of maintenance. Refineries, chemical and process plants all have heat recovery steam generators unit, which is an essential part in a plant for energy recovery and process purposes. Failure or absence of it would dramatically affect plants' operations and production rate.

Many systematic frameworks and problem solving tools have been modeled to provide the ideal maintenance program that would be cost effective and offers high reliability. One such tool is called Failure Mode and Effect Analysis (FMEA), which is used to predict problems that might arise.

1.2 Problem Statement

Based on the feedback of the operation of HRSG, the reliability of HRSG is difficult to assess and this creates problem to ensure maximum operational performance of HRSG. One option is to undertake FMEA analysis of the HRSG. This approach is adopted for the HRSG at UTP Gas District Cooling (GDC) plant.

1.3 Objectives and Scope of Study

The objectives of this project are:

1. To identify the critical equipment in HRSG by knowing the failure modes and causes that has an effect on reliability, safety, availability and maintainability of the system.
2. To develop a methodology of using FMEA on Heat Recovery Steam Generator (HRSG)

The scope of this analysis will only be focusing on UTP's HRSG in the Gas District Cooling (GDC) plant.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews and gathers all the required knowledge on the usage of some problem solving tools that are being used in a real life working environment and the suitability of each tools for failure analysis of water tube boilers.

2.2 Problem Solving Tools

According to James J. Scutti et al. (1990), when an equipment or a component encounters a failure, failure analysis must be carried out to investigate and identify the characteristics and causes that contributed to such failures. Reason being is that when carrying out such investigation or failure analysis, the main objective for it is to prevent the same errors or failures from repeating again in the future. Understanding the key attributes of a particular failure and identifying the likely causes of failure is the process of failure investigation. The process flow chart for failure investigation is as shown below in Figure 2.1.

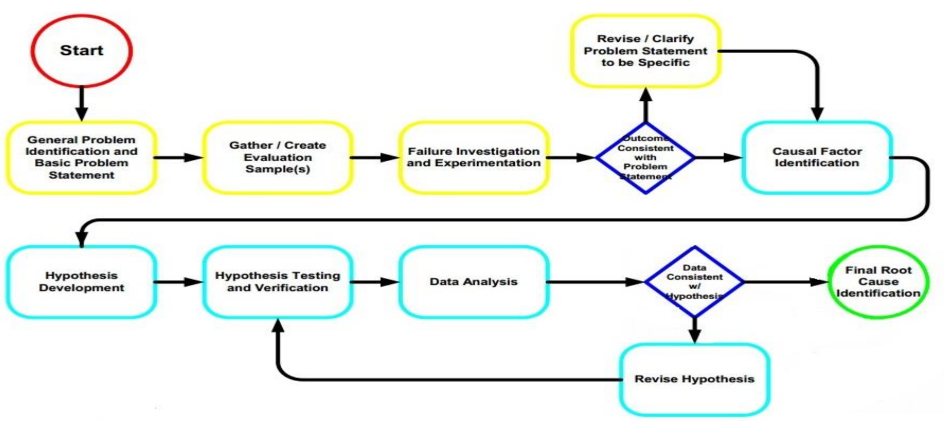

Figure 2.1: Process Flow for Failure Analysis

2.2.1 Root Cause Analysis (RCA)

A root cause is the fault of a problem, where root cause failure analysis (RCFA) or root cause analysis (RCA) is one of many methods to identify these root causes. A root cause is the source of a certain problem and once it has been identified, the next logical step to take is to erase this root cause. Once erased or removed from the picture, the faulty or undesirable outcome will be prevented from happening and reoccurring. According to James J. Scutti et al. (1990), when performing RCA, one must know the three levels of root cause analysis, namely physical roots, human roots and latent roots

According to James J. Scutti et al. (1990), physical roots refer to the equipment problem where it is usually solved on the component level findings through laboratory investigation and engineering analysis. A failure that is caused by human factor is governed under the human roots, such as human error. Latent root on the other hand helps identify the causes which lead to the human error, as well as organizational or procedural and environmental factors which is outside the realm of control. There are various tools that may assist in performing RCA investigation, such as the Ishikawa Diagram.

2.2.2 Ishikawa Diagram

Invented by Kaoru Ishikawa in the 1960s, the Ishikawa diagram, or more commonly known as either cause and effect diagram or fishbone diagram, is a very convenient tool in a variety of problem solving situations. According to Illie G. et al. (2010), the Fishbone diagram is an analysis tool that provides a systematic way of looking at effects and the causes that create or contribute to those effects. According to J.A. Doshi et al. (2012), when used by a cross functional team and brainstorming method, the Ishikawa diagram proves to be a more powerful and effective tool as different causes of the problem could be identified from different point of view. The Ishikawa diagram is represented by the shape of a fish bone, a main horizontal line with bevel line segments branching out from it as shown in Figure 2.2.

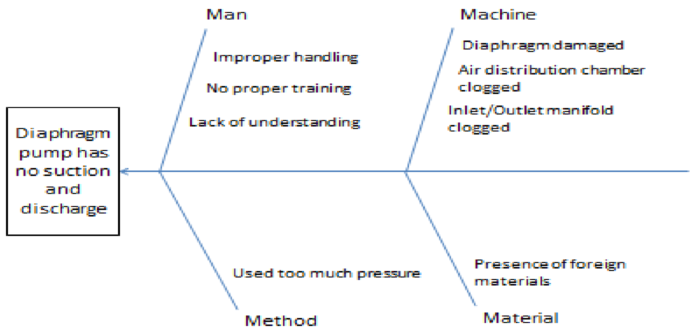

Figure 2.2: Ishikawa Diagram

Ishikawa diagram is to be used when a problem or an event occurs due to multiple causes. As seen in the figure above, these causes can be identified or categorized as People, Process, Equipment, Materials, Environment and Management. Sometimes, FMEA and Pareto can be utilized to prioritize the various causes identified. According to Illie G. et al. (2010), a few conditions must be fulfilled when utilizing the Ishikawa diagram. Such conditions are as listed below:

i. Probability of occurrence and impact can be determined.
ii. An operational valence with management objective
iii. Causes that contributed to the problem must be characterized by probability, possibility or frequency of occurrence
iv. Main causes must also be taken into account as effects, be it may of secondary order. Furthermore, sub-causes, also known as side effects, which represent the causes for secondary effect, must fulfill the same conditions as the main cause.
v. An effect must not turn into a cause and must have no bijective correlations.

2.2.3 Failure Mode Effect Analysis (FMEA)

Failure Mode Effect Analysis (FMEA) is a method for defining schemes of maintenance equipment in a way that it considers all failure modes for that particular asset or equipment. According to National Aeronautics and Space Administration (NASA) (2000) each system function and the dominant failure modes associated with each failure are addressed by FMEA and the consequences of the failures are examined. FMEA also defines policies to eliminate consequences of failure by designing out the problem, carrying out condition based monitoring (CBM) and time based monitoring (TBM). It is a systematic method to identify :-

i. How can an item fail
ii. Potential causes and effects of failure
iii. Relative significance of mode
iv. Actions to prevent failure from happening

To implement FMEA, a subsystem or equipment is chosen from the equipment hierarchy where the primary and secondary function of the equipment is defined. Primary function is the purpose or reason that the equipment was acquired in the first place while secondary functions are other functions that the asset may perform. It is also important to note that functions should be described in a quantitative manner.

FMEA then proceeds to identify ways of which the function of the equipment could fail, which is the function failure. Causes of failure of the equipment, failure modes, are identified followed by the effects of the failure and consequences for each effect. Although there may be multiple failure modes in existence for one equipment function failure, most of the time the effects of the failure are repetitive or similar in nature, from a system function perspective. Proactive tasks are then developed in order to maintain or prevent such failure from happening again.

According to George E. Dieter et al. (2013) developing a FMEA requires taking consideration of three factors. The first factor is the severity of the failure. The second factor is the probability of the failure to occur. The third and last factor is the probability of detecting the failure. These three factors are rated where the ratings are given in the Tables 2.1, 2.2 and 2.3 below.

Table 2.1: Occurrence of Failure Rating (George E. Dieter, 2013)

Rating	Approximate Probability of Failure	Description of Occurrence
1	$\leq 1x10^{-6}$	Very Remote
2	$1x10^{-5}$	Remote
3	$1x10^{-5}$	Very slight chance
4	$4x10^{-4}$	Slight chance
5	$2x10^{-3}$	Occasional
6	$1x10^{-2}$	Moderate
7	$4x10^{-2}$	Frequent
8	0.20	High
9	0.33	Very High
10	≥ 0.50	Extremely High

Table 2.2: Detection Failure Rating (George E. Dieter, 2013)

Rating	Description of Detection
1	Almost Certain to detect
2	Very High Chance of detection
3	High Chance of detection
4	Moderately High Chance of detection
5	Medium Chance of detection
6	Low Chance of detection
7	Slight Chance of detection
8	Remote Chance of detection
9	Very Remote Chance of detection
10	No Chance of detection of detection

Table 2.3: Severity Rating (George E. Dieter, 2013)

Rating	Severity Description
1	Unnoticeable Effect
2	Very Slight Effect Noticed by Users
3	Slight Effect, Annoyance May Occur
4	Slight Effect, Users May Return Product
5	Moderate Effect
6	Significant Effect
7	Major Effect
8	Extreme Effect
9	Critical Effect
10	Hazardous

These three ratings are combined to form the risk priority number (RPN). The RPN value ranges from 1, least risk, to 1000, greatest risk (G.E. Dieter, 2013) The equation for RPN is as shown below:-

$$RPN = (\text{Severity of failure}) \times (\text{Occurrence of Failure}) \times (\text{Detection Rating})$$

The purpose of finding the RPN values for a design, system or an equipment is so that one may focus on the "vital few" problems (G.E. Dieter, 2013). This can be done by setting a benchmark of an RPN value and working on any potential failures that has RPN value than the benchmark RPN value (G.E. Dieter, 2013).

2.3 Boilers

Boilers are categorized into several types according to its application as shown in Figure 2.3, which are mainly in power, chemical and refinery plants. Boilers usually have long service life as according to Boiler Comparison Guide (2008) from Bryan Boilers, boilers such as water tube boilers have a service life of 35 to 40 years. The easiest way to categorize the boilers is through identifying whether it is used for either energy recovery or process purposes. According to V. Ganapathy (2003), in process purposes, waste gas steams from an inlet temperature are cooled by means of boilers to a desirable outlet temperature for other processes. Plants are mostly chemical industry plants such as acid or hydrogen plant. In these plants, as mentioned before, cools down gas steam to a desirable temperature before being transferred to a specialized reactor for other processes when required. In regards to the usage of boilers in energy recovery purposes, V.Ganapahty (2003) mentions that, in energy recovery applications, on the other hand, the gas is cooled as much as possible while avoiding low temperature corrosion. In order to achieve to objective of energy recovery, flue gas heat from incinerators, kiln and furnaces are cooled down to a temperature as low as it can be achieved, so long as it does not produce low temperature corrosion. Classifications of boilers can be viewed in the figure below.

