

University of Southern Queensland
Faculty of Engineering & Surveying

Corrosion in the boiler tubes of the Tuas South
Incineration Plant, Singapore

A dissertation submitted by

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Abstract

Incineration of refuse has evolved into a widely used, established technology with reliable modern facilities operating on a fully commercial basis in some advanced countries including Singapore. However this method for processing refuse has produces pollutants such as Carbon Monoxide (CO), Hydrochloride (HCl) and Sulphur Dioxide (SO₂). Inside the incinerator, these gases could cause corrosion and tamper with the efficiency of the incinerator.

One such common occurrence of corrosion is the growth of slag, due to exposure to high HCl concentration. This could affect the thermal efficiency of the incinerator due to leakage of heat at elevated temperatures. It could also lead to corrosion-fatigue, which would affect the structural integrity of the superheater tube.

The aim of this report, therefore, is to study the causes of corrosion to the incinerator, in particular, the superheater tube, and to recommend measures that could minimize the occurrence of the corrosion with a view to prolong the lifespan of the tube.

The report begins with an introduction of the Tuas South Incineration Plant (TSIP), where the project was carried out, with an overview of the process flows in the plant undergone by the refuse, flue gas, wastewater and feedwater.

The report next looks at the typical components of refuse ending up in an incinerator, how these refuse components alter the characteristics of gases in flue gas, and how these gases could affect the performance and integrity of the boiler. The report will establish that the burning of plastics will release HCl which creates an environment that sets the stage for a continuous attack on the metal structure of the boiler. Another finding is that the presence of excess free oxygen in the furnace might affect the burning of refuse in the combustion process. This is attributed by the fact that free oxygen could react with the metal of the superheater tube to produce iron oxide (rust).

The report will also outline the analysis on the causes of corrosion on a critical part of the boiler component – the superheater. The analysis will establish that the corrosion caused by hydrogen chloride (HCl) found in flue gas is a general corrosion on the tubes.

Besides theoretical calculations, the report also reported on the experimental measurements and observations carried out, to complete the analytical component of the project. The experiment is performed by placing specimens (SA192-CARBON STEEL) in two different furnaces of an actual incinerator (TSIP) over a period of time to determine the extent of corrosion. The exact conditions experienced in a furnace are therefore replicated, to get as realistic a result as possible.

Another avenue addressed by the report is the feasibility of material replacement. Two candidates identified are nickel-chromium and nickel-chromium-molybdenum steel. Both are viable alternatives to achieve the same performance, and have several characteristics that are superior to carbon steel. After a careful consideration of the costs involved, including depreciation, the costs of installation, maintenance and operation, it was found that it may make more economics sense to use nickel-chromium steel. However, while apparent theoretically, in reality the commercial availability of nickel-chromium steel tubes needs to be ascertained. And more importantly, while it may have a long lifespan in theory, in practice it could be retired well before it has reached its life because of the service considerations of the particular boiler.

The report ends with several recommendations on measures that could minimize the occurrence of the corrosion with a view to prolonging the lifespan of the superheater, taking into consideration that there has yet to be a feasible solution that could completely eliminate the problem. Recommended measures include reviewing existing operational practices (such as proper mixture of refuse), installing additional equipment (to prevent the gases from coming into contact with the tubes; to ensure that the gases are thoroughly mixed; and to remove deposits by installing retractable soot blowers with wide access lanes) and to manually clean deposits at the interval of six months after its annual overhaul works.

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Noorahmad bin Ali

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Signature

Date

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Introduction

Incineration has been used as method for processing waste since the beginning of the century. Over the past few decades it has evolved into a widely used, established technology with reliable modern facilities operating on a fully commercial basis in some advanced countries. Modern incineration plants are now almost always built with energy recovery units in place.

While there is energy recovery, waste incineration is not a source of renewable energy in its strict sense. This is because waste, a by-product of modern civilization, is a non-sustainable resource. Renewable energy also conjures up images of clean production and non-pollutive emissions, whereas incineration of wastes produces such pollutants as Carbon Monoxide (CO), Hydrochloride (HCL) and Sulphur Dioxide (SO₂). Inside the incinerator itself, these gases could already cause corrosion and tamper with the efficiency of the incinerator.

One such common occurrence of corrosion is the growth of slag, due to exposure to high HCl concentration, on the surface of the superheater¹ which could affect the thermal efficiency of the incinerator and hence lead to exhaust gases leaving at elevated temperatures. It could also lead to corrosion-fatigue, which would affect the structural integrity of the Superheater tube.

Aim

The aim of this report, therefore, is to study the causes of corrosion to the super heater tube surface of the incinerator, and to recommend measures that could minimize the occurrence of the corrosion with a view to prolong the lifespan of the tube.

¹ The super heater tube is found in the boiler and carries steam. It is however exposed to flue gas as the latter travels from the furnace to the chimney.

Format of Report

- The report begins in Chapter 1 with an introduction of the Tuas South Incineration Plant (TSIP), where the project was carried out. TSIP is one of the four municipal incineration plants in Singapore. This chapter gives an overview of the incineration plant, including the process flows undergone by the refuse, flue gas, wastewater and feedwater.
- Chapter 2 looks at the typical components of refuse ending up in an incinerator, how these refuse components alter the characteristics of gases in flue gas, and how these gases could affect the performance and integrity of the boiler. The chapter goes on to calculate the percentage of free oxygen in the flue gas given the amount of excess air introduced during firing, and includes a brief mention on the precautionary measures necessary in sampling flue gas and TSIP combustion control philosophy.
- Chapter 3 outlines the analysis on the causes of corrosion on a critical part of the boiler component – the super heater. The analysis will establish that the corrosion is caused by hydrogen-chloride (HCl) found in flue gas. While not a cause of corrosion, the report will also identify that slag, which is deposited on the super heater by the rising ash-carrying flue gas, could potentially impair the structural integrity of the tubes and its performance in conveying steam at the optimum temperature.
- Chapter 4 shifts from theoretical calculations to experimental measurements and observations, to complete the analytical component of the project. The experiment will be performed by placing specimens in two different furnaces of an actual incinerator (TSIP) over a period of time to determine the extent of corrosion. The exact conditions experienced in a furnace are therefore replicated, to get as realistic a result as possible.

- The feasibility of material replacement is addressed in Chapter 5. Carbon steel is the mainstay constituent of the Superheater but is there another material which is equally effective in performance yet has better corrosion-resistance properties, longer lifespan and economically more viable? A literature research on material properties will reveal that nickel-chromium and nickel-chromium-molybdenum steel are viable alternatives to achieve the same performance, and have several characteristics that are superior to carbon steel

Project Objectives

- To identify the components of solid wastes
- To determine the composition of flue gas
- To analyze the effect of corrosion growth on the surface of the super heater tube
- To explore ways to minimize the corrosion rate growth on the super heater tube surface.

Project Methodology

The project was carried out employing the following methodology:

- Tuas South Incineration solid waste analysis to determine the refuse composite example plastic.
- Using 'Orsat' analyzer to calculate percentage volume of free oxygen, carbon dioxide and carbon monoxide in the flue gas.
- Experimental analysis of Martin-stoker boiler combustion control to determine the behaviour of HCL, excess O₂ and the third zone temperatures.
- Using USQ (Stress analysis) lectures to determine the theoretical stresses due to pressure on the super heater tube.
- Investigation and analysis of corrosion
- Cost Analysis for final consideration and decisions

Chapter 1

Introduction of Tuas South Incineration Plant in Singapore

- 1.1 Background
- 1.2 TSIP
- 1.3 Process Description
 - 1.3.1 Refuse Flow
 - 1.3.2 Ash Flow
 - 1.3.3 Flue Gas Flow and Lime Injection for Flue Gas Treatment
 - 1.3.4 Waste Water Treatment System
 - 1.3.4.1 Waste Water Flow
 - 1.3.4.2 Refuse Waste Water
 - 1.3.4.3 Ash Waste water
 - 1.3.5 Feedwater, Steam and Condensate System
 - 1.3.5.1 Steam Flow
 - 1.3.5.2 Condensate Flow
 - 1.3.5.3 Boiler Feedwater Flow
 - 1.3.5.4 Chemical Flow
 - 1.3.5.5 Drain Flow

1.1 Background

In Singapore, about 90% of the refuse is incinerated and the remaining non-incinerable waste landfilled. Prior to 1979, all refuse was disposed of at landfills. To reduce the over-reliance on landfills and the fact that most of Singapore's refuse is combustible and suitable for incineration, the first incineration plant was built at Ulu Pandan in 1979. The number of incineration plants now stands at four. These incineration plants generate energy from the heat that is produced in the process of burning the refuse.



Figure 1.1A: Existing and Future Refuse Disposal Sites in Singapore

The plants formed part of a growing effort in terms of land, labour and resources geared towards providing the means to dispose of the increasing refuse generated in Singapore. 1992 figures revealed that 6,200 tonnes of refuse was generated per day in Singapore (Refer to Figure 1.1B) and this has increased to 8,000 tonnes per day in the year 2002. In land-scarce Singapore, dumping of refuse has been a dying trend. Incineration has

proven to be the most effective method of refuse disposal given that 90% reduction in volume could be achieved by this method.

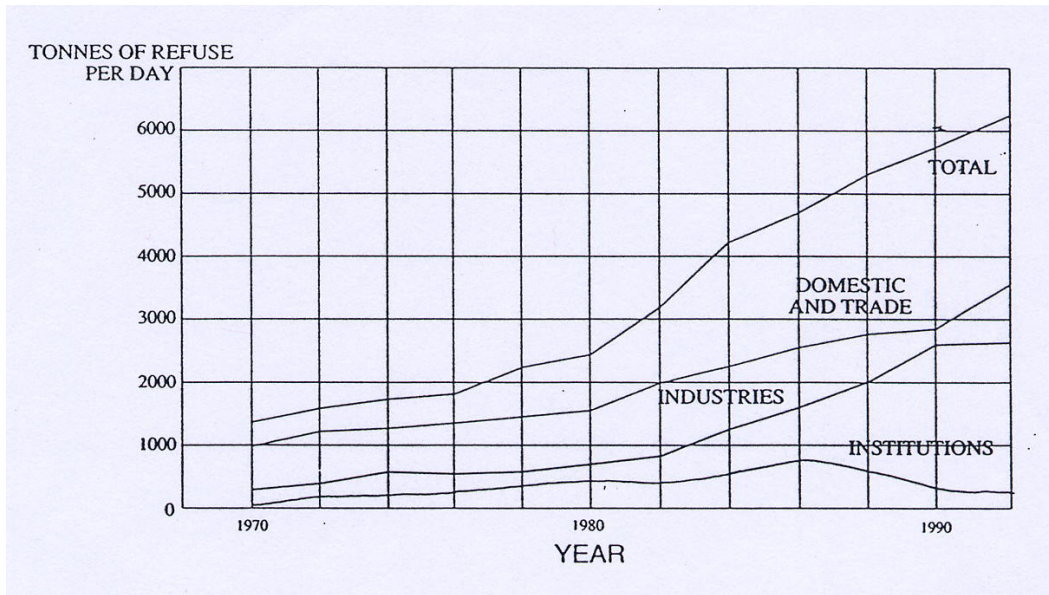


Figure 1.1B: Average Daily Refuse Generation Chart

Source: TSIP Yearly Report in Year 2002, 2003 & 2004

In line with the good environmental practice of recycling, much of the by-products of the incineration process is put into good use and recovered. The heat released from the combustion of refuse is used to generate electricity through a comprehensive boiler steam plant and turbo-generators system. Scrap metal is extracted from the ash and is sold to a local steel mill. Fly ash is collected and used for making pavement block.

1.2 **TSIP**

The Tuas South Incineration Plant (TSIP), built at a cost of approximately \$900 million², is the fourth and latest municipal refuse incineration plant in Singapore (Refer to Figure 1.2A). It is also the largest in terms of capacity, designed to incinerate 3,200 tonnes of refuse per day. The completion of the plant in June 1998 meant that the refuse incineration capacity in Singapore has increased from the average 1,500 tonnes per day to 4,700 tonnes per day, thereby enabling all incinerable refuse to be disposal of by incineration. TSIP stands on reclaimed land, approximately 10.5 ha, in the west of

² Source: ESD Annual Report 2002

Singapore. The plant was built with state-of-the art technology. The various processes are highly automated and controlled via a Digital Control System (DCS). Modern equipment incorporating advanced technology is used in the plant to ensure a higher level of efficiency and reliability.

TSIP boasts some of the most sophisticated system in combustion control and flue gas treatment. These include the Advanced Automatic Combustion Control (AACC), Flue Gas Conditioning Units and Electrostatic Precipitators, all of which enable the plant's dust and smoke emission to comply with the stringent Clean Air Act requirement. Two chimneys were constructed high enough to maximize the dispersion of the flue gases by winds. Combustion air is drawn from the storage bunker, keeping the bunker at sub-atmospheric pressure and consequently preventing the odour of refuse in the bunker from escaping. The refuse in the bunker is fed by refuse cranes into the six incinerators. TSIP, together with the other 3 incineration plants, and the Offshore Semakau Landfill, will meet the refuse disposal needs of Singapore for the next fifty years, and help in achieving a clean living environment for all Singaporeans.

1.3 **Process Description**

In order to give a better understanding of how refuse is treated, it is necessary to outline the different kinds of flows involved in the refuse incineration process. The entire process can be broken down into five flows:

1. Refuse flow
2. Ash flow
3. Flue gas flow
4. Waste water flow
5. Steam flow (which is generated from the waste heat of the furnace)

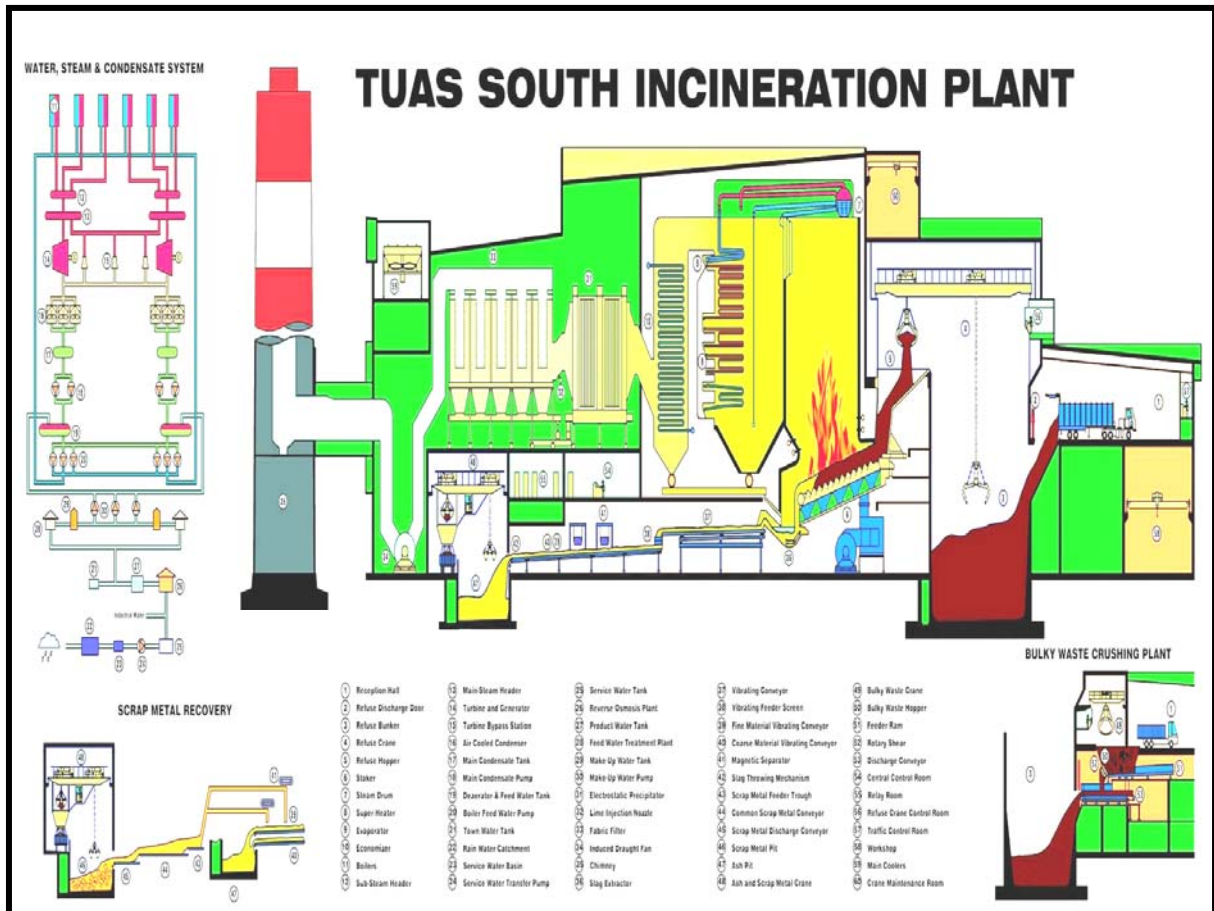


Figure 1.2: Overview of Tuas South Incineration Plant

1.3.1 Refuse Flow

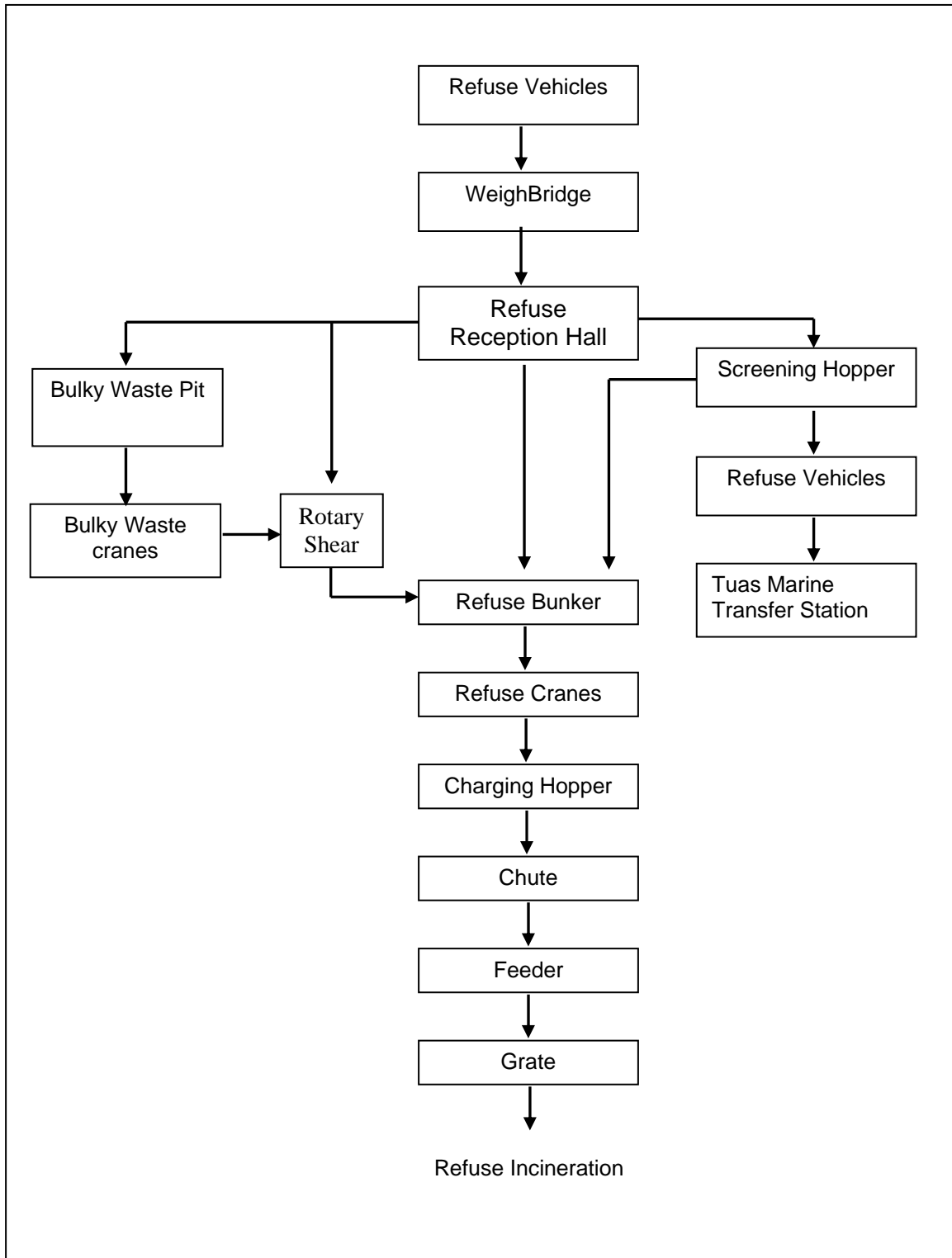


Figure 1.3.1.1 : Schematic Diagram for Refuse Flow

Refuse, garbage and other kinds of waste are first collected from residents and industries by refuse collection trucks. Once the trucks arrive at the plant, they are weighed by the one of the three weighing platforms at the weighbridge prior to being allowed to discharge their refuse into the enclosed refuse bunker. The weighbridge also undertakes the task of recording the weight, source and type of refuse carried by the refuse vehicle automatically in a computer (Refer to Figure 1.3.1.1). After the refuse trucks have unloaded the refuse into one of the two refuse bunkers, the empty trucks are weighed again before they leave the plant to determine the weight of refuse disposed.



Figure 1.3.1.1: Overview of WeighBridge
Source: TSIP Operation Manual 2002

The refuse is discharged into the refuse bunker through one of the 27 refuse discharge bays at the reception hall (Refer to Figure 1.3.1.2). The refuse is temporarily stored in the refuse bunker until it is loaded into the charging hopper located on the feeding side of the incinerator. Bulky wastes are discharged separately for crushing. All discharge bays are provided with hydraulic operated doors, which can be controlled manually or automatically.



Figure 1.3.1.2: Overview of Refuse Truck Discharged Refuse into the Refuse Bunker

Source: TSIP Operation Manual 2002

Refuse screening is an important function of the plant. The refuse brought into the plant has to be screened before it is allowed to be discharged into the bunker. Generally, refuse collected by the refuse collector do not pose any problem to the incineration process as the vehicles only collect domestic refuse from housing estates and trade premises. Therefore, only refuse brought in by private waste disposal contractors needs to be screened.

The screening facilities are installed at the refuse reception hall to screen and segregate non-incinerable waste or bulky waste from waste, which can be charged into the incinerators. Screening of refuse is done through visual inspection of the waste on the refuse trucks before and during disposal so as to ensure that only incinerable waste is disposed of in the refuse bunker. When unacceptable waste was detected, the refuse has to be manually removed. At times, the refuse collectors had to enter the bunker storage

area to retrieve the unacceptable waste. Another screening operation was the use of bulldozers in the refuse reception hall where the trucks were randomly selected to discharge their loads onto the floor before the discharge chutes leading into the refuse bunker. Bulldozers will then sift through the pile of refuse on the floor and unacceptable waste was reloaded onto the refuse truck for transportation to the correct disposal area (Refer to Figure 1.3.1.3).



Figure 1.3.1.3: Overview of Screening Bulky Waste at the Refuse Reception Hall

Source: TSIP Operation Manual 2002

The fully enclosed refuse bunker is capable of storing 9,600 tonnes of refuse. At the refuse bunker, three overhead grab cranes will feed the refuse into the charging hopper. Each crane has the capacity to grab about 10 cu.m or 6 tonnes of refuse. These cranes are operated from 3 control rooms, which oversee the entire refuse bunker. The rotary and cutter shear will cut and crush bulky wastes such as tree trucks and furniture into small pieces before being fed into the incinerator (Refer to Figure 1.3.1.4).



Figure 1.3.1.4 a: Operator control the overhead grab cranes to feed the refuse into the Charging Hopper

Source: TSIP Operation Manual 2002



Figure 1.3.1.4 b: Rotary and Cutter Shear cut and crush bulky wastes

Source: TSIP Operation Manual 2002

Refuse in the charging hopper is transported the drying portion of the incinerator stoker by the refuse feeder. After it is dried, the refuse passes to the combustion portion of the stoker where it is incinerated at a high temperature. Finally, it is delivered to the post combustion portion of the stoker where the cinder remnants of the refuse are allowed to burn themselves out (Refer to Figure 1.3.1.5).



