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Reliability Based Analysis of Process Air Compressor in the Petrochemical Industry

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Abstract The performance and reliability based analysis of process air compressor in the petrochemical industry was carried out. The lognormal model was used for reliability analysis, while the Weibull probability distribution and chi test technique were used to analyzed the sample test questions. The failure based results indicated that for every 1% increase in the lognormal probability, the failure rate increased by 2.4% when compare with that of the Weibull distribution. The Reliability indicates that the reliability of the system for 50days of operation is 36.8%. This increased to 38.8% at the MTBF of 365days. Therefore, there exist a relationship between the system reliability and the failure rate. Base on the chi square test at 0.05 and 0.01 levels of significance it was concluded that "Most Machinery failures are lubrication oriented". Therefore, careful preventive maintenance process that is condition based should be followed in order to improve the plant energy efficiency.

Keywords: *reliabiity, failure, mean time to failure (MTBF), lubrication, Weibull distribution, lognormal probability, chi test technique, Air compressor*

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1. Introduction

The concept of reliability is as old as man himself. Man has long been concerned with the problem of unreliability of products used. Will "this" function satisfactorily? Will "that" last long? These are some of the familiar questions he has been asking all along. According to Reskytor [1] reliability is the property of an object to retain in time, within the predetermined limits, all the parameters ensuring the performance of the required functions in the preset service conditions. The American National Aeronautics and Space Administration (ANASA) defines reliability as the probability of a device performing adequately for the period of time intended under the operating conditions encountered, while Balaguru [2] conceives that reliability of a unit (or product) is the probability that the unit performs its intended function adequately for a given period of time under the stated operating condition or environment.

Common to all definitions is that "Reliability" is associated with; probability, intended function, time and operating conditions. If (t) is the time till the failure of the unit occurs, then the probability that it will not fail in a given environment before time (t). Thus, reliability is always a function of time. It also depends on the environmental conditions which may or may not vary with time. Since it is a probability, its numerical value is always between one and zero.

However before delving into the topic Using reliability analysis to improve the performances of rotor dynamic system, an understanding of the term "failure" is needed.

According to Lewis [3] a system or a machine is said to fail when it ceases to perform its intended function. On the other hand, Shigley and Charles [4] consider a machine or machine component to have failed when it is no longer capable of performing its required function in a satisfactory manner.

Bain [5] defined failure as any change in a machine part or component which causes it to be unable to perform its intended function satisfactorily, also failure as the inability of a component to retain in time, within the predetermined limits all the parameters ensuring the performance of the required function in the present service conditions [1]. Failure can also be defined as an event arising from complete loss of operationally.

A process air compressor is a device that converts power using either electric motor, diesel or gas engine into potential energy stored in pressurized air. The compressed air then is held in the tank until called into use. According to design and principle of operation, they can be classified as positive displacement compressors and negative displacement compressors. Process air compressors are used in petrochemical industry. In present scenario of the demand of energy efficiency is increasing, optimization and effective maintenance plan will enhance sustainable performance [6]. In petrochemical plant, compressors are running in a corrosive and high temperature conditions [7]. Jennings [8] and Crowder [9] used fault tress technique to rank the various risk associated with the petrochemical industry machinery and their corresponding consequences without considering the probability prediction of time-to-failure of the plant. Ayyab and Chia [10] used reliability goal and subsystem criteria to evaluate the stressed machinery subsystem of the plant without the consideration of the impact of performance indicators and probabilistic review of the plant with time.

Therefore, the research seeks to use probability models to analyze the reliability and time-to-failure of the process air compressor in the petrochemical industry.

2. Methodology

2.1. Area of Study

Compressors in three process plants namely; Olefins Plant, Ethylene Plant, Propylene Plant with Power Plant and utilities in a Petrochemicals Plant were covered. These plants have been in operation since 1993 and there have not been a work on the performance of the operating compressors.

2.2. Sampling Procedure

A random sample of production personnel (chief operator, panel operator, field operator) and maintenance personnel (mechanical superintendent, supervisor) involve in the operation and maintenance of the machinery in question were taken from which the questionnaire was structured.

2.3. Data Collection

Data was acquired through a set of questionnaires and extracts from log books. 30 questionnaires were distributed to respondents in Production and Maintenance Departments of the plant, who are involved in the operation and maintenance of the Petrochemicals Plant.

Out of the 30 questionnaires administered, 12 were completed and returned. This represents an overall response of 40%. Analysis and discussion of data is based on the 12 completed questionnaires. The overall responses were analyzed.

