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ASSESSMENT OF SOME PERFORMANCE CHARACTERISTICS OF REFUSE BOILER BEFORE AND AFTER OVERHAUL USING FAILURE MODE EFFECT AND FAULT TREE ANALYSES

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Abstract:
A pioneer palm oil boiler unit, in an immense power self-contained oil mill, impaired by many years of accumulated depreciation, was rebuilt in the pattern of a design-out scheme aimed primarily at rehabilitating the entire boiler system to a state of functionality. The research work studied the pre-maintenance and post maintenance performance relativities through statistical analysis of data collected and also developed Failure Mode and Effect Analysis (FMEA), and Fault Tree Analysis (FTA) worksheets for the boiler unit. It is hypothesized that the pressure build up and discharge rates in a boiler system is normally distributed under normal operational mode. The effectiveness of the maintenance work carried out on the boiler enhanced the processing capability of the entire plant. The study revealed that under a single shift operating mode (8 hours), a time saving of 72 minutes arising from the effectiveness of the plant overhaul carried out is achieved.

Keywords: T-policy model; serviceability level; bunch stripper; Failure Mode and Effect Analysis; Fault tree analysis; criticality matrix.

1. Introduction

Production equipment and facilities are subject to deterioration arising, more often than not, from passage of time, obsolescence, physical deterioration and corrosion. It therefore appeals to reason that as a company maintains its production facilities, so it maintains its profit. This study is inclined to determine the level of improvement in output as brought about by the maintenance operation carried out on the boilers and other production equipment in the palm oil mill studied. The focus of the research is also sharpened by the determination of the level of the boiler system reliability and efficiency. The boiler is a unit of the palm oil mill that uses wastes resulting from processing of fresh fruit bunch (ffb) for its firing. The steam generated is used to power steam engine for electric power generation and for other processing equipment and facilities described later. It is therefore a self-contained oil mill that provides its power needs.

The literature on maintenance of equipment and facilities is vast. Notably, [1] studied maintenance policies under imperfect information using Markovian model. The model presented by Sengupta [1] is a marked variation of that presented by Luss [2] and a continuous time version of the models by Rosenfield[3]. While [2] assumes that the replacement action must be taken immediately after an inspection, [1] differs, noting that there are situations where a replacement needs not necessarily be preceded by an inspection. This study leans towards the opinion in [1] because our investigation revealed that the Palm Oil Mill was faced with problem of capital rationing and so there were instances where faults were detected during inspection but were not promptly rectified owing to financial straits. Moreover, in this case study, there was dearth of maintenance data and manufacturer's equipment manuals were not available (imperfect information) and this further justifies the adoption of the model in [1], however, with some modifications. Besides, Segunpta suggested that when a defect is observed for the first time, an inspection is scheduled some units of time later and then followed by an optimal policy. Accordingly, in this study, complete overhauling followed inspection and a maintenance schedule was established which involves maintenance record keeping that will subsequently facilitate the estimation of transition probability matrix.

Moreover, [4] reported on T-policy models which estimates the expected average cost per unit time in maintenance. The authors used g-renewal function in the derivation of the formula. They claimed that under a T-policy (age dependent), total renewal or rejuvenation of the system can bring the failed system to a level which is somewhere between new and prior to failure. This model is particularly relevant to this research setting since it considered the following factors: age of plant, cost of repair and a complete rejuvenation of the plant, all of which were taken into cognizance in our maintenance proposal.

Relatedly, a recent study focused on the performance of a boiler system fired with pulverized coal [5]. It noted that boiler system can be disaggregated into these subsystem for the purpose of performance evaluation namely feed water system, steam system and fuel system. Their analysis employed Fault Tree Analysis (FTA) which furnishes causes and consequences explanation, and then Hazard and Operability (HAZOP) study that identifies potential hazards. The present study employed Failure Mode and Effect Analysis (FMEA), Criticality Matrix, and Fault Tree Analysis (FTA). While the boiler system they studied was fired with pulverized coal, the one in our own case study is fired with fresh fruit bunch wastes that are abundantly generated on a continuous basis.

Representative studies that have employed FMEA and FTA include: [6] which applied the tools to power generating system in Balbina plant in Brazil; [7] which carried out various experimental failure tests on steam tubes of boiler furnaces in Najebia Power Plant; and [8] which studied reliability analysis of a system of boiler used in garment industry in Banganlore, India. Moreover, at local level (Nigeria), [9] designed, developed and evaluated the performance of a pilot palm fruit bunch stripper. The study spotlighted the effect of machine speed and the ffb resident time in the sterilizer on the output capacity, efficiency and quality performance efficiency. The paper claimed that at a machine speed of 2500 rpm, the machine performance parameter was adjusted best.

Finally, and interestingly too, we review the study [10] that offers guidelines on the assessment of residual life of boiler systems. The study's assessment is limited to creep damage, high temperature fatigue and the nature of repairs that can be carried out. The research appears to align, in terms of maintenance philosophy, with the present study. In other words, it helps to situate the current study globally. Again, the study by Ozor and Onyegegbu [11] reports on modelling preventive maintenance scheduling for deteriorating systems. The paper emphasizes the supportive role of maintenance in manufacturing function. Further, the use of reliability models in examining production system dysfunction is reported in [12]. The authors applied the model in Sanitary Towels Production Plant and concluded that such model is a powerful tool that could be used to improve the performance of a production system, if properly applied. Relatedly, quality improvement cycle technique is discussed in [13]. The study emphasizes on-line quality and condition maintenance culture. Moreover, the study on mechanized palm fruit processing by Nwankwojike et al[14] describes palm oil processing flow diagram similar to the ones considered in the present study.

The purpose of this study can be resolved into the following objective statements:

1. to appraise the maintenance effectiveness of the maintenance operation carried out on the plant; and

2. to ascertain the level of improvement in production output brought about by the system overhaul undertaken.

1.1 The Case Problem

It is pertinent, at this juncture, to give a brief account of the problems that prompted this research. Our client has twin boiler units (Figure 1) each of capacity 1000 litres, providing two streams of steam (at a working pressure of 100psi) that meet at the concourse of two pipes drawn from each boiler. From the confluence, steam is supplied to a steam engine, sterilizer, a bunch stripper, a digester, a centrifugal press, a set of four clarifiers, settling tanks and other miscellaneous units of the Palm Oil processing plant. The boilers which were installed in the first quarter of 1952 (precisely 61years today) had been operating without any real, major maintenance overhaul carried out on them. On account of the following:

(i) collapsed chimney
(ii) completely stripped lagging materials
(iii) dilapidated base
(iv) internal water shell bulges arising from occasional firing of boiler without sufficient water
(v) accumulated sludge at the base of the water chambers
(vi) excessive corrosion occasioned by leaky factory roof
(vii) pressure losses from corroded steam pressure pipes and control valves
(viii) miscellaneous boiler faults arising from the general state of disrepair of the unit among others,

The boiler system completely broke down and management of the mill could no longer cope with the situation and so they sought technical assistance to rejuvenate the boiler units and the entire mill.

1.1.1 Thermodynamic Consideration

In considering the thermodynamic analysis of the Palm Oil Mill, Figures 1-5 that follow readily provide insight and enlightenment and hence make the case problem to be better understood. Figure 1 depicts the twin boiler whose aspects of performance characteristics were assessed. Figure 2 and 3 are critical components of the boiler – the former (pressure release valve) was overhauled while the latter (pillar valve) was retrofitted in the form of design out scheme. Figure 4 depicts the schematic of the internal geometry of the twin boiler. Flue gas that glides on the inner conical shell helps to further dry the steam in the steam compartment. Figure 5(a) represents a thermodynamic model of the boiler and the associated complementary machines, equipment and facilities. Figure 5(b) depicts the T-S state diagram useful for the determination of some thermodynamic parameters such as specific steam consumption, thermal efficiency, heat supplied to boiler, and so forth.