Figure 1.3.1.5: Burning of refuse in the furnace

Source: TSIP Operation Manual 2002

The combustion of refuse in the furnace is an exothermic process, requiring no auxiliary fuel to sustain it. Built with six runs of incineration grates, the incineration furnace contained the burning refuse, which will be spread and conveyed through it. The grate surface of the furnace comprises of 13 fixed and moving step grates arranged alternatively in an inclined gradient. These grate bars are made of alloy steel, which are fitted in such a way as to allow air to pass through the gaps. The air for combustion is drawn from the refuse bunker and is preheated by steam before being introduced into the furnace via the underside of the incineration grates (Refer to Figure 1.3.1.6). The refuse fed into the grate will start combustion actively on the Reverse-Acting type of incinerator stoker grates. The combustion of refuse on the grate is completed at approximately $\frac{1}{2}$ to $\frac{2}{3}$ way in the lengthwise direction of the grate, and thereafter the so-called after burning take place. The burnt refuse passes through the clinker roller at the last stage and drops into the slag extractors.

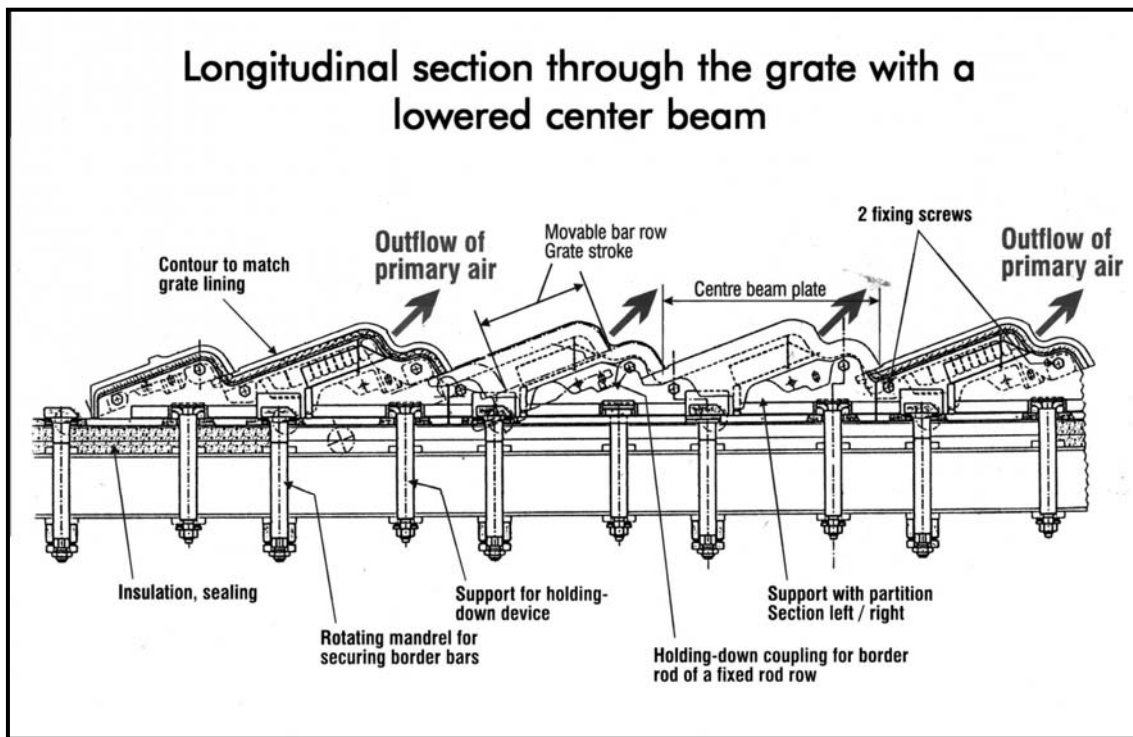


Figure 1.3.1.6: Schematic diagram for stoker grate

Source: TSIP Operation Manual 2002

Automatic control of the combustion process in the furnace is made possible through a digital control system, which regulates the air distribution in the furnace and the refuse-feeding rate according to its heating value.

1.3.2 Ash Flow

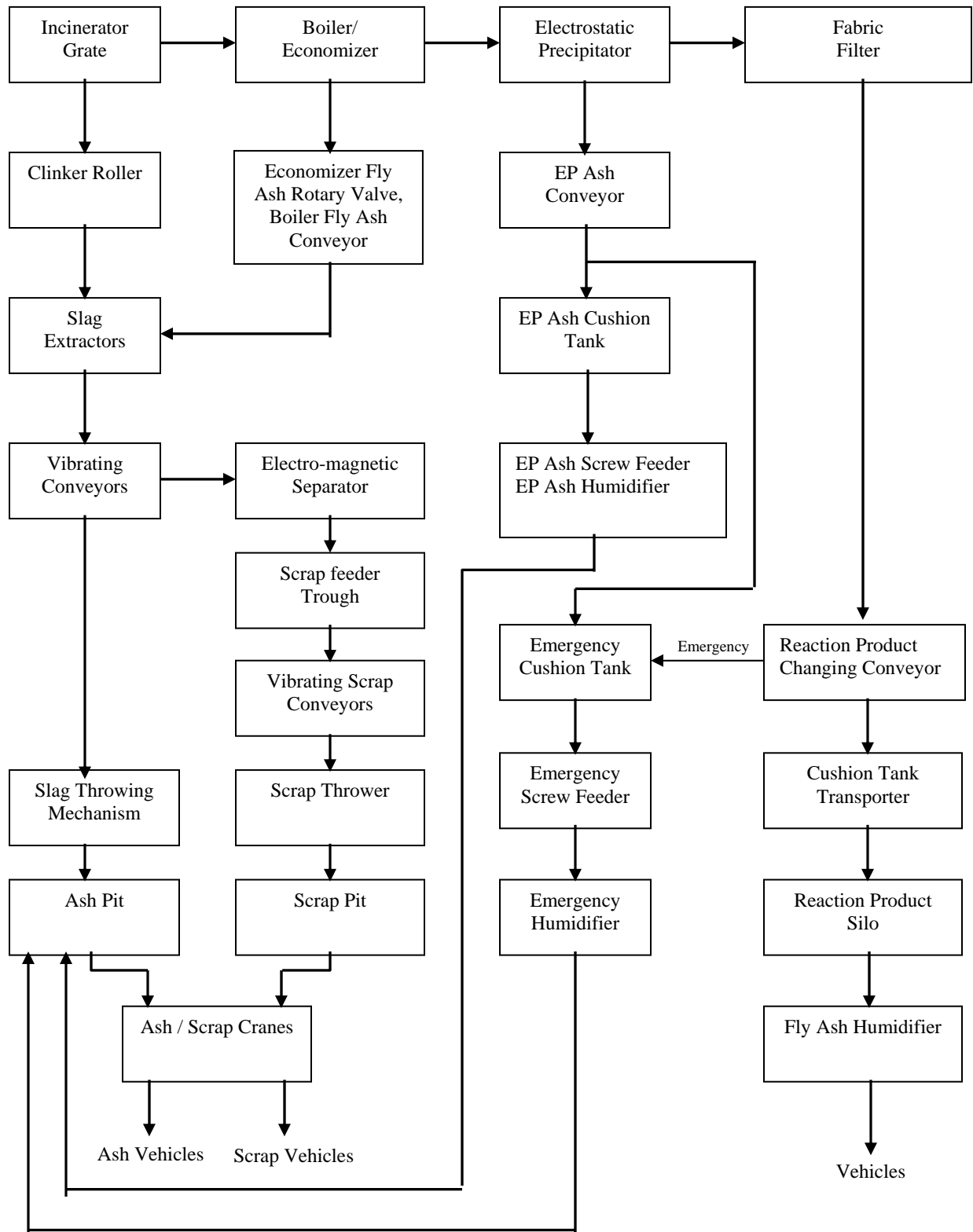


Figure 1.3.1.7 : Schematic Diagram for Ash Flow

(1) Burned Residue

The burnt-out slag on the grate is discharged via the clinker roller into the slag extractor (2 slag extractors for each incinerator), where they are extinguished and cooled by the water bath inside the slag extractors. Cooled slag is discharged from the slag extractor onto the vibrating feeder that feeds slag to the vibrating screen station. The slag discharged from the vibrating feeder is separated into material smaller than and larger than 300mm by the vibrating screen station. The separated slag that is smaller than 300mm is discharged onto the fine material vibrating conveyor and the remaining slag onto the coarse material vibrating conveyor. And they are thrown into the ash pit by the slag throwing mechanism.

Scraps in the slag transported via the fine material vibrating conveyor are separated by the two overhead Electro-magnetic Separators before the slag is conveyed into the ash pit. The electro-magnetic separators discharge the scrap metal onto the scrap feeder trough that transfers the scrap to the common scrap vibrating conveyor. And that conveyor transports the collected scrap metal to the scrap pit via the scrap discharge conveyor and associated scrap throwing mechanism. The ferrous metals are then sold as scrap to the local steel mill.

The riddling discharged from underneath the grate is sent to the slag extractors by air, which is tapped from the primary air duct. The riddling ash is mixed with the slag from the grate and discharged into the ash pit, via the vibrating feeder, screen station, vibrating conveyors and slag throwers.

(2) Fly Ash and Reaction Product

The fly ash collected at the bottom of the boiler and economizer is conveyed to the slag extractors, according to the flow pattern below:

- Boiler fly ash: boiler fly ash conveyor → slag extractor
- Economizer fly ash: boiler fly ash rotary valve → boiler fly ash conveyor → slag extractor

Slag and scrap discharged into the ash/scrap pit are loaded onto the ash vehicles by ash cranes. Three units of ash cranes are installed with one unit on common stand-by. The fly ash collected by the Electrostatic Precipitators (EP) is conveyed to the EP ash humidifier by the fly ash conveyor before being discharged into the ash pit. The reaction products, unreacted lime and fly ash collected by fabric filters are conveyed to the reaction product silos by the auxiliary compressed air system. Alternatively, the reaction products can also be conveyed to the emergency humidifier in case of emergencies. The reaction product silos consist of two silos, with one silo serving for three boilers. Each twin silo is separated into two storage spaces with one being in use and the other being for stand-by. The reaction product is discharged onto the truck by the reaction product humidifier and transported to the landfill. Each reaction product discharging line has the capability for direct loading of drying reaction products.

The overhead ash crane in turn loads the remaining ash stored in the ash pit onto ash trucks, which then send the ash to the Tuas Marine Transfer Station where they are unloaded onto barges and transported to the offshore Pulau Semakau Landfill for disposal (Refer to Figure 1.3.2.1 A & B).

The lifespan of Pulau Semakau is expected to last 30 years till 2030. If the rising trend of waste generation is not curtailed, lifespan might be shorter than 30 years.

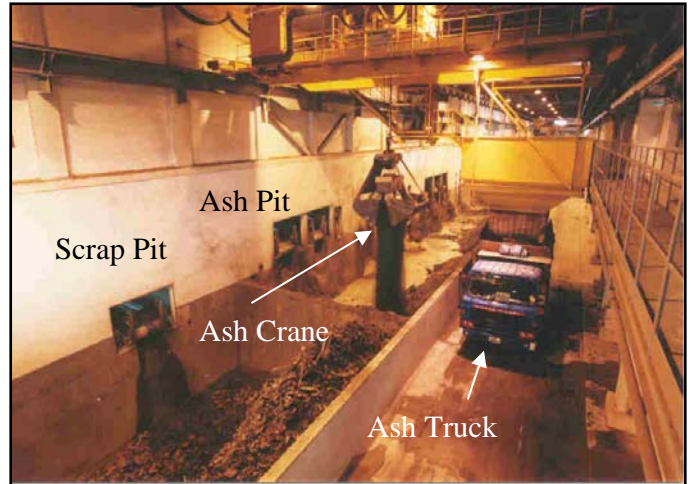


Figure 1.3.2.1A: Overview of ashes and scraps are separated and transported to the respective pit before loading onto the truck by overhead crane.

Source: TSIP Operation Manual 2002

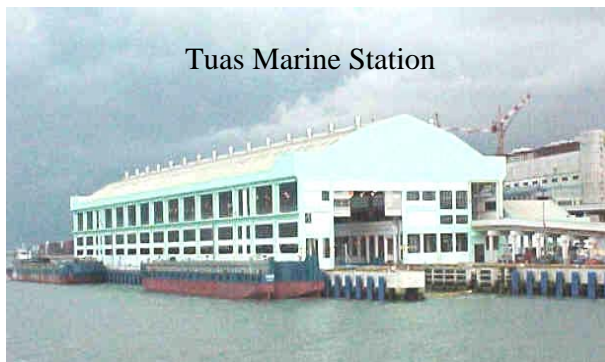
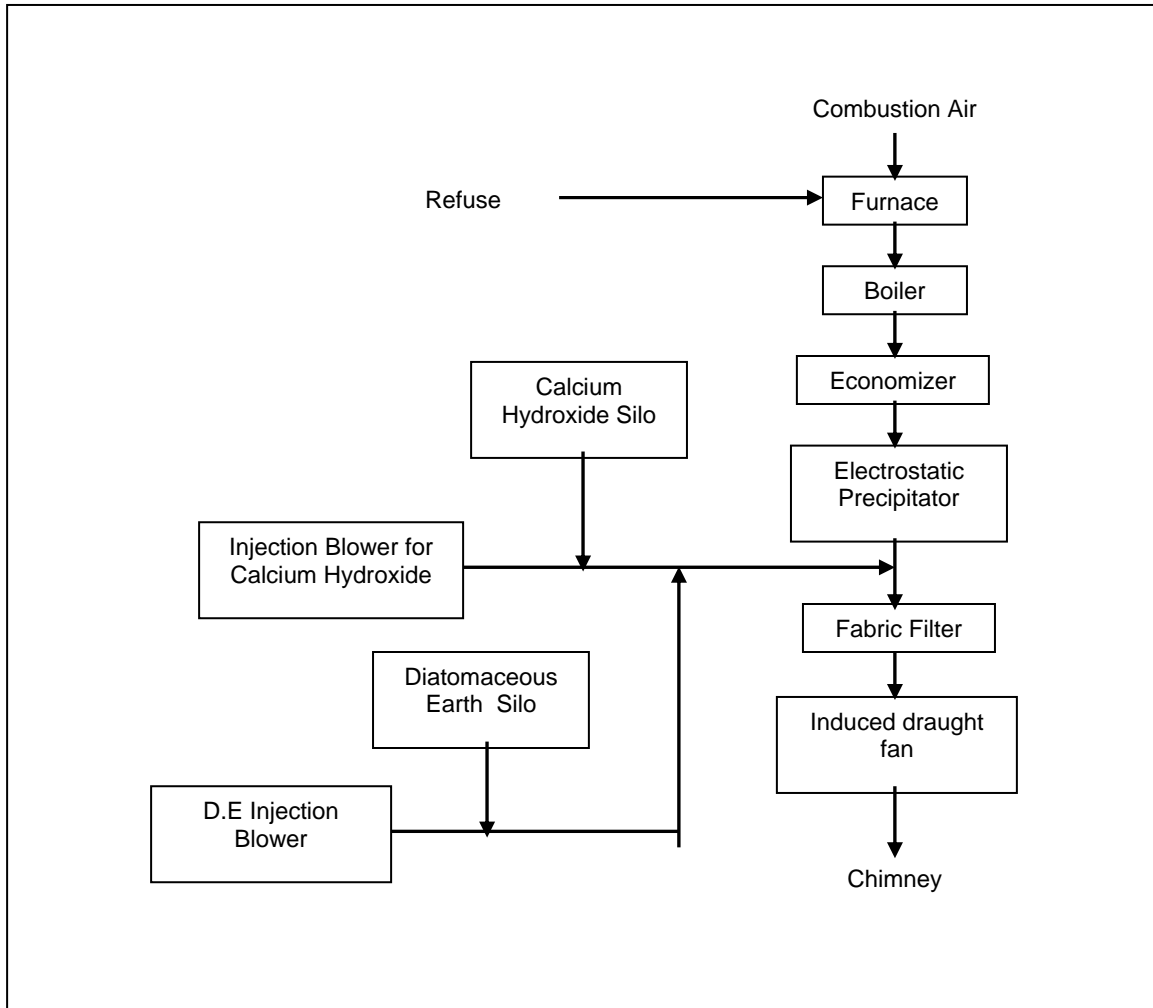


Figure 1.3.2.1B: Overview of ashes being sent to the Tuas Marine Transfer Station before dispose at Offshore Pulau Semakau Landfill

Source: TSIP Operation Manual 2002

1.3.3 Flue Gas Flow and Lime Injection for Flue Gas Treatment

Figure: 1.3.2.2 Schematic Diagram for Flue Gas Flow & lime Injection for Flue Gas treatment



The high temperature gas generated from the combustion of refuse is cooled down to approximately 165-200°C in passing through the boiler and economizer. After being cooled down, the flue gas enters a two-zone Electrostatics Precipitator (EP), which is capable of removing up to 99.5% of large-sized dust particles content in the flue gas (Refer to Figure 1.3.3.1). After passing through the EP, slacked lime powder is injected into the flue gas by injection blowers to remove harmful (HCL, SO₂) content. The reaction product (lime powder) and remaining dust particles are trapped in the Fabric

Filter Bags made of glass fibres, which are Teflon-coated for high temperature and acid resistance. The bags are pulsed with a stream of compressed air to remove the accumulated reaction product, which is pneumatically transported to the humidifiers and discharged to ash truck for land filling. As flue gas is passed through the Fabric Filters, acid gases in the flue gas (HCl,SO₂) are further removed by the neutralizing reaction with calcium hydroxide.

Reaction products together with the fly ash in the Fabric Filter are then periodically removed by air back washing. The reaction products are then conveyed to the reaction products silos. The treated flue gas from which Hydrochloride (HCl), fly ash and other gas components have been removed are drawn by the induced draught fan and discharged into the atmosphere through one of two 150m tall chimney.

Diatomaceous earth (DE) is only injected at the time of shut down of the incinerator for pre-coating, and also when the filter bags are completely replaced. This is to help prolong the life span of the filter bags.

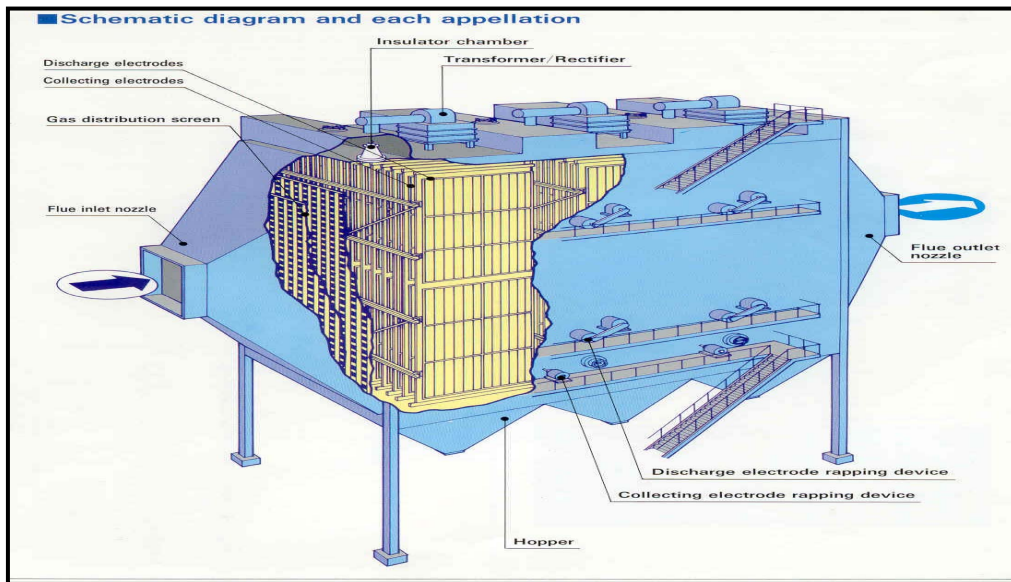


Figure 1.3.3.1: Overview of Two-Zone Electrostatic Dust Precipitator

Source: TSIP Operation Manual 2002

Arrows in Figure 1.3.3.2 below shows the flow of the flue gas path of the boiler.

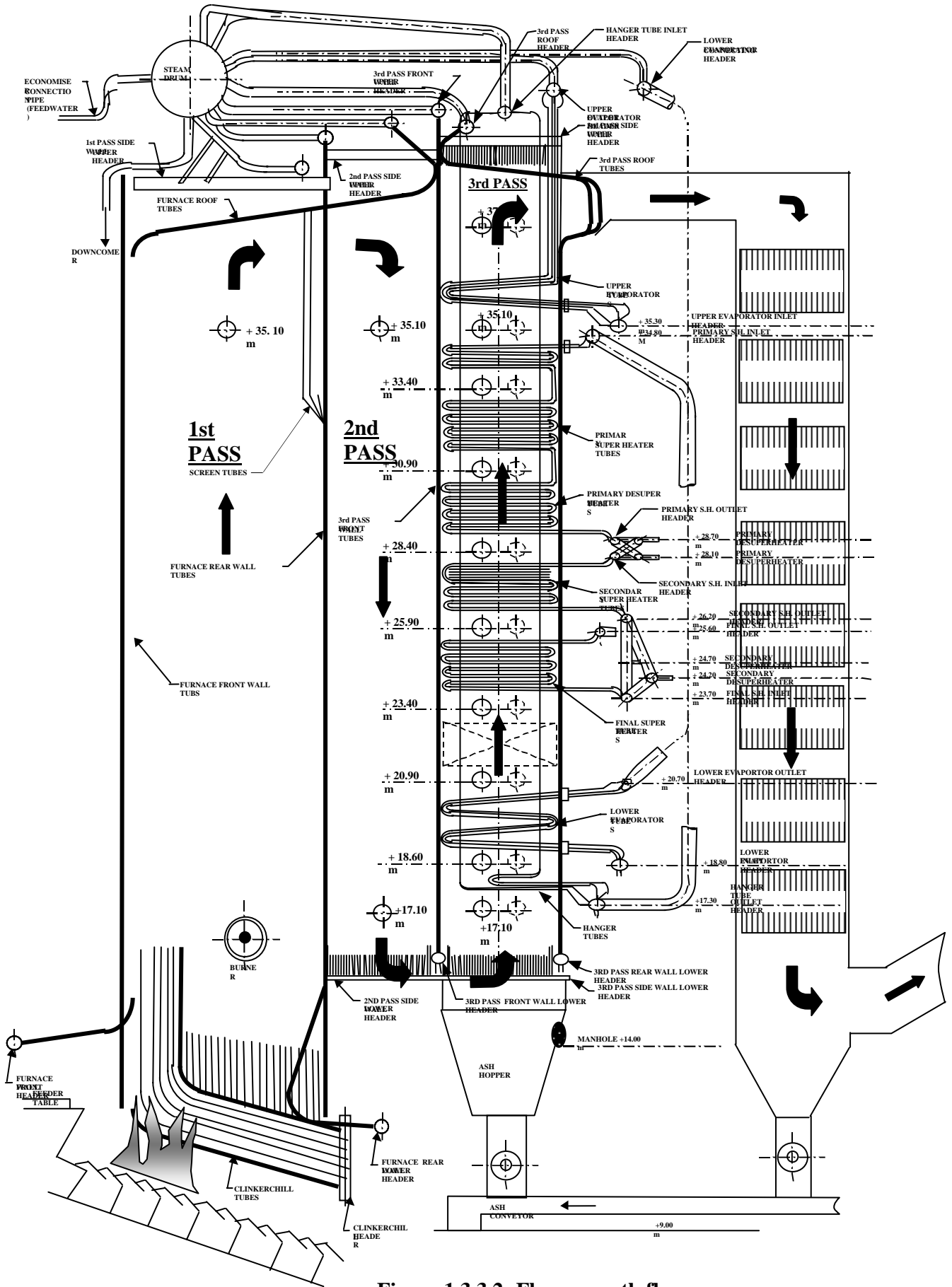
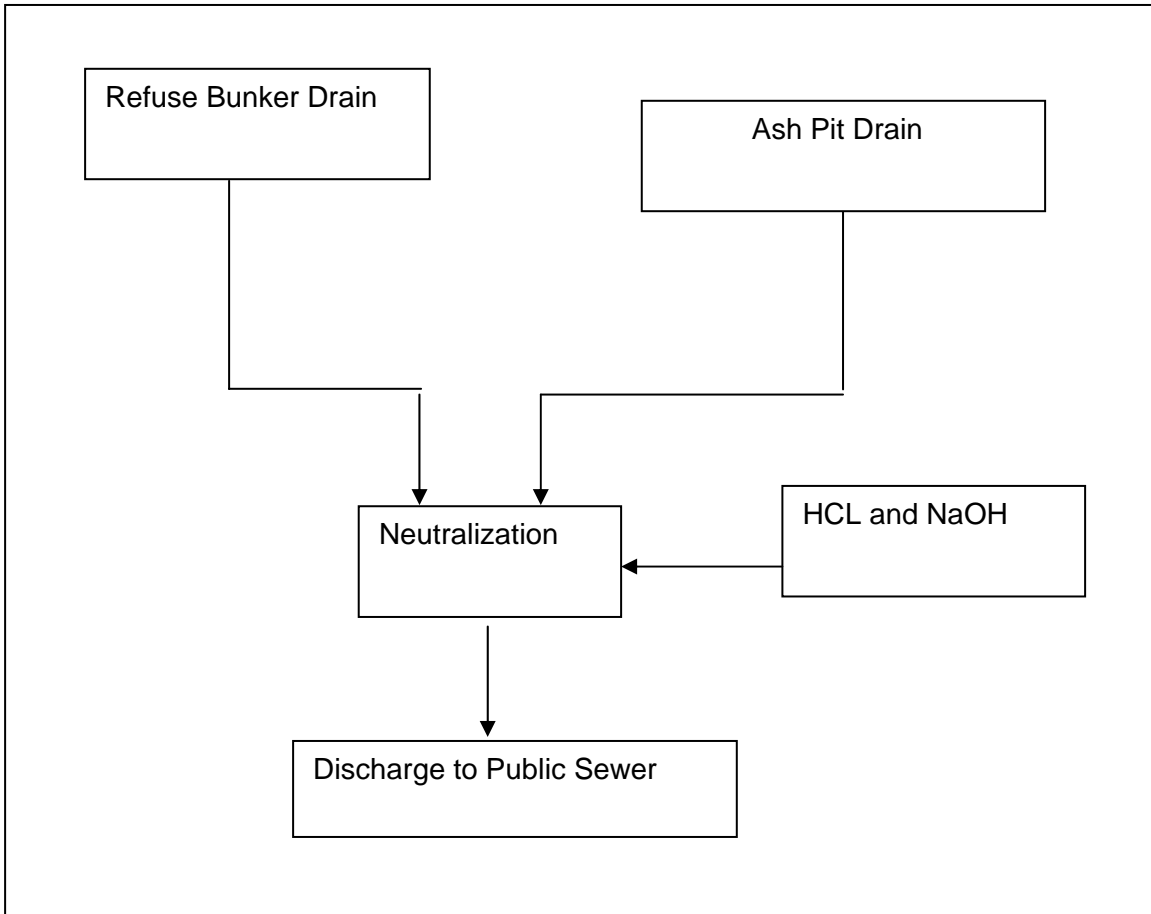


Figure 1.3.3.2: Flue gas path flow

1.3.4 Waste Water Treatment System

Figure 1.3.3.3 Schematic Diagram of Waste Water Flow



1.3.4.1 Waste Water Flow

In a refuse incineration plant, there are various kinds of waste water generated. They are classified into two categories. They are refuse waste water and ash water. Refuse waste water and ash waste water are consumers from the following sources/ or system.