2.4. Research Design

The study adopted a descriptive and inferential analysis on randomly selected sample.

3. Theoretical Formulation and Analysis

There are different types of statistical models used in analyzing any engineering data. The accuracy of such analysis depends on whether the chosen model is appropriate; choice of a wrong model can lead to serious errors. Some of these equations and statistical models are:

3.1. Wiebull Distribution

The exponential distribution has limited application as a time to failure model because of “no wear out” or aging is not realistic for many services; The Weibull takes care of this limitation and has the following properties [11].

a. Increasing hazard rate
b. Decreasing hazard
c. Constant hazard rate.

It fits into large number of failure characteristics of equipment. The most general form of Weibul Law is given by (Lewis 1987)

$$F_{(t)} = 1 - \exp\left[-\left(\frac{t-\alpha}{\eta}\right)^{\beta}\right] \tag{1}$$

$$R_t = 1 - F_{(t)} \tag{2}$$

From equation 3.1 and 3.2, we have

$$R_t = \exp\left[-\left(\frac{t-\alpha}{\eta}\right)^{\beta}\right] \tag{3}$$

where α is the location parameter, β is the shape parameter, R_t is the reliability of the plant, F_t is the failure rate of the plant.$and\ t\ is\ the\ time$

A study on the form of the instantaneous failure rate $\lambda(t)$ shows that:

$$for\ \beta < 1\ \lambda_{(t)}\ is\ decreasing$$

$$for\ \beta = 1\ \lambda_{(t)}\ is\ constant$$

$$for\ \beta > 1\ \lambda_{(t)}\ is\ increasing$$

Also according to Gaka and Tabaszewski, [12] hazard rate can be expressed as:

$$H_{(t)} = \alpha\beta t^{(\alpha-1)} \tag{4}$$

Where α is the shape of the distribution, β is the scaling parameter that determines the spread of the values

$$\alpha = \frac{3.084}{\ln\ln T_{\infty} - \ln\ln T_t} \tag{5}$$

$$\beta = \left(T_{\infty}\right)^{\alpha} \tag{6}$$

$$S^2 = \sum X_i^2 - \frac{1}{n}\left(\sum X_i\right)^2 \tag{7}$$

$$b = \frac{0.607L_2 - 0.2570L_1}{n} \tag{8}$$

$$W = \frac{nb^2}{S^2} \tag{9}$$

$$W_p = \beta_0 + \beta_1 \ln(n) - \beta_2 [\ln n]^2 \tag{10}$$

Where Tt is the time to failure at a given instant, T_{∞} is the time to failure at infinity, X_i is the sample response from the questionnaire, n is the total sample response, w_p is the percentiles for Weibull distribution test.

3.2. Log Normal Distribution

The lognormal model has many uses in engineering. It can be derived as the appropriate model where failure of a unit occurs when damage has reached a specific level. The model has been used to model stress failure mechanism, such as failure caused by rupture. In such models it is assumed that the rupture was caused when crack in the structure reached a given size and the growth of the crack at any instant is a random proportion of its size at that time.

It is also used in the analysis of mechanical fatigue of wear.

From Spiegel and Stephen [13], the probability density function is given by;

$$f_t = \frac{1}{\delta(2\lambda)} \exp{-1/2} \left(\frac{\ln \ln t - \mu}{\delta} \right)^2 \frac{1}{t} \qquad (11)$$

Where δ is the shape parameter, μ the scaling parameter.

The mean time between failures MTBF, between nth, and the n+1th failure as given by [3] is

$$\begin{aligned} &Mean\ Time\ Between\ Failure(MTBF) \\ &= \int_t^{\infty} (t - t_n) f^n(t)\, dt \end{aligned} \qquad (12)$$

Where t_n is the time that the nth failure occurred, t is the time to failure.

3.3. Gama Distribution

This is used when the time to failure of a system is made up of redundant units and where redundant units are switched on when the operating units fail. It is also used when failure is caused by accumulation of damage. However, for the purpose of this study, the Weibull, lognormal, the chi-square test and the F-test are used for analysis.