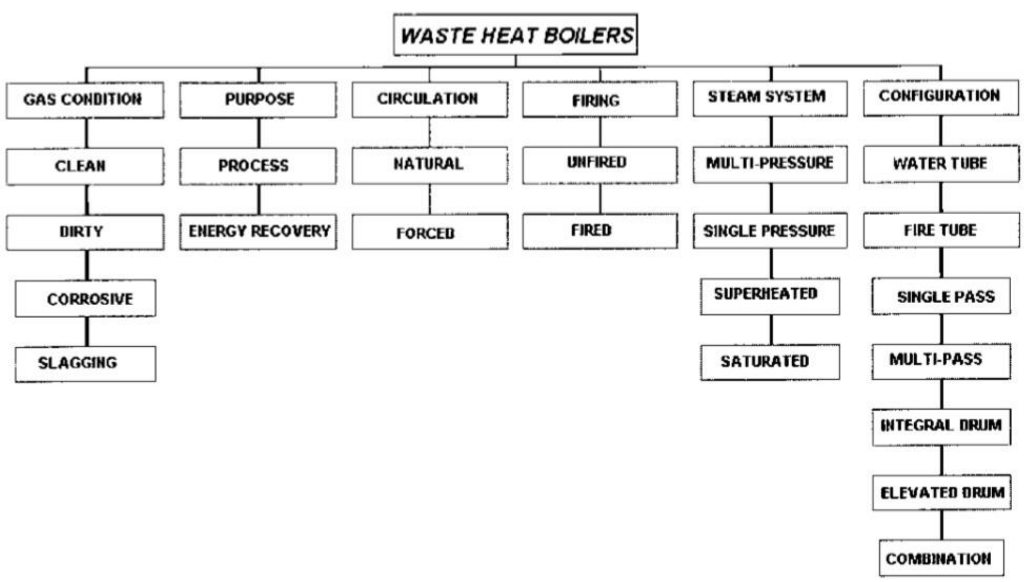

Figure 2.3: Boiler Classifications (V. Ganapathy, 2003)

Another standard way of categorizing a boiler is by identifying the whether the flue gas flows either inside or outside the tubes. By knowing this, we can classify the boiler to be as either fire tube boiler or water tube boiler. By referring to the table below, we can determine which boiler is more suitable for its desired application.

Table 2.4: Fire Tube vs Water Tube Boilers (V. Ganapathy, 2003)

Variable	Fire tube boiler	Water tube boiler
Gas flow	Small—less than 50,000 lb/h	50,000 to millions of lb/h
Gas inlet temperature	Low to adiabatic combustion	Low to adiabatic combustion
Gas pressure	High—even as high as 2000 psig	Generally less than 2 psig
Firing	Possible	Possible
Type of heating surface	Bare tube	Bare and finned tubes
Superheater location	At inlet or exit of boiler	Anywhere in the gas path using screen section
Water inventory	High	Low
Heat flux-steam side	Generally low	Can be high with finned tubes
Multiple steam pressure	No	Yes
Soot blower location	Inlet or exit of boiler	Anywhere inside boiler surfaces
Multiple modules	No	Yes

2.3.1 Water Tube Boiler

For this project, we will be focusing on water tube boiler in a HRSG as shown in Figure 2.6. As mentioned before, a boiler can be classified whether its gases are flown either inside or outside the tube. A water tube boiler is a boiler in which hot gases flows outside and surrounds the tube and water is heated inside the tube. A fire tube boiler on the other hand, basically is the opposite of the water tube boiler, where hot gases flows inside the tube and is surrounded by water on the outside. Water tube boiler has a few advantage, one is such that, it can achieve a bigger heating surface by just adding more number of tubes into it. Furthermore, compared to a fire tube boiler, the flow of water inside the tube is much faster due to having convectional flow which results in higher efficiency as the rate of heat transfer is high.

2.3.2 Working Principle of Water Tube Boiler

A water tube boiler has a very simple working principle. According to M.M. Rahman et al (2008), a water tube boiler has two drums known as, steam drum and mud drum which are interconnected via down-comer tubes and riser tubes. Water in the lower drum and in the riser connected to it, is heated and steam is produced in them which comes to the upper drums naturally. Steam is produced by means of heating the water inside the mud drum and riser tube. Steam produced will naturally flow upwards into the steam drum. Inside the steam drum, steam is separated naturally from the water inside the steam drum, which is fed via feed water inlet valve. The steam is stored above the water surface. Colder water which as mentioned before, is fed via feed water inlet valve into the steam drum, pushes the lighter hot water inside the mud drum upwards through the riser tube, thus creating a one convectional flow of water in the system. When the steam generated is too abundant, it will disrupt the convectional flow of the system and thus affecting the rate of production of steam, this can be solved by releasing some of the steam through the steam outlet. This process and water tube boiler design is illustrated in Figure 2.4 and Figure 2.5 respectively:-

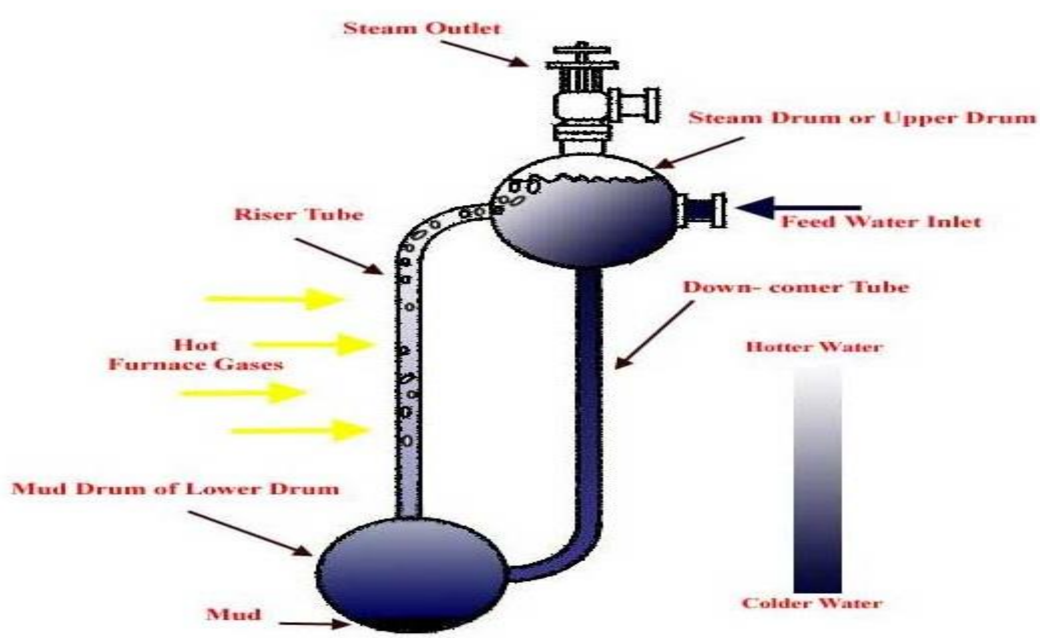

Figure 2.4: Water Tube Boiler Conceptual Diagram (source: www.electrical4u.com)

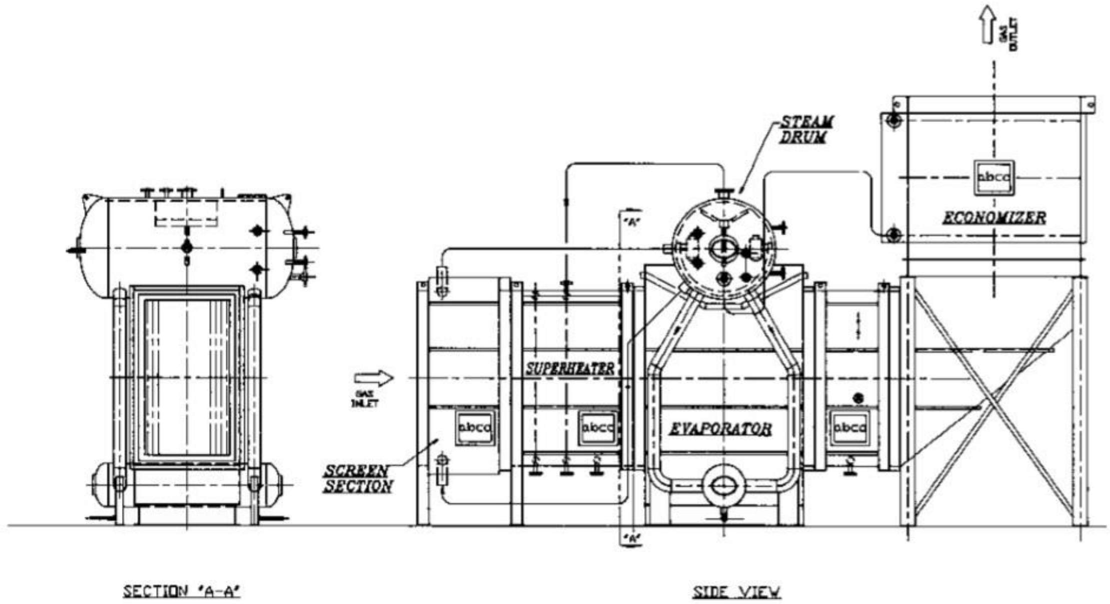

Figure 2.5: Front View and Side View of a Water Tube Boiler Equipped With Economizer and Superheater (V. Ganapathy, 2003)

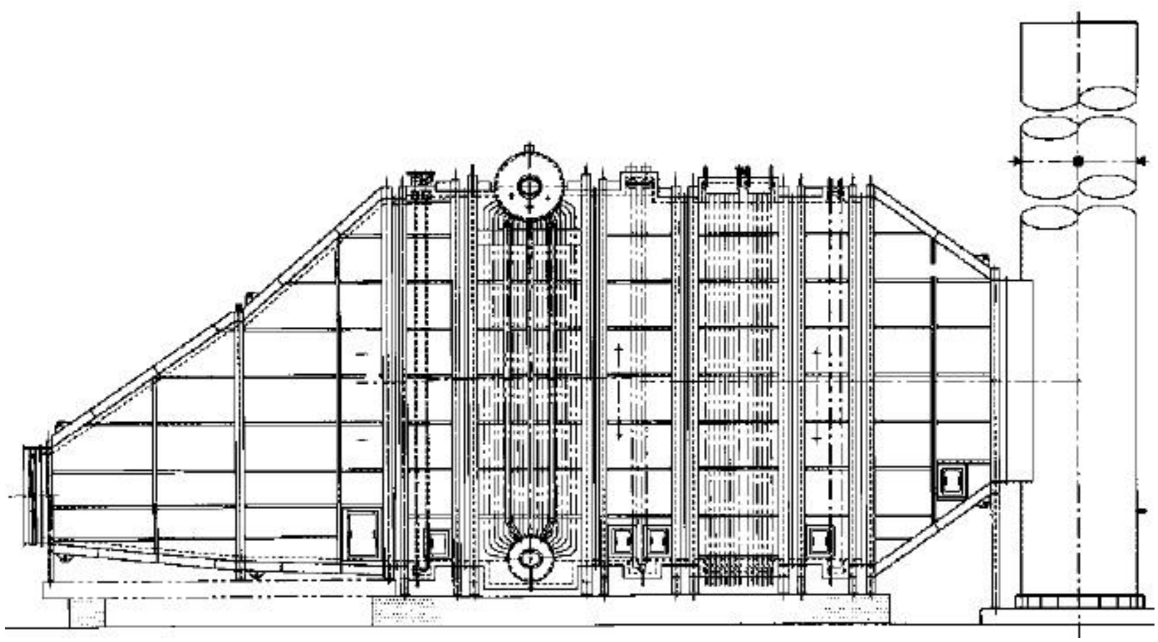

Figure 2.6: Unfired HRSG (V. Ganapathy, 2003)