1.3.4.2 Refuse Waste Water

- Reception Hall
- Refuse bunker fire fighting system
- Flushing water from auxiliary system

From the above consumers, the refuse waste water will be transferred to the refuse bunker and finally it is collected in a refuse drain tank. It will then pump the refuse waste water out to the neutralization buffer basin by refuse drain pump. Waste water from the refuse bunker is treated by a refuse drain treatment facility and injected into the furnace where it eventually evaporates whereas ash pit waste water is pumped to ash sedimentation. Water used for ash cooling and flue gas treatment is cleaned and purified by separate waste water treatment equipment. After impurities and turbidity in the waste water are removed by filtration and other processes, the clean water is discharge into the public sewer. (Refer to Figure 1.3.4.1).



Figure 1.3.4.1: Overview of Treated Water discharged to Public Sewer

Source: TSIP Operation Manual 2002

1.3.4.3 Ash waste water

- Drainage from reaction product silo building and ash pit driveway
- Flushing water from auxiliary system water treatment plant
- Boiler and turbine house drainage

From the above consumers, the ash waste water will be collected in ash and scrap pit drain chamber. Finally the ash sedimentation pump will pump out the ash waste water to the neutralization buffer basin.

1.3.4.4 Neutralization Buffer Basin

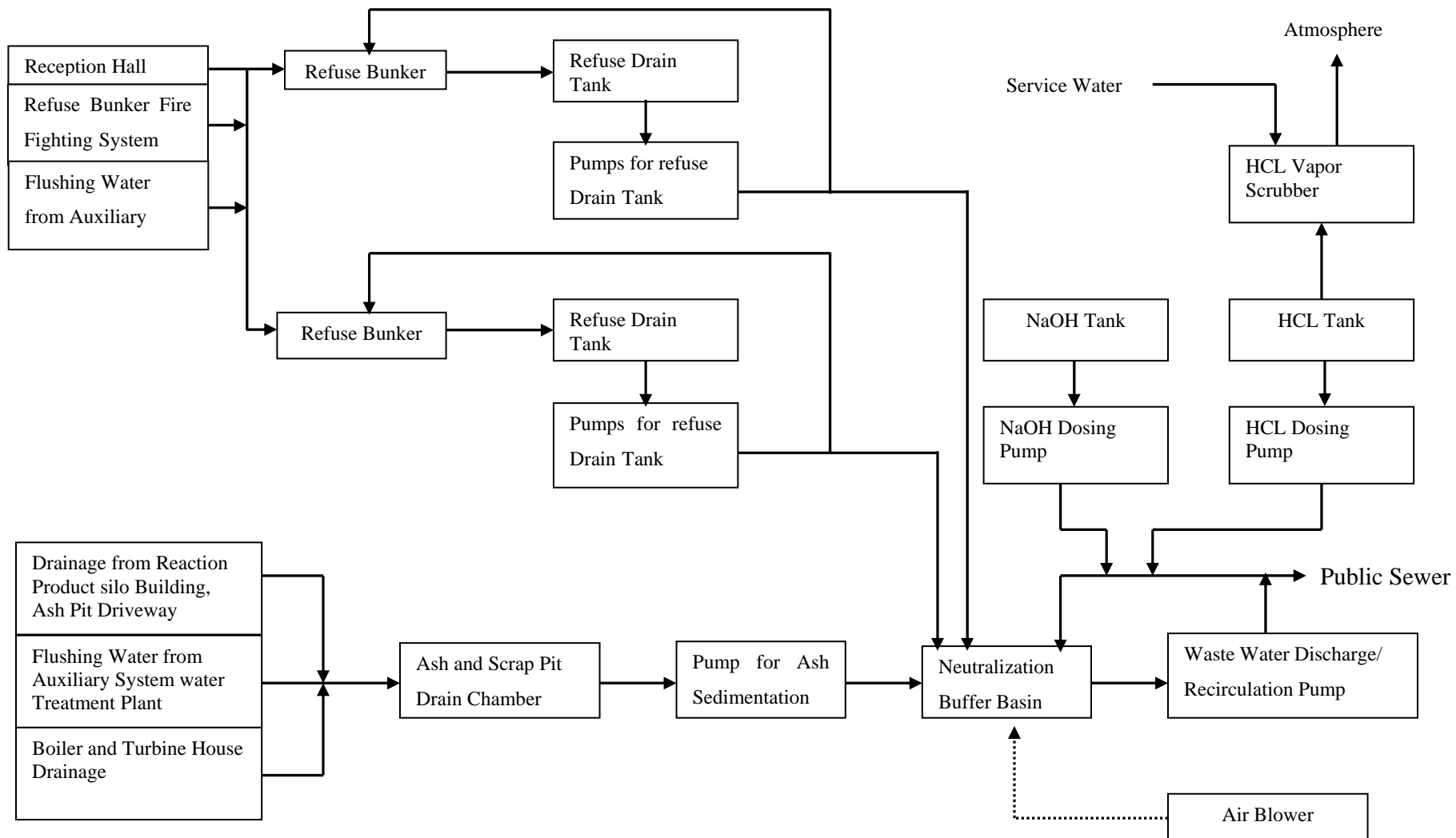
Both refuse waste water and ash waste water will be stored in the neutralization buffer basin. When the neutralization buffer basin unable to accept both waste water, the latter will be sprayed into the refuse bunker through the dust suppression spray system.

In order to prevent sludge and solid from settling in the neutralization buffer basin, waste water is agitated by air using air blower. Before waste water can be discharge to the public sewer, they have to be treated to a acceptable range of pH value.

The waste water in neutralization buffer basin is neutralized by dosing HCL at 33 percent or NAOH at 45 percent into the circulating waste water.

The pH range of waste water is expected to be 6 to 9 before it can be safely discharge to the public sewer by waste water discharge or circulating pump. However, when the pH value is not within the range, air blower is needed by dosing HCL or NAOH into the circulation pipeline and agitating by air. But once the pH is within the range, dosing pump will be operated intermittently until pH is adjusted to the acceptable pH value.

Figure 1.3.3.4 Schematic Diagram for Waste Water Treatment System



1.3.5 Feedwater, Steam and Condensate System

1.3.5.1 Boiler Circulation Circuits

To remove heat from the boiler surfaces, it is necessary that adequate and positive water and steam circulation be provided (in a predetermined direction) throughout the boiler circuits. The flow of water, steam, or other fluid within the boiler is called circulation.

When heated, water decreases in density and tends to rise to the top of the vessel; conversely, cooler water tends to drop to the bottom. When water is heated to the boiling point, small steam bubbles form on the heated surface. These bubbles cling to the metal (because of surface tension) until they become large enough to overcome the tension or until they are swept away by water circulation.

Steam is much lighter than water and rises rapidly. At the surface the steam bubbles burst, releasing the steam. The movement of steam through the water creates turbulence and circulation.

1.3.5.2 Description of Boiler Circulation

The water tube boiler is of the top supported, natural circulation type with one steam drum, and its general arrangement is shown above. The boiler circulation circuits are shown in Figure 1.3.5.2 Unheated downcomers are located along the drum length, and connected to each of the lower headers. Each wall tube circulation circuit is independent. For example, the circulation circuit of the furnace front wall tubes and roof tubes is as follows:

- a) From the steam drum, boiler water is fed to furnace front wall header through the downcomer.
- b) Flowing up through the furnace front wall tubes and roof tubes, the feedwater becomes a mixture of steam and water by absorbing heat from the flue gas.
- c) The mixture of steam and water is collected in the furnace roof header and flows through the riser tubes and back to the drum.

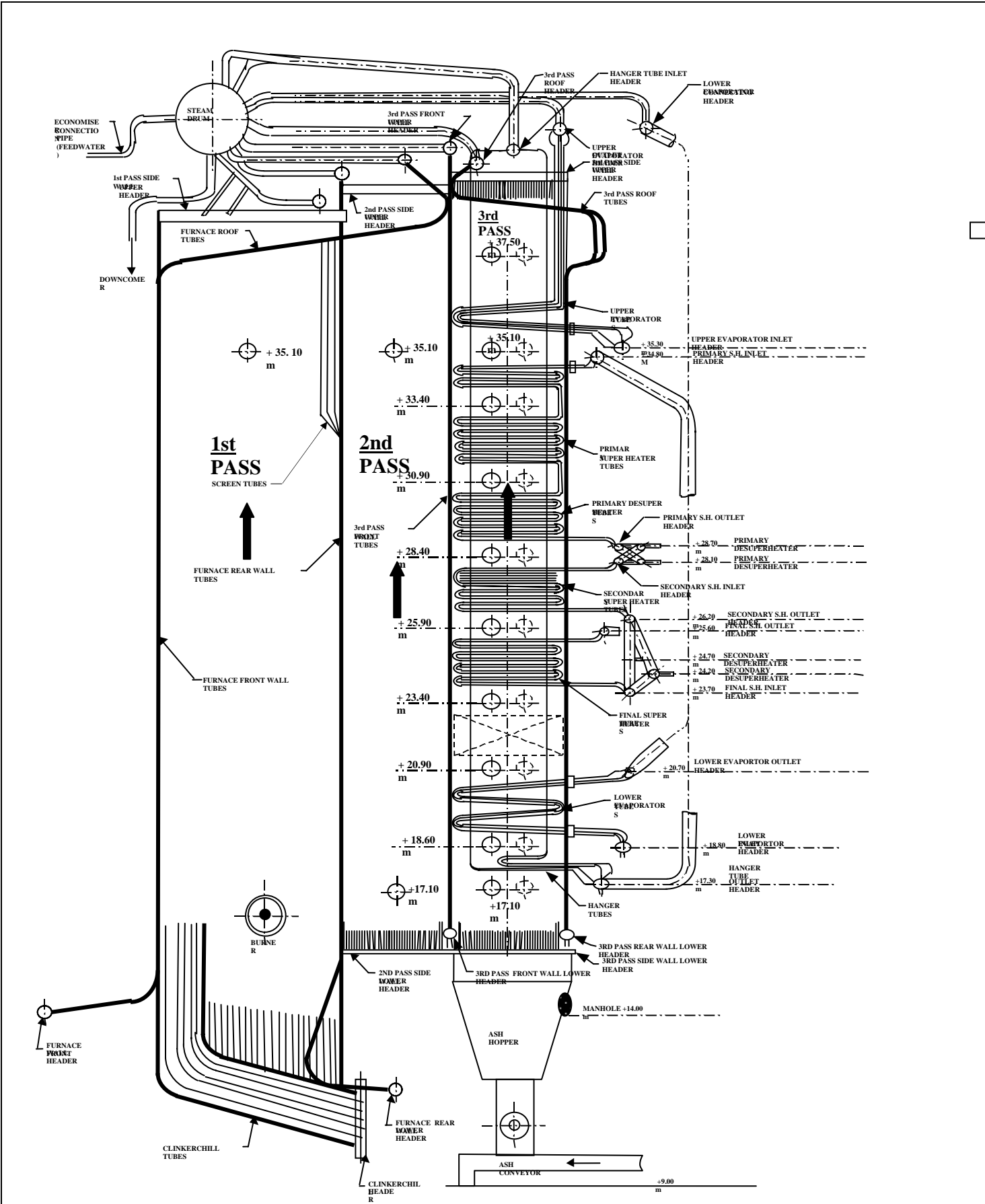


Figure 1.3.5.2: Boiler circulation

1.3.5.3 Steam Drum Internals

The interior of the Steam Drum is shown in Figure 1.3.5.3, the flow of steam and water is indicated by arrows below. The steam and water mixture entering the Drum from the Riser Tubes, is collected in the chamber formed by the internal Baffle Plates. From this chamber the mixture is first led through the Cyclone Separator (centrifugal type) which are arranged in one row along the length of the Drum. A separating force is created by spinner vanes located at the bottom, which impose a centrifugal motion to the mixture as it travels upward through the separators, throwing the water to the outside and forcing the steam to the inside. A portion of water flowing upward along the inner surface of the cylinder flows out to the outside through the multi holes of the cylinder.

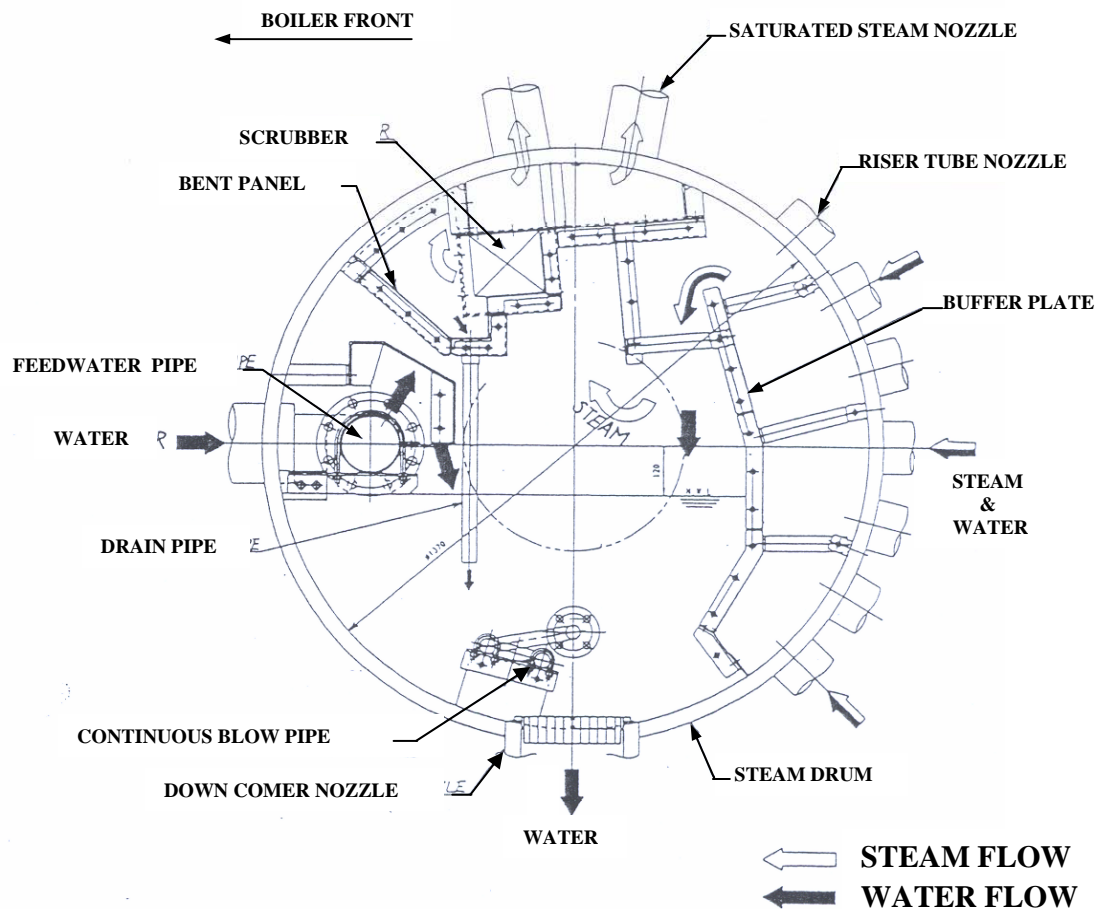


Figure 1.3.5.3 : Steam Drum Internals

1.3.5.4 Steam Flow

High pressure steam of approximately 37 bar and 370°C that is generated from each boiler, is channeled into two sub steam headers and led to two main steam headers, from where the steam is distributed to each of the facilities. Each steam header serves three boilers. Steam is distributed from the main steam headers to the two steam turbine units and three systems of turbine by-pass stations. Steam is also distributed from the main steam header to two turbine driven boiler feedwater pumps, turbine seal systems and ejector units. Steam for sootblowers on the three boilers is supplied from each sub steam header.

Additionally, back up steam for deaerators, steam heating of the Electrostatic Precipitators (Eps), Fabric Filters and reaction product silos is branched off from each main steam header and supplied after the pressure is reduced by the pressure-reducing valve. Steam for the boiler feedwater treatment plant is branched off from each main steam header and supplied after the pressure is reduced by the pressure-reducing valve. High-pressure steam used in the second stage of the steam air pre-heater is directly supplied as steam of approximately 42 bars from the steam drum of the boiler. Low-pressure steam used in the first stage of steam air pre-heater is supplied from the turbine first bleed steam lines or the back up steam after the pressure has been reduced.

The heat from the combustion is used to generate steam in boilers. The boiler produces superheated steam at 33 bars and 370°C, which is expanded through two steam turbines. Each turbine drives a generator to produce electricity for the plant and for feeding into the grid (refer to Figure 1.3.5.4). Each turbo-generator set is rated at 35 MW. The outage of a turbo-generator can be quickly resolved by channeling the steam to the other set to maximize power generation. Any excess steam is then diverted through a pressure reducing station. The exhaust steam is condensed by Air Cooled Condensers (ACC). The plant's generators are synchronized with the Public Utilities Board (PUB) grid. About 20% of the electricity generated is consumed by the plant equipment during operation while the excess 80% is sold to the PUB through 10.5 / 66 kV transformers.



Figure 1.3.5.4: Overview of turbine room that steam turbine drives a generator to produce electricity.

Source: TSIP Operation Manual 2002

The incinerator and turbo-generator units together with their auxiliary equipment are operated and monitored from a Central Control Room (CCR). The main system is a microprocessor based totally distributed digital control system (TDCS 3000). Large Screen Display shows the status of essential equipment and Close Circuit Television (CCTV) monitors the combustion status of each incinerator unit. The monitors for the operator consoles are of the LCD type. Its features include low radiation, heat and glare emissions. This reduces eye fatigue for the operators (Refer to Figure 1.3.5.5). The system also monitors the combustion conditions in the furnace, regulate air supplies and adjust refuse-feeding rate according to the calorific value of the refuse.



Figure 1.3.5.5: Overview of Monitoring and Control System

Source: TSIP Operation Manual 2002

1.3.5.4 Condensate Flow

Turbine section

The schematic diagram below shows exhaust steam from Steam Turbines (SA10D, 20D) is to be led to Air Cooled Condensers (ACC)³(QA10B, 20B), being condensed therein, and is to be sent to Main Condensate Tanks (MCT)⁴(RM10B, 20B). Condensate is also collected from the Bypass Station (when the turbine is not in operation) in Exhaust Drain Tanks (RK10B, 20B) and is first transferred into Vacuum Flash Tanks (RM12B, 22B) by means of Exhaust Drain Pumps (RK11D, 21D, 31D, 41D) before returning back into the Main Condensate Tanks. Condensate in the Main Condensate Tanks is to be sent to the Feedwater Tanks (RL10B, 20B) by means of Main Condensate Pumps (RM11D, 21D, 31D, 41D) via Main Air Ejectors⁵(QD13B, 14B, 23B, 24B), Gland Steam Condensers (SG15B, 25B), Condensate Cartridge Filters (UB11B, 21B), L.P. Heaters (RH17B, 27B). The condensate is then deaerated by the Deaerator inside the Feedwater Tanks and heated

³ ACC - to convert steam into condensate by cooling thru the use of Fans

⁴ MCT – to receive the condensate from the respective ACC

⁵ MAE -

up to 120°C ~ 130°C together with the Make-Up Water before leaving the Feedwater Tank.

Boiler Section

Condensate from 1st Stage S.A.H. is to be collected in two Main Flash Tanks (RU10B, 20B), via S.A.H. Drain tanks and is to be sent to the Feedwater Tanks (RL10, 20B) by Main Flash Tank Pumps (RU11D, 12D, 21D, 22D). Condensate from the 2nd stage S.A.H. (1 - 6NE20B) is to be collected in the S.A.H. Drain Tanks (1 ~ 6 RU2B1) placed close to the S.A.H. and is to be returned directly to the 2nd S.A.H. Condensate Return Headers (RU5, 6) before entering into the Feedwater Tanks (RL10B,20B). Condensate from Steam Heating pipes, such as E.P.(1 ~ 6NL10), FF, RG is also returned to the two Main Flash Tanks (RU10B, 20B), and is also pumped into the Feedwater Tanks (RL10, 20B) by the Main Flash Tank Pumps (RU11D, 12D, 21D, 22D).