3.4. The Chi-square Test (χ^2)

Is a measure of discrepancy existing between the observed and the expected frequencies. The symbol χ^2 is the Greek letter Chi. The test was first used by Gupta [14]-. It is defined as:

$$\chi^2 = \sum \left(\frac{O - E}{E} \right) \qquad (13)$$

Where O is the observed frequencies, E is the expected frequencies.

$$E = \frac{R_T x C_T}{N} \qquad (14)$$

Where E is the expected frequency, R_T is the total for the row containing the cell, C_T is the total for the column containing the cell, N is the total number of observation

$$Degree\ of\ Freedom\ df = (C - 1)(r - 1) \qquad (15)$$

Where C is the number of row, r is the number of column.

$$\begin{aligned} &Failure\ Rate(FR) \\ &= \frac{Numbers\ of\ failure}{Total\ numbers\ of\ machines\ under\ test} \end{aligned} \qquad (16a)$$

Or

$$Failure\ Rate(FR) = \frac{Numbers\ of\ failure}{Operating\ time} \qquad (16b)$$

$$\begin{aligned} &Mean\ Time\ Between\ Failure(MTBF) \\ &= \frac{Operating\ time}{Numbers\ of\ failure} \end{aligned} \qquad (17)$$

$$Availability(A) = \frac{MTBF}{MTBF + MTTR} \qquad (18a)$$

Where $MTBF$ is the mean time between failures, $MTTR$ is the mean time to failures.

Or

To determine the value of χ^2, the steps required are:

i. Take the differences between the observed and the expected frequency and obtain the square of these differences i.e. obtain the values of $(O - E)^2$.

ii. Divide the values of $(O - E)^2$ obtained in step (II) by the respective expected frequencies and from equation (13) we obtain the total as

$$\sum \frac{(O - E)^2}{E}.$$

This gives the value of χ^2, which can range from zero to infinity. If χ^2 is zero it means that the observed and the expected frequencies completely coincide. The greater the discrepancy between the observed and the expected frequencies the greater shall the value of χ^2.

4. Results and Discussions

The Weibull distribution and the chi-square test was used to test the two hypothesis, while the lognormal was used to analyze the reliability of the systems. In addition, the MTBF, MTTR and the availability of the machines was determined. The Weibull distribution model was used to test hypothesis 1, failure data of a compressor (25-k-1A) each treated as a system obtained from maintenance and operation logs were used.

4.1. Test Question I: Are Machinery Failure Rate Dependent on its running Hours?

Failure data of compressor (25-k-1A) was treated as a system, located in power plant and utilities was analyzed using the Weibull distribution model. Table 1 show the time to failure of the compressor.

Table 1. Time to Failure in Hour for Process Air Compressor 25-k-1A

Time-to-failure, hours	Failure Order Number out of Sample Size of 6
16	1
34	2
53	3
75	4
93	5
120	6

Table 2. Analytic Test of Failure using Weibull Distribution Technique for 25-K-1A

N	T_i	$\ln(T_i)$	$F(T_i)$	y_i	$(\ln T_i)^2$	y_i^2	$(\ln T_i)y_i$
1	16	2.7726	0.1091	-2.1583	7.6873	4.6582	-5.9840
2	34	3.5264	0.2645	-1.1802	12.4352	1.393	-4.1620
3	53	3.9703	0.4214	-0.6030	15.7632	0.3637	-2.3943
4	75	4.3175	0.5786	-0.146	18.6407	0.0213	-0.6303
5	93	4.5326	0.7355	0.2851	20.5445	0.0813	1.2923
6	120	4.7875	0.8909	0.7955	22.9201	0.6328	3.8083
Σ		23.0068		-3.007	97.9909	7.1502	-8.0699

The steps for determining the parameters of the Weibull representing the data, using probability plotting, are outlined in the following instructions. First, rank the times-to-failure in ascending order as shown next.

Consider the same data set from Table 1 given above (with six failures at 16, 34, 53, 75, 93 and 120 hours). Estimate the parameters and the correlation coefficient using rank regression on Y, assuming that the data the 2-parameter Weibull distribution we have Table 2.

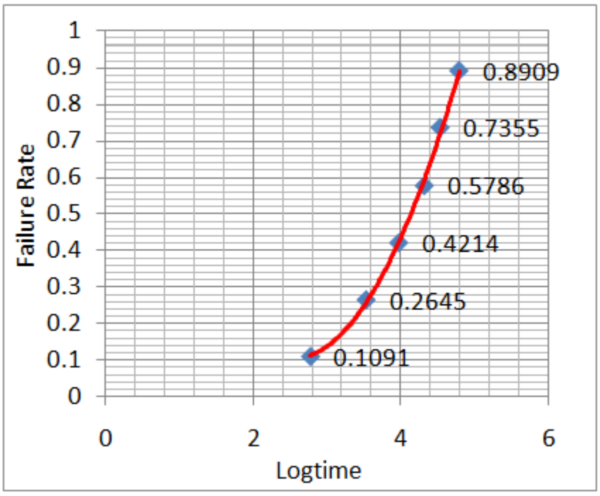

Figure 1. Variation of Failure Rate with Logtime for Process Air Compressor 25-K-1A