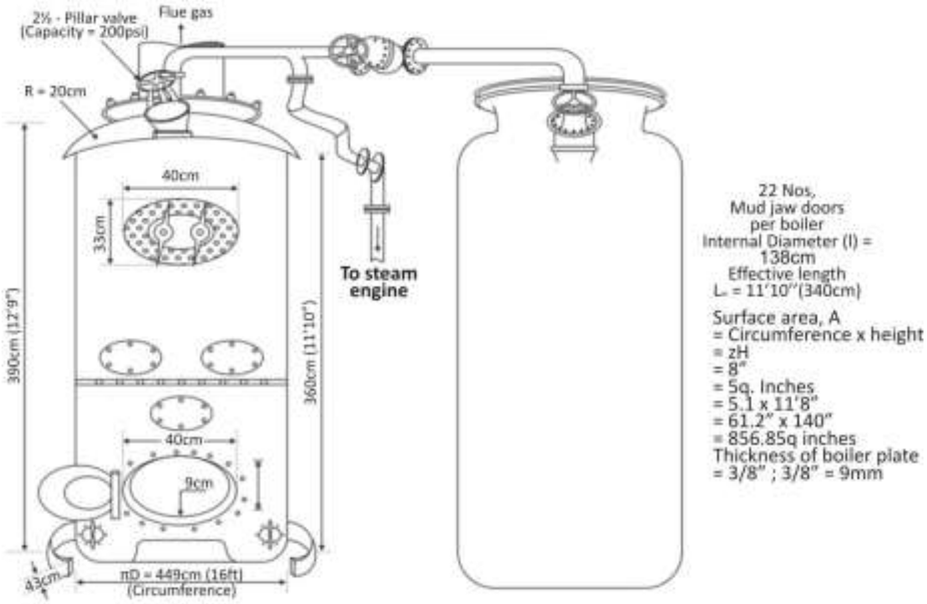

Figure 1: Twin boiler units

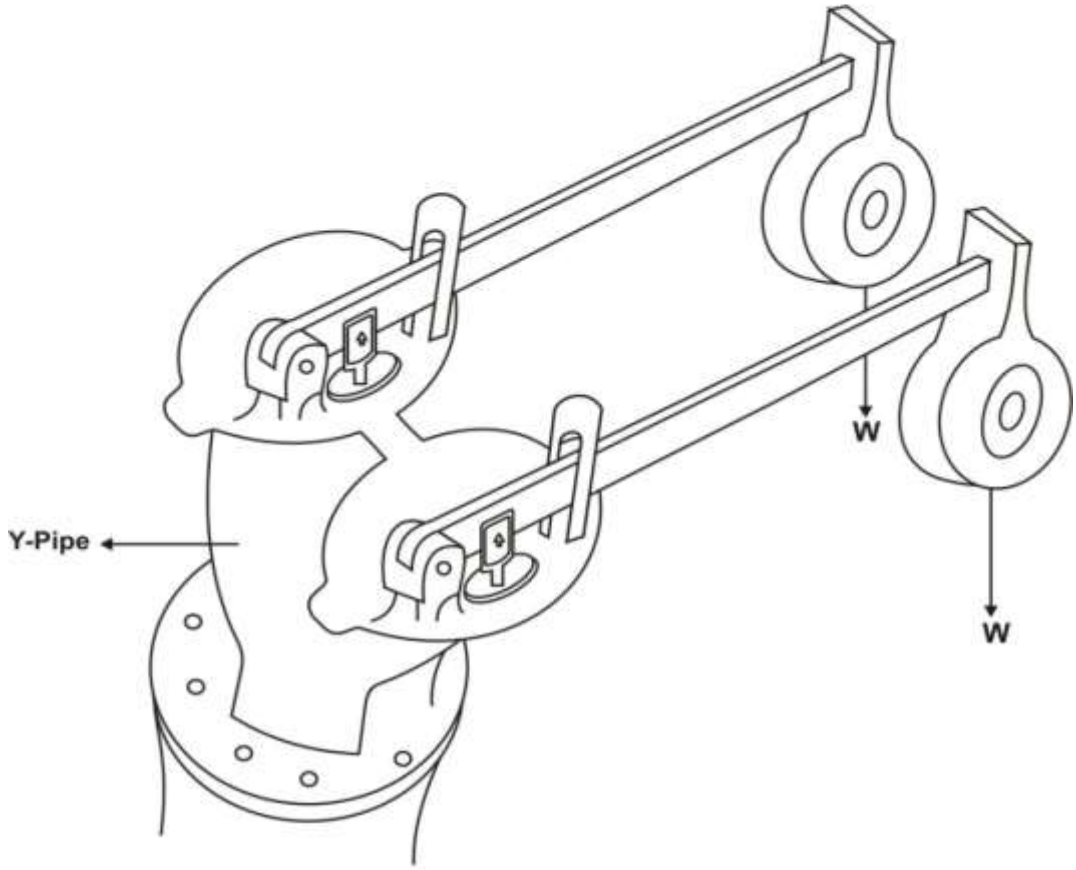

Figure 2: Pressure release valve

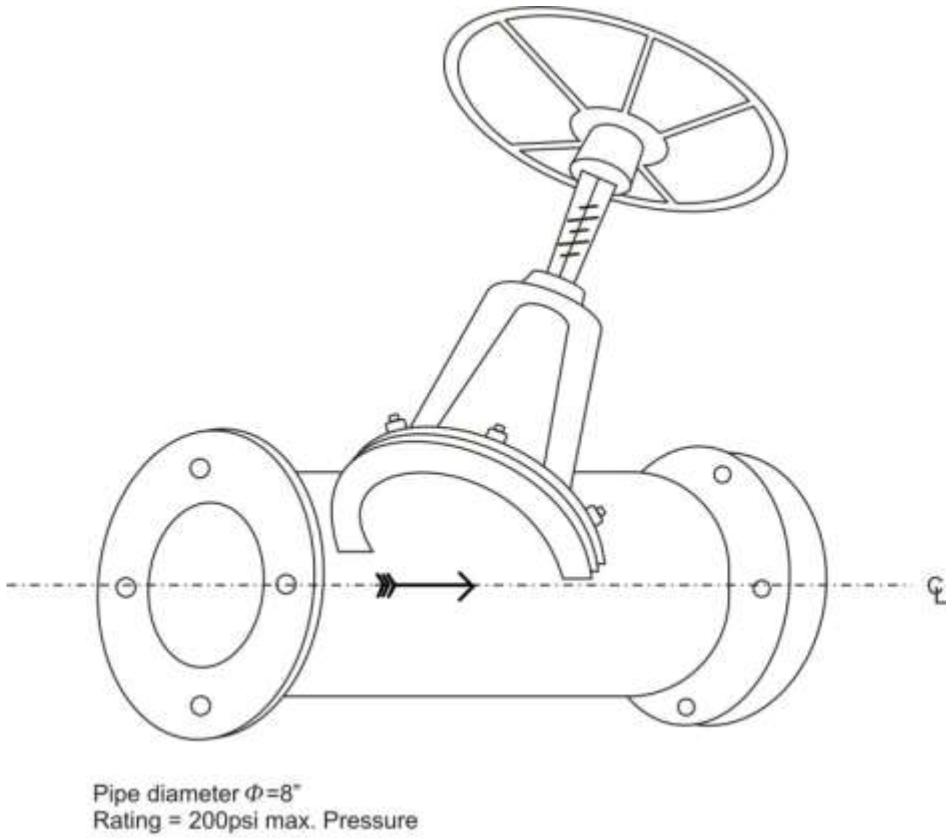

Figure 3: Pillar valve

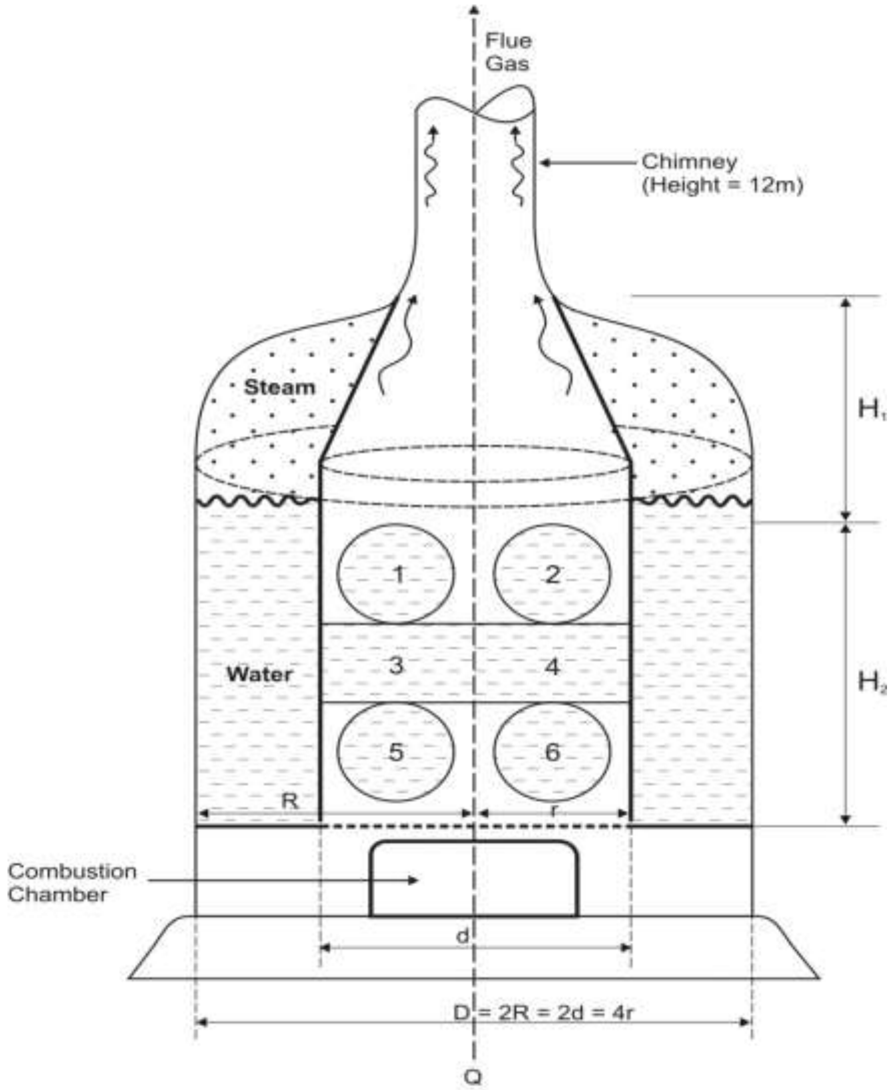

Figure 4: Internal Geometry of boiler

The work energy is the heat dissipated in the sterilizer including the heat converted to torque by steam engine to operate the bank of process equipment. Substantial part of waste steam is channeled to a network of half-inch diameter cast iron (CI) pipes embedded in a thin concrete floor. The condensed steam is used for general purpose applications.

Process wastes, principally ffb, are charged into boiler furnace to generate heat for steam production. The geometry of the upper part of the furnace is atypically conical thereby promoting gliding of flue gas on the conical shell of the steam chamber (see Figure 4). The resulting steam is hence dry at 100psi which is the operating pressure.

The boiler shell is 9mm thick. Chimney column is 14.6 metres which is sufficiently high to promote draught speed and hence stochiometric combustion. Feed water for the boiler is supplied from a nearby stream (brook). A one-cylinder steam engine receives steam from any of the twin boilers in operation at a particular time. The steam turbine provides torque needed by a bank of process machines and equipment. Also, the sterilizer, which is a pressure vessel, receives steam from the boilers. The sterilizer steam-heats the newly harvested fresh fruit bunches to enable the debuncher (bunch stripper) readily defruit the bunches. Bank of process machines and equipment include: sterilizer, bunch stripper, series of conveyors, digester, centrifugal extractor, clarifiers, nut/fibre separator, kernel/shell separator, electric alternator for power generation, and so forth. The clarifier uses steam to refine the palm oil obtained from the centrifugal extractor. Waste steam is channeled to the winding pipe embedded in the concrete floor.