2.3.4 Heat Recovery Steam Generators

Gas processing and chemical plant have extensively utilized Heat Recovery Steam Generator (HRSG) for power generation or other applications. HRSG basically is a large heat exchanger where it converts water to steam through the use of exhaust gas from an external heat source. According to V.Ganapathy (2003), HRSG can function in different mode depending on the need. These modes are known as cogeneration and combined-cycle mode as shown in Figure 2.7 and 2.8. He also goes on further to say that steam produced in combined-cycle is used to drive a steam turbine generator to produce electricity while cogeneration mode are mainly used for application purposes, such as chemical processing and Gas District Cooling (GDC), as what is utilized by UTP.

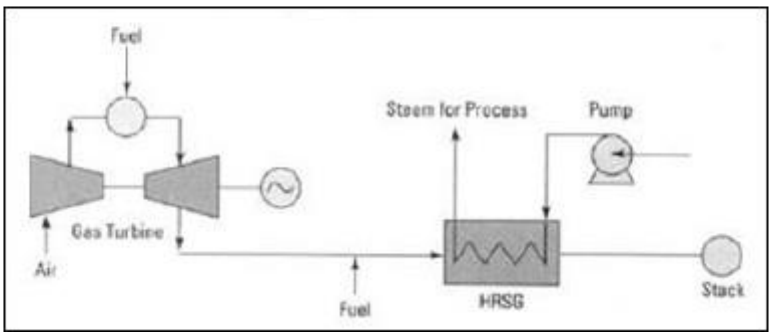

Figure 2.7: Cogeneration HRSG (V. Ganapathy, 2003)

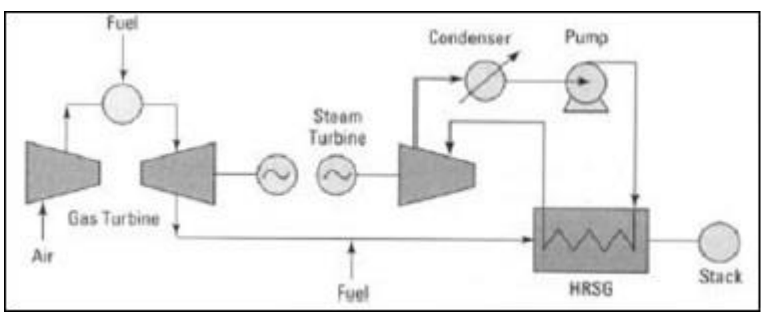

Figure 2.8: Combined-Cycle HRSG (V. Ganapathy, 2003)

As seen in Figure 2.9, three main components make up a HRSG. They are superheater, evaporator and economizer. These components act as the heat exchanger by means of tube bundles. The process flow starts with the feedwater entering the economizer tubes to be pre-heated until it reaches close to a saturation temperature.

The now saturated liquid then flows into the evaporator where steam generation occurs. The evaporator section is basically a water tube boiler as mentioned in section 2.3.2 which consists of a steam drum, mud drum, riser and down comer tubes. Also mentioned before in section 2.3.2 is the working principle of a water tube boiler, the evaporating process happens in the risers. Theses mixture of saturated steam and water are then separated in a drum. The saturated steam is then heated again in the superheater section, where it being the section closest to the flue gas inlet, to produce superheated steam for other purposes. In this project, as mentioned, the HRSG is of the unfired type. Specifications of fired and unfired HRSG are as shown in Table 2.5 below.

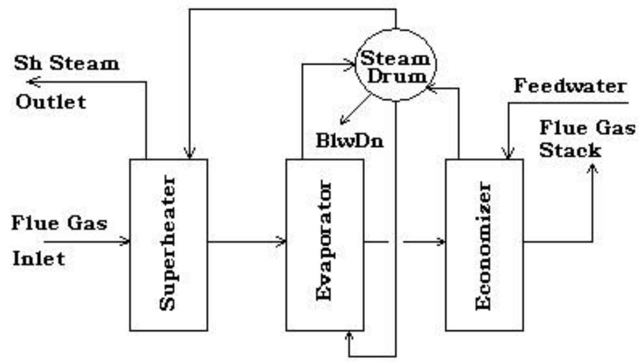

Figure 2.9 : HRSG Main Components

Table 2.5: Features of Unfired and Fired HRSG (V. Ganapathy, 2003)

	Unfired	Supplementary-fired	Furnace-fired
Gas inlet temp to HRSG, °F	800–1000	1000–1700	1700–3200
Gas/steam ratio	5.5–7.0	2.5–5.5	1.2–2.5
Burner type	No burner	Duct burner	Duct or register
Fuel	None	Oil or gas	Oil, gas, solid
Casing	Internally insulated, 4 in. ceramic fiber	Insulated or membrane wall	Membrane wall, external insulation
Circulation	Natural, forced, once-through	Natural, forced, once-through	Natural
Backpressure, in. WC	6–10	8–14	10–20
Configuration	Single- or multiple-pressure steam	Single- or multiple-pressure steam	Single-pressure
Other	Convective design, finned tubes	Convective design, finned tubes	Radiant furnace, generally bare tubes

2.3.3 HRSG in UTP's Gas District Cooling (GDC) Plant

Serving as the datum of this project, the HRSG in UTP's GDC plant is the focus of this research. According to M.A.A Majid et al. (2006), the plant utilizes the combination of cogeneration and GDC plant and is equipped with two steam turbines capable of generating 4.2 MW of electricity. He went on further to add that this plant has two 1,250 tons of refrigeration (RT) absorption chillers, boilers and HRSGs, a 10,000 tons of thermal storage tank and four 325 RT electric chillers (ECs). The plant is meant to operate for 24 hours. A schematic diagram of the plant can be seen in Figure 2.10 below.

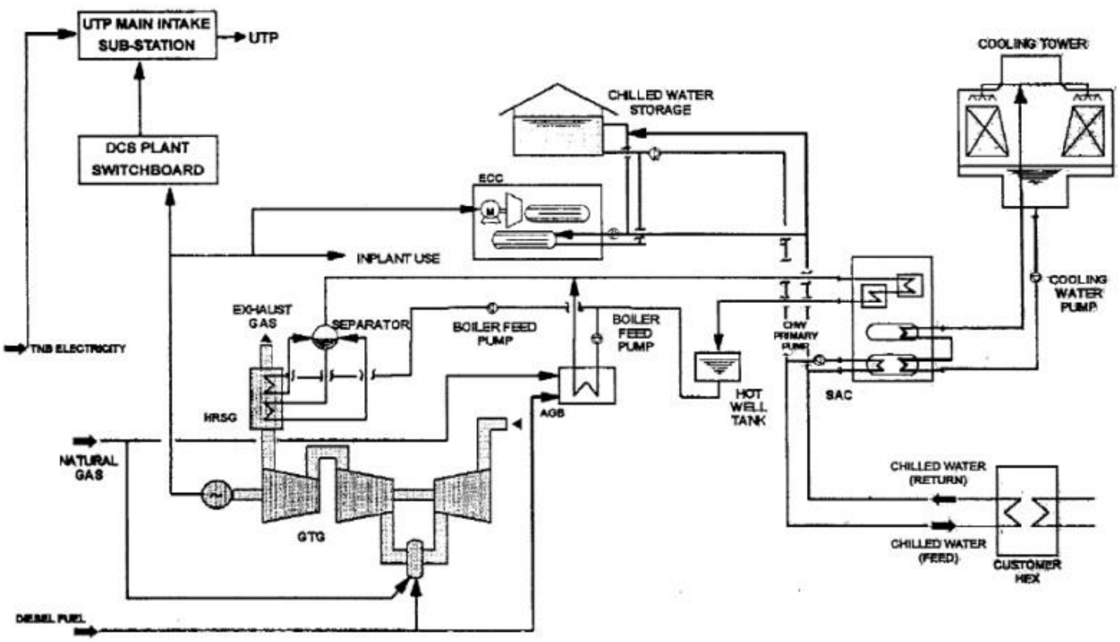

Figure 2.10: Process flow of UTP's GDC Plant (M.A.A Majid, 2006)

2.3.4 HRSG Failures

Heat recovery steam generators often operate at high pressure and temperature condition, thus it is crucial to know potential failures that can occur as failures in a steam generator often lead to catastrophic consequences, even fatalities. In this section we will identify some of the failures that exist in HRSG that has been identified in recent studies and investigations.

Flow Accelerated Corrosion (FAC) is one of the main causes of failures in steam generators. Occurs on the waterside of the tube, FAC takes away the protective oxide layer of the tube and cause the layer to be thinned. This will lead to rupture and burst and could injure workers and cause casualties.

In a study conducted by F.C Anderson et. al (2003), it was stated that FAC normally happens in low pressure (LP) regions of the HRSG such as LP evaporator tubes and economizer tubes mainly due to the fact that in this area, most of the equipment is made up of carbon steels, which are known to be vulnerable to FAC attacks, such as SA178 welded tubes and SA192 seamless tube in accordance to the rule provided by ASME Code.

Water treatment chemicals such as ammonia and hydrazine that are used to control the oxygen and pH level of the boiler feed water might have not been added enough into the boiler feed water and thus leading to FAC. There are several other factors which influence FAC and according to F.C. Anderson et al. (2003), these factors can either be from the concentration of trace elements in the tubes and the role of pH level in the circulating water.

In the LP region of the HRSG, the equipments are mostly made up of carbon steel materials and these carbon steels contain minute amount of trace elements such as chromium. The rate of FAC is affected by the amount of chromium present in the carbon steel tubes which amounts normally from 0.15% to 0.25%. As according to F.C Anderson et al. (2003), the higher the concentration of chromium in the carbon steel tubes, the lower the rate of FAC attacks. As shown in Figure 2.11.