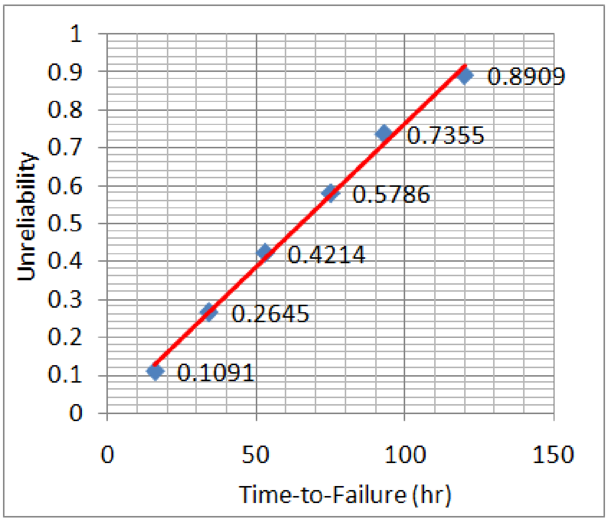

Figure 2. Plot of Unreliability of the Air Compressor against Time-to-Failure

Figure 1 and Figure 2 show the results of the weibull distribution and lognormal probability. The figures show a linear progression such that as the failure rate and log time increases as the machinery time to failure increases. This is an indication that if the machinery is not adequately maintained, the air compressor will fail before the life cycle. It further show that for every 1% increase in the lognormal probability, the failure rate increases by 2.4%.

The result shows a weibull analysis of the air compressor for 6 different sample time to failure as predicted from design. The result indicates that for a period of 25 operating hour, minor failure may occur in the sub system and the overall life cycle can be extended if effective maintenance is sustained.

Further analysis show that from equation 7 we have that

$$S^2 = 97.9909 - \frac{1}{6}(23.0068)^2 = 9.823$$

$$b = \frac{0.6071(7.1502) - 0.2570(-8.0699)}{6} = 1.069$$

$$W = \frac{6 \times (1.069)^2}{9.823} = 0.69.$$

The value of W obtained is compared to the 0.05 and 0.95 critical values computed from the above equation.

$$W_{(0.05)} = 0.1320 + 0.10792 \ln 6 + (-0.006487)(\ln 6)^2$$
$$= 0.4094.$$

Similarly,

$$W_{(0.95)} = 1.46218 + (2111) \ln 6 + 0.012914 (\ln 6)^2$$
$$= 0.9216.$$

The result show that the value of W lies between the two numbers, therefore machinery failure rate is dependent on its running hours that is Weibull distribution is accepted. Appendix II shows the percentiles of Weibull distribution for the W test to validate the result output. It therefore demands that an effective condition monitoring technique be put in place to monitor the operation and performance as the operation hour increases. Cost effectiveness and production optimization can be achieved if a proactive maintenance strategy is maintained.

4.2. Hazard Rate Analysis of Compressor 25-K-1A

The hazard rate for the process air compressor using Weibull distribution is estimated from

$$H_{(t)} = \alpha \beta t^{(\alpha - 1)}$$

$$\alpha = \frac{3.084}{\ln \ln T_\infty - \ln \ln T_t}$$

$$\beta = (T_\infty)^\alpha$$

At $T_{90} = 1.8$ time at $P_i = 90$; at $T_{63} = 0.4$ time at $P_i = 63$; at $T_{10} = 1.2$ time at $P_i = 10$

$$\alpha = \frac{3.084}{\ln T_{90} - \ln T_{63}} = \frac{3.084}{\ln 1.8 - \ln 0.4} = 2.05$$

$$\beta = (T_{10})^{-\alpha} = (1.2)^{-2.05} = 0.688 \approx 0.69.$$

This shows that the hazard rate of the compressor for the period under review is increasing since $\alpha > 1$.

4.3. Test Question II: Are Most Machinery Failures Lubrication Oriented?

30 questionnaires were administered with relevant question to detect the cause of failure. The data generated in this respect shows that distribution between lubrication related and non-lubrication related failures are in the ratio of 4:8.