TUAS SOUTH INCINERATION PLANT

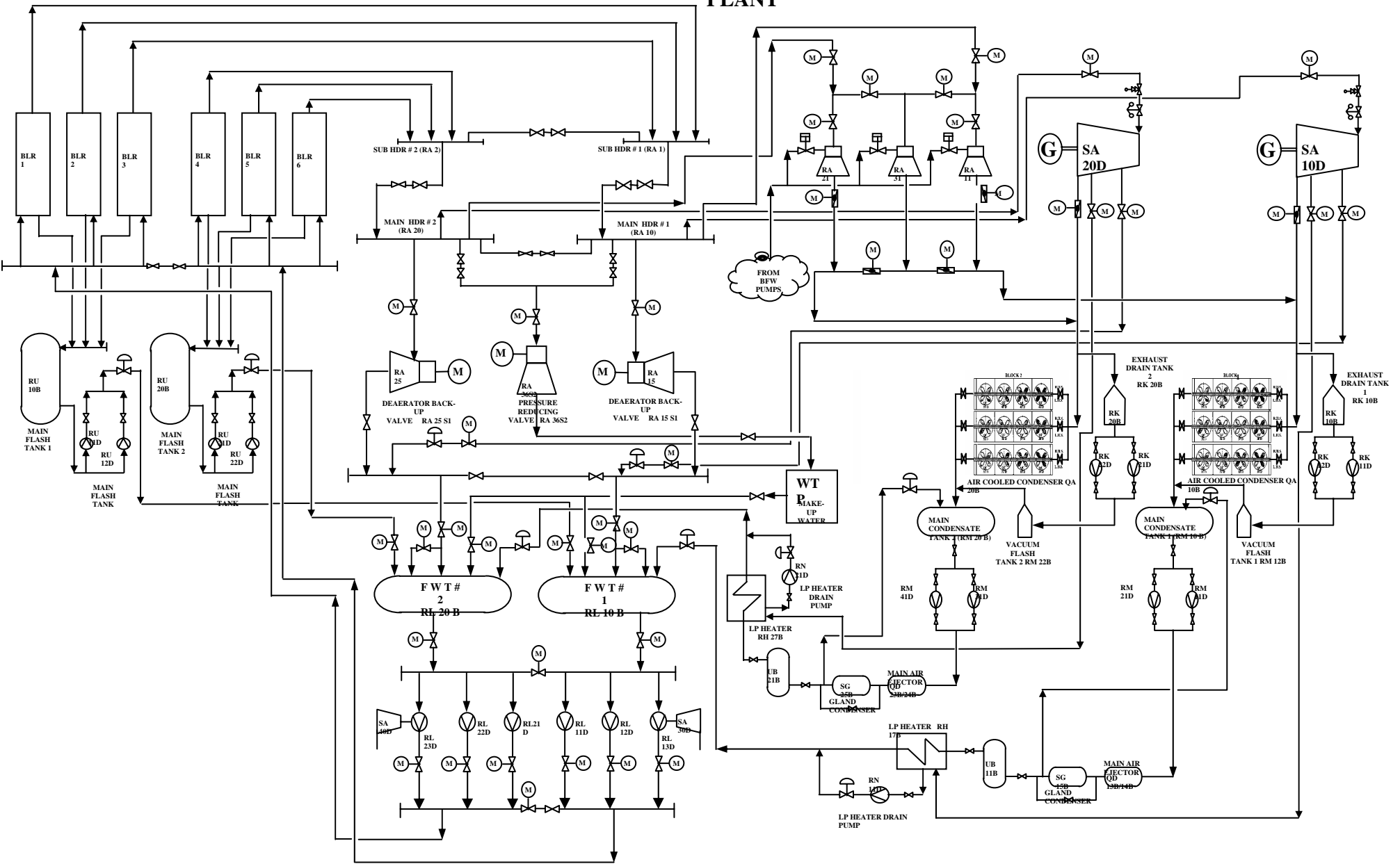


Figure 1.3.3.5 Schematic Diagram :Feedwater, Steam & Condensate System

1.3.5.6 Boiler Feedwater Flow

Potable Public Utilities Board (P.U.B) water stored in the town water tanks placed at the roof of the administration building is sent to the boiler feedwater treatment plant by town water booster pumps and is treated into demineralized water (pure water). This demineralized water is sent to the feedwater tanks by make-up water pumps to be used as make-up water for boilers.

The feedwater, after being stored in the feedwater tanks is fed to each boiler by large/small boiler feed water pumps.

1.3.5.7 Chemical Flow

Boiler dosing compounds such as Na_3PO_4 , etc is introduced into the boiler feedwater to control residual hardness in the boiler water. This chemical is stored in the Na_3PO_4 “Dissolving and Dosing Tanks” and is injected into the feedwater pipeline at the point after feedwater control valve by Na_3PO_4 dosing pumps.

Oxygen scavenger (N_2H_4) and corrosion inhibitor for condensate (Amine) are dosed into the feedwater and turbine condensate for the removal of residual oxygen and for adjustment of the pH value.

These chemicals are stored in N_2H_4 /Amine dosing tank and injected into the feedwater pipeline at the point before the boiler feedwater pumps, between the main condensate tank and air cooled condensers by N_2H_4 /Amine dosing pumps.

1.3.5.7 Drain Flow

- The continuous blow down water from the boiler drum is firstly flashed in the boiler’s blowdown flash tank, before being sent to the atmospheric dirty drain tank.
- The drain water stored in the atmospheric dirty drain tank is passed through the dirty drain coolers and discharged into the service water basins.

Chapter 2

Waste Fuel Firing

2.1 Introduction

2.2 Background

2.3 Analysis of Solid Wastes

2.4 Combustion Theory and Calculations

2.4.1 Theoretical Air for Combustion

2.4.2 Excess Air and Percentage of Oxygen in Flue Gas

2.4.3 Excess Air Calculation

2.4.4 Flue Gas Analysis

2.4.5 Flue Gas Sampling

2.5 TSIP Combustion control system

2.1 Introduction

Solid waste typically contains plastic materials, papers, food waste, leather & textiles, glass and others. These typical components of refuse ending up in an incinerator and are sources of chlorine and sulfates than can form corrosive agents during the combustion of refuse boiler. This chapter looks at these how typical refuse components alter the characteristics of gases in flue gas, and how these gases could affect the performance and integrity of the boiler. The chapter goes on to calculate the percentage of free oxygen in the flue gas given the amount of excess air introduced during firing, and includes a brief mention on the TSIP Stoker combustion control system and precaution measured when sampling flue gas.

2.2 Background

Wastes have been fired in boilers in a number of industries for many years both as a means of waste disposal and for energy recovery. For waste disposal it means large reduction of its waste volume up to about 90% of reduction. Which its running cost can be offset by heat recovery. Well-established examples are the firing of bagasse, which is the residue from the processing sugar in sugar factories, and of blast furnace gas in steel works. With increasing fuel and energy costs, consideration is now being given to energy recovery by the firing in boilers of any combustible wastes, which can, in turn, reduce fuel and final product production costs.

The type of waste product being burned, and also the combustion process required to burn the waste, have a large influence upon the design of the boiler used. Particulate carryover, in the case of solid fuels, and corrosive properties of the products of combustion are significant considerations.

As the non-homogeneous composition of the refuse waste are used as fuels, it becomes necessary to carry out tests to determine the most suitable methods of firing good combustion in waste-boilers, these and a continuous process of boiler development is required.

2.3 Analysis of Solid Wastes

Some of the most common “Waste Fuels” which have been collected from domestic and industrial sources for the past three years. These are given in Table 2.3.1

Incinerator (Year)	2002	2003	2004
Sample Date:	25/9	27/10, 29/10,31/10,1/11 & 2/11	13/9, 15/9 & 17/9
% Domestic Waste	44.9	48	51
% Industrial Waste	55.1	52	49
A) Composition (wt % in wet base)			
Food	4.19	26.75	8.14
Horicultural	13.78	1.00	1.74
Paper	22.62	24.81	30.45
Plastic	20.30	24.45	29.03
Wood	27.27	4.60	10.53
Textile	3.71	6.67	2.81
Leather & Rubber	0	0	0
Ferrous Metals	3.43	3.22	2.38
Non-Ferrous Metals	0.32	1.08	0.82
Glass	2.24	3.97	2.05
Ceramic/stone/others	2.14	3.38	12.06
B) Properties			
Moisture (wt%)	42.61	35.11	37.84
Incombustible (wt%)	18.66	19.81	17.35
Combustible (wt%)	38.73	45.08	44.81
NCV (KJ/kg)	9,340	10,033	9,540

Table 2.3.1: Analysis of Solid waste

Average of Refuse Analysis Results for Samples

Source: TSIP Yearly Report in Year 2002, 2003 & 2004

Where

NCV = Net Calorific Value

wt % = Weight Percentage

Element	2002	2003	2004
Carbon	20.58 %	21.02 %	20.35 %
Hydrogen	2.94 %	3.23 %	3.15 %
Nitrogen	0.46 %	0.44 %	0.32 %
Sulphur	0.18 %	0.12 %	0.17 %
Chlorine	0.18 %	0.19 %	0.44 %
Oxygen	13.75 %	17.0 %	19.67 %

Table 2.3.2: Element Analysis of Refuse

Source: TSIP Yearly Report in Year 2002, 2003 & 2004

Table 2.3.1 clearly shows that the percentage disposal of “Plastics” content has increased gradually over the past three years. As a plastic contains Hydrochloride (HCl), the incineration of plastics released HCl which in turn acidified the flue gas. The acidic nature of the flue gas caused by HCl created an environment that set the stage for a continuous attack on the metal structure of the boiler, such as the super heater tube. The situation was aggravated by reducing conditions, which existed due to the heterogeneous nature of fuel, the deep fuel beds used, and hence the difficulty in achieving the correct air-to-fuel ratio at all points in the furnace.

Another consideration is the percentage of moisture content in the environment inside the furnace. The presence of moisture might make the burning of refuse relatively difficult once the moisture content is excessive during the initial drying period in the furnace. Moisture in refuse reduces the efficiency of the boiler by discharging heat up the stack in the form of highly superheated vapor (H₂O). The water present in the refuse (wet refuse) consumes latent heat of vaporization (from the available energy) to become water vapor in the flue gas. And these can further increased the corrosion rate at superheater tube.

Moreover, it is clear from Table 2.3.2 that the percentage of oxygen content in the furnace is above the recommended value of 9 %. The presence of excess free oxygen in the furnace might affect the burning of refuse in the combustion process and may lead to poor boiler performance. This is attributed by the fact that free oxygen could react with the metal of the tube at the third zone to produce iron oxide (rust).

2.4 Combustion Theory and Calculations

A chemical equation expresses the principle of conservation of mass in terms of the conservation of atoms. A simple chemical equation expressing the complete combustion of carbon and oxygen to carbon dioxide is as follows:



For refuse combustion calculation, the following air composition is used:

	Oxygen (O₂)	Nitrogen (N₂)
Volumetric Analysis	21 %	79 %
Gravimetric Analysis	23.3 %	76.7 %

The following table gives the atomic weights and molecular weights of some of the substance in combustion process:

Substance	Atomic Symbol	Atomic Weight	Molecular Symbol	Molecular Weight
Hydrogen	H	1	H ₂	2
Carbon	C	12	–	–
Oxygen	O	16	O ₂	2 x 16 = 32
Sulphur	S	32	–	–
Nitrogen	N	14	N ₂	2 x 14 = 28
Carbon Dioxide	–	–	CO ₂	12 + 32 = 44
Carbon Monoxide	–	–	CO	12 + 16 = 28
Sulphur Dioxide	–	–	SO ₂	32 + 32 = 64

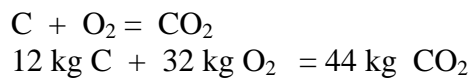
Table 2.4.1: Weight of some common elements

2.4.1 Theoretical Air for Combustion

Theoretical air is the quantity of air required to burn all the combustible elements present in the refuse completely and it is referred to as stoichiometric air. If the air is more than the stoichiometric, it is called excess air.

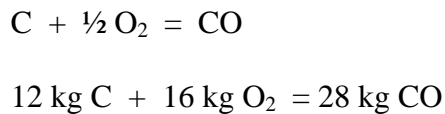
For Elements

a) Carbon

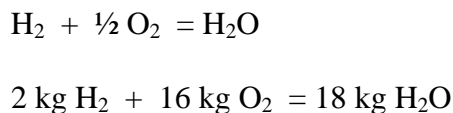


Hence, 12 kg of carbon requires 32 kg of oxygen for complete combustion. Thus 1 kg of carbon would require $32 / 12$ or 2.67 kg of oxygen. Since air contains 23.3 % by weight of oxygen, quantity of air required is $2.67 \times (100 / 23)$ or 11.46 kg of air.

Similarly, 1 kg of carbon would require 1.33 kg of oxygen or 5.72 kg of air to burn to 2.33 kg of carbon monoxide.

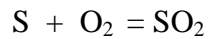


b) Hydrogen



Here, 2 kg of hydrogen requires 16 kg of oxygen for complete combustion. Thus, 1 kg of hydrogen would require 8 kg of oxygen or 34.33 kg of air.

C) Sulphur



Here, 1 kg of sulphur requires 1 kg of oxygen or 4.29 kg of air.

2.4.2 Excess Air and Percentage of Oxygen in Flue Gas

In practical combustion systems, air in excess of the theoretical requirement is necessary for complete combustion because of limited reaction time and the imperfect mixing of the fuel and air. Furthermore, inert gas molecules like nitrogen obstruct the reaction between active molecules of refuse and oxygen.

Air for combustion is divided into primary air and secondary air. Primary air provides a main percentage of combustion air, but more importantly, controls the amount of refuse that can be burned. Secondary air helps in burning refuse completely. The volatile gas that escapes from the refuse is completely burned by secondary air. Most of the refuse incinerators lack of control of this secondary air resulting on incompletely burned of gases or more excess air in furnace chamber.

The quantity of excess air to be used is a matter of compromise, with no excess air, incomplete combustion may occur resulting in losing available heat and black smoke emission, whereas too much excess air will reduce the temperature of the furnace and carrying away extra heat to the chimney. Too much excess air will also increase the amount of sulphur trioxide (SO_3) produced from sulphur dioxide (SO_2), which in turn combines with the water vapor to produce sulphuric acids. Sulphuric acid is deposited on the cooler surfaces of the boilers particularly down stream equipment where temperature is lower. The dew point corrosion might cause rapid corrosion to all metallic components.

The percentage of oxygen (O₂) in flue gas is an indicator of the quantity of excess air used in boilers; the higher percentage of oxygen (O₂) the higher the excess air used. The recommendation percentage oxygen (O₂) in the flue gas for common boilers is about 9 % (9 % in refuse incineration plant). The analysis of flue gases is done by an instrument call an “Orsat” which give the percentage volume of the amount of free oxygen, carbon dioxide and carbon monoxide in the flue gas. For complete combustion, the percentage of carbon monoxide (CO) should be zero.

2.4.3 Excess Air Calculation

The immediate calculation below carries with it the assumption of perfect combustion (i.e. 0 % excess air) of refuse.

For all calculations, the elemental component of refuse as based on Year 2004 is as follows:

Carbon (C) = 20.35 %

Hydrogen (H) = 3.15 %

Sulphur (S) = 0.17 %

The following products of combustion are formed for 1 kg of refuse:

$$\text{CO}_2 = (0.2035 / 12) \times 44 = 0.746 \text{ kg CO}_2$$

$$\text{H}_2\text{O} = (0.0315 / 2) \times 18 = 0.2835 \text{ kg H}_2\text{O}$$

$$\text{SO}_2 = (0.0017 / 32) \times 64 = 0.0034 \text{ kg SO}_2$$

$$\text{N}_2 = [(0.2035 / 12) \times 44] [76.7 / 23.3] + [(0.0315 / 2) \times 18] [76.7 / 23.3] + [(0.0017 / 32) \times 64] [76.7 / 23.3]$$

$$= 2.456 + 0.933 + 0.011$$

$$= 3.40 \text{ kg N}_2$$

Total quantity of flue gas formed is **4.433 kg**

If the calculation is repeated at 5 % excess air:

$$\text{N}_2 = 3.40 \times (1 + 0.05) = 3.57 \text{ kg N}_2$$

$$\text{O}_2 = (3.57 - 3.40) \times (23.3 / 76.7) = 0.052 \text{ kg O}_2$$

To convert the above data to percentage by volume on a dry basis, it is necessary to find the moles of dry products formed.

$$\text{CO}_2 = 0.746 / 44 \text{ mole} = 0.017 \text{ mole CO}_2$$

$$\text{SO}_2 = 0.0034 / 64 \text{ mole} = 0.0000531 \text{ mole SO}_2$$

$$\text{N}_2 = 3.57 / 28 \text{ mole} = 0.1275 \text{ mole N}_2$$

$$\text{O}_2 = 0.052 / 32 \text{ mole} = 0.001625 \text{ mole O}_2$$

$$\text{Total:} \quad 0.1462 \text{ mole Dry Flue}$$

Thus, 0.1462 mole of dry product is formed at 5 % excess air.

$$\begin{aligned} \text{Percentage of Oxygen (O}_2\text{) in flue gas} &= (0.001625 / 0.1462) \times 100 \% \\ &= 1.11 \% \end{aligned}$$

Repetitive calculations using incremental percentages of excess air produce the following table. It shows the variation of excess air with percentage of Oxygen (O₂) in flue gas (for refuse incineration plant):

% Excess Air	% O₂ in Flue Gas
5 %	1.11 %
10 %	1.53 %
15 %	2.24 %
20 %	2.88 %
30%	4.04 %
40 %	6.43 %
50 %	7.46 %

Table 2.4.3.1: Variation of excess air with percentage of oxygen (O₂) in flue gas for refuse firing boiler

2.4.4 Flue Gas Analysis

In the continuous recording of flue gas analyzer sampling, gas is continuously drawn from a selected location, and samples are analyzed at intervals of 1 minute or longer. Both the analysis and the recordings of the results are automatic. The analysis does not include all the constituents of the products of combustion, and instruments are selected accordingly.

The amount of O₂ in the flue gases is significant in defining the status of the combustion process. Its presence always means that more oxygen (excess air) is being introduced than is being used. Assuming complete combustion, low values of O₂ in the flue gases reflect moderate (nearly correct) excess air and reduced heat losses to the stack, while higher values of O₂ means needless higher stack loss. The quantitative determination of total air (total air = 100 + percent excess air) admitted to an actual combustion process

requires a complete flue gas analysis for CO₂, O₂, CO and N₂ (by difference) or the direct measurement of the air supplied by a suitable fluid meter.

The approximate percent total air from the flue gas analyzed may be determined from the curves of the following Figure 2.4.4.1 which used in conjunction with Orsat formula that has long been used for approximating the percent excess air from an Orsat analysis is:

$$\% \text{ Excess Air} = 100 \times \left[\frac{(\text{O}_2 - (\text{CO} / 2))}{(0.264\text{N}_2 - (\text{O}_2 - (\text{CO} / 2)))} \right]$$

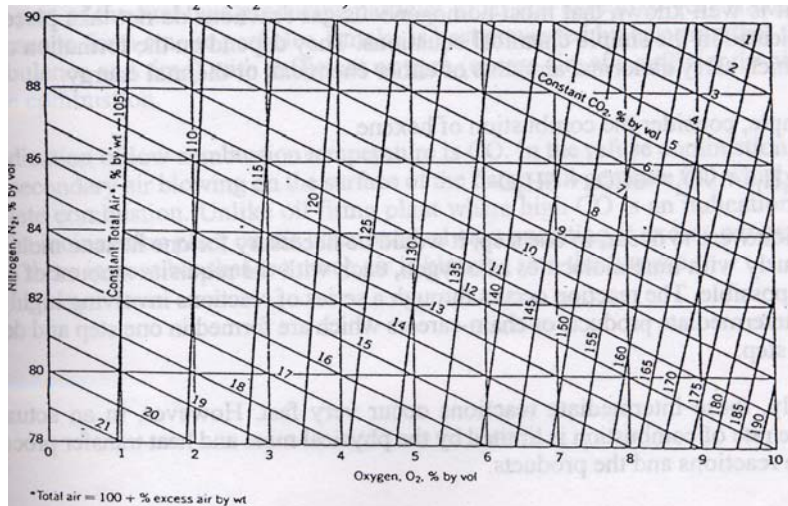


Figure 2.4.4.1: Chart for Approximating Total Air from the Flue Gas Analysis

Source: Singapore Incineration Plant Handout

2.4.5 Flue Gas Sampling

Great care should be taken to secure truly representative sample of the gas for analysis. The usual practice for a manually operated gas analyzer is to take successive samples from a number of points, laid out in checkerboard fashion over a cross section of the flue or area traversed by the gas. The number of sampling points and their positions are best determined by trial analyses of gas samples from tentative locations. If the values from point to point vary widely, more sampling locations across the plane should be used.

Gas samples are drawn at regular intervals over a relatively long period (during the entire period of a formal test). Unless operating conditions are exceptionally uniform, a few samples drawn at irregular intervals are of little use in obtaining a true analysis.

Fixed-position samplers of the branch-pipe type, extending into the flue area, are likely to give misleading results, since the proportion of gas drawn into each branch may not correspond to the flows over the flue cross section. A better arrangement is to insert a single sampling element in the flue, at a location established by thorough preliminary analyses, from which samples can be drawn representing a fair average. Samples for the automatic mechanical gas analyzers are frequently drawn through single sampling pipe carefully located in this manner.

2.5 TSIP Combustion Control System

In TSIP refuse is burned under controlled conditions and heat is recovered to provide steam for electricity generation. In TSIP its combustion control system has managed to maintain a stable steam condition in the boiler. It is actually being able to burn the composition of the refuse which are changing every moment. However others factors that contribute corrosion in the boiler such as outlet flue gas temperature, HCl, carbon monoxide (CO) and excess O₂ are not being properly integrated into the control system so that an ideal combustion situation can be achieved.

In normal operation of the Mitsubishi-Martin type incinerator its purpose of Automatic Combustion Control (ACC) are for stabilization of combustion state and generation steam amount. The combustion control system maintains a target steam flow rate by adjustment of air and refuse-fuel flows. The control system, therefore, responds to changes in amount of the steam generate. Figure 2.5.1 show the average of one day flue gas temperature taken for operating boiler no: 6 at difference amount steam generated. And figure 2.5.2 show percentage of oxygen content when boiler is operated at difference load.

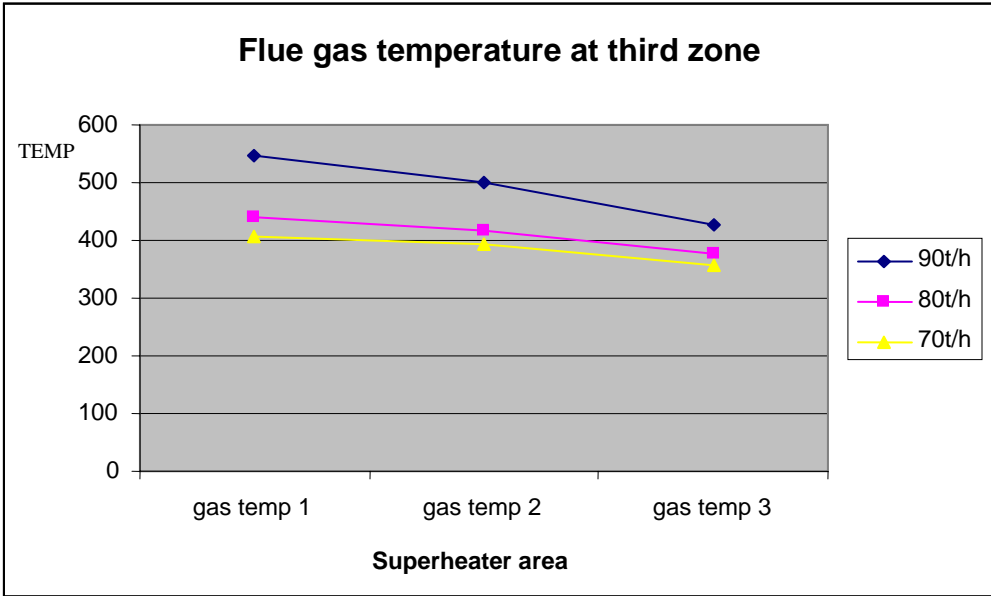


Figure 2.5.1: Flue Gas Temperature at third pass section in the furnace

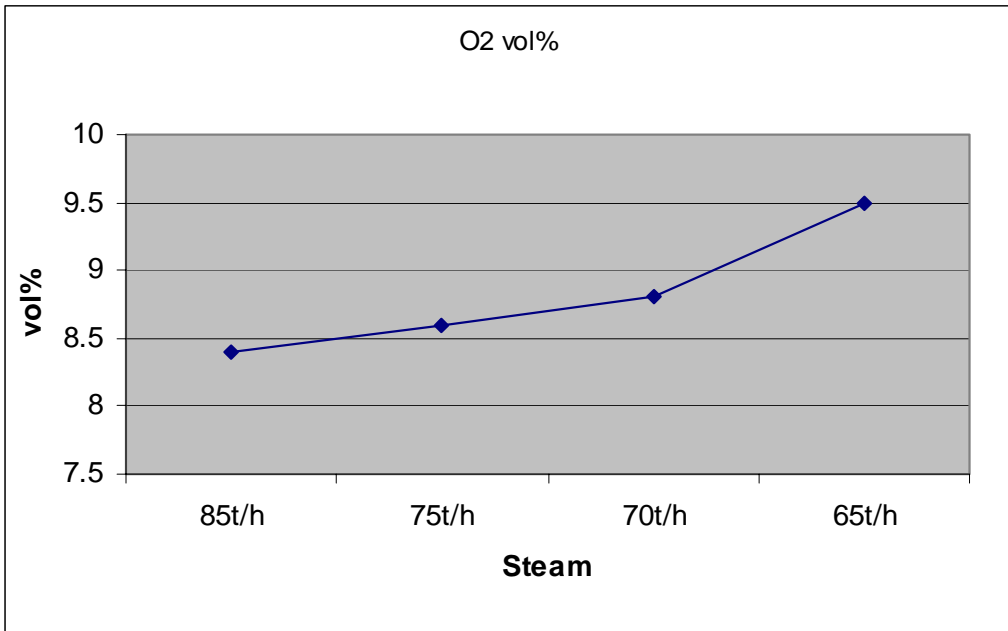


Figure 2.5.2: Oxygen content in the furnace at difference load

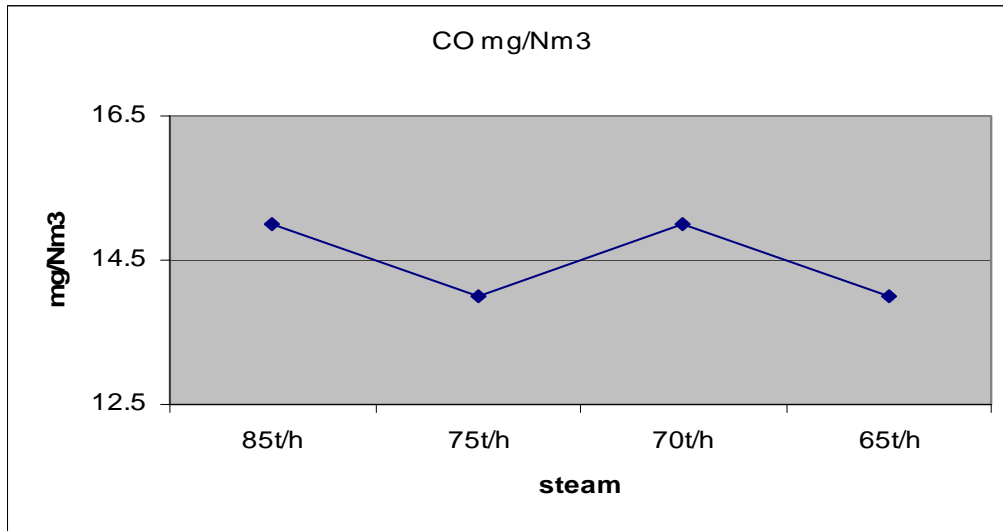


Figure 2.5.3: Carbon monoxide content in the furnace at difference load

As calculated 50% excess air condition implies approximately 7.5% (refer to table 2.4.3.1) oxygen remains in the boiler exhaust stack. When boiler is operated at load of 65 to 85 ton per hour the oxygen percentage content was 9.5 to 8.4 and this more than 50% excess used for the combustion. Carbon monoxide content in figure 2.5.3 indicated that there is no difference of incomplete combustion.