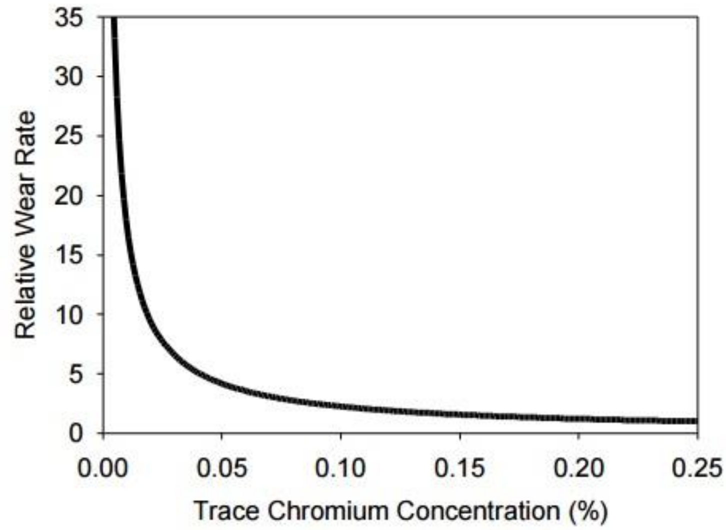

Figure 2.11: FAC-Chromium Concentration Relationship (F.C Anderson, 2003)

Even though the ASME code states that the tubes are to be made up of carbon steel tubes, F.C Anderson et. al. (2003) states that it did not provide the information regarding the concentrations of chromium in the carbon steels, thus the magnitude of FAC attacks are unknown and vary across the entire HRSG.

The boiler feed water pH level also plays an important role in contributing to the rate of FAC attacks. In LP evaporators, there are significant amount of ammonia concentration that may affect FAC as stated by F.C Anderson et al. (2003). He also went on further to state that the lower the pH level of the boiler feed water the higher the rate of FAC as represented by the graph in Figure 2.12. Boiler feed waters are meant to be in a basic state, having a pH level normally between 8.7 to 9.4. If there happens to be a drop of pH level in the boiler feed water, it could contribute to an increasing rate of FAC.

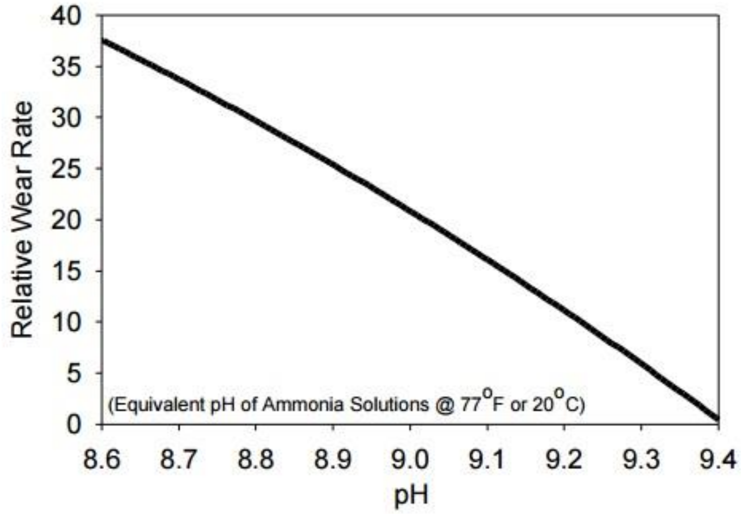

Figure 2.12: Relationship of FAC attacks and pH level (F.C Anderson, 2003)

F.C. Anderson et al. (2003) also conducted an investigation on an HRSG with failed evaporator tubes which have operated for the past 6 years (52,560 hours). It was discovered that the failed tube, after thorough examination, had suffered FAC attack. The main reason to the tube's failure was due to the low concentration of the trace element, chromium. It only contains 0.01% of chromium. It was proven that a higher concentration of chromium would not had to deal with FAC problems as another neighboring tube was also removed for examination and was discovered that it had 0.10% chromium and suffered no FAC attacks. An image of the failed tube can be observed in Figure 2.13 below.

Figure 2.13: Leaking Evaporator Tubes (F.C Anderson, 2003)

To detect a tube suffering from FAC is a little difficult, especially with finned tubes as according to F.C. Anderson et al. (2003) conventional methods in detecting FAC such as the usage of eddy current and ultrasonic testing would provide little result as the fins would disrupt the signals significantly. Other methods that could prove a little useful is the laser profilometry, which measures the inner diameter of the tube of interest with rotating laser probe.

Another case can be observed in an investigation carried out by R.M. Sharip et al. (2007) at an unfired HRSGs in Lumut Power Plant. Six HRSG's have also been operating for the past 6 years (52,560 hours) and 4 out of 6 HRSGs have shown signs of FAC in several locations. According to a study by conducted by N.K. Mukhopadhyay et al. (1999) on life estimation of an economizer tubes, it was found out that economizer tubes are capable to last as long as 100,000 hours.

According to R.M. Sharip et al (2007), several factors may contribute for FAC, such as boiler feedwater pH, temperature, turbulence and concentration of oxygen. An example of a FAC attack is as shown in Figure 2.14 below.

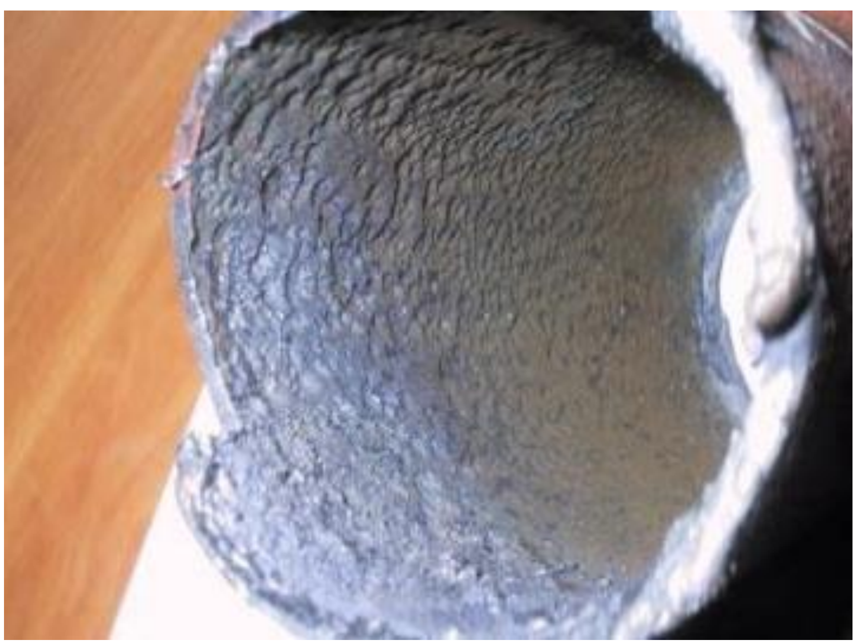

Figure 2.14: FAC attack on tube wall (R.M Sharip,2007)

He also states that combined with a specific temperature window and an unsuitable water chemistry may lead to FAC (R.M. Sharip, 2007). R.M Sharip (2007) added on that FAC generally occurs at operating temperature range of 80-230 ^{o}C. Table 2.6 below shows recorded failures in the economizer section.

Table 2.6: Tube Failures in Lumut Power Plant (R.M Sharip,2007)

Unit	Date of Repair	No. of Days	Location	No. of Tubes Replaced	Original Tube Material & WT (mm)	New Tube Material & WT (mm)
HRSG 11	22nd Feb – 2nd March	9	HP Econ 4	4	SA178 C / 2.8	SA213 T22 / 3.5
HRSG 13	7th June – 15th June	9	HP Econ 2	8	SA178 C / 2.8	SA213 T22 / 3.5
HRSG 12	28th June – 15th July	18	HP Econ 1C & 2	32	SA178 C / 2.8	SA213 T22 / 3.5
HRSG 23*	May (Scheduled Outage)	~ 3	HP Econ 5	1	SA178 C / 2.8	SA213 T22 / 3.5
HRSG 23**	26th July – 31st July	6	HP Econ 1C	1	SA178 C / 2.8	SA213 T22 / 3.5
HRSG 21	19th Sept – 4th Oct	16	HP Econ 1C & 2	11	SA178 C / 2.8	SA213 T22 / 3.5
HRSG 13 (2nd failure)	25th Sept – 2nd Oct	8	HP Econ 2	7	SA178 C / 2.8	SA213 T22 / 3.5

FAC problems are frequently encountered where carbon or low alloy steel material is present as shown in Figure 2.15. As according to Jonas O. (2004), these areas include economizers, evaporators, feedwater pipes in drums. Other areas include as highlighted in figure below

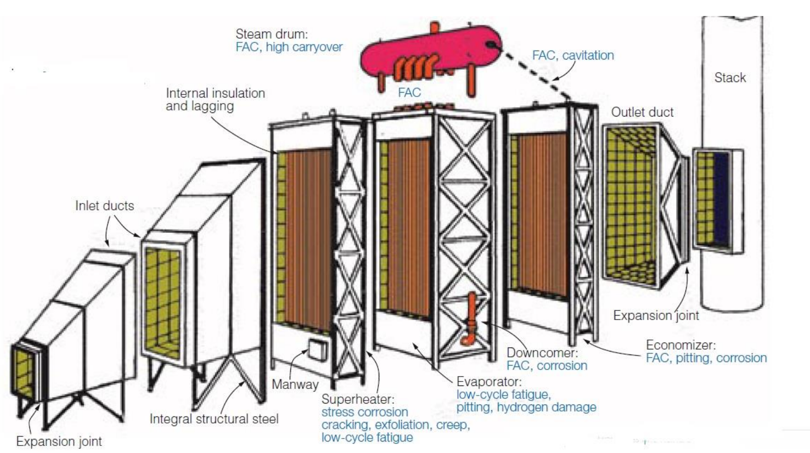

Figure 2.15: Other Failure Areas Including FAC (Jonas O., 2004)

Another prominent type of failure that has occurred in HRSGs that have been identified over the past years is corrosion fatigue. Corrosion fatigue by definition according to K.B. Mcintyre (2002) is a combination of fluctuating stress and the presence of a corrosive environment will lead up to cracking. Furthermore, he states that in water tube boilers, this failure tend to occur at the higher pressure region of the boiler, such as the steam drum. As shown in Figure 2.16 below, a steam drum suffered a corrosion fatigue attack as it was discovered during an inspection after 16 years in operation. If allowed to continue, this failure could lead to a boiler explosion. This steam drum underwent an engineering redesign to prevent such failure. Corrosion fatigue failure tends to happen when corrosion is allowed to happen and there is a lot of start and stop cycle.

Figure 2.16: Corrosion Fatigue on a Steam Drum, (K.B. Mcintyre, 2002)

F.C Anderson et al. (2003) states that corrosion fatigue tends to happen to locations associated trapping corrosive impurities which lead to high stress factors such as socket welded joints and partial penetration joints. He went on further to state that the one of the causes that contributed to the occurrence of this type of failure could be rooted from the inadequate quality control during fabrication. Another evidence of a corrosion fatigue failure that has occurred in HRSG can be seen in another study conducted by F.C. Anderson et al. (2003) where in his study shows that several tubes to header joints from the high pressure economizer sections had suffered a kind of failure after running for roughly 3 years (26,280 hours).