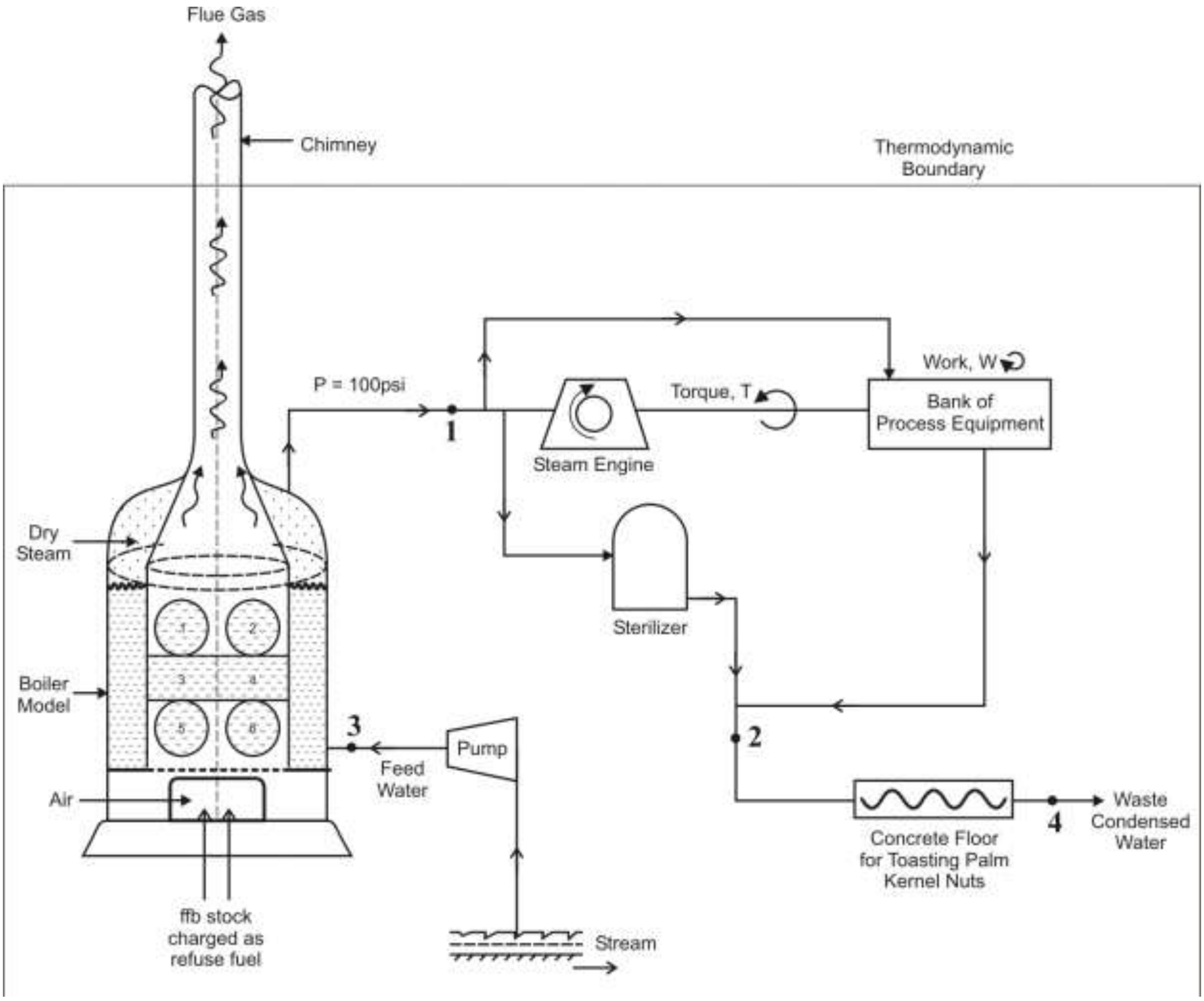

Figure 5: (a) A thermodynamic Model of boiler

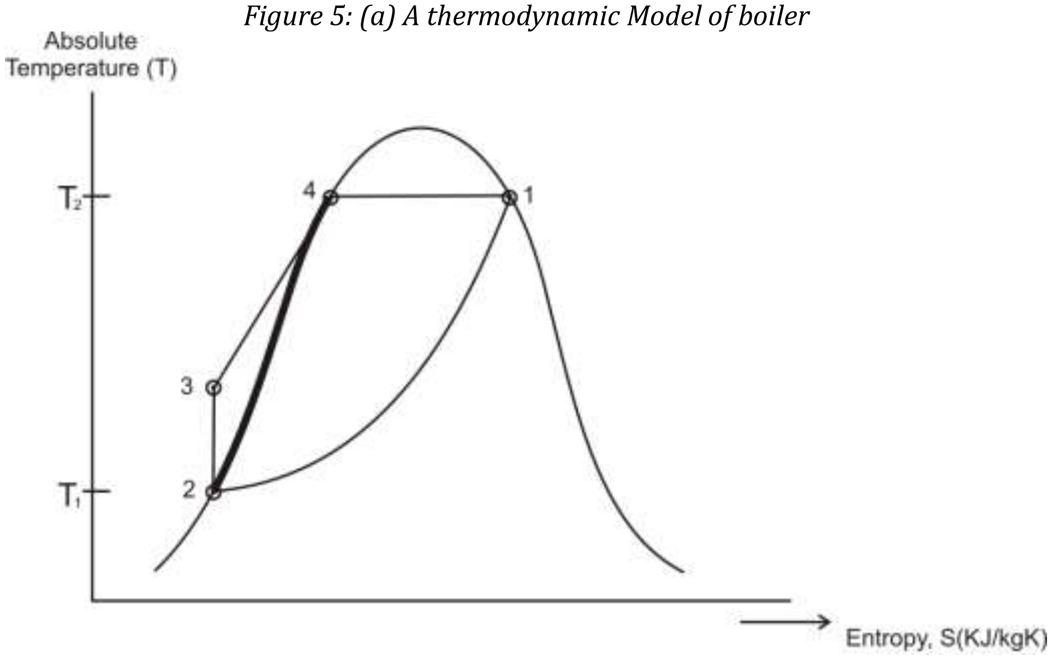

Figure 5(b): T-S State diagram

1.1.2 System Description

We offer a thumb nail description of the boiler components together with the functional block diagram as frames of reference for the FMEA work sheet that follows later.

Boiler Unit – This unit is a heat exchanger whereby water is converted to steam upon heating with fuel. In the study considered, the boiler is a pioneer type, fired with waste palm bunch stock. It has water tube stacked in a criss-cross fashion above the fire chamber. These tubes link the water/steam chamber formed by concentric shells of the boiler (see Figure 4).

The boiler components are itemized below. The functional schemes are explained as follows:

1. Boiler Tube/Shell – Boiler tubes are linked to the internal shell of boiler. The outer and inner shells form a concentric chamber, with the tubes linking them. Water in the chamber and in the connecting tubes is heated by fire in the fire chamber and steam is formed.
3. Pillar Valve – This prevents steam built up in the steam chamber from escaping to the pipe lines except when the valve is operated. The rating is 200psi. It is mounted on top of the boiler (See Figure 3).
4. Chimney – This unit conducts the flue gases from the fire chamber to the atmosphere. It facilitates draught speed build-up and thus ensures complete (stoichiometric) combustion of the palm bunch stock used as fuel.
5. Mud Door Unit – This is a special provision for gaining access to mud collection (precipitation) location. The mud doors are opened so that desludging function can be performed. After desludging, the entire water chamber is flushed and new gasket materials used to fix back the mud doors.
6. Pressure Lines – This is simply a mild steel pipes used as conduit to supply steam from boiler to places of need.
7. Fire Bars – This is the base for the bunch stock fuel fired to provide heat. It is made of cast iron bars.
8. Pressure Gauge – This is used to measure the pressure on the steam chamber.
9. Sight Glass – This is a glass tube (manometer) to measure the water level in the boiler.
10. Feed Water Pump – This is a device for pumping water from the nearby stream to the boiler.