It is due to control philosophy of Automated Control System for Mitsubishi-Martin type incinerator that objective of controlling corrosion attack in tube at third zone are not being properly understand.

Literature review of corrosion control in the refuse boiler is best by studying or even visiting existing incinerators that have successfully implemented them. The Camden Resource Recovery Facility in USA, to control the furnace condition in targeting corrosion attack in furnace, furnace exit- temperature control loop is use to control its furnace condition.

Chapter 3

Cause of Corrosion and Leakage in the Boiler Super Heater Tube

- 3.1 Introduction
- 3.2 Corrosion
- 3.3 Types of Corrosion
 - 3.3.1 High Temperature Corrosion
 - 3.3.2 Oxygen Corrosion
- 3.4 Analysis of superheater tube thickness measured value.
- 3.4 Location of the Super Heater Tube in the boiler
- 3.5 Environment Condition in the boiler at the Location of Super Heater Tube
- 3.6 Analysis on Raw Hydrochloride (HCL) and Oxygen Content during Combustion Process

3.1 Introduction

Chapter 3 outlines the analysis on the causes of corrosion on a critical part of the boiler component – the super heater. It will provide some empirical measurements of heat transfer rate, surface temperature of the super heater tube, Hydrochloride (HCl) and the thickness of the dry ashes accumulated. The analysis will establish that the corrosion is caused by hydrogen-chloride (HCl) found in flue gas. While not a cause of corrosion, the report will also identify that slag, which is deposited on the tube surface by the rising ash-carrying flue gas, could potentially impair the structural integrity of the super heater tubes its performance in conveying steam at the optimum temperature.

3.2 Corrosion

Million of dollars are lost each year because of corrosion. Much of this loss is due to the corrosion of iron and steel, although many other metals may corrode as well. Corrosion is the rotting or deterioration of a metal by chemical reaction. It implies the transformation of a metal, in its elementary form, e.g. iron oxide or copper sulphide as a result of its interaction with its environment. This tendency to corrode exists because a metal wants to attain a more stable (less reactive) state. The problem with iron as well as many other metals is that the oxide formed by oxidation does not firmly adhere to the surface of the metal and flakes off easily causing “pitting”. Extensive pitting eventually causes structural weakness and disintegration of the metal.

3.3 Types of Corrosion

Two types of fired-side corrosion can occur in boilers:

- (a) High Temperature Corrosion
- (b) Oxygen Corrosion

3.3.1 High Temperature Corrosion

Introduction

High temperature corrosion is a form of corrosion that does not require the presence of a liquid electrolyte. Sometimes, this type of damage is called “Dry Corrosion” or “Scaling”. The term oxidation is ambivalent since it can either refer to the formation of oxides or to the mechanism of oxidation of a metal, i.e. its change to a higher valence than the metallic state. In most corrosive high temperature environment, oxidation often participates in the high temperature corrosion reactions, regardless of the predominant mode of corrosion. Alloys often rely upon the oxidation reaction to develop a protective scale to resist corrosion attack such as sulfidation, carburization and other forms of high temperature attack. For Fe base alloys the formation of volatile iron chlorides, instead of protective oxide, is the main driving force, Ni base alloys being more resistant.

High temperature corrosion has been a feature of boilers associated with mass burning refuse incinerators, particularly when there are heating surfaces exposed to the gases in the combustion chamber or high metal temperatures. It is believed that the high hydrochloride (HCl) content of the gases is a major cause of this. This HCl results from the high chloride content of the “Plastics” contained in the refuse. The situation is aggravated by reducing conditions, which exists due to the heterogeneous nature of the fuel, the deep fuel beds used, and hence the difficulty in achieving the correct air-to-fuel ratio at all points, in the furnace. It will be realized that the bonding salt, sodium pyrosulphate, will be present in most cases. This substance is highly corrosive to steel, and if allowed to persist will cause corrosion to take place beneath the deposits.

In general, the result of high temperature corrosion will be a reduction in the outside diameter of the superheater tubes and quite often, to flatten one face. Both of these processes have been detected during off-load inspection. (See Figure 3.3.1.1)

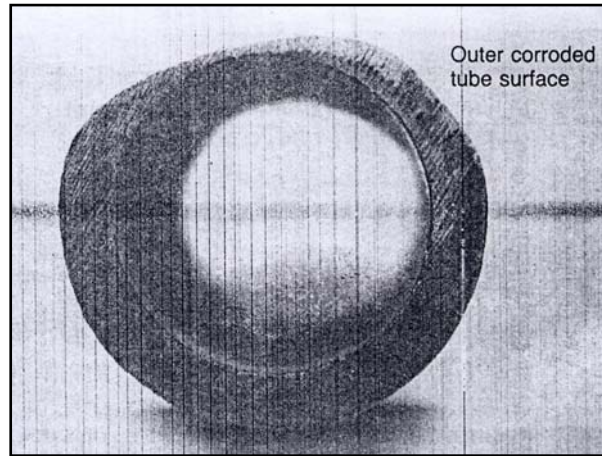


Figure 3.3.1.1: Effect of high temperature corrosion acts on the tube surface

3.3.2 Oxygen Corrosion

Introduction

The presence of excess free oxygen in the boiler environment has results in pitting attack on the superheater tube metal as shown in Figure 3.3.2.1 when it is of a localized area. Oxygen will also unite with the superheater tube metal in a general way to produce iron oxide (rust). Free oxygen can be produced as the temperature of the boiler environment rises, and the oxygen is forced out of solution. The oxygen then attaches itself in the form of a gas to a heating surface of the boiler to start the chemical reaction between oxygen and iron. The solubility of oxygen in environment varies with the temperature of the environment solution; it is generally assumed that oxygen comes out of solution usually above 371°C.

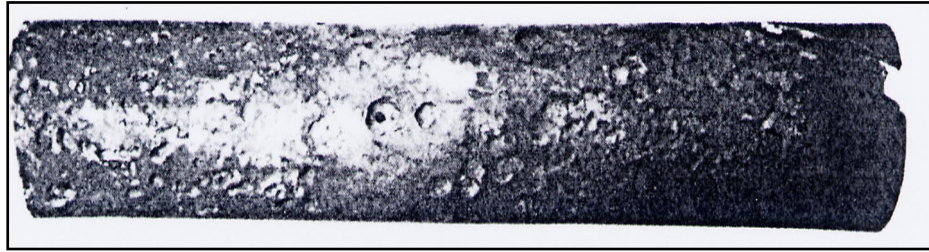


Figure 3.3.2.1: Pitting attack from oxygen on outside surfaces of boiler tube

The formation of rust can occur at some distance away from the actual pitting or erosion of iron as illustrated below. This is possible because the electrons produced via the initial oxidation of iron can be conducted through the metal and iron ions can diffuse through the water layer to another point to the metal surface where oxygen is available. This process results in an electrochemical cell in which iron serves as the anode, oxygen gas as the cathode, and the aqueous solution of ions serving as a “Salt Bridge” as shown below in Figure 3.3.2.2.

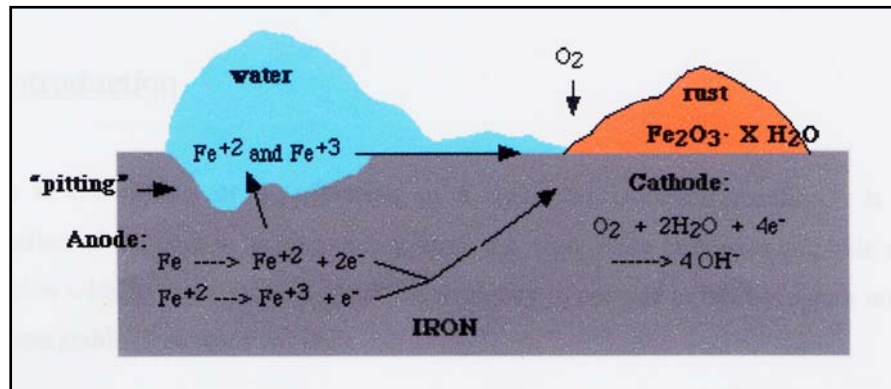


Figure 3.3.2.2: Salt Bridge

The involvement of water accounts for the fact that rusting occurs much more rapidly in moist conditions as compared to a dry environment.

3.4 Analysis of superheater tube thickness measurement.

Figure 3.3.2.3 The wall thickness average measurements

Taken from boiler annual overhaul record for the of year 2002, 2003 & 2004.

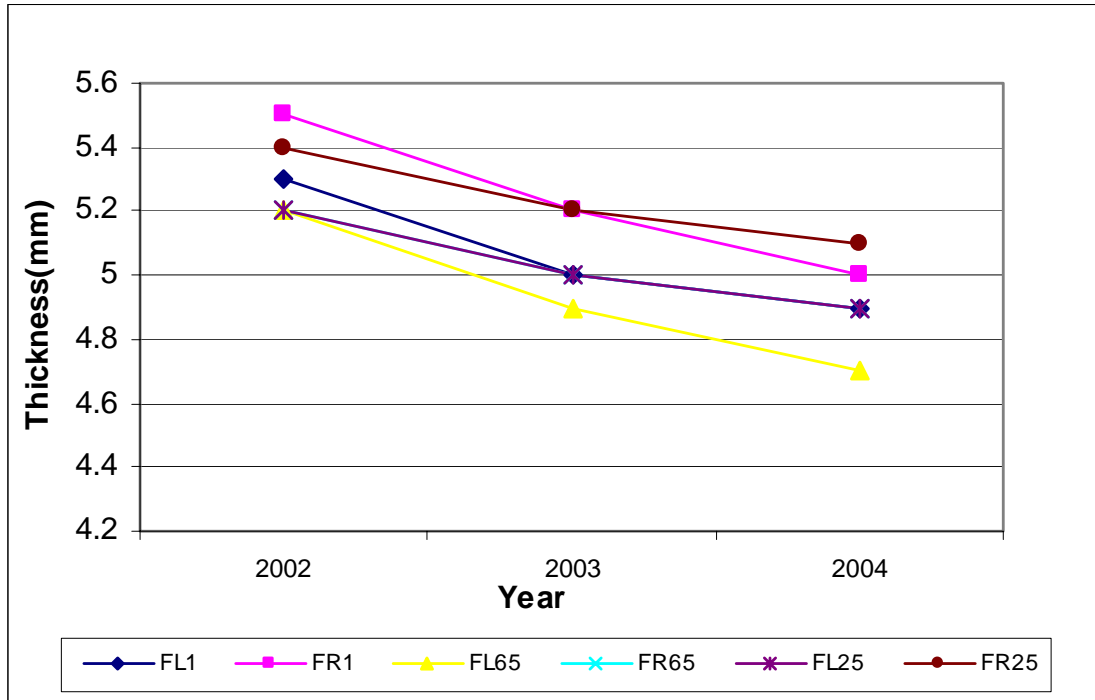


Figure 3.3.2.3 Superheater tube outside diameter reading

It was observed that from boiler annual report the superheater tubes in the 3rd zone experienced uniform thinning/corrosion problems. This general corrosion is characterised by an even, general wasting away of metal from the corroding surface. Where a metal is in contact with an acid (HCl) eg High-temperature corrosion or oxidation phenomena these virtually occur in dry environment.

3.4 Location of the Super Heater Tube in the boiler

The combustion of refuse in the furnace is an exothermic process, requiring no auxiliary fuel to sustain it. The flue gases are generated in the combustion process through burning of refuse. The furnace has four-flue gases passes. The mode of heat transfer to the tubes in the first two passes is by radiation. The super heater tubes are installed after the lower evaporator tubes in the third pass section before the flue gases are treated. Figure 3.4.1, shows the actual location of the super heater tube in the furnace.

The incineration process uses abundant air for complete combustion. However, the combustion process itself releases many pollutants in the form of dust and gaseous pollutants such as Hydrochloride (HCl), Sodium dioxide (Sox) and dioxins, which causes the boiler tubes inside the furnace to be corroded.

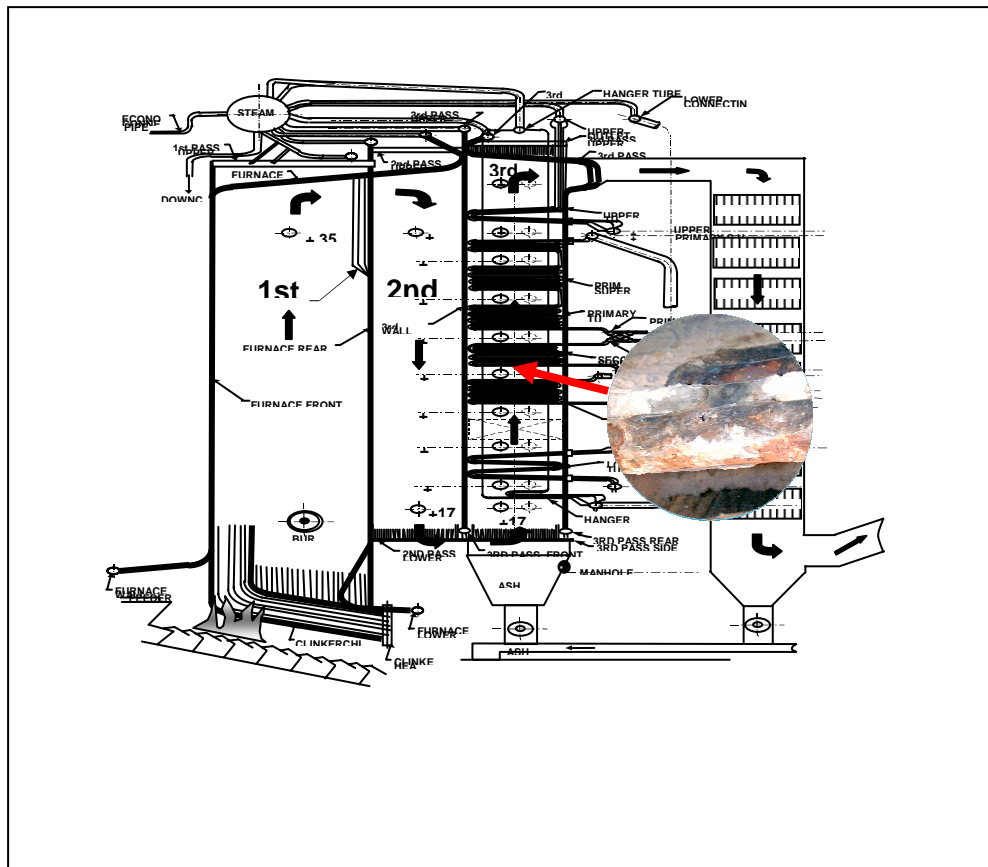


Figure 3.4.1: Location of the super heater tube in the furnace.

3.5 Environment Condition at the Location of Super Heater Tube

The high temperature gases generated from the combustion of refuse are cooled down to approximately 400°C to 470°C in passing through the wall tubes in the first two zones before flowing across the lower evaporator tube in the bottom area of the third zone.

The combustion gases in the third zone then raises and goes through super heater tubes area. Then the flue gas got into the economizer tube area through upper part of the third zone before flow into the equipment in it downstream, EP and Fabric Filter. Base on the data collected in the actual super heater tube located for one Week at difference operating load, Figure 3.5.1 shows that the environment temperature in the third pass section of the furnace is maintaining constantly at an average of 387°C, 437°C and 464°C.

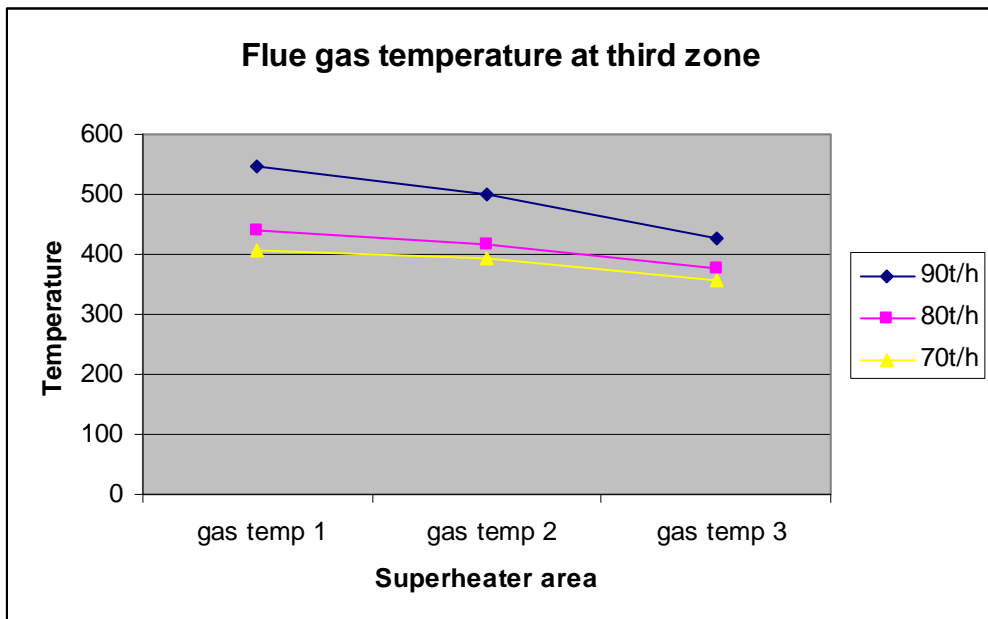


Figure 3.5.1: Flue Gas Temperature at third pass section in the furnace

It can be seen that the environment temperature condition is much under the influence of boiler operating load, which if boiler's operating load much higher it causes reducing atmosphere and minimum temperature at the tube. If these conditions do exists, the hydrochloric acid will attack the tube metal. This is the main reason for tube metal

wastage by the corrosive action of gaseous hydrochloric acid, set free particularly when burning PVC and other chlorinated plastics, as well as from heating sodium chloride and other chlorides always abundantly present in household refuse. Research has also shown that it would be desirable to limit boiler exit flue gas operating temperature at 600⁰C and steam operating pressure not acceding design limit, taking into account the effects of the respective saturated steam temperature of water-cooled evaporator tubes being a function of the boiler operating temperature. Because these can maintain the boiler exit flue gas operating temperature at desired limit and reduced corrosive attack on the tube.

In Hamm Plant in Dortmund, Germany, their superheater tubes had life spans of 10,000 to 12,000 hours because of the high flue gas temperature before the superheater of about 650⁰C leading to corrosion by Chlorine. The Plant then set the upper operating limit of 600⁰C for the exit flue gas temperature before the incinerator units are shut down for cleaning. This frequent cleaning cycle of once every 4 to 6 months prevented the flue gas temperature from reaching the upper limit of 600⁰c, thus extending the lifespan of the superheater tubes to 20,000 hours.

There is also the possibility of the percentage of moisture content to be significantly increased/decreased in the environment at the third zone section in the furnace depending on how low/high the operating temperature is. Once the operating temperature is decreased, which in turn increases the percentage of moisture content, the mixture molten ash and moisture would rapidly increase the ‘Slag’ generated on the surface of the super heater tube at the third pass section in the furnace (Refer to Figure 3.5.2).

Moreover, the formation of corrosion slag deposits is caused by the deposition of molten ash on surfaces receiving heat by radiation such as the furnace and radiant sections of the super heater. Entrained in the gas stream, molten ash particle strike the super heater tube surfaces becoming chilled then solidify. (Refer to Figure 3.5.3).

This ‘Slag’ will follow the flue gases, which flow in an upward direction across the superheater tube before flowing to the superheater tubes.

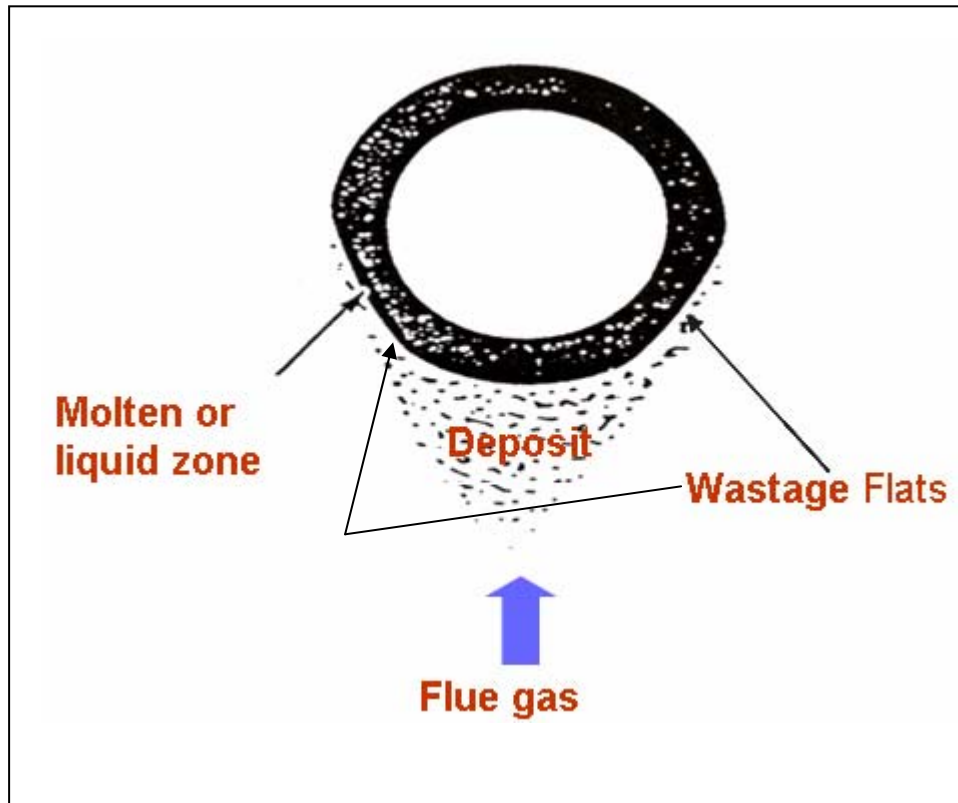


Figure 3.5.2: Wastage Profile on TSIP superheater tube

The solidified 'Slag' begins to distribute all over the surface of the super heater tube and eventually covers over the entire length of tube. Since the slag itself is quite corrosive due to the mixture of acidic gases such as HCl and Sox that are involved in its formation. Slag thus formed attacks the protective iron oxide layer and in course of time eats away the tube metal and weakens the tube material strength. Ash slag and soot deposits on the tube act as insulators that prevent heat transfer. It also restricts the flow of the flue gas, which is show in Figure 3.5.3.