According to F.C Anderson et al. (2003), the joints are done in accordance to the ASME Code, where partial penetration weld was utilized and through visual inspection, cracks have been found to form in these areas that were highly associated with high stress. The remedial method to reduce corrosion fatigue attacks on these tubes as proposed by F.C. Anderson et al. (2003) is to modify the geometry design of the components or change the mode of operation as to reduce the cyclic stress on the component of interest.

Moving on to the next HRSG failure is the fire side corrosion or in the case of an unfired HRSG, it would be referring to the sides of the components that are exposed to the flue gas produced from the gas turbine. According to the Water Purification Handbook (n.a) by G.E., fire side corrosion is a process where a component is corroded by the impurities and contaminants present in the flue gas. These components are called fuel-ash and as according to the Water Purification Handbook (n.a), high ash oils are oils used to produce flue gas which deposit high amount of ash, which is any oil exceeding 0.05% ash while low ash oils contain less than 0.02%. This is better understood by viewing the Table 2.7 below.

Table 2.7: Analysis of Residual Oils (Water Purification Handbook, n.a)

	High Ash	Medium Ash	Low Ash
Specific Gravity, at 60 °F	0.9548	0.9944	0.9285
Viscosity SSF at 122 °F, sec	240	200	100.5
Calorific Value, Btu/gal	147,690	152,220	147,894
Bottom Sediment & Water, %	0.1	0.4	0.1
Sulfur, %	1.93	2.26	0.62
Ash, %	0.06	0.04	0.02
Vanadium, ppm	363	70	6
Sodium, ppm	16	50	9
Nickel, ppm	48	19	14
Aluminum, ppm	9	1	10
Iron, ppm	12	3	1

One such case of fire side corrosion can be seen in a study conducted by A.U. Malik et al. (2013) on a cogeneration plant in Saline Water Conversion Corporation (SWCC), where failed economizer tubes caused a boiler to be tripped. The tubes had experienced a fish-mouthed rupture as wide as 0.28 cm as shown in Figure 2.18 after precisely 4 years of operation. By chemical analysis through EDX profiling on the tube, as shown in Figure 2.19, it was found out that the fireside of the tube had high content of Magnesium, Sulfur and Magnesium. These findings show that the flue gas had high ash content and the plant was using high ash oils.

Figure 2.17: A ruptured Economizer Tube due to Fireside Corrosion (A.U. Malik, 2013)

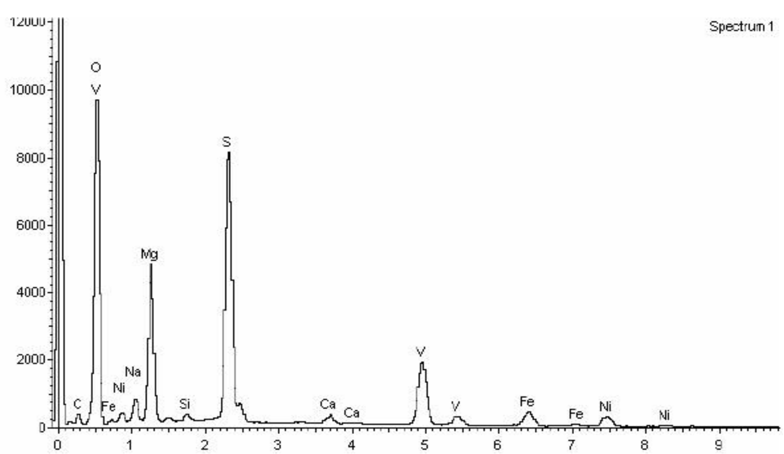

Figure 2.18: High Content of Vanadium, Sulfur and Magnesium on tube surface (A.U. Malik, 2013)

A.U. Malik et al. (2013) concluded that the tubes had experienced ruptured due to its inability to withstand the pressure inside the tube. The reason being is that the tube had suffered severe corrosion on the external surface due to the condensation of sulfuric acid at dew point and thus contributed to the metal thinning of the tube which ultimately resulted in the rupturing of the tube.

Another case study involving fire side corrosion can be observed from a study conducted by S. Srikanth et al. (2003). In this study, a waste heat boiler in a power plant had been operating for 50,000 hours before several tubes including an evaporator tube suffered some failures. It was later identified that the tube suffered fire side corrosion as from visual inspection, it can be seen that the external surface of the tube had some form of sticky yellow deposit. Through chemical analysis, S. Srikanth et al. (2013) found that the yellow deposit was due to the reaction between the impurities present in the flue gas, dominantly sulfur, with the metal surface of the tube.

A.U. Malik et al. (2013) proposed a solution to counteract the problem of fireside corrosion by installing a high powered soot blowing system which could minimize the chances of acid dew-point corrosion taking place. He also went on further to add that by dwindling the amount of sulfur content would highly reduce the chances of a fire side corrosion by opting for low ash oils.

Temperature plays an important role in preventing tube failure. Tubes might encounter failure such as dew-point corrosion if poor temperature management was taking place. Dew-point corrosion as according to A.U. Malik et al. (2013) is the product of a lowered flue gas temperature below the dew-point of acid condensation. In his study, A.U. Malik et al. (2013) have identified several economizer tubes that were reported of exhibiting leakages in SWCC also after 4 years. Upon visual inspection, it was discovered that the tube had formation of small holes around the weld area as seen in Figure 2.20. Through chemical analysis by using EDX profiling on the tube as shown in Figure 2.21, it was found out that the high Sulfur content. A.U. Malik et al. (2013) stated that, the condensation of Sulfuric acid is in the temperature range of 120 to 150 ^{o}C.

Figure 2.19: Formation of Hole Around Weld Area (A.U. Malik, 2013)

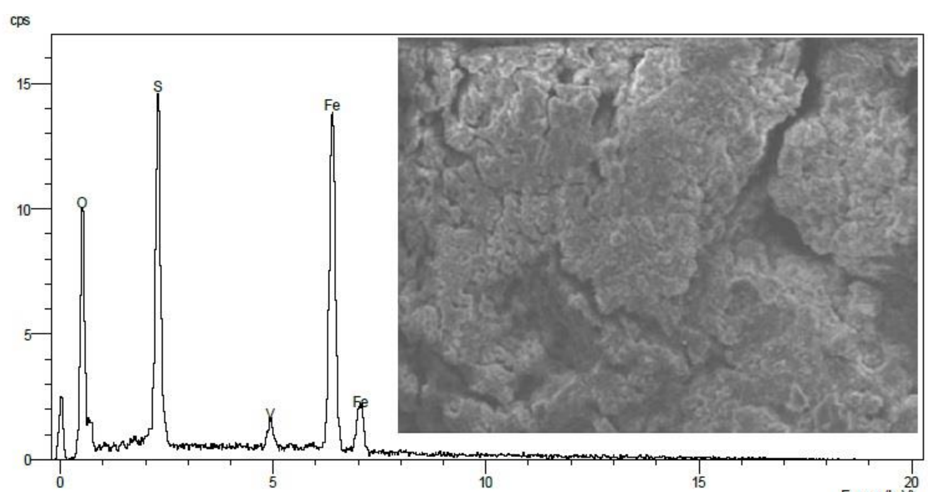

Figure 2.20: EDX Profiling on the Economizer Tube (A.U. Malik, 2013)

The remedial method in fighting dew point corrosion as proposed by A.U. Malik et al. (2013), is that by fixing the economizer's temperature well above the dew-point of acid condensation is highly recommended. A.U. Malik et al.(2013) also went on further to add that installing a proper temperature monitoring device to monitor the temperature of the economizer tube would prove useful as well.

Furthermore in another case of boiler failure can be seen in a research conducted by A.M. Heyes (1999) on a bagasse boiler with a design temperature and pressure of 293ºC and 35 bar respectively. This boiler is capable of generating 40,800kg of steam per hour. The boiler had recently been replaced with new tubes but had failed after four years since the replacement. The boiler, upon visual inspection had suffered leakages from its roof water tubes. An illustration is provided below:-

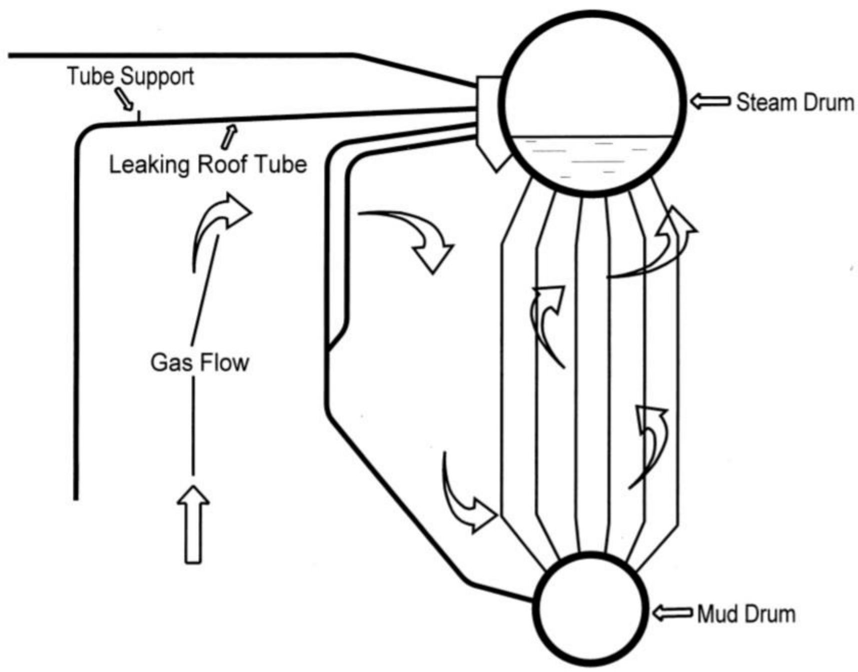

Figure 2.21: Roof Tube Leakage of a Bagasse Boiler (A.M. Heyes 1999)

According to A.M. Heyes (1999), upon receiving three samples of the tube, investigation was conducted and upon visual inspection, it was found out that the tubes had suffered cracking and pitting on the lower side of the tube. Oxygen pitting is one of the most common problems faced by boilers. Oxygen elements are highly corrosive and attacks are electrochemical process in nature, when they are found inside high temperature waters as even small amount of it could cause some serious damage to any part of the boiler, which in this situation, is the roof tubes. An overall reaction is represented by the following:-

$$Fe+\frac{1}{2}O_2+H_2O \rightarrow Fe(OH)_2$$

With the aid of high temperature water circulating throughout the boiler tubes, this not only supplies sufficient, but abundant energy to help accelerate the pitting formations. Pitting formations could also lead to crack as it affects the structural integrity of the material. Figure 12 shown below shows one of the tube samples gathered and as can be seen, pitting and cracking are clearly visible. By using an electron microscopy with magnifications x65, this can be seen in a much more detailed picture, as shown in Figure 2.23 and 2.24.