11. Steam Injection Jump – This is a special provision for pumping water into the boiler when feed water can no longer be employed on account of hazards inherent in assessing the steam chamber. It is powered by the steam in the boiler.
12. Synchronous Valve – This is a pressure regulating valve that can isolate or combine the steam from the two boilers.
13. Blow Down Valve – This is the discharge valve of the boiler. Similar valve is also found in the sterilizer.
14. Metering Valve – This valve permits steam to different types of meters provided.
15. Safety Valve – This is simply a device for automatic regulation of boiler pressure so that the operating pressure cannot be exceeded.

Figure 6 depicts the functional block diagram of the boiler system. The figure explains the functional relationships among boiler components. It offers insight that enables the FMEA worksheet that follows later to be better understood.

2. Materials and Methods

Data for this research work were obtained through direct observation and operational record of the Oil Mill. The data are of two classes. The first is pre-maintenance data obtained before shutdown for maintenance. The second set of data which is post maintenance was obtained during test running. The data relate to boiler pressure characteristics (firing rate) and the processing times.

For the boiler performance characteristics, a set of readings comprising data relating to pressure build-up from 0 - 100psi was taken before the plant was shut down. Further readings could not be taken because of time limitation. There was pressure from Oil Palm Mill management to shut down. Upon pressure build-up, two sterilizer loads of ffb were processed and the processing time noted. However, processing times for 4 days were taken from the operational record. After maintenance, replicates of pressure build-up rate were noted and processing times for 15 days were also recorded.

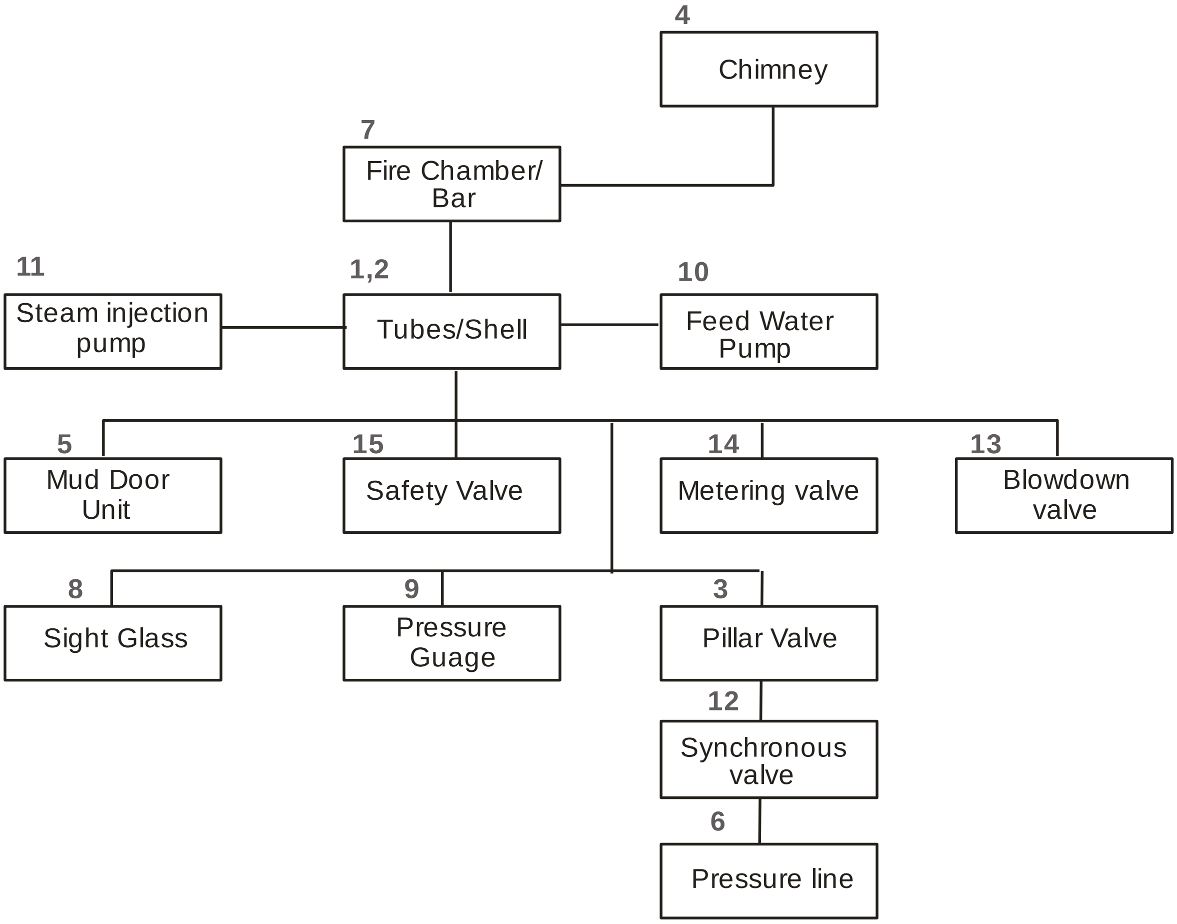

Figure 6: Functional block diagram of the boiler system

As stated earlier, the boiler had accumulated depreciation that greatly impaired its performance. It was felt that the best measure of boiler performance then was pressure build-up rate. Other performance measures were considered but were not used because there was dearth of boiler performance and signal detection indicators. It was further felt that measuring the processing time before and after maintenance would give indication of improved serviceability level achieved.