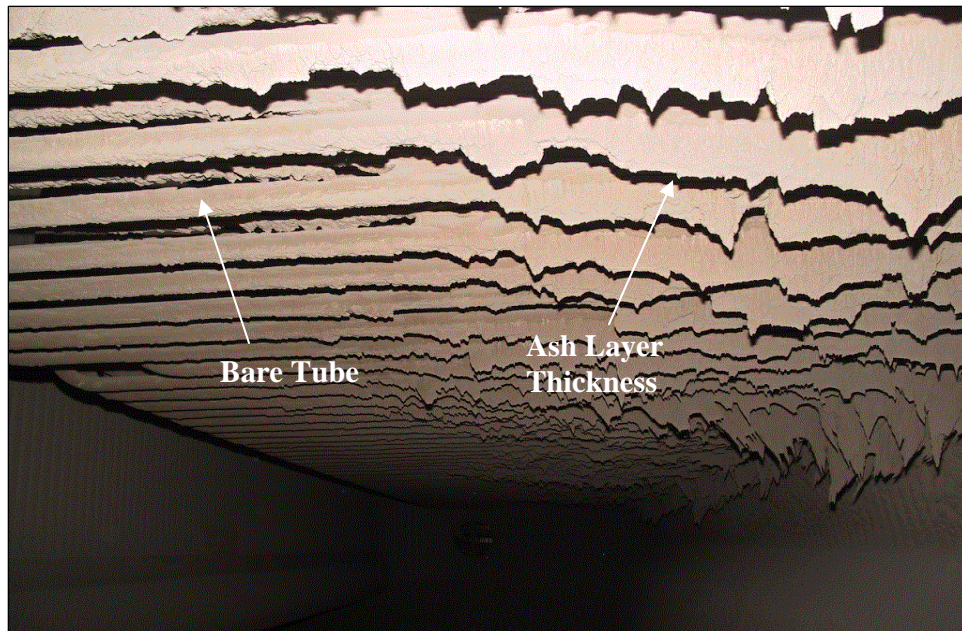


Figure 3..5.3: Overview of slag accumulated on the tube surface

This slag would significantly affect the properties of the tube in the boiler. The slag is thickened as times goes by, depending on the amount of flue gas passed through the superheater tube in third zone of the furnace. When the ash layer builds to a particular thickness, the film of liquid/moisture can no longer support the weight, the ash layer falls off exposing the bare tube to the high temperature environment, and the local heat flux jumps. This sudden rise in heat flux means a sudden rise in temperature and creates a locally high stress. As the ash layer reforms, the insulating effects of the ash reduces the metal temperature. Over several (or many) such cycles, corrosion-fatigue cracks form.

As can be appreciated for the description above, leakage and corrosion on the surface of the super heater tube will eventually occur, which is shown in Figure 3.5.3B.

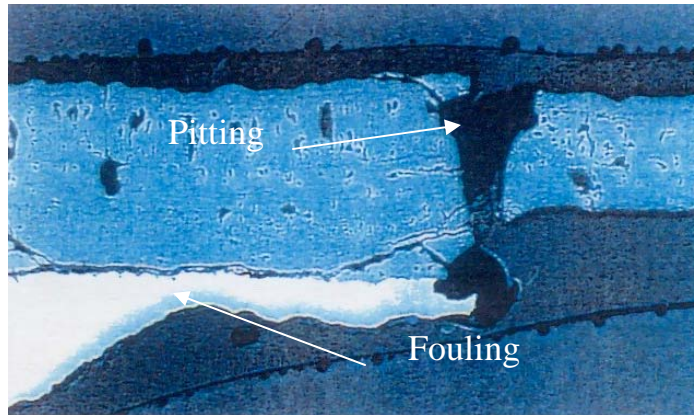


Figure 3.5.3A: Schematic view of corrosion penetration on the tube

Moreover, from the Figure 3.5.3A, small gather holes (pitting) can be observed at the leakage area of the pipe. The holes are smaller in the inside compared to the outside area of the pipe. There are no deformations nor uneven thickness distribution were seen from the inside or the outside of the pipe except for small gather holes (pitting)

These facts indicated that the small holes were caused by the corrosion from the outer surface of the tube by the covered slag and acidic gases. Thus making some small holes digging into the tube and finally penetrates through the tube thickness. This causes steam to leak out through the small holes and washed away adhered substances as well as tube metals, which in turn enlarge the holes (pitting). There is evidence to indicate that high temperature environment raising the corrosion potential of carbon steel above the critical potential for pitting when Hydrochloride is present. In addition, we discovered that Fouling on the inner surface of the tube is due to poor water treated in the water treatment plant causes another effect that forms an internal corrosion to rapidly destroy on the metal lead to the failure of an entire boiler performance.



Figure 3.5.3 B: Effect of corrosion on the super heater tube



Figure 3.5.3.C Scaling on tubes surface in the third zone before the deposits were cleaned.

3.6 Analysis on Raw Hydrochloride (HCL) and Oxygen Content during Combustion Process

Refuse is also likely to contain chlorinated plastics; there is thus a potential risk, due to the release of chlorine compounds and their interaction with other substances, of creating complications with both deposits and corrosion. From the previous chapter 2, we noticed that the percentage disposal of “Plastics” content is increasing gradually throughout the past three years which in turn means high Hydrochloride (HCl) content will pollute the environment in the furnace causing an acid to form and add to the attack on boiler metal such as the super heater tube.

The composition of the gas at outlet of the boiler exit was measured during the combustion process. The gas measurements were carried out on boiler number 6 at four different operating temperatures of the steam load. Figure 3.6.1 shows that the presence of raw HCl is linear to the operating temperature of the steam load. Higher HCl is produced as more refuse-plastic is burned to operate boiler at higher operating temperature. As mentioned in chapter 2 there is an increase of 8% of plastic materials arriving at TSIP each year.

In view of the problem mentioned above, it could be able to predict that the lifespan of the pipe depends on the behaviour of HCl (acidic gas) content which will attack the super heater tube uniformly. But other factors that cause localized corrosion on the super heater tube may force immediate boiler outage.

Moreover, we realized that the actual percentage volume of oxygen content in the furnace environment is 9.5%, which is above the recommended percentage volume of 9% (Refer to Figure 3.6.2). Excess oxygen will gradually make the metal of the superheater tube flake off easily causing “Pitting” problem. Extensive pitting eventually causes structural weakness and disintegration of the metal.

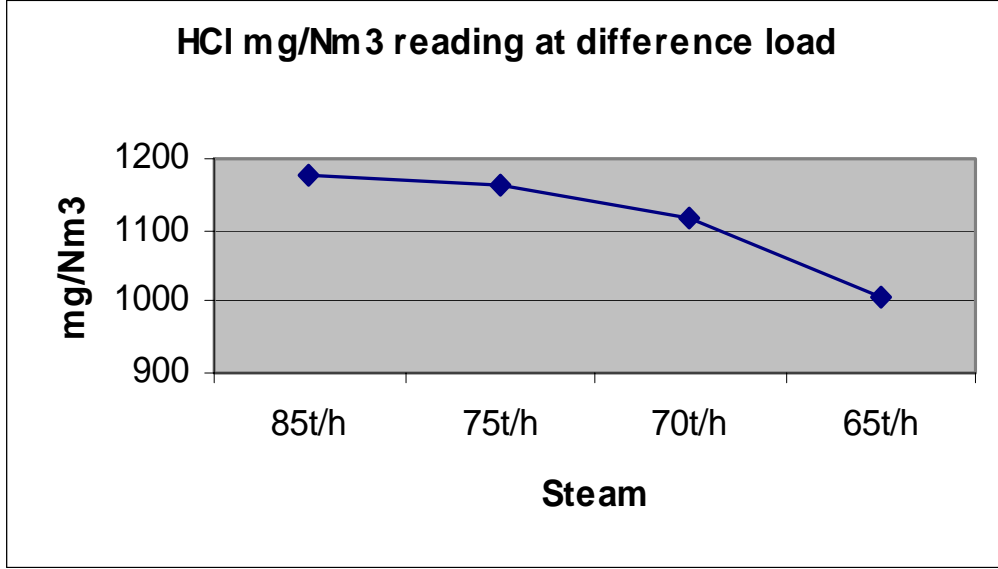


Figure 3.6.1: HCl inside the furnace with respect to load.

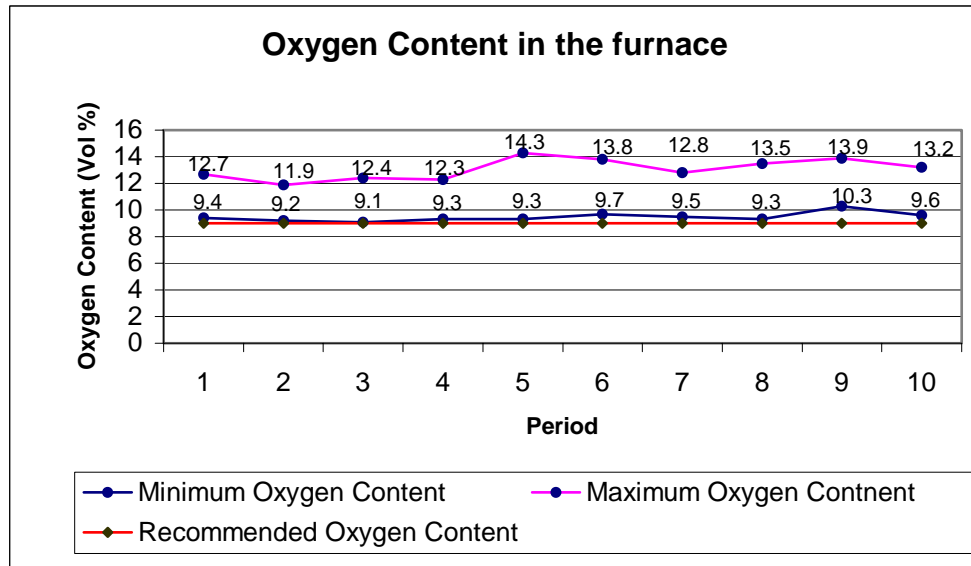


Figure 3.6.2 : Oxygen Chart obtained from the furnace.

Chapter 4

Experimental

- 4.1 Introduction
- 4.2 Experimental Procedures
 - 4.2.1 Safety Aspect
 - 4.2.2 Permit-To-Work Procedures
- 4.3 Analysis on Corrosion of the Test Specimens in the Superheater location
 - 4.3.1 Observation
 - 4.3.2 Analyzing the ash deposited at the Superheater tube
 - 4.3.3 Tube metal temperature
 - 4.3.4 Experiment
 - 4.3.5 Studies of TSIP incinerator Fly Ash
- 4.4 Stress Calculation in the Superheater tube
 - 4.4.1 Internal Pressure in the superheater tube obtained through experimental
 - 4.4.2 Stress calculation

4.1 Introduction

Corrosion in any system depends upon two major factors – material used and environmental conditions. Different materials may corrode at different rates in a given environment. When corrosion takes place, the surface of the metal dissolves and a new layer is exposed. Depending on a large number of conditions, the corrosion may be fairly even over the whole surface (i.e. Uniform attacks) or it may be concentrated at some points.

So the field test in high temperature environment of the TSIP boiler is part of this project to study the caused of the boiler tube corrosion. This to evaluate the environmental conditions in the boiler that produced by the incineration of refuse of the corrosion attack on the present tube used and its experimental analysis results will focus on Slag Growth Rate, Heat Transfer Rate and Metal Temperature of the super heater tube behavior for a period of the test.

4.2 Experimental Procedures

These high temperature corrosion experiments will be conducted on a mild steel boiler tube, ASME SA-192 steel cut from the original superheater tube, of nominal dimensions: 42.7 mm outer diameter by 11.35mm inner diameter. All samples of the tube were hand sanded to remove a coating on the outside of the tube and to provide a uniform surface finish. 'ASTM G111'- Guide for Corrosion Tests in High Temperature are used as a guild in this experimental.

The corrosion tests will be performed in a third-zone furnace with temperature range of 400°C to 550°C. The boiler will be burning a well mixed refuse in the bunker with constant operating temperature. The third zone is simulation of the real environment to conduct this high temperature corrosion test. Tests were conducted, where the gas and specimens will be at approximately the same temperature. Unfortunately the specimens

are not being able to test where the flue gas is at a higher temperature than the metal as in the real situation of the burning boiler.

Flue gas compositions of CO, SO₂, HCl and O₂ will be monitored and recorded using computer-controlled digital controllers via our analyzer system. Percentage of water vapor (H₂O) is also added in the recording sheet, to study the extent of water vapour combine with the flowing flue gas mixtures. The test will be carried out at three boiler of TSIP.

The boiler load or its operating temperature will be maintained through out the experimental period. The exposure of the specimen will be carried for one month period for each test.

4.2.1 Safety Aspects

Boiler will be shut down for mounting of the specimens in the third zone boiler. Specimens should be mounted in such a way that they are securely held and are electrically isolated from contact with all other metals part of the boiler. The brackets and bolt used to secure the specimens should be fully resistant to the test environment. In this test a stainless steel grade is used for the brackets and bolts. This is to prevent dropping off specimens in the boiler and loss of data if the secured bolts failed in the corrosive environment.

In general any work that needs to be carried out in the boiler required a valid Permit – To-Work endorsed by the appropriate authority and the necessary precautions must be taken. Usually a competent person (Charge Engineer or Licensed Electrical Worker) must also be assigned to monitor closely the progress of the work. This is to ensure that the live equipment is safely isolated or disconnected prior to access. In this case for instances, when working in the boiler, both boilers ID fan and FD fan needs to be ‘off ‘and electrically isolated. The Permit-To-Work system is continually enforced by the shift Charge Engineer under the overall supervision of the Assistant Manager

(Operation). Disciplinary actions will be taken on any person found working illegally on any equipment. In addition to the Permit-To-Work system, the heads of individual sections on duty must assured their staff are properly briefed, trained and equipped for any work they are to carry out on any plant equipment. Equipment/ work places must be checked before commencement of work. In this experimental work there is a need to enter the boiler to mounts the specimens so additionally gas checking procedure by the chemist and the supervisor of the relevant section. This is to ensure that any toxic, explosive and hot gases are adequately removed and proper ventilation has been provided by the supervisors of the relevant section. All access into any confined spaces must be carried-out by at least two persons.

4.2.2 Permit- to- Work Procedure

Before the proposed work is carried out on live equipment, PTW forms are to be completed in duplicate by the engineer or his designated subordinate(s) intending to work on such equipment. If the charge engineer considers that the nature of the work and timing is acceptable, he or his authorised subordinates will proceed to carry out the necessary isolation to ensure that the section of the plant where work is intended to be carried out is made safe. Proper and clear signboards must also be displayed to indicate that the equipment is under maintenance.

The shift staff in charge of the equipment must also be properly briefed on the nature of the job. High voltage switching is to be carried out only by an authorised person. When a PTW form is issued, it becomes a Permit to carry out work within the validity period specified. One copy is to be retained by the applicant and the duplicate is to be kept in the Central Control Room. The applicant should counter-check on the isolation. During the maintenance, the respective supervisor and console operator must know the status and progress of work by checking at local. On completion of work, the applicant must ensure that all tools and test equipment are withdrawn and the workplace is cleaned.

The Charge Engineer then counter checks that the section of the plant under the PTW has been cleared and ready for normalisation before proceeding to remove the isolation and normalise the equipment. If the work cannot be completed within the day, the applicant must inform the Charge Engineer regarding the equipment status. The PTW must return to the Central Control Room for filing. The applicant must report to the Charge Engineer before resuming work on the next day. If the work is suspended or cannot be completed within the given period in the PTW, new application for PTW is required when work is resumed.

A PTW is required for entry into any restricted areas such as switchgear room and the confined spaces. All plant personnel and contractors must obtain their PTW from the Charge Engineer through the supervisors of respective sections. The supervisor of the relevant section must assure that their contractors have taken all necessary safety precautions before commencement of works.



Figure 4.2.2.1: Specimen location

4.3 Analysis on Corrosion of the Test Specimens in the Superheater location

4.3.1 Observation

During the operation of boilers, the variation of flue gas composition attributed by the variation in composition of refuse supplied causes the percentage content of HCl to be inconsistent in the environment inside the furnace. One of the problems with heat recovery boilers behind incinerators of solid, liquid or municipal solid wastes is “High Temperature Corrosion” associated with the formation of complex eutectics which have a low melting point and deposit as slag on superheater tube surfaces. This is difficult to get rid of and results in high temperature corrosion, fouling problems and consequent higher exit gas temperature from the boiler and lower steam generation. Another concern in these applications is the presence of corrosive gases such as chlorine and hydrogen chloride, which corrode the boiler tubes, particularly those operating above metal temperature of 371°C, resulting in tube thinning and failure. Chlorine attacks steel even at 230°C to 330°C. In addition, several non-ferrous salts are formed with chlorine, which also have very low melting points. These also deposit on low temperature surfaces such as superheater tubes and corrode them.

With the combination of moisture (including excess air) and HCl in the flue gas flow across the superheater tube, the surface of the superheater tube would then be corroded. The thickness of corrosion deposits on the surface of the superheater tube increases gradually with respect to time.

4.3.2 Analyzing the ash deposited at the Superheater tube

The steam generated in the boiler is wet saturated steam and contain some moisture. This moisture is vaporized and further heat to produce dry saturated steam. The superheater is the equipment that such dry saturated steam is formed. The superheater is mounted at the third pass, where steam is super heated is formed. As accumulation of the ash deposited at the tube increased the flue gas and steam operating temperature after hours of

operating. The boiler then needs to be shut down for tube cleaning.

Experimental analysis was carried out to find the effect condition of ash deposited at the superheater tube. Figure 4.3.2.1: shown the third pass gas temperature at three difference points before the tube is cleaned.

Figure 4.3.2.2 : shown the third pass gas temperature at the three difference points after the tube is cleaned.

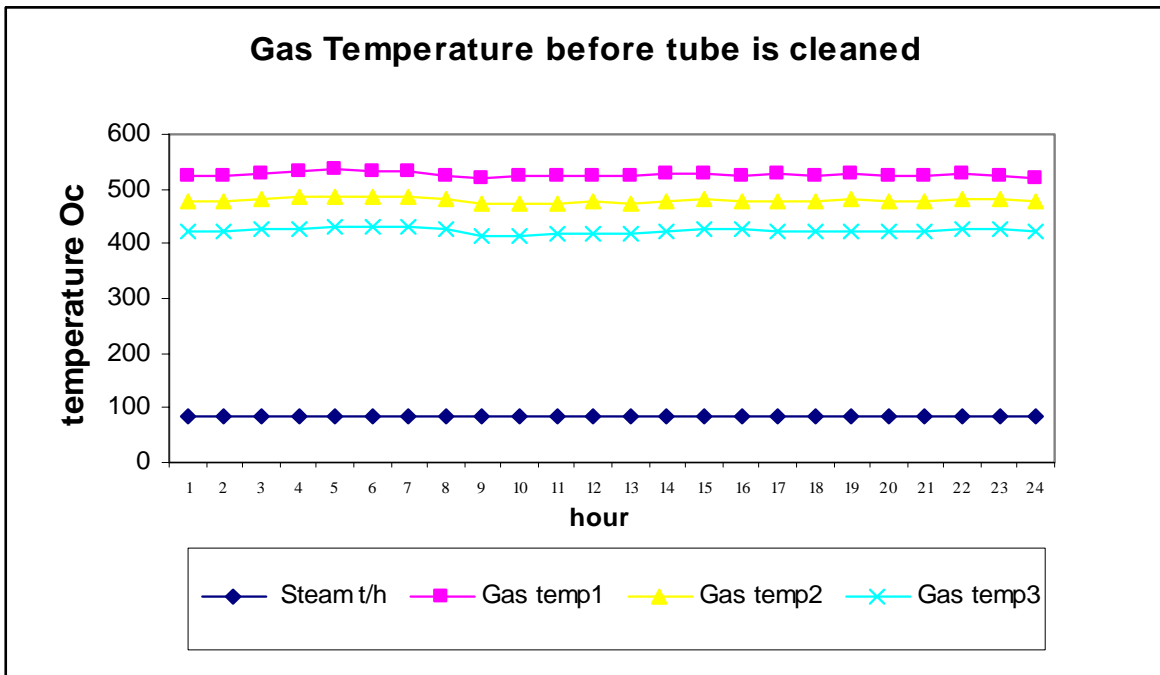


Figure 4.3.2.1 : Temperature of the flue gas taken **before** boiler was shutdown

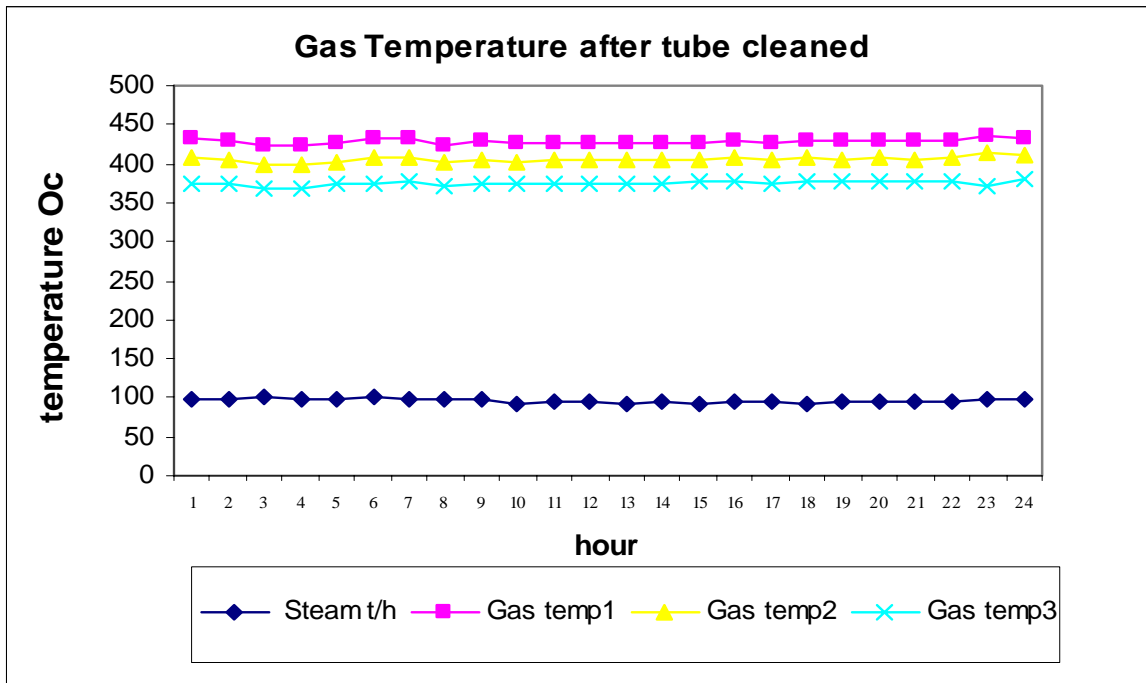


Figure 4.3.2.2 : Temperature of the flue gas taken **after** boiler tube was cleaned

This boiler number six was operated at about 100 ton per hour of steam after the boiler tube is cleaned. This is a maximum boiler capacity. It was observed that although boiler operating at maximum capacity, its exit flue gas operating temperature is much low that when it was operated at 85 ton per hour of steam at the tube which was not cleaned.

With this analysis it can be concluded that the ash deposited has caused higher exit flue gas and steam operating temperature. This increased the temperature on the tube surface of the superheater which is one of the factors that caused corrosion on the tubes. The thickness of the scaling can be related to the exit flue gas operating temperature.

The main reason for tube metal wastage is the corrosive action of gaseous hydrochloric acid (HCl), set free particularly when burning PVC and other chlorinated plastics, as well as from heating sodium chloride and other chlorides always abundantly present in household refuse. Research has also shown, however, the certain conditions have to exist for the aforementioned metal wastage to take place. Thus, metal wastage only takes place in the simultaneous presence of a reducing atmosphere and a certain minimum temperature at the tube surface. If these conditions do exist, the hydrochloric acid will

attack the tube metal. Figure 4.3.2.3 shows the increasing temperature of the metal surface for a period of six months. Both steam and flue gas temperature remained constant at same steam load after this period. This analysis confirmed that deposits layer build at the surface of cleaned tube reached its average maximum thickness after six months after in operation. Figure 4.3.2.4 and 4.3.2.5 shown the analysis of deposits growth of the tube surface.