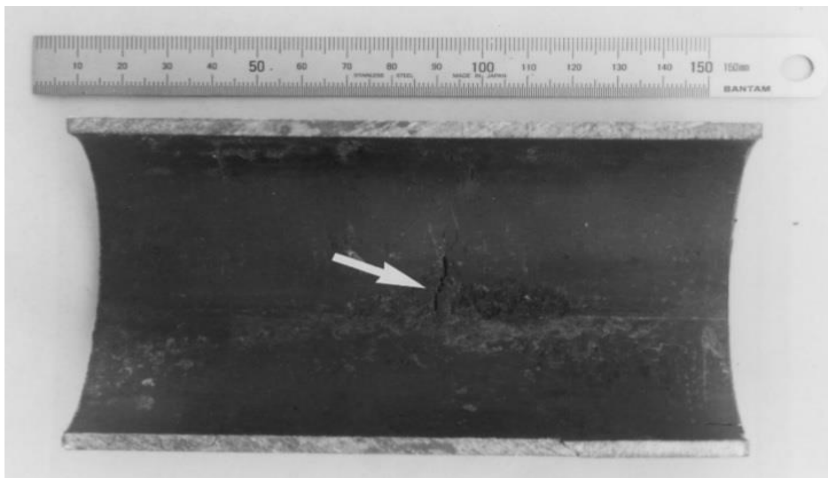

Figure 2.22: Pitting and Cracking on the Internal Surface of the Tube (A.M. Heyes, 1999)

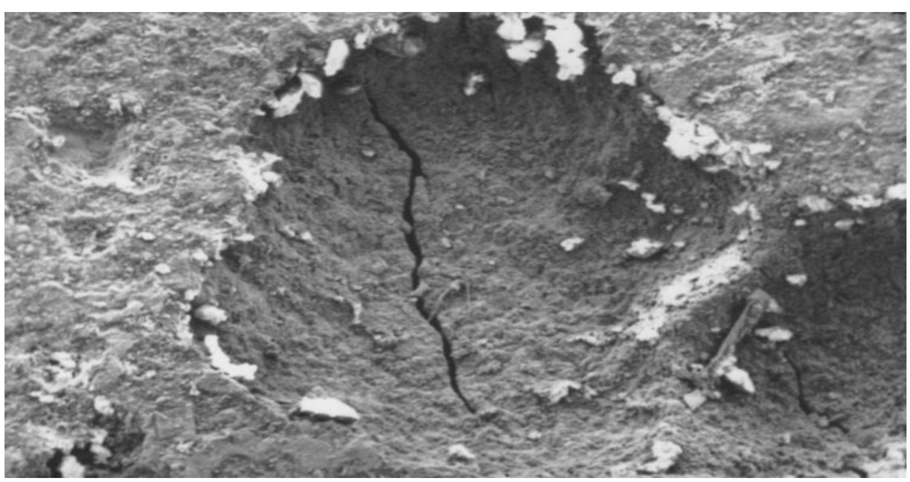

Figure 2.23: Magnification x65 View of Crack and Pitting Surface (A.M. Heyes,1999)

A.M Heyes (1999) has identified that the main cause that contributed to oxygen pitting on these tubes are due to lack of maintenance that was supposed to be carried out during the wet storage period. A.M Heyes (1999) has also proposed that in order to avoid such failures to occur again, to prevent air or other gaseous such as nitrogen, the boiler should be filled completely with water and the pH level should be maintained around 11 pH. In addition to that, A.M Heyes (1999) also goes on further to add sulfite, the more sulfite needed to be add if longer storage of the boiler is needed. The amount is set to 100 ppm at least. In regards to the crack that has occurred, A.M Heyes (1999) states that this is probably due to the tube experiencing harmonic oscillations.

Next, the failure that shall be discussed is hydrogen attack. According to M. Djukic et al. (2005), hydrogen attack is a problem faced by engineers frequently. By definition as stated by M. Djukic et al. (2005), hydrogen attack is basically when methane gas is formed along ferrite grain boundaries due to the presence of high pressure and temperature in its surrounding which forces the carbon element present in steel to react with hydrogen atoms. The attack decarburizes the tube and thus lead weakened the tube’s structure. In an investigation conducted on a thermal fossil fuel power plant boiler, several evaporator tubes have been found to be in an extensive damage after a boiler trip. The tubes suffered failure in the form of a window fracture as seen in figure below after 73,000 hours of operation. The tubes had to be replaced.

Figure 2.24: Evaporator Tube Window Fracture (M.Djukic, 2005)

Boiler feed pump plays an important role in providing feed water to the rest of the HRSG component and to maintain the circulation within the HRSG. Should a pump fail, the whole HRSG unit would have to stop. Therefore, a pump failure is important to investigate.

One persisting type of failure that affects a boiler feed water pump is cavitation. Cavitation usually occurs around the impeller of the pump where the pressure is low. Bubbles are formed in this region and will eventually collapse and implode inside the pump and cause excessive vibration that could cause various wear to the pump's component, such as bearing, mechanical seal, and impeller failure.

An example of cavitation in pump can be seen in a case study by Flowserve (2010) where a boiler feed water pump for a coal fired power plant had suffered severe cavitation. The pump had operated for every 3000 hours and for the first 15,000 hours, after being reported of producing loud noise and excessive vibration the pump had exhibit signs of cavitation as pointed out by the red arrows in Figure 2.26.

Figure 2.25: Cavitation Signs on Pump's Diffuser (Flowserve, 2010)

Flow instability was discovered to be the main contributor the pump's failure. This is because the pump had operated below the pump's best efficiency point (BEP). According to Flowserve (2010), the solution to overcome this problem was to adjust the parameters of operation so that the pump could operate at BEP.

CHAPTER 3

METHODOLOGY

3.1 Overview

In order to systematically analyze each failure for every component and identify their effects on systems operation, FMEA is used to analyze and characterize these failure modes. This section will be discussing on the procedures of carrying out FMEA analysis. The flow of the research work can also be illustrated as shown in the flowchart below:-

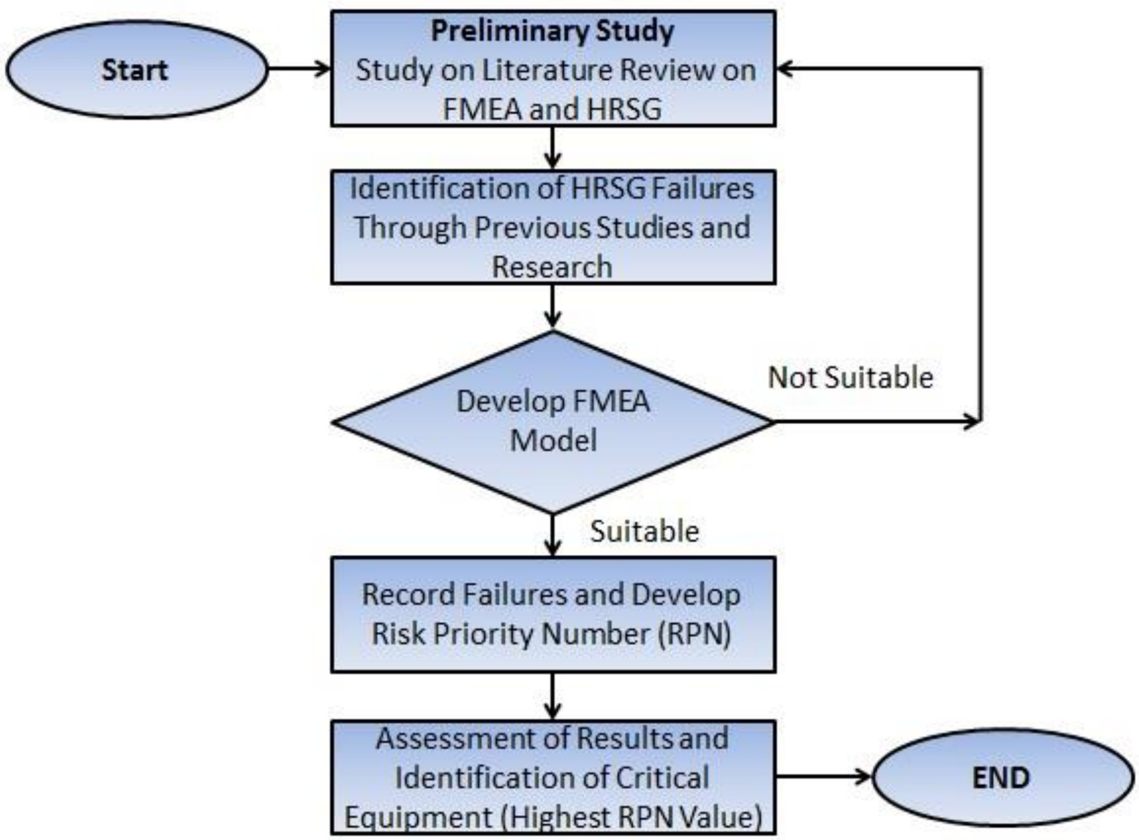

Figure 3.1: Flowchart of Study

Results obtained from FMEA study conducted on HRSG were based on previous studies, researches and investigation from the literature and was used as a guide to identify the common failures that occur in a water tube boiler and to provide a comprehensive view on the failures and failure areas.

Risk Priority Number (RPN) was developed after equipment failures were identified. Each failure was provided with remedial methods to overcome those failures.

Steps conducted for FMEA in this study are as shown below:-

1. Identifying Physical Indenture Levels

   Equipment hierarchy was identified.

2. Identifying Function

   Function of equipment/sub-assemblies of interest was identified.

3. Identifying Failure Modes

   All possible failure modes for each functional failure and for each component was listed and identified.

4. Identifying Failure Effects

   For this step, effect on each failure was identified if no action is taken to predict, prevent or detect the failure.

5. Identifying Failure Consequences

   Assessment for failure consequences was carried out in this step. Assessment was based on the most possible worst-case scenario. More than one consequence was identified.

6. Risk Priority Number (RPN) Ranking

   Every expected equipment failure was rated based on the Severity(S), Occurrence (O) and Detection (D) rankings. Failure with highest RPN value was identified to be the critical equipment.

7. Recommended Action

   Suggested failure management task was proposed in this step. For every equipment or component failure, recommended task was planned in order to contain and prevent each of this failure from repeating again in the future.