The bunch waste and fibre were as usual loaded on the fire chamber and ignited after water level in the boiler was checked. As the flame in the fire chamber developed, pressure build up in the boiler was noted against time. At the operating pressure of 100psi, the sterilizer was charged with steam after which processing began. The time it took for the fruits to be processed on each processing unit of the mill was noted. The processing units of the Mill include the following: sterilizer, bunch stripper, digester, centrifugal expeller, nut/fibre separator and nut cracker. The measuring instruments used were pressure gauge and stop watch. It would be noted that there are different types of conveyors such as: fresh fruit bunch (ffb) elevator, fruit conveyors, and fruit elevator.

The criteria for success is that the pressure build up rate and processing time after maintenance should be less than the respective corresponding values before maintenance. It is hypothesized as follows:

$$H_0: \mu_0 = \mu_1, \text{and } H_1: \mu_1 < \mu_0 \qquad (1)$$

where H_0 = null hypothesis; H_1 = research hypothesis

μ_0 , μ_1 = average process time in minutes before and after maintenance respectively.

The data analysis procedure was undertaken as follows:

i. The time it took for a batch of ffb to be processed through the various units of the mill were recorded and analyzed.
ii. The rate of pressure build-up in the boiler was recorded and a plot of pressure against time was undertaken.

iii. The boiler unit was resolved into the smallest component of a system and a block diagram was developed which facilitated the formulation of Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA).
iv. The entire project was resolved into appropriate activities and events to facilitate the estimation of the time devoted to boiler activity in relation to other activities in the entire scheme.

Based on the FMEA and FTA carried out, it was found expedient to undertake some modifications of the pillar valve and the pressure line system to enhance boiler performance. Other jobs modification carried out include: mud door gasket improvisation (original material was difficult to source) and lagging of the boiler.

2.1 Thermodynamic Analysis

At a working pressure of P = 100psi (≈ 7 bar),
steam temperature, $t_s = 311^0C$

Heat supplied to boiler:

$Q_{14} = h_1 - h_4 = h_{g1} - h_{f4}$ (2)

Work done by process equipment through torque supplied by steam engine:

$W = \Delta Q = h_1 - h_2$ in $\frac{kJ}{kg}$ of steam (3)

$h_2 = h_f + x\, h_{fg}$, x = dryness fraction (4)

Practically, $x = 0.70$

$W_{12} = h_1 - h_2 = h_{g1} - h_{f2}$ (5)

$h_1 = h_g$ at $t = 311^0C$ and p = 7bar.

Specific steam consumption, SSC:

$$SSC = \frac{3600}{W}\ \text{kg/kwh} \quad (6)$$

Thermal Efficiency (Rankine)

$$\eta = \frac{h_1 - h_2}{h_1 - h_3} \quad (7)$$

Boiler is heated by radiation, conduction and convection

(i) Furnace heat transfer by radiation:

$$T = \kappa\left(\frac{H}{A}\right) \quad (8)$$

where T is the gas temperature, κ is a constant which depends on the fuel and excess air in a combustion product, H is the heat input rate in Watts, and A is the effective (projected) water-cooled absorption surface area (m^2): $30 \le \kappa < 40$, for wood

(ii) Heat supply by conduction:

$$\phi = \frac{Q}{A} = \frac{k_s(T_1 - T_2)}{e} \quad (9)$$

e = thickness of boiler shell (=9mm)

k_s = conductivity of steel = $3\text{x}10^{-3}$W/m K

T_1 = flame and gas temperature

T_2 = temperature of inner surface of water tube.

(iii) Heat flux by conduction (ϕ)

In the radiant section of a boiler, the 4th power of the wall temperature is typically less than 2% of the 4th power of the mean flame and gas temperature [15].

$$\therefore \left(\frac{T_w}{T}\right)^4 < 2\% = 0.02 \times (922)^{1/4} \quad (10)$$

$T_w = 184.4^0C$. (11)

2.2 Test for Process Improvement

Let X_1 and X_2 represent random variables that denote the difference in values between steam on and steam off before and after maintenance respectively. Thus, using this concept, the mean and standard deviation of the variates (X_1 and X_2) were computed. Then from standard statistical texts, the Z-test statistic is given by,

$$Z = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_1^2}{n_1} - \frac{S_2^2}{n_2}}} \quad (12)$$

$$S_1^2 = \frac{1}{(n_1 - 1)}\left[\sum_{l=1}^{12} x_1^2 - n_1\bar{x}_1^2\right], S_2^2 = \frac{1}{(n_2 - 1)}\left[\sum_{i=1}^{5} x_2^2 - n_2\bar{x}_2^2\right] \quad (13)$$

where n_1, n_2 are sample sizes as contained in Tables 2 and 3 respectively that follow.

Using two-tailed test ($Z_{\alpha/2}$), α = 0.05, reject H_0 if $Z_{cal.} > Z_{tab.}$ and conclude that there is a time saving between processing time before and after maintenance; processing time after maintenance being shorter.

3. Results

The results of the study are represented hereunder:

3.1 Thermal Efficiency, η and Specific Steam Consumption, SSC

At a working pressure of 100psi (≈ 7bar), steam temperature, $t = 311^0C$ and from steam tables, the thermal efficiency η and the SSC are determined using equations (6) – (7) and the results are shown in Table 1.

Table 1: Determination of η and SSC

Relevant Steam Table values	Thermal Efficiency and SSC
$h_f = h_3$=167.5KJ/kg h_{fg}=2406.2KJ/kg dryness fraction, x = 0.70 h_2=1851.84KJ/kg h_1=2764KJ/kg	η=54.2% SSC =3.94kg/kwh

3.2 *Performance Characteristics*

Post maintenance test results suggest that the modification carried out greatly enhanced the boiler system overall performance. Sample test results for boiler performance before and after maintenance were plotted on the same set of axes as depicted in Figure 7.It is evident from the figure that there is about 40 minutes time lag between the two performance characteristics .Remarkably, it is noticeable that whereas performance characteristics after maintenance reached 100psi in about sixty minutes, that before maintenance progressed slowly and eventually failed to attain the operating pressure limit of 100psi. The comparison-contrast of the two results confirms that the maintenance work carried out on the boiler was effective. Notice further that the two curves, which are graphically similar, are ballparks of *ogive*. This is expected because they are representations of cumulative heat supply to the boiler and *ogive* denotes a curve of cumulative distribution function. Notice too that the pre-maintenance curve appears erratic.

3.3 Process Capability Result

Furthermore, Tables 2 and 3 respectively represent the processing times for pre- and post-maintenance periods. Table 4 and 5 were generated from Table 2 and 3 for the purpose of calculations that follow. Further, applying equations (12) and (13) to Tables 4 and 5:

Z=2.353999, $Z_{\propto/2}$ for $\frac{\alpha}{2}$ = 0.25 significance level is 1.96

Hence Z_{cal} = 2.353999> $Z_{\propto/2}$ =1.96.Our experimental data do not provide enough evidence for us to accept the null hypothesis that mean processing time before and after maintenance are equal. Thus μ_0 = 63 minutes and μ_1 = 51 minutes leading to a time saving of 12 minute per batch. The difference is considered very significant. This is noticeable on a day where a normal batch of 6 loadings in one shift is carried out, translating to a total saving of 12x6 = 72 minutes which is more than an hour. Hence, where a double shift is considered, 144 minutes or 2 hours 24 minutes is saved.