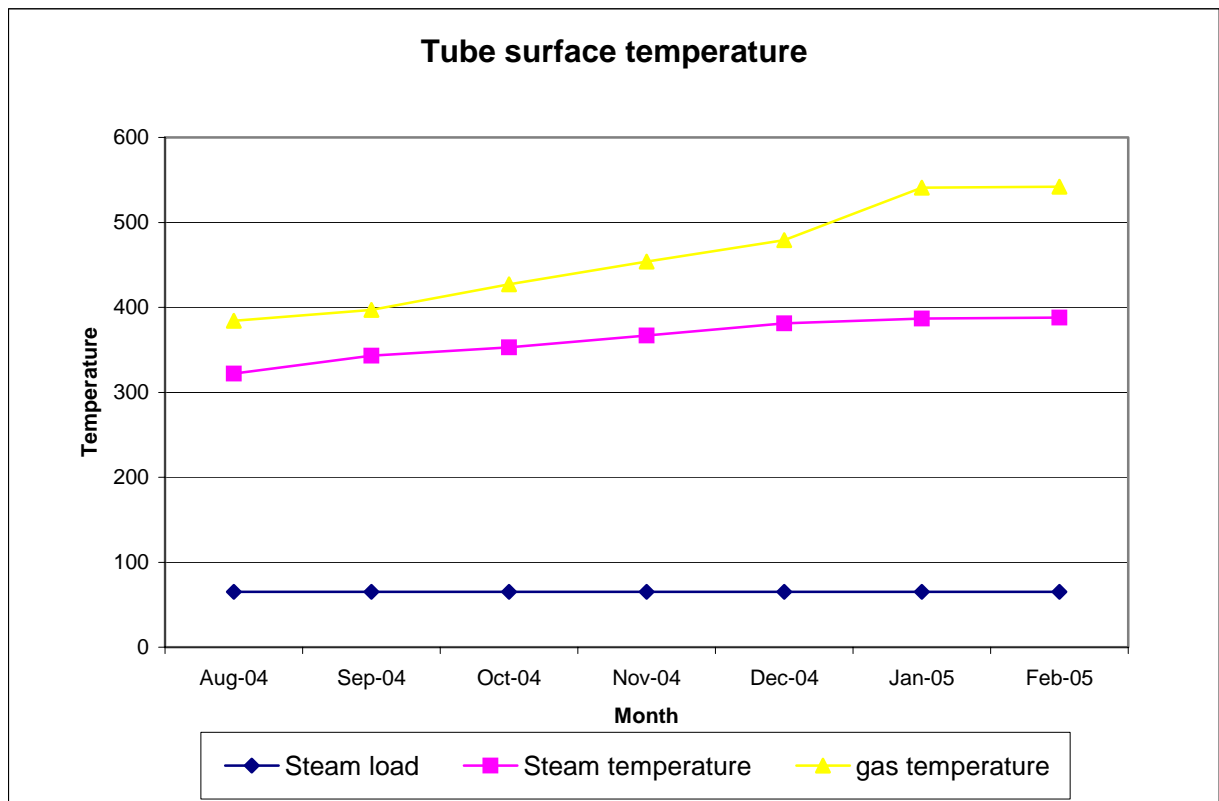


Figure 4.3.2.3 : The increased of the tube metal temperature based on both its gas and steam temperature.

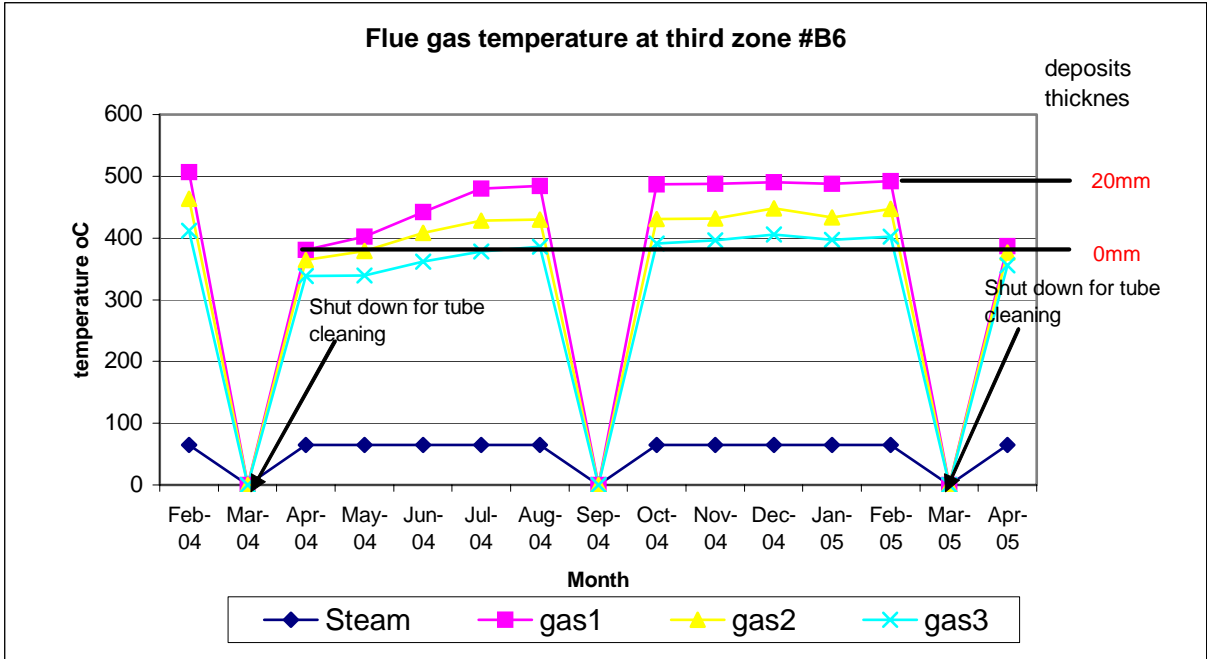


Figure 4.3.2.4: Deposit growth of boiler #6 tubes

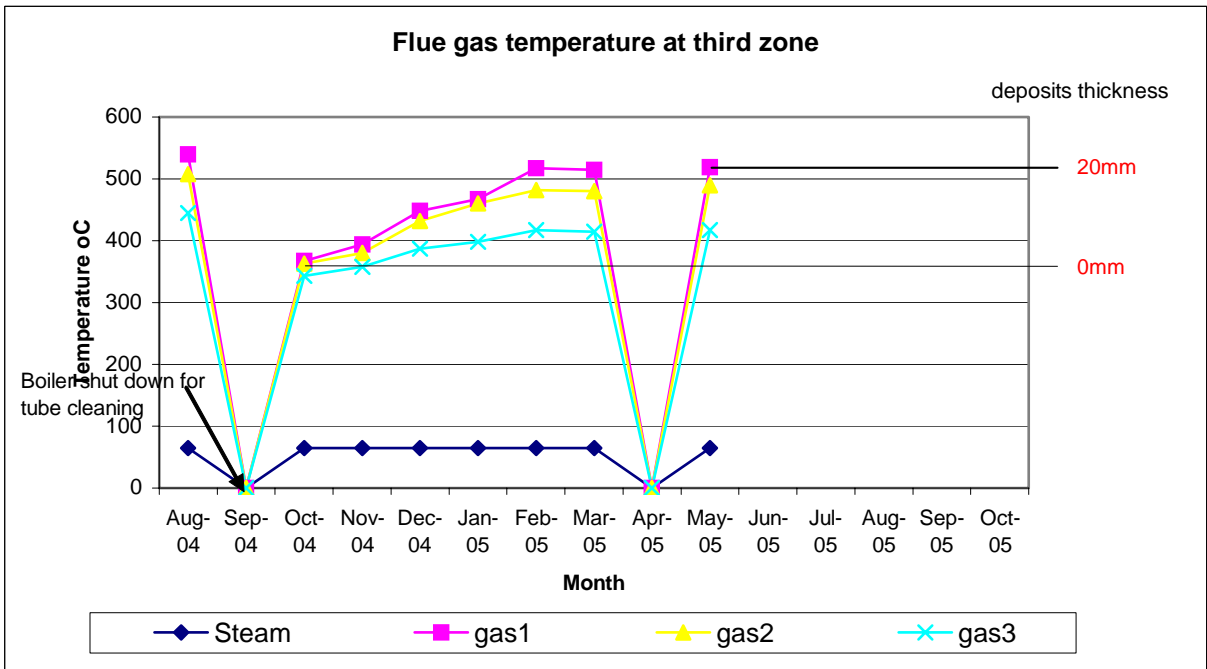


Figure 4.3.2.5: Deposit growth of boiler #3 tubes

The thickness of the deposits was measured locally on the tubes surface at selected points. Measurement was done at the shutdown boiler before the work on tubes cleaning is carried out. It was found that the average thickness of the deposits is 20mm thick. This thickness measurement is taken as a maximum average deposits thickness on the tubes.



Picture 4.3.2.6 : Tubes surface before and after cleaning of deposits.

4.3.3 Tube metal temperature

Tube metal temperatures of the superheater vary throughout the year after the tubes were cleaned. Highly sophisticated techniques of analysis and much experience go into predicting what these temperatures will be; these temperatures rarely turn out exactly as predicted, due to all the variables involved. So these analyze is done to predict that ash deposits build at the tube influence the increased metal temperature.

The amount of literature on ash deposits related issues is immense. In any heat transfer activities its effectiveness depends on surface absorptivity (R. P. Gupta et al –ref 1). The deposits on the tube have a significant influence on the heat transfer rate. As shown in figure 4.3.3.1 when boiler with maximum deposits on its superheater tubes it needed higher gas and steam temperature to produce a same load compared to a cleaned tubes. This is also increasing the metal temperature of the tube. Metal temperature for boiler #2 tube is higher as it gas temperature₂ at point 3 is **557°C** and steam temperature₂ is **384°C**. While at same boiler load of steam 65 ton per hour metal temperature for boiler #6 is at gas temperature₆ of **403°C** and steam temperature₆ of **344°C**. It is at lower range compared to boiler #2. It is also shown in figure D that boiler #2 which is due for tube cleaning produced a flue gas temperature₂ of above **600°C** when steam load is increased to 85 ton per hour. Under TSIP boiler operating design inlet flue gas to superheater at 600°C and above may increase corrosion rate. Steam load of 85 ton per hour is well below maximum load of 100 ton per hour.

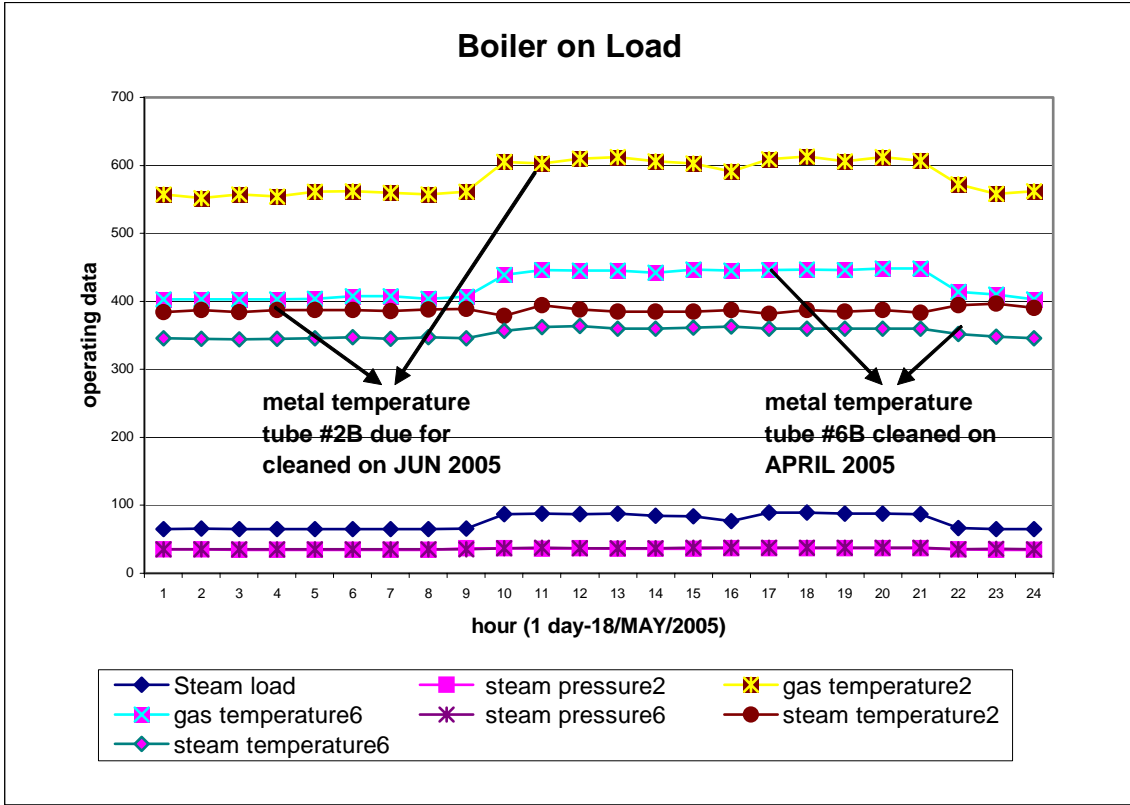


Figure 4.3.3.1: Two boiler on same load, boiler#2 due for its tube cleaning and #6 its tube cleaned on April 2005

4.3.4 Experiment

An experiment was carried out using specimens, which have the same properties and characteristics as the superheater tube. The test specimens were placed at two different boilers. The test specimens were carbon steel tubes 148 mm long 42.7 mm in diameter and 10 mm in thickness. Tests started by the introduction of burning refuse in the incineration process with the constant steam load of 75 tonnes/hour for each boiler. Test temperature range was monitored and controlled between 400°C to 470°C, and HCl concentration varied from 700 mg/Nm³ to 1000 mg/Nm³. Two thermocouples and one HCl analyzer sensor were placed at locations below the superheater tube and next to the specimen to monitor and control the “Temperature & HCl Concentration”. Total test duration was 1 month at each boiler, at which time the boiler was shutdown and the specimen was cooled with a continuous airflow at the fluidizing velocity.

Corrosion around the circumference of a test specimen was determined using an “Image Analyzer” (Refer to Figure 4.3.4.1) for inspection immediately after cooling. Vernier Caliper was used to measure the corrosion thickness on surface diameter of the specimen after testing (Refer to Figure 4.3.4.2 & 4.3.4.3). Figure 4.3.4.4 & 4.3.4.5 shows the experiment results of corrosion growth on the surface of the specimens with a period of one month each at three different boilers. The corrosion has slightly eaten away the metal of the tube with an average thickness of 60 microns for the two specimens. This result shows that there is a potential risk of the tube to fail within a year (minimum thickness requirement is 3.32 mm) if the slag accumulation on the tube is allowed.

The Nikon ME 600 Image Analyzer was chosen as the equipment to analyze the corrosion behavior on the surface of each specimen placed at two different boilers respectively. From the Figure 4.3.4.2 & 4.3.4.3, we observed that all the two specimens have common corrosion defects, which have several similar forms of cavities which were confined to a point or small area on the tube surface. This type of corrosion is called “Pitting”, which ate away the metal and penetrated through the tube surface causing severe damaged to the superheater tube. This pitting corrosion is due to the deposits slag accumulated on the tube surface, which will reduce the heat transfer rate. Pits formed

under simultaneous stress and corrosion is always shaper and deeper than pits formed in the same time under stress-free conditions. The more repetitive the stress, the faster will be the pitting action. At low-cycle repetitive stress, pitting will proceed entirely by normal corrosion, and the section will fail by normal tension failure or when the resisting area is thinned down so the stress rises proportionately at constant steam load.

Moreover, the test specimens did not exhibit any cracking lines on the tube surface because cracking normally occurs when the wall thickness of the tube is too thin to withstand the fluid pressure. Pit cracking that occurs on the tube surface usually begins at surface defects, pits or irregularities. These points act as stress-concentration points with the corroding medium intensifying the pitting action. The more repetitive the stress, the faster will be the pitting action, which again will increase the stress concentration. A cumulative effect can materialize that will cause a failure well below a predicted endurance stress.



Figure 4.3.4.1 : Nikon ME 600 Image Analyzer

Test Specimen Data:

Material : Carbon Steel
Length: 148mm
Diameter: 42.7mm
Thickness: 10mm

Test Condition:

Boiler is running at constant steam load of 75 t/h
Test temperature range between 400 to 470 deg°C
HCL concentration between 700 to 1000 mg/NM³



Figure 4.3.4.2 : Specimen Corrosion Thickness Measurement for
Boiler # 1



Figure 4..3.4.3 : Specimen Corrosion Thickness Measurement for
Boiler # 2

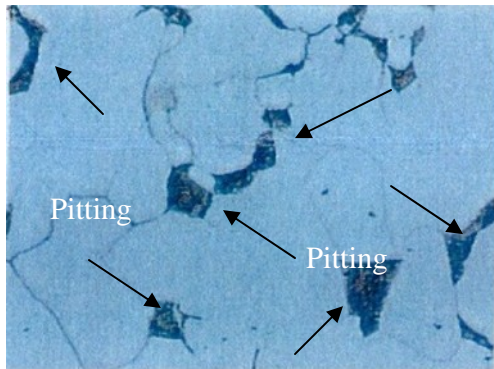


Figure 4.3.4.4: Test specimen for boiler #1

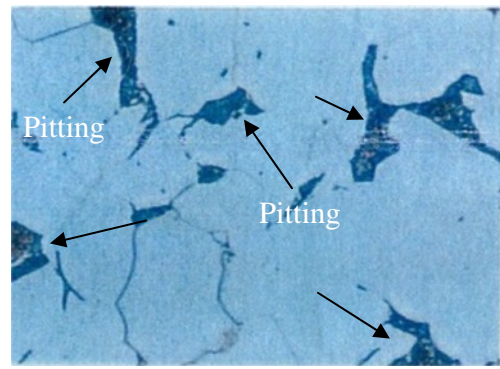


Figure 4.3.4.5: Test specimen for boiler # 2

From the above analysis, the superheater tube in contact with Hydrochloride (HCl) and Moisture (inclusive of Oxygen) Content would have an increased chance of corrosion at elevated temperatures from the combustion of refuse. With increasing HCl concentration and percentage volume of Oxygen content in the environment of the furnace, the maximum corrosion rate of the superheater tube increases and the corrosion region broadened which causes a noticeable increase in wastage, particularly with down time corrosion where HCl can react with moisture (include of oxygen) to cause severe pitting attacks on the surface of the superheater tube.

4.3.5 Studies of TSIP incinerator Fly Ash

Figure 4.3.5.1 and 4.3.5.2 shown the result characterization of the fly ash at the superheater.

Characterization and stabilization of the fly ash

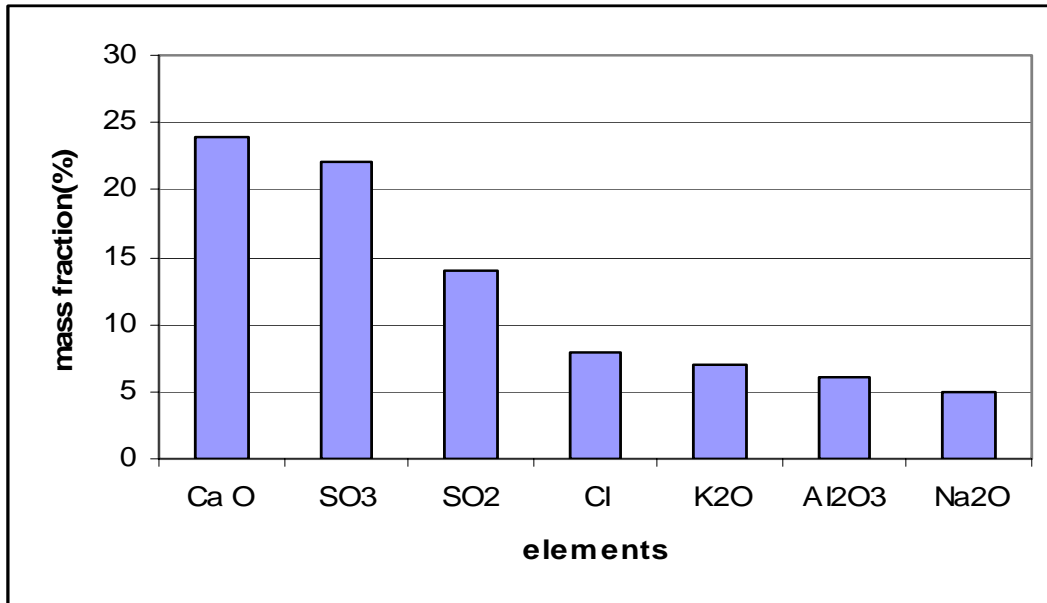


Figure 4.3.5.1 Distribution of elements in TSIP fly ash

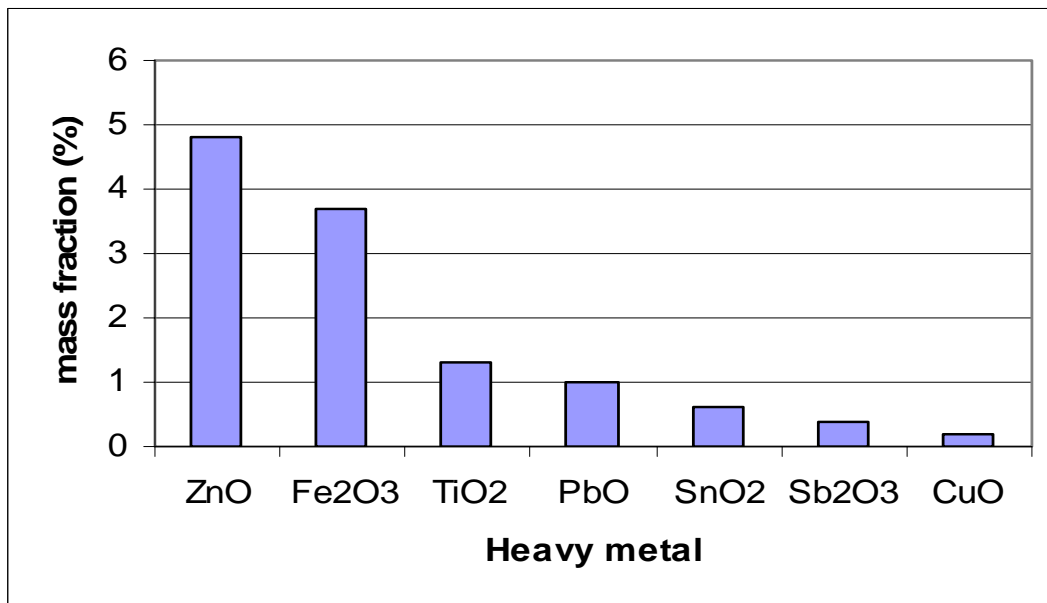


Figure 4.3.5.2 Distribution of heavy metal in TSIP fly ash

4.4 Stress Calculation in the Superheater tube

Based on design data of TSIP boilers its superheater tube maximum internal pressure is at 45 bars. Its maximum steam temperature in the superheater shall be less than 400°C. The average maximum steam temperature taken for 24 hours after boiler was in running for 12 months is 385°C. Its actual steam temperature is below the design steam temperature limit.

4.4.1 Internal Pressure in the superheater tube obtained through experimental

The first loading for a superheater tube that is important in considering its strength is that of internal pressure. Figure 5.1.1 shows that internal pressure of the superheater tube, which has been taken for the period of a one day to determine the actual internal pressure for ease in calculating the stress in superheater tube. The boiler was later shutdown for tube cleaning.