3.2 Mathematical Model

The formula developed for Risk Priority Number (RPN) is as shown in Equation (1) below. The ratings for Occurrence, Detection and Severity are as stated in section 2.2.3 in Tables 1, 2 and 3 respectively. The method for determining the appropriate ranking for Detection (D) and Severity (S) were based on the findings of previous studies in the literature review .The calculation involved in obtaining the appropriate ranking for the probability of occurrence as prepared in Table 2.1 is as shown below with the operating hours to failure of the equipment divided by the life expectancy of the equipment in Equation (2). The conversion of years to hours for operating time to failure is as shown in Equation (3).

$$\text{RPN} = \text{Occurrence (O)} \times \text{Detection (D)} \times \text{Severity (S)} \tag{1}$$

$$\text{Probability of Occurrence (O)} = \frac{Operating\ Hours\ to\ Failure/Inspection}{Life\ Expectancy\ of\ Component} \tag{2}$$

$$\text{Operating Time (years)} \times \frac{365\ Day(s)}{1\ year} \times \frac{24\ Hours}{1\ Day(s)} = \text{Operating Time (hours)} \tag{3}$$

3.3 FMEA Model

The Failure Mode Effect Analysis model developed in this project was a model which consisted of sections which identify the Unit/Subunit, Failure Mode, Failure Effect, Failure Causes, Failure Consequences, Severity, Occurrence, Detection, RPN and Recommended Actions as shown below with a simple example of a bicycle's tire problem. The rankings for Severity (S), Occurrence (O) and Detection (D) were based on the ranking tables 2.1, 2.2 and 2.3 respectively.

Main Equipment: Bicycle

Function: As mode of transportation to move around from one area to another.

Unit/Sub Unit	Failure Mode	Failure Effects	Failure Causes	Failure Consequences	S	O	D	RPN	Recommended Action
Tire	Flat and out of air	Tire cannot rotate properly	Punctured by a nail	Unable to ride bicycle	2	2	3	12	Remove nail and cover the punctured hole and pump air into the tire
									Replace tire with a new one

Table 3.1: Proposed FMEA Model of Study

3.4 Key Milestone and Gantt Chart

The project covers two semesters. The key milestone of the project can be seen as in Table 3.2 for FYP 1 and Table 3.3 for FYP 2. Table 3.4 shows the Gantt chart for FYP 2.

Table 3.2: FYP I

Subject	Targeted Week	Status
Project Title Selection	1-2	Completed
Theoretical Research	2-6	Completed
Extended Proposal	6-8	Completed
Proposal Defense	8-10	Completed
Interim Report	14	Completed

Table 3.3: FYP 2

Subject	Targeted Week	Status
Project Work	1-5	Completed
Progress Report	6-7	Completed
Oral Presentation	14	Incoming
Final Submission	15	Incoming

Table 3.4: Gantt Chart

Week No. / Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Continuation of Study on FMEA															
Proposing FMEA Model															
Research on HRSG Failures from previous Researches and Studies															
Collecting and Tabulating Data and Preparation of Progress Report															
Submission of Progress Report															
Preparation for Presdex Poster Presentation															
Pre Sedex Poster Presentation															
Continuation of Study on HRSG Failures															
Preparation for Viva presentation															
Viva Presentation															
Preparation for Technical Paper and Hardbound Dissertation Submission															
Final Submission															

Process

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Failure Mode Effect Analysis

Step 1: Identification of Physical Indenture Level

The indenture levels of the heat recovery steam generator as per Figure 4.1.

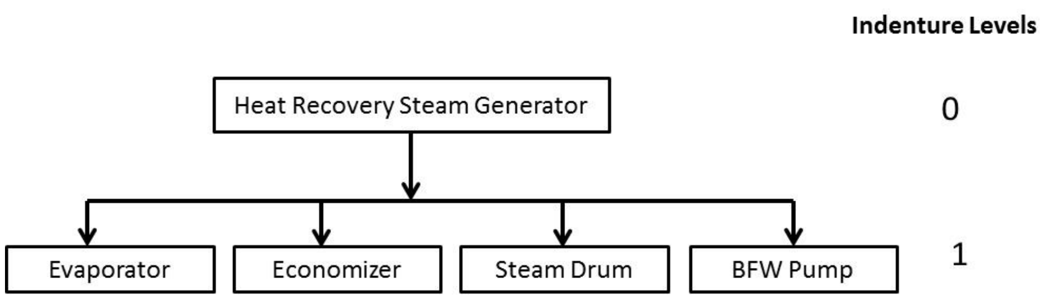

Figure 4.1: Physical Indenture Level of HRSG

Step 2: Identifying Function

The basic function of Heat Recovery Steam Generator is to utilize the waste heat of an exhaust gas of a turbine to heat up water in the tubes and pipes to be converted to steam for power generation and process purposes. The main components of HRSG in general are Superheater, Evaporator and Economizer. However the HRSG under this study has only the evaporator and economizer .The process flow of the HRSG is as shown in Figure 4.2. The operating condition of the HRSG is as shown in the table 4.1 based on operating manual of UTP Cogeneration GDC:

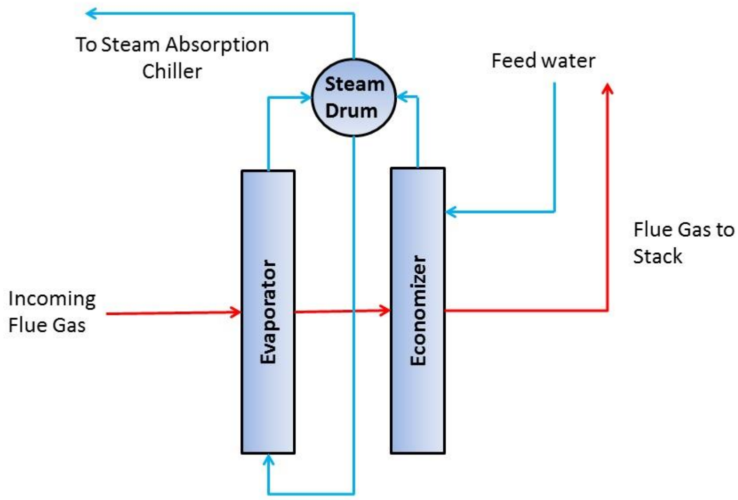

Figure 4.2: Process Flow of HRSG at UTP GDC

Table 4.1: Operating Parameters of UTP HRSG GDC

Constant Parameter	
Mass Flow rate of flue gas, $\dot{m}_g$ (kg/s)	20
Inlet Flue Gas Temperature, t_1 (°C)	500
Steam Pressure, P_s (bar)	9
Saturation Temperature, $t_{sat@P}$ (°C)	175.36
Approach Point, Δt_A (°C)	10
Feed water Temperature, t_d (°C)	90
Ambient Temperature, $t_{ambient}$ (°C)	34

Step 3: Identification of Failure Modes

From the literature, several potential failure modes have been identified as per Table 4.2.

Table 4.2: Failure Mode

Failure Modes	Leakage
	Cracks
	Deposition on tube surface
	Rupture
	Excessive vibration
	Loud Noise

Step 4: Identification of Failure Effects

Table 4.3 below shows failure effects identified in correspondence to their failure modes.

Table 4.3: Failure Effects

Failure Effects	Disruption of Circulation
	Steam Generation Disrupted
	Potential Tube Rupture
	Disruption of feed water supply to evaporators
	Tube Fracture
	Leakage of feed water
	Potential Boiler Roof Explosion
	Inefficient flow
	Potential to damage other pump's components

Step 5: Failure Causes

Shown in Table 4.4 are the failure causes identified.

Table 4.4: Failure Causes

Failure Causes	Flow Accelerated Corrosion
	Hydrogen Damage
	Fire side Corrosion
	Corrosion Fatigue
	Dew-Point Corrosion
	Cavitation

Step 6: Developing Risk Priority Number (RPN)

In this section, RPN numbers are developed by applying Equations (1), (2) and (3) from section 3.2 based on the combination of occurrence (O), detection (D) and severity (S) ranks in Tables 2.1, 2.2 and 2.3 respectively. This section will be calculating RPN for every failure recorded.

Evaporator:

i. Assumption that is involved in this section is that, according to literature review from Bryan Boilers (2008), a water tube boiler as a whole can have a service life of up to 40 years (350,400 hours). The life expectancy of 350,400 hours for the boiler was adopted for the evaporator tubes.

ii. Calculation for Flow Accelerated Corrosion (FAC):

Tube failed after 6 years (52,560 hours) of operation. FAC is hard to detect with conventional methods because of the finned tubes, even with the usage of laser profilometry proven to be difficult. Ranking for D = 8. FAC can have terrible consequences once the tube completely failed and can cause injury and even death. Ranking for S = 10. Ranking for O = 8 as justified by calculation below.

Probability of Occurrence (O): $\frac{52{,}560\ hours}{350{,}400\ hours} = 0.15 \approx 0.2$

RPN for FAC = 8 x 8 x 10 = 640

iii. Calculation for Oxygen Pitting:

Tube failed after 4 years (35,040 hours). The tube failure was detected through visual inspection therefore it has a very high change of detection. Ranking for D = 3. The failure of the tube could cause loss of steam production time but nothing severe. Ranking for S = 2. Ranking for O = 7 as justified by calculation below.

Probability of Occurrence (O): $\frac{35{,}040\ hours}{350{,}400\ hours} = 0.1$

RPN for Oxygen Pitting = 7 x 3 x 2 = 42

iv. Calculation for Hydrogen Damage:

Tube failed after 73,000 hours of operation. The tube suffers failure by window fracture was detected through visual inspection. Tube failure was almost certain to detect. Ranking for D = 1.The failure of the tube could have hazardous effect to staff such as injury and death. Ranking for S = 10. Ranking for O = 8 as justified below.

Probability of Occurrence (O): $\frac{73{,}000\ hours}{350{,}400\ hours} = 0.21$

RPN for Hydrogen Damage = 8 x 1 x 10 = 80

v. Calculation for Fire side Corrosion:

Tube failed after 50,000 hours of operation. The tube failure was detected through visual inspection as yellow sticky deposits started to form around the tube. The failure has a very high chance of detection. Ranking of D = 2. The tube failure could cause severe injury and even death. Ranking for S = 10. Ranking for O = 7 as justified below.

Probability of Occurrence (O): $\frac{50{,}000\ hours}{350{,}400\ hours} = 0.14$

RPN for Fire side Corrosion = 7 x 2 x 10 = 140

Economizer:

i. The life expectancy of economizer tube is adopted from a study done by N.K. Mukhopadhyay et al. (1999) where the life expectancy of the economizer tubes is 100,000 hours.

ii. Calculation for FAC

Tube failed after 6 years (52,560 hours) of operation. The tube failures were discovered through visual inspection when it was seen to have caused leakages. Ranking of D = 2. The tube failure could cause severe injury and even death. Ranking for S = 10. Ranking for O = 10 as shown in calculation below.

Probability of Occurrence (O): $\frac{52{,}560\ hours}{100{,}000\ hours} = 0.52$

RPN for FAC= 10 x 2 x 10 = 200

iii. Calculation for Dew-Point Corrosion

Tube fails after 4 years (35,040 hours). Small holes were discovered from the tube at weld area when the tube shows signs of leaking. Ranking of D = 2. The leakage of feed water affects the circulation of the boiler water and thus affects the steam generation rate and production time. Ranking for S = 6. Ranking for O = 9 as justified below.