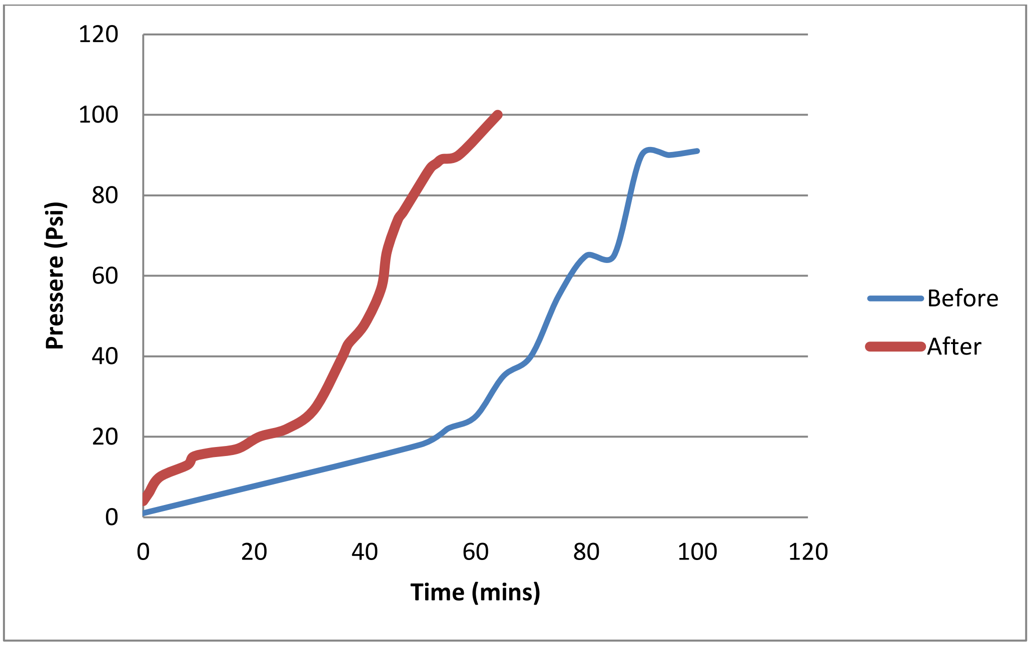

Figure 7: *Comparative Performance Characteristics of the Boiler Unit before and after Maintenanance.*

Table 2: Processing Time for FFB before Maintenance

Date	S/N	Start Loading	Stop Loading	Steam on to sterilizer	Steam off to sterilizer	Discharge	Sterilizer Pro- cessing time
30/6/99	1 2 3	2.20 9.40 11.45	2.30 9.50 11.55	7.25 9.55 12.10	8.40 10.45 1.00	9.35 11.40 2.05	75 50 50
Single 1/7/99	1 2 3	2.10 10.40 12.20	2.20 10.50 12.30	8.25 11.00 12.35	9.30 11.50 1.30	10.35 12.15 2.15	65 50 55
Single 1/7/99	1 2 3	2.20 9.15 11.20	2.30 9.25 11.30	7.00 9.35 11.50	8.35 10.25 12.55	9.10 11.15 2.00	95 50 65
Single 5/7/99	1 2 3	8.40 11.15 1.50	8.50 11.25 2.00	9.00 12.00 2.05	10.25 12.50 3.15	11.10 1.45 4.00	85 50 70

Table 3: Processing Time for FFB after Maintenance

Date	S/N	Start Loading	Stop Loading	Steam on to sterilizer	Steam off to sterilizer	Discharge	Sterilizer Pro- cessing time
28/8/99	1 2 3	12.45 2.30 4.05	12.55 2.40 4.15	1.00 2.45 4.20	1.45 3.30 5.00	2.25 4.00 5.55	45 45 40
4/9/99	1 2 3	8.55 10.40 12.30	9.10 10.50 12.40	9.15 10.55 12.45	10.00 11.35 1.40	10.35 12.25 2.35	45 40 55
26/10/99	1 2 3	12.00 9.20 11.45	12.10 9.30 11.55	7.25 9.35 12.00	8.35 10.15 1.10	9.15 11.40 3.40	70 40 70
29/10/99	1 2 3	12.15 9.00 11.25	12.25 9.10 11.35	7.00 9.15 11.40	8.15 10.00 12.40	8.55 11.20 2.15	75 45 60
1/11/99	1 2 3	8.15 10.20 12.25	8.25 10.30 12.35	8.30 10.35 12.40	9.20 1.25 1.45	10.15 12.20 2.55	50 50 65
5/11/99	1 2 3	11.20 9.15 11.15	11.30 9.25 11.25	7.20 9.30 11.55	8.40 10.45 1.00	9.10 1.10 2.30	80 75 65
Single 8/11/99	1 2 3	8.30 10.15 2.20	8.40 10.25 12.30	8.45 10.30 12.35	9.35 11.30 1.40	10.10 12.15 2.45	50 60 65
3/1/2000	1 2 3 4	3.00 8.50 10.50 12.20	3.10 9.00 11.00 12.30	7.25 9.30 11.15 12.50	7.55 9.55 12.00 1.25	8.45 10.45 12.15 2.15	30 25 45 35
1/2/2000	1 2 3 4	2.20 8.50 10.45 12.50	2.30 9.00 10.55 1.00	7.20 9.20 11.25 1.15	7.55 10.00 12.00 2.00	8.45 12.45 2.45 8.35	35 40 35 45

Table 4: Processing time before maintenance

	X_1	X_1^2
1	75	5625
2	50	2500
3	50	2500
4	65	4225
5	50	2500
6	55	3025
7	95	9025
8	50	2500
9	65	4225
10	85	7225
11	50	2500
12	70	4900
	760	50750

This is a major enhancement of productivity when the annual cost saving is considered. By this analysis, it is clear that the maintenance work carried out in the boiler and other units has greatly enhanced the processing capacity of the plant.

3.4 Failure Mode and Effect Analysis Result

Table 6 shows the FMEA worksheet which highlights the various ways by which the system can fail and the impact of such failures on the entire boiler system performance. From the table, a criticality matrix of Figure 4, showing the region needing most attention, was developed.

Table 5: Processing time after maintenance

S/N	X_2	X_2^2	S/N	X_2	X_2^2
1	45	2025	16	80	6400
2	45	2025	17	75	5625
3	40	1600	18	65	4225
4	45	2025	19	50	2500
5	40	1600	20	60	3600
6	55	3025	21	65	4225
7	70	4900	22	30	9000
8	40	1600	23	25	625
9	70	4900	24	45	2025
10	75	5625	25	35	1225
11	45	2025	26	35	1225
12	60	3600	27	40	1600
13	50	2500	28	35	1225
14	50	2500	29	45	2025
15	65	4225			

Table 6: FMEA Worksheet of a Twin Pioneer Boiler System

S/N	**Component Description**	**Failure Mode**	**Probability Class**	**Local Effect**	**System Effect**	**Severity Class**	**Comments**
1.01	Boiler tubes	Leak	D	Steam/water leaks to fire chamber	Reduced flow; blow out likely	1	Resort to using second boiler
1.02	Boiler Shells	Cracks/ Pitting	D	Steam/water leaks to fire chamber	Reduced flow; blow out likely	1	Resort to using second boiler
1.03	Pillar Valve	Leak	B	Pressure retention problem	Severe boiler pressure loss; inablility to utilize steam	2	Repair/ replacement necessary.
1.04	Chimney	Pitting	A	Reduced draught speed	Poor fuel combustion	3	Repair/ replacement necessary.
1.05	Mud Door Gasket	Leak	D	Severe steam leakage; reduced flow	Steam blow out likely	1	Replace Gasket

S/N	Component Description	Failure Mode	Probability Class	Local Effect	System Effect	Severity Class	Comments
1.06	Pressure Lines	Leak or Crack	D	Leakage of feed water to the atmosphere; steam oozes out	Reduced flow, loss of pressure indication	2	Welding/ replacement of pipe imminent
1.07	Fire bars	Fracture	A	Low firing rate	Reduced steam build up or generation rate	3	Replace firing bars
1.08	Pressure Gauge	Seizure	C	No reading on gauge	Loss/no pressure indication	4	Though not critical to operation of system, it should be replaced
1.09	Sight glass	Crack	C	Loss of water steam	Water level detection inhibited	4	Not critical to operating the system.
1.10	Feed water Pump	Seizure	C	Loss of water to boiler	Boiler lacks water	3	Alternative means of water supply sought
1.11	Steam feed water pump	Seizure	D	Loss of steam	Forced outage	1	Operation of boiler unit inhibited.
1.12	Synchronizing Valve	Leak	C	Loss of steam	Drop in working pressure	4	Not critical to operation of system.
1.13	Blowdown Valve	Locked	C	Regulatory problem i.e. boiler cannot discharge water	Regulation inhibited	3	Repair/ replace valve
1.14	Metering Valves	Leak	B	False readings	Steam pressure reading inhibited	4	Not critical to the operation of the system
1.15	Safety Valves	Leak	A	Excessive pressure build up	Blow out likely	1	Operation hazard imminent.