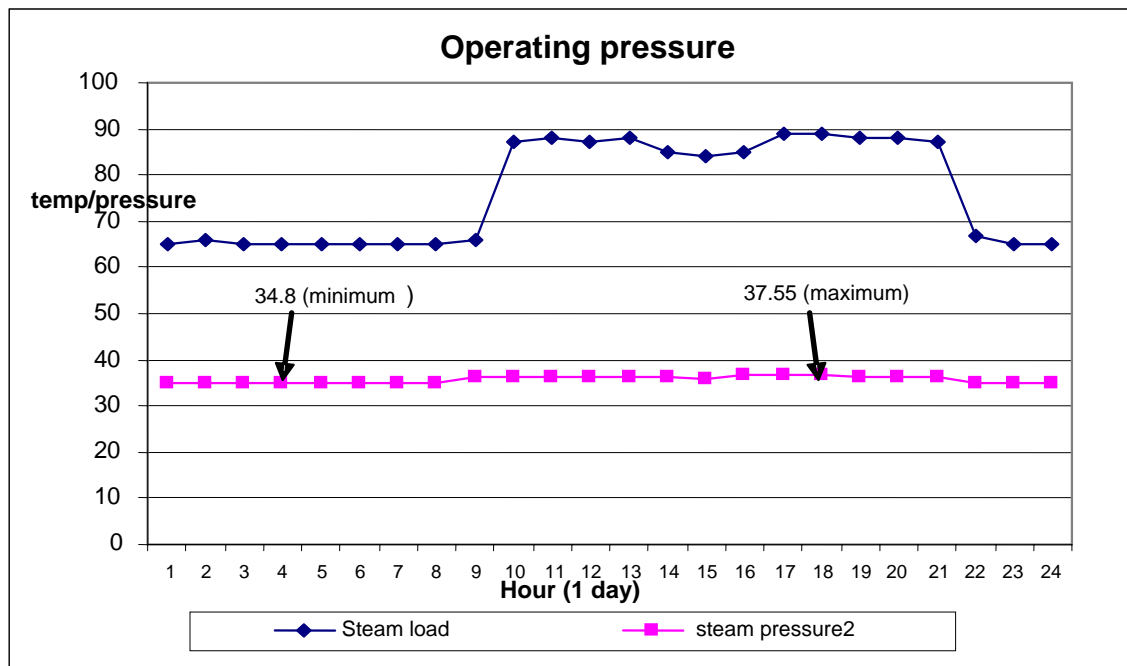


Figure 4.1.2: Maximum and Minimum internal pressure in the superheater pipe

4.4.2 Stress Calculation

The internal pressure was taken from the Figure 5.1.2 with the maximum pressure of **37.55 bars**. Thus we are now taking into consideration in which only internal pressure (P_i) acts on the Superheater tube. The theoretical equation to predict the radial and tangential stresses in the superheater tube is given as:

$$\text{Radial stress} = [(a^2 P_i) / (b^2 - a^2)] [1 - (b^2 / r^2)]$$

$$\text{Tangential stress} = [(a^2 P_i) / (b^2 - a^2)] [1 + (b^2 / r^2)]$$

Where a = Internal radius of the tube (m)

b = External radius of the tube (m)

r = Variable radius of within the tube (m)

P_i = Internal Pressure (N/m² or Pascal)

t = Tube thickness(m)

Calculation

At $r = a$

$$\begin{aligned} \text{Radial Stress} &= [(a^2 P_i) / (b^2 - a^2)] [1 - (b^2 / r^2)] \\ &= [(0.01635^2 \times 37.55 \times 10^5) / (0.02135^2 - 0.01635^2)] [1 - (0.02135^2 / 0.01635^2)] \\ &= -3.775 \text{ MPa} \end{aligned}$$

Hence

At $r = b$

$$\begin{aligned} \text{Radial Stress} &= [(a^2 P_i) / (b^2 - a^2)] [1 - (b^2 / r^2)] \\ &= [(0.01635^2 \times 37.55 \times 10^5) / (0.02135^2 - 0.01635^2)] [1 - (0.02135^2 / 0.02135^2)] \\ &= 0 \end{aligned}$$

At $r = a$

$$\begin{aligned}\text{Tangential Stress} &= [(a^2 \text{Pi}) / (b^2 - a^2)] [1 + (b^2/r^2)] \\ &= [(0.01635^2 \times 37.55 \times 10^5) / (0.02135^2 - 0.01635^2)] [1 + (0.02135^2 / 0.01635^2)] \\ &= 14.405 \text{ MPa}\end{aligned}$$

Hence

At $r = b$

$$\begin{aligned}\text{Tangential Stress} &= [(a^2 \text{Pi}) / (b^2 - a^2)] [1 + (b^2/r^2)] \\ &= [(0.01635^2 \times 37.55 \times 10^5) / (0.02135^2 - 0.01635^2)] [1 - (0.02135^2 / 0.02135^2)] \\ &= 10.650 \text{ MPa}\end{aligned}$$

It can be seen that the maximum of both stresses occurs at the inner radius. Thus

$$\begin{aligned}\text{Maximum Tangential stress} &= [(a^2 \text{Pi}) / (b^2 - a^2)] [1 + (b^2/a^2)] \\ &= \text{Pi} [(a^2 + b^2) / (b^2 - a^2)] \\ &= \text{Pi} [(a^2 + b^2) / (b + a)(b - a)]\end{aligned}$$

Since $r_{\text{mean}} = (b + a)/2$ & $t = b - a$

$$\text{Maximum Tangential stress} = \text{Pi} [(a^2 + b^2) / 2r_m t]$$

and if thin walled tube then,

$$a^2 + b^2 = 2r_m^2$$

$$\text{Maximum Tangential stress} = \text{Pi} [2r_m^2 / 2r_m t]$$

$$\begin{aligned}\text{Maximum Tangential stress} &= \text{Pi} r_m^2 / t \\ &= [\text{Pi} (b-t/2)]/t\end{aligned}$$

Hence,

$$t \cdot (\text{Maximum Tangential stress}) = P_i b - P_i (1/2)$$

$$t \cdot [\text{Maximum Tangential stress} + P_i (1/2)] = P_i b$$

if we multiplying both sides by 2, then

$$t \cdot (2 \cdot \text{Maximum Tangential stress} + P_i) = P_i (2b) \quad \text{where } 2b = D_{\text{outside}}$$

$$t = [(P_i D_o) (2 \text{ Maximum Tangential stress} + P_i)]$$

It can be observed that Radial stress always is a compressive and Tangential stress always is a tensile stress.

Chapter 5

Material Selection

5.1 Introduction

5.2 Comparison of Properties

5.2.1 Selection of Materials

5.2.2 Service Requirements of a material

5.3 The Incumbent – Carbon Steel

5.4 Alternative Metals

5.4.1 Nickel-chromium Steel

5.4.2 Nickel-chromium-molybdenum Steel

5.5 The Next Step

5.1 Introduction

The Superheater is a component of a series of inter-connected tubes, which carry water and steam around the boiler. The steam transfers heat away from the flue gas before the latter undergoes treatment for removal of particles and harmful gases. The main purpose of the Superheater is therefore to cool down the flue gas. In order to achieve this, it has to be made of a material that allows quick exchange of heat from the flue gas to the steam. This material is found in carbon steel, which is that used in many modern incinerators such as TSIP.

However, any consideration in material selection must also factor in other relevant properties that could affect the performance of the Superheater, such as structural integrity, corrosion resistance, ease of maintenance, and finally cost. This chapter explores other materials which could function as well as carbon steel in heat transfer property but differs in other properties as described. Cost analysis will be carried out in the following chapter.

5.2 Comparison of Properties

5.2.1 Selection of Materials

In choosing a material for a specific application certain criteria need to be considered:

- a) The ability of the material to withstand service conditions
- b) The method(s) by which it will be shaped
- c) The overall cost and in some cases the availability of the material

In some cases, a number of materials may be satisfactory in respect of fulfilling the service requirements. Normally, the chosen material is based on the cost of forming and shaping of the material whereby, the lowest overall production cost will be the top priority. Thus the cheapest material may not necessarily be the one that is used. A more

expensive material maybe capable of being formed very cheaply and so gives a lower overall production cost.

5.2.2 Service Requirements of a material

The service requirements of a material may involve properties that fall under one or all of the following three headings:

- Mechanical Properties

- a) Tensile strength
- b) Elasticity
- c) Toughness
- d) Stiffness (Young's modulus)
- e) Hardness
- f) Fatigue resistance
- g) Resistance to creep
- h) Frictional properties

- Physical Properties

- a) Relative density
- b) Melting-point
- c) Thermal conductivity
- d) Coefficient of expansion
- e) Effect of temperature / changes of properties
- f) Electrical conductivity
- g) Magnetic properties

- Chemical Properties

- a) Resistance to oxidation
- b) Resistance to electrolytic corrosion
- c) Resistance to degradation by electromagnetic radiation

5.3 The Incumbent – Carbon Steel

Currently, the superheater is made up of plain carbon steel tubes to perform its function in extracting heat from the flue gas to the steam. Carbon steel is used because of two considerations:

1. Its ability to be shaped and worked with relative ease
2. Its relatively low cost for replacement as compared with other alloy steels

The latter factor will be considered in the next chapter.

However, normal steel corrodes rapidly when left uncoated. At higher temperatures, corrosion in the form of oxidation occurs even more rapidly. The corrosion of carbon steel is due partly to electrolytic action between different phases in the structure of the steel. In the case of the refuse burning boiler, corrosion is accelerated by the presence of corrosive gases.

5.4 Alternative Metals

Candidates having the potential to replace carbon steel as the material in which the superheater is made of should be able to function yet be more attractive in their properties. One such property would be a longer lifespan over carbon steel such that it would be able to be maintained less frequently than carbon steel.

Two such candidates are nickel-chromium and nickel-chromium-molybdenum steel. A table 6.4.1 listing their chemical composition, mechanical properties, maximum working temperature and maximum working pressure are listed below.

Types Of Metals	Chemical Composition %	Tensile Strength (Nmm⁻²)	Maximum Working Temperature(°C)	Maximum Working Pressure (bar)*
Carbon Steel	0.06-0.18 C 0.27-0.63 Mn 0.05 P 0.06 S	414	371	45
Nickel-Chromium Steel	1.0-3.5 Ni 0.5-1.75 Cr	990	800	60
Nickel-Chromium- Molybdenum Steel	1.65-2.0 Ni 0.4-0.9 Cr 0.2-0.3 Mo	1700	1150	75

Table 5.4.1: Summaries the chemical composition, mechanical properties, maximum working temperature and maximum working pressure.⁶

* Provided adequate thickness exists.

⁶ Source: R. A. Higgins 1984 Engineering Metallurgy Vol 1 Applied physical metallurgy Hodder and Stoughton

Resistance to oxidation is effected by adding chromium. This element coats the surface with a tenacious layer of oxide, which protects the metal beneath from further attacks. Nickel toughens the alloy by restricting grain-growth, but increased strength at high temperatures is achieved by adding small amounts of tungsten, titanium, zirconium or molybdenum.

5.4.1 Nickel-chromium steel

Nickel-chromium steel is a good candidate due to the following reasons:

- a) It increases the hardenability of the steel thus prevent cracking and distortion
- b) Chromium increases the metal's resistance to corrosion and oxidation
- c) Nickel not only increases hardenability but also increases the toughness of the steel
- d) The higher content of carbon in steel will cause it to harden from the shutting down and starting up of the boiler
- e) Nickel also prevents the growth of austenitic structure of the metal
- f) Chromium enhances the steel at high temperature

5.4.2 Nickel-chromium-molybdenum steel

Nickel-chromium-molybdenum steel is the other good candidate owing to the following additional properties that it has over nickel-chromium steel:

- a) Unlike nickel-chromium, it does not suffer the same from a defect known as 'temper brittleness'.
- b) Temper brittleness can be largely eliminated by adding about 0.3 per cent molybdenum to the steel, thus establishing the well known range of 'nickel-chrome-moly steels'

As the two candidates are primarily carbon steel with a few additives to enhance their properties over plain carbon steel, it may be necessary to highlight the principal effects

the main alloying elements had on metals belonging to the carbon family. This is outlined below:

- Nickel, Ni
 - a) Toughens steel by refining grain.
 - b) Strengthens ferrite.
 - c) Causes cementite to decompose – hence used by itself only in low-carbon steel

- Chromium, Cr
 - a) Stabilizes carbides and forms hard chromium carbide – hence increases hardness of steel.
 - b) Promotes grain-growth and so causes brittleness.
 - c) Increases resistance to corrosion.

- Molybdenum, Mo
 - a) Reduces “temper brittleness” in nickel-chromium steels.
 - b) Stabilizes carbides.
 - c) Improves high-temperature strength

5.5 The Next Step

Having identified suitable metals in which to construct the superheater, the decision to remain status quo or to have carbon steel replaced by either one of the two candidate metals would depend on economic sensibility – the costs involved for either one option.

Chapter 6

Cost Analysis

6.1 Introduction

6.2 Components of Costs

6.2.1 Capital Cost - Depreciation

6.2.2 Installation Cost

6.2.3 Operating Cost

6.2.3 Maintenance Cost

6.3 Cost Evaluation

6.4 Practical Considerations

6.1 Introduction

The preceding chapter explored possible alternatives to carbon steel in the construction of the superheater. Nickel-chromium steel and nickel-chromium-molybdenum steel are viable alternatives to achieve the same performance, and have several characteristics that are superior to carbon steel. However, the final consideration in material selection must be the cost involved in selecting the material, as this would affect the economic viability of the entire project.

This chapter compares the costs of using each of the respective metal identified in Chapter 6. In the end, as in most cases, this would determine the material chosen finally.

6.2 Components of costs

The difference in the cost of using a material other than carbon steel for the superheater is not merely restricted to the cost of the material; ie. it is not simply that a material that is costlier than carbon steel is necessarily less economical in the overall cost analysis. There are other cost factors that could weigh against a cheaper material selection. This could very well be the case if the costs of installation, maintenance and operation are taken into consideration along with depreciation.

6.2.1 Capital cost – depreciation

Depreciation relates directly to the capital cost of the material and its lifespan. For all intents and purposes, a cheaper material depreciates favourably economically than a pricier alternative which has the same lifespan. However, typically, a more expensive material can last longer. This holds true for carbon steel, nickel-chromium and nickel-chromium-molybdenum. A table showing the depreciation of each of these metals is shown below:

Metal	Cost per metre length (\$/m)	Total Cost (A)* (\$)	Lifespan (B) (years)	Depreciation (A/B) (\$/yr)**
Carbon Steel	5.83	5755.20	10	580
Nickel-Chromium steel	25.45	25125.10	20	1260
Nickel-Chromium-Molybdenum steel	48.32	47703.70	25	1910

Table 6.2.1.1 Cost depreciation of each of metals

*The total cost is derived by multiplying the material cost per metre length by the total length of the superheater. For TSIP, each superheater is 17.95 metres long. However, as there are 55 sets of superheater in each boiler, the length of superheater in each boiler is $17.95 \times 55 = 987.25\text{m}$.

**Rounded off to the nearest \$10.

The calculations above shows that carbon steel, depreciating at an annual cost of **\$580** only, is by far the metal of choice in terms of depreciation.

6.2.2 Installation cost

The installation of the superheater is labour-intensive with limited use of machines in the tightly confined space of the boiler. The major component of the superheater installation cost is thus labour cost. However, the labour costs depicted in this section do incorporate some components of the use of equipment and all other mechanical devices necessary to aid the worker in the installation works, as otherwise it would not be possible to accomplish. It also includes other overheads, insurances and deployment costs – hence their seemingly inflated quantum when compared to a layman’s expectations.

For carbon steel superheater, the figures quoted were excerpted from actual work done previously. As nickel-chromium steel and nickel-chromium-molybdenum steel superheater had never been installed before, the figures were derived based on the average of quotes obtained by two local companies (M/s Sing Hoe Metal Pte Ltd and M/s A G

Supply Pte Ltd) with experience in mechanical and pipe installation in the boiler environment.

A table of comparison on the installation costs of the superheater for the various material configuration is as follows:

Metal	No. of workers (A)	Period of installation (B) (days)	Labour cost (C) (\$ per worker day)	Lifespan (D) (years)	Installation Cost ([AxBxC]/D) (\$/yr)
Carbon Steel	10	21	250	10	5250
Nickel-Chromium steel	10	21	300*	20	3150
Nickel-Chromium-Molybdenum steel	10	21	350*	25	2940

Table 6.2.2.1 Installation costs of the superheater for the various materials

*The higher labour costs for nickel-chromium steel and nickel-chromium-molybdenum steel were attributed by the companies to the higher skills involved in the shaping and welding of these higher grade materials.

The calculations above shows that nickel-chromium-molybdenum steel, while more expensive to install, has the lowest annual installation cost (**\$2940**) among the three metals owing to the need of installing it less frequently due to its longer lifespan.

6.2.3 Operational cost

Operational costs refer to the cost of operating the boiler for a given superheater material. In this instance, it can be envisaged that the component of operating costs includes the cost of energy required to allow heat exchange between the flue gas and the steam without and within the superheater respectively. It is however inconceivable that there will be any substantial difference in cost of operating the boiler for different superheater material. This is because the boiler and turbine system is a net generator of energy. The cost component associated with superheater operations is therefore redundant.

6.2.4 Maintenance cost

Maintenance costs, when referring to the superheater, may be incurred when the boiler is shutdown when maintenance works need to be carried out on the superheater. At the present rate, each boiler of the TSIP is shutdown every 12 months for regular maintenance of its components, including the superheater. There has never been any occurrence whereby the boiler is shutdown because of the superheater. As the superheater is made up of carbon steel, the lowest grade of the three metals under study, it is envisaged that the present maintenance schedule will continue even if, and especially so, when the two higher grades of metals are used.

For the actual cost of maintenance on the superheater, the difference in this cost for the different superheater material is also negligible, due to the same nature of maintenance work required on the superheater; ie. slag and ash removal. As in operating cost, the cost component associated with superheater maintenance is also therefore redundant.

6.3 Cost Evaluation

The summary table consolidating the costs associated with the superheater is shown below. The figures have all been calculated on an annual cost basis.

Metal	Depreciation (A) (\$/yr)	Installation Cost (B) (\$/yr)	Total Cost (A+B) (\$/yr)
Carbon Steel	580	5250	5830
Nickel-Chromium steel	1260	3150	4410
Nickel-Chromium- Molybdenum steel	1910	2940	4850

Table 6.3.1 Annual costs for each metal

Based on the table, it is apparent that it makes more economics sense to use Nickel-Chromium steel as it exhibits the lowest annual cost (**\$4410**).

6.4 Practical Considerations

It is therefore seemingly apparent that nickel-chromium steel is a better choice than carbon steel in both properties (corrosion resistance) and cost. While a theoretical recommendation could be made for carbon steel to be replaced with nickel-chromium steel, in reality such a hasty recommendation needs to be tempered. For one, the commercial availability of nickel-chromium steel tubes needs to be ascertained. More importantly, the lifespan used for all 3 metals in calculating depreciation and installation costs above are rarely achieved in practice. This is due to the fact that the superheater could very well be replaced before the lifespan of the metal is reached, because of the service considerations of the particular boiler.

It seems therefore that ways to mitigate corrosion on the superheater bears more weight than material selection, as is borne in reality. The cost analysis exercise is therefore more often than not just an exercise. Nevertheless it should not be discounted but rather encouraged in pursuit of a more comprehensive assessment.

Chapter 7

Conclusions

Conclusions

This project set out to explore the causes and effects of corrosion on the surface of the superheater tube in the furnace of an incinerator.

A main component of the project is a study carried out in the furnace of an actual incinerator. The exact conditions experienced in a furnace combustor are therefore replicated, where high temperature corrosion normally occurs, which is above 371°C.

Observations, empirical analyses and experiments carried out under the project revealed that the presence of Hydrochloride (HCl) in flue gas unequivocally increases the corrosion rate on the superheater tube surface. A further finding was that the presence of corrosive gases, such as chlorine and hydrochloride, corrode the boiler tubes, particularly those operating above 371°C, resulting in tube thinning and failure.

The HCl concentration depends on the plastic content of the refuse thrown in into the incinerator. This will determine how fast or slow will the corrosion growth on the surface of the superheater tube. The high corrosion rates observed at elevated temperatures were a result of an accelerated oxidation and a reduced scale adhesion.

From literature research on possible superheater material, nickel-chromium steel and nickel-chromium-molybdenum steel are found to have corrosion-resistance properties which are superior to carbon steel, which is the material most commonly used for superheater. Cost analyses reveal that it is theoretically most economical to construct the superheater out of nickel-chromium steel, but the practical and service considerations of using this material must be taken into account.

Another finding of the project is with regards to slag formation on the surface of the superheater tube. Slag formed on the surface of the superheater must be removed; otherwise it could result in high temperature corrosion. The removal of slag formation is a serious problem. By implementing intelligent retractable soot blowers, it is possible to

reduce slag formation rate on the superheater surface. This could restrict gas temperature at the tube surface. The six months period for the maximum deposits to form at the superheater tube suggest that an annual cleaning of the tube is not enough to prevent high temperature corrosion.

Continuous measurement of combustion air and flue gases is a necessity in modern practice to accomplish effective avoidance of High HCl Concentration, which affects the properties of tube materials. Moreover, monitoring the amount of air content in the furnace is recommended as air content is an added another factor in the corrosion process. The amount of oxygen used in the furnace can be determined by installing a device that can continuously record and give the desired information.

Burning of refuse fuel require a high excess air, a good air distribution could lead to complete mixing and burning of the flue gas that could avoid corrosive situation.

Chapter 8

Recommendations

Recommendations

Listed below are several measures that can be taken to minimize the formation of slags and the associated problems of corrosion. However there has yet to be a feasible solution which could completely eliminate the problem.

- 1) High temperature corrosion can be mitigated by (i) preventing the gases from coming into contact with the tubes until combustion is complete; (ii) ensuring that the gases are thoroughly mixed by the use of at least 100% excess air; and (iii) injecting secondary air. Protection from excess temperatures can be achieved by covering the tubes with refractory material or by making the furnace independent of the boiler. Even after taking these precautions it is necessary to prevent tube metal temperatures to go above 425°C if high temperature corrosion of superheater tube is to be avoided. This limits the steam conditions that can be used with incinerators if high availability is required.
- 2) Oxygen corrosion on the inside of the water tubes can be prevented:
 - a) Externally by the use of deaerators in order to extract the air out of the water before it is fed to the boiler
 - b) Chemically by the use of oxygen-scavenging chemicals. Chemicals commonly used for this purpose are sodium sulfite, hydrazine and catalyzed hydrazine.
- 3) Proper mixture of refuse is relatively important because it could lead to a reduction in the percentage of plastic content in the refuse. The practice helps maintain the HCL content in the furnace which in turn could mitigate the acidic environment which is conducive for corrosion attack on boiler metal.
- 4) If the gas temperature entering the convection sections is cooled adequately, slagging can be minimised. Cooling can be accomplished by using a large radiant

furnace section. However this is expensive and makes the boiler design more complicated.

- 5) Flue gas recirculation could be used to re-circulate and mix cool gases from the boiler exit with the hot incoming gases, thus reducing the temperature of the gas let to the boiler. However this increases the mass flow through the boiler and hence its initial cost. Operating costs are increased by using the recirculation fan.
- 6) Retractable soot blowers with wide access lanes (spaced tubes) are suggested for removing the deposits as soon as they form so as to prevent metal temperature fluctuations when slag accumulates on the surface of the superheater tube. This method would mean a higher capital cost (the cost of the superheater is higher due to lower log-mean temperature difference) but could be compensated over the lifespan of the tube by lower depreciation costs (lower maintenance and replacement costs spread over a longer life).
- 7) To clean the superheater tube at the interval of six month.

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Appendix

Appendix A: Project Specification

Appendix A
University of Southern Queensland
Faculty of Engineering and Surveying

**ENG4111/2 Research Project
PROJECT SPECIFICATION**

For: Noorahmad Bin Ali

Topic: Investigation of corrosion on boiler tube of Tuas South Incineration Plant

Supervisor: Dr Nigel Hancock
Dr. Wenyi Yan
Mr Ghazali (NEA-TSIP)

Project aim: The aim of this project is to study the causes of corrosion to the incinerator, in particular, the super heater tube, and to recommend measures that could minimize the occurrence of the corrosion with a view to prolong the life span of the tube.

PROGRAMME: Issue A 21 March 2005

- 1) Research on past history record of Super heater tube.
 - Measurement tube record (done during boiler overhaul)
 - Leakages
- 2) Analysis of the incoming waste to the plant.
 - To identify the component of the solid waste.
- 3) Calculating and flue gas sampling testing.
 - To determine the composition of the flue gas.
- 4) Determine the percentage of HCL and OXYGEN content in the flue gas.
- 5) Analyze the effect of corrosion growth on the surface of the super heater tube.
- 6) To calculate the stresses on the Super heater tube surface due to pressure and temperature.
- 7) To explore ways to minimize the corrosion on the tube surface.
 - Viable material replacement
 - Controlling the environmental condition that could reduce corrosion.

As time permits:

- 8) Design and implement the measured system on one of the boiler.

AGREED:

_____ (Student) _____ (Supervisor)

Dated : _____