Probability of Occurrence (O): $\frac{35{,}040\ hours}{100{,}000\ hours} = 0.35$

RPN for Dew Point Corrosion = 9 x 2 x 6 = 108

iv. Calculation for Corrosion Fatigue

Tube fails after 3 years (26,280 hours) of operation. The tube failure in the form of cracks at joint welds was discovered through visual inspection during. Ranking of D = 2. The tube failure could cause HRSG trip therefore, loss of production time and even injury. Ranking for S = 8. Ranking for O = 9 as justified below.

Probability of Occurrence (O): $\frac{26{,}280\ hours}{100{,}000\ hours} = 0.26 \approx 0.30$

RPN for Corrosion Fatigue = 9 x 2 x 8 = 144

v. Calculation for Fire Side Corrosion

Tubes fail after 4 years of operation (35,040 hours).The tube failure was discovered when the boiler tripped and tube exhibits a fish mouth rupture upon inspection. Ranking of D = 1The tube failure could cause HRSG trip therefore, loss of production time and even injury. Ranking for S = 8. Ranking for O = 9 as shown below.

Probability of Occurrence (O): $\frac{35{,}040\ hours}{100{,}000\ hours} = 0.35$

RPN for Fire Side Corrosion = 9 x 1 x 8 = 72

Steam Drum

i. Life expectancy for steam drum is adopted from Bryan Boilers (2008), the same as which was used for evaporator tubes which is 40 years (350,400 hours)

ii. Calculation for Corrosion Fatigue :

The steam drum was discovered to have propagating crack after 16 years (140,160 hours) of operation. The tube failure in the form of cracks at the drum was discovered through visual inspection during. Ranking of D = 3. The steam drum crack could lead to boiler roof explosion and cause severe damage and even death if left unchecked. Ranking for S = 10. Ranking for O = 9 as shown below.

Probability of Occurrence (O): $\frac{140{,}160\ hours}{350{,}400\ hours} = 0.4$

RPN for Corrosion Fatigue = 9 x 3 x 10 = 270

BFW Pump:

i. Due to being unable to find reliable information regarding the life expectancy of boiler feed pump due to its various operating parameters across different plants, for convenience sake, the pump's life expectancy is assumed to be 100,000 hours.

ii. Calculation for Cavitation :

The pump had failed after the first 15,000 hours of operation. The pump suffered cavitation failure after it was discovered to have been vibrating excessively and producing loud noises. Ranking of D = 1.The pump's failure stops the incoming flow of feed water to other boiler components and therefore boiler is tripped. When tripped, steam generation is halted and production time is loss. Ranking for S = 6.

Therefore, Probability of Occurrence (O): $\frac{15{,}000\ hours}{100{,}000\ hours} = 0.15 \approx 0.20$

RPN for Cavitation = 8 x 1 x 6 = 48

Step 7: Recommended Actions

In Table 4.5 recommended actions were identified in correspondence to the identified potential failures.

Table 4.5: Recommendations

Recommendations	Implement a pH monitoring device
	Tube Repair
	Add significant amount of oxygen scavengers
	Engineering redesign proper to operation
	Drum repair
	Wet storage only for one month in which after shall proceed to implement dry storage procedures
	Changing to low ash oils
	Maintain pH feed water at pH 9.0
	Installing a powerful soot blowing system
	Install temperature monitoring device
	Modify geometry design of tube joints
	Change Mode of operation
	Adjusting pump's parameters of operation so that it would function at BEP

All of this identified data are then tabulated in an FMEA table as seen in Table 4.6 to give a more comprehensive view. By viewing the data provided in Table 4.6, we can safely say that leakage failure associated with Flow Accelerated Corrosion (FAC) at the evaporator tubes have the highest RPN value of 640, thus making evaporator tubes the critical component of a HRSG unit

Main Equipment: Heat Recovery Steam Generator (HRSG)

Equipment Function: HRSG is a large heat exchanger which generates power through the conversion of water to steam

Table 4.6: FMEA on HRSG.

Unit/Sub Unit	Failure Mode	Failure Effects	Failure Causes	Failure Consequences	O	D	S	RPN	Recommended Action
Evaporator	Leakage	Disruption of circulation	Flow Accelerated Corrosion	Loss of generated power	8	8	10	640	Tube Repairs
		Steam generation disrupted		Loss of production time					Implement a pH monitoring control on the feed water.
		Potential tube rupture		Injury or Death					
		Potential Tube fracture	Oxygen Pitting	Loss of steam production time	7	3	2	42	Add significant amount of oxygen scavenger
		Disruption of circulation							Wet storage until one month, in which after should implement dry

									storage procedure
	Fracture	Potential tube rupture	Hydrogen Damage	Boiler Trip Loss of production time Injury or death	8	1	10	80	Tube replacement.
	Deposition on tube surface	Potential Tube Rupture	Fire side corrosion	HRSG trip Loss of power generation Injury or death	7	2	10	140	Changing to low ash oils Installing a powerful soot blowing system
Economizer	Leakage	Potential Tube Rupture Disruption of feed water supply to evaporators	Flow Accelerated Corrosion	Loss of production time Loss of power generation Injury or Death	10	2	10	200	Implement a pH level monitoring device. Tube repairs. Maintaining the feed water level by pH 9.0.
		Potential Tube rupture Disruption of	Dew-point corrosion	Loss of production time	9	2	6	108	Temperature of economizer are to be maintained above dew

		feed water supply to evaporators		Loss of power generation					point temperature Install a temperature monitoring device
	Cracking	Tube fracture. Disruption of feed water supply to evaporators.	Corrosion Fatigue	HRSG trip Steam generation reduced. Loss of power generation Injury	9	2	8	144	Modify geometry design of tube joints Change mode of operation
	Rupture	Leakage of feed water Disruption of feed water supply to evaporators	Fire-side corrosion	HRSG trip Steam generation reduced. Loss of power generation Injury	9	1	8	72	Installing a powerful soot blowing system Changing to low ash oil which has lower sulfur content.
Steam Drum	Cracks	Potential boiler roof explosion	Corrosion Fatigue	Loss of production time	9	3	10	270	Engineering redesign proper to operation. Drum repair.

BFW Pump	Excessive vibration	Inefficient flow	Cavitation	Boiler trip	8	1	6	48	Adjusting the pump's parameter of operation so that it would operate at BEP.
	Loud Noise	Potential to damage other pump's components							

4.2 Discussion

According to the calculations in section 4.1 and the FMEA table in table 4.6, analysis was conducted on several sub unit of the HRSG, namely the evaporator, economizer, steam drum and boiler feed water (BFW) pump. Each of the sub unit was discovered to have several failures associated with it. In this study, most of the failures identified are mostly corrosion related. Sub units that are heavily affected by corrosion related failures are found to be the economizer and the evaporator tubes.

According to table 4.6, BFW pump was identified of having suffered cavitation failure. The failure mode of this pump is having reported to have loud noise and exhibiting excessive vibration throughout the operation. When such event is taking place, the pump would not produce an efficient flow. A pump failure could lead to an entire HRSG to trip, as it is crucial in maintaining and feeding the feed water's circulation inside the HRSG to produce steam. The pump attains an RPN value of 48.

Another sub unit that was recorded in table 4.6 with having RPN of 270 is the steam drum. Steam drum acts as a buffer and separator unit for steam generation. Under extremely long operations, steam drum has been identified to suffer corrosion fatigue attack as cracks have been discovered on the surface of the drum. Due to its role of storing and separating steam inside, steam drum is subjected to high pressure, and failures such as cracks could lead to explosion and cause huge damage to the HRSG unit and even injure other people.

In this study, economizer tubes have been discovered to have suffered failures such as leakage, cracks and rupture all of which could lead to highly dangerous outcome. It was identified that economizer tubes mostly suffer from corrosion related failure causes. Such failures causes are flow accelerated corrosion (FAC), dew-point corrosion, fire side corrosion and corrosion fatigue. Economizer tubes are vital in an HRSG unit as it preheats the feed water and reduce the flue gas's temperature before exiting the stack so as not to endanger the environment.

FAC related failure have been identified of having an RPN of 200 due to difficulty in detecting the failure as the corrosion process takes place inside the tube and is almost impossible to detect visually before the leakage happens. Failures in the economizer tube could lead to the entire HRSG to trip and this would prove very costly.

Failure modes that have been identified for the evaporator tubes in this study are in the form of leakage, fracture and deposition on the surface. Failure causes associated with these failure modes are later identified as flow accelerated corrosion (FAC), oxygen pitting, hydrogen damage and fireside corrosion. All of which having direct impact on the structural integrity of the tube.

Evaporator tubes are usually covered with fins to increase the heat transfer area between the surface and the oncoming flue gas which it utilizes the heat for the conversion of feed water to steam. This however, provides difficulty to engineers and maintenance team to detect failures such as leakage on the tubes. Leakages are a matter to be highly concerned with when evaporator tubes are involved since it is operating at a high temperature and pressure.

The failure of the tubes could lead to not only loss in production time or power, but also undesirable consequences such as injury and death. Leakages associated with FAC are deemed to be the most highly hazardous due to the elusiveness as it was the economizer tube, only that now the tube of interest operates in a higher temperature and pressure compared to the economizer tube.

Evaporator tubes are made up of carbon steel materials and this steel are highly susceptible to corrosion. Thus having proper control of the feed water’s pH level is crucial. The corrosion process takes place on the waterside of the tube and the thinning of the metal layer inside the tube are usually hard to detect only after the leakage has happened. Due to the severity and the difficulty in detecting this type of failure, FAC related leakages have the highest RPN value, which is 640, compared to other failures and making evaporator tube the critical equipment.

CHAPTER 5

CONCLUSION & RECOMMENDATION

Failure Mode Effect Analysis (FMEA) provides a systematic model and framework to conduct an investigation regarding potential failures that may occur on any equipment, in this case a HRSG unit. The author has identified that by applying FMEA on HRSG unit, a comprehensive view of an entire system and sub system of interest can be achieved, and this can be of great value to maintenance team who aims to reduce and prevent future failures that might occur.

By understanding and knowing potential failures that might occur at various area of the HRSG, the team can plan appropriate scheduled maintenance program for the component of interest and prevent critical failures by focusing on the most critical equipment, which is the equipment with the highest RPN value. In this study, the critical equipment identified was the evaporator tube due to having highest RPN value of 640.

Even though utilizing FMEA has benefits, it could prove to be somewhat difficult to practice in real working environment because of the need to consume a lot of time to complete the investigation due to the meticulous nature of the analysis. Another flaw of this investigation of FMEA is that it does not take into account other errors such as human error into the analysis. This is somewhat important as plants are operated by men, and being men, they are prone to commit mistakes. The issue of human error needs to be addressed too in determining failures in plants and it is highly recommended somehow in the future that human error are included in an FMEA study.

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