Probability of occurrence can be defined at the levels stated below, where

D	High Probability	> 0.2 F
	(Possible)	$P > 10^{-3}$
C	Medium Probability	0.1-0.2F
	(Improbable)	$10^{-6} < P < 10^{-3}$
B	Low probability	0.01 – 0.1F
	(Very improbable)	$10^{-9} < P < 10^{-6}$
A	Very low probability	< 0.01F
	(Virtually impossible)	$P < 10^{-9}$

where F = overall system failure probability

P = probability of occurrence

Reference to the criticality matrix shows that the boiler tubes, boiler shells, mud door gaskets, steam feed water pump and pressure lines are the regime of subsystems/ components deserving priority maintenance. This approach guided/informed our decision to modify the pillar valve pressure line system. The improvisation of mud door gasket eliminated a lot of leakage that hitherto hampered visibility on account of steam that shrouded the operational/work area.

This modification made the operation of the pillar valve more user-friendly. It will be recalled that before this modification the operator was subjected to more hazards due to the configuration of pressure lines. Whereas FMEA table (Table 6) traces the mode of failure and the effect it has on the overall system, Figure 9(a-d) represent the Fault Tree Analysis (FTA) which traces the remote and immediate causes of these faults.

3.5. Criticality Matrix Result

The consequence of the failure mode (severity ranks) could be described with the aid of Figure 8. The numerals in Figure 8 are explained as follows:

1. Catastrophic – complete loss of system.
2. Critical – severe reduction in functional performance resulting in a change in operational state.
3. Major - Degradation of their functional output.
4. Minor – No effect on performance.

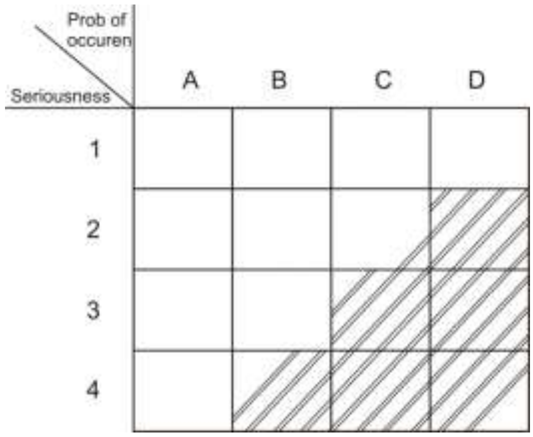

Figure 8: *Showing criticality matrix*

From the criticality matrix, we can deduce that: maintenance service providers should give particular attention to failure modes 1.01, 1.02, 1.05, 1.11 and 1.15 which are serial numbers in Table 6.

Deductively, the critical areas are:

a. D1 D2 D3
b. C1 C2
c. B1

3.6 Faulty Tree Analysis Result

Figure 9(a-d) that follow depict the Fault Tree Analysis. It is a conceptual scheme for fault diagnosis.

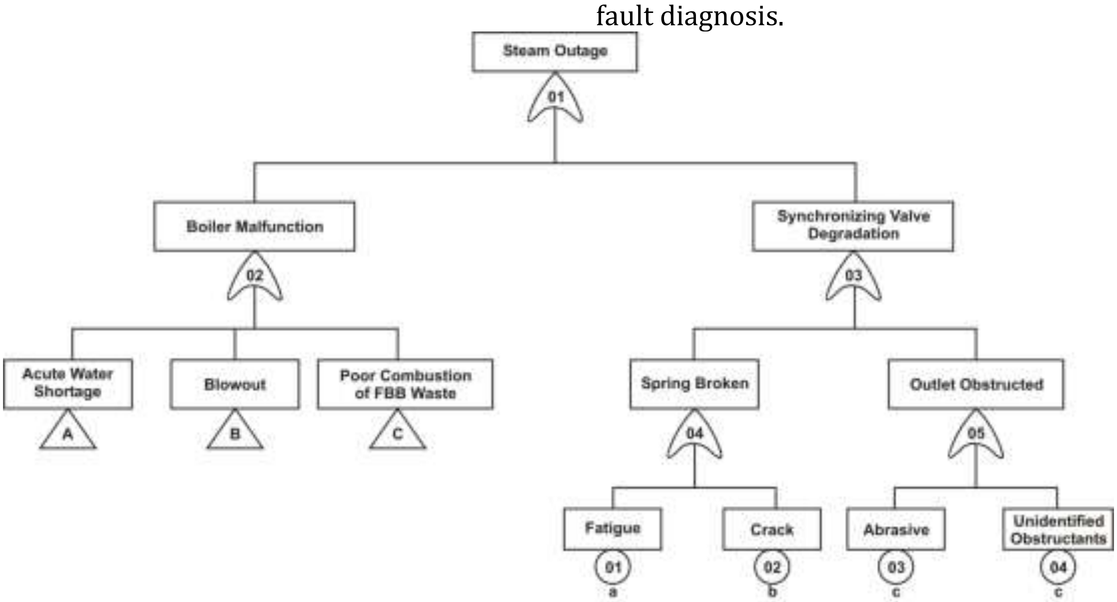

Figure 9a: FAULTY TREE ANALYSIS (FTA)

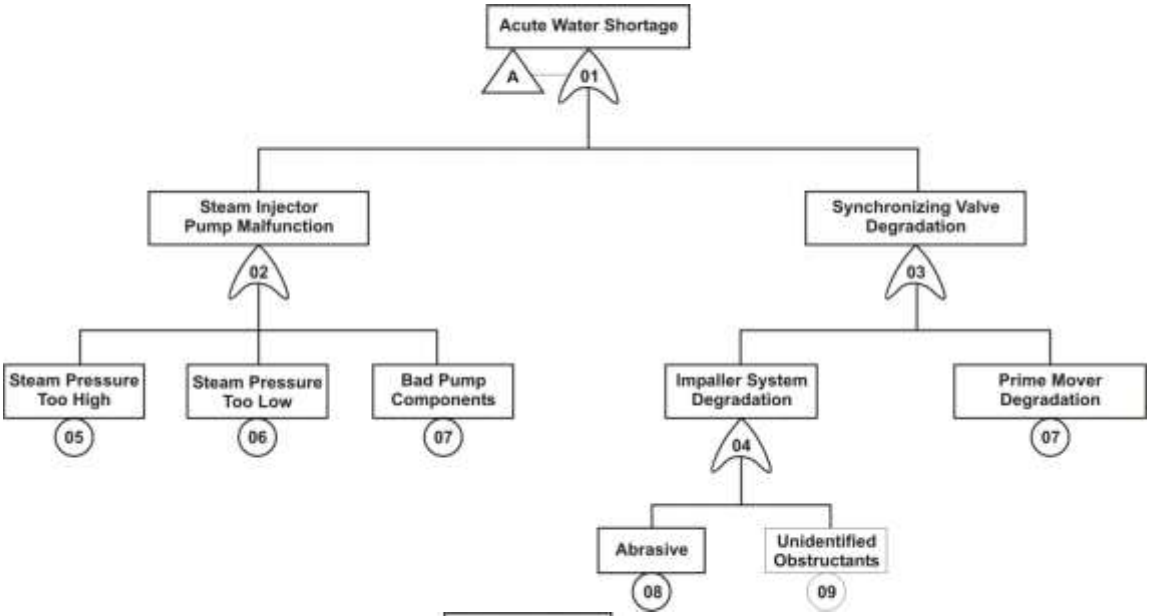

Figure 9b: Fault Tree Analysis (linking A)

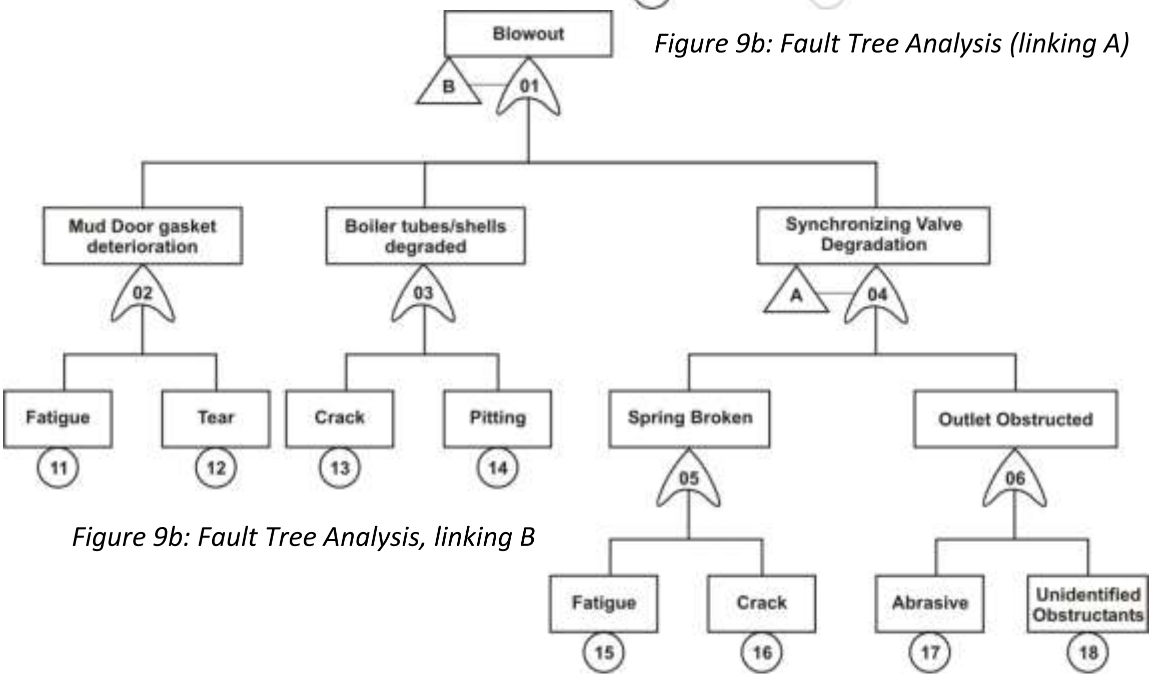

Figure 9b: Fault Tree Analysis, linking B

Figure 9c: Fault Tree Analysis for synchronous valve

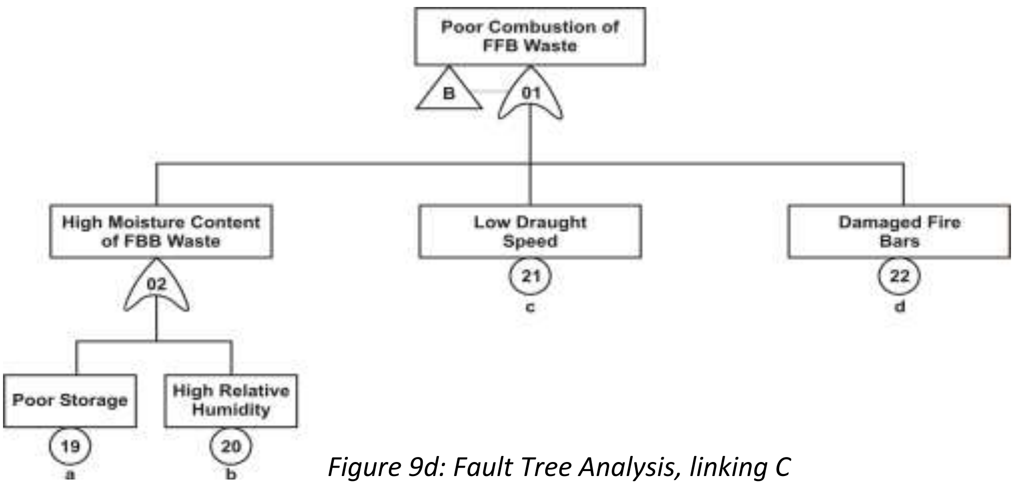

Figure 9d: Fault Tree Analysis, linking C

4. Discussion

A major modification involving the replacement of these two pillar valves, one for each boiler, restructuring of the steam supply lines made up of high carbon steel pipes, lagging of the boiler, replacement of the mud doors and inspection hole gaskets, leakages control, provision of cast iron fire bars, design-out scheme, fabrication and reinstallation of chimneys, provision of new pressure gauges and water sight glasses among other miscellaneous replacements, have greatly enhance the reliability of the boiler system.

Note, too, that a lot of major overhaul and replacement was carried out on all the units of the plant ranging from sterilizer, fresh fruit bunch conveyors, bunch stripper, fruit elevator, digester, centrifugal extractor, steam engine, clarifiers, special palm oil reciprocating pump, fibre/nut separator, cracker to other miscellaneous units. The overall effect is the enhancement of system reliability. This is evident from the results of the performance characteristics of the boiler and the comparison of the processing time before and after the overhaul of the system.

During post overhaul test carried out, it was observed that the mean time to failure (MTTF) is a good reflection of quality maintenance undertaken by the maintenance team. Only in few cases were there some failures on account of teething problems usually inherent in post overhaul testing. This is not abnormal because the bath-tub curve explains that such teething problem is a characteristic of system reliability.

In all these cases encountered and even up to thirty-six (36) months after the overhaul was undertaken, there had never been neither catastrophic nor major failure in the system. It will be recalled that the client was intending to discard the boiler unit because they felt that the unit had outlived its useful economic life.

In an initial proposal we did make it clear to them that the unit would still serve several years if the boilers were used in their normal operational mode. The level of system reliability achieved through good engineering practices has proved us right. We did also add that the material of the boiler is of superior quality and cannot be obtained anywhere now, because the boiler system was built when demand for such material were not high. The FMEA carried out revealed that boiler tubes, boiler shells, mud door gaskets, steam feed water pump and safety valves are critical components of the boiler system. Accordingly, these components require regular inspection and preventive maintenance. They should be checked for leaks, cracks, pitting, fracture and seizure as the case may be. Again, components in D probability class are potential sources of system reliability degradation and therefore require special attention. This should be highlighted in the inspection programme for maintenance staff to note. Aside, the criticality matrix results corroborate the findings of the FMEA to the effect that components that fall under I and D are potential areas for system degradation. They constitute the axis of evil.

5. Conclusion

In all that ensued we can conclude therefore that the boiler plant has a very high useful economic life as compared to automobiles and other plants using diesel fuel. This plant in question (boiler) has operated for a total of 61 years and has the potential to operate for the next 50 years when operated under a T-policy which depends on the critical age of the plant. Moreover, this energy source (boiler) uses low grade fuels (waste) from the palm bunch. It is interesting to note that these wastes have high calorific value and this is why it is able to raise steam in such a reliably small time of 1 hour even when large volume of water in the boiler is involved. The plot of pressure build up rate (see Figure 7) suggests that boiler pressure characteristics are normally distributed. A saving of 72 minutes in processing time achieved is a good index of the maintenance effectiveness.

6. Recommendation

This field research, from both the theoretical and practical points of view, demonstrates the relevance of steam technology in processing applications. It further shows that steam engine, though disregarded as extant, it still finds relevance in developing countries like Nigeria where public supply has remained problematic. Thus, in view of the epileptic nature of our public power supply, Nigeria should be thinking in terms of appropriate technology, that is where this research work displays its relevance. This is because the much talked about nuclear energy is unsafe considering the Japanese experience. Then, solar energy, geothermal energy, tidal wave energy, wind energy etc. can only be harnessed as supplement to the main grid

It is therefore expedient that the result of this research work should be carried further to miniaturizing boilers, turbines, steam engines, etc in order to produce domestic electricity supply. Steam has various uses; however, space and scope of this research work would not permit us to enumerate them. Suffice it to say that Nigeria should focus on steam energy as an alternative and cheap energy source.

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