The result shows that out of 12 respondents, 33.0% are lubrication related failures, while 67% are not lubrication related. Chi-square Test will be used for the sample question. The Chi-square Test (χ^2) is a measure of discrepancy existing between the observed and the expected frequencies. The symbol χ^2 is the Greek letter Chi. The analysis of the result from the questionnaires were analyzed using the expected frequency formulation and result shown in Table 3.

Table 3. Observed and Expected Frequencies Analysis

Observations (O)	Expected Frequencies	$(O-E)^2$	$\frac{(O-E)^2}{E}$
8	9.4	2.89	0.36
4	5.9	1.9	0.475
			$\sum \frac{(O-E)^2}{E}$ $= 0.85$

Hence the degree of freedom (*df*);

$$\begin{aligned} df &= (c-1)\ (r-1) \\ &= (4-1)\ (2-1) = 3. \end{aligned}$$

Test the theory at 0.05 level where $df = 3$, χ^2 0.05 = 7.8 using Appendix (IV).

Since 0.85 less than 7.80 we cannot reject the theory at0.05 level of significance.

To test the theory at 0.01 level of significance, we have for $df = 3$, χ^2 0.01 = 11.34.

Since 0.85 is less than 11.34, we can say that most machinery failures are lubrication oriented of 0.01 level of significance. Thus, base on the chi square test at 0.05 and 0.01 levels of significance we can also say that “Most Machinery failures are lubrication oriented”.

The lognormal distribution is used to analyze the reliability of the process air compressor (25-K-1A), whose failure is characterized by wear as a result of poor lubrication. The time to failure of the compressor is shown in Table 1.

From Figure 1, $Y_{90} = 1.61$ *and* $Y_{10} = 1.16$.

Therefore

$$\sigma^* = \frac{2}{5}(Y_{90} - Y_{10}) = {}^{2}\!/_{5}(1.61 - 1.16) = 0.18.$$

To estimate the value of μwe used $\mu^* = Y_{50}$, where μ^* is the estimated values of μ.

Therefore at $Y_{50} = 1.38$, we have that.

The mean value

$$(T) = \frac{1}{n}\left(\sum T_1\right) = \frac{1}{25}(33.85) = 1.35.$$

The standard deviation

$$S = \sqrt{\frac{n\sum T_2 - \left(\sum T_1\right)^2}{n(n-1)}} = \sqrt{\frac{25 \times 47.1 - 33.8^2}{25(25-1)}} = 0.230.$$

From the analysis, the probability of anytime to failure can be obtained. For example, the probability that the time to failure of the compressor of (3.1 months) is obtained by taking the logarithms of 3.1 i.e., in (3.1) = 1.2 is located on the Y axis and the corresponding values on X-axis gives the value of P as $\approx 10.5\%$.

The probability of failure of the pump can be obtained from

$$U_p = \frac{\ln t - \mu}{S} = \frac{\ln t - m}{\sigma}$$

where $\sigma = \sigma^* = 0.18$ *and* $M = \mu^* = 1.38$.

The probability of failure $\varphi_{(u)}$ can be obtained from normal distribution Tables (Appendix (V)) depending on the value of $\frac{\ln t - m}{\sigma}$ from which the reliability can be determined.

4.4. Analysis of Reliability of the Compressors

The reliabilities after 4 years, 5 years and 6 years of operation was estimated as follows:

i. Reliability after four (4) years of operation

Probability of failure after 4 years

$$U = \frac{\ln 4 - 1.38}{0.18} = 0.034$$

$$\phi_{(u)}\ \textit{from Appendix}(IX) = 0.612 \textit{at}\ U = 0.034.$$

However, Reliability (R) = 1- Probability of failure

Therefore R (t) after 4years $= 1 - \phi_{(0.034)} = 1 - 0.512 = 0.48 = 48\%$

ii. Reliability after 5 years

Probability of failure after 5 years

$$U = \frac{\ln 5 - 1.38}{0.18} = 1.27$$

$$\phi_{(u)} \ from\ Appendix(IX) = 0.898\ at\ U = 1.27.$$

Therefore R (t) after 5years $= 1 - \phi_{(1.27)} = 1 - 0.898 = 0.10 = 10\%$.

iii. Reliability after 6 years

Probability of failure after 6 years

$$U = \frac{\ln 6 - 1.38}{0.18} = 2.28$$

$$\phi_{(u)} \ from\ Appendix(IX) = 0.988\ at\ U = 2.2.$$

However, Reliability (R) = 1- Probability of failure

Therefore R (t) after 6years $= 1 - \phi_{(2.28)} = 1 - 0.988 = 0.012 = 1.2\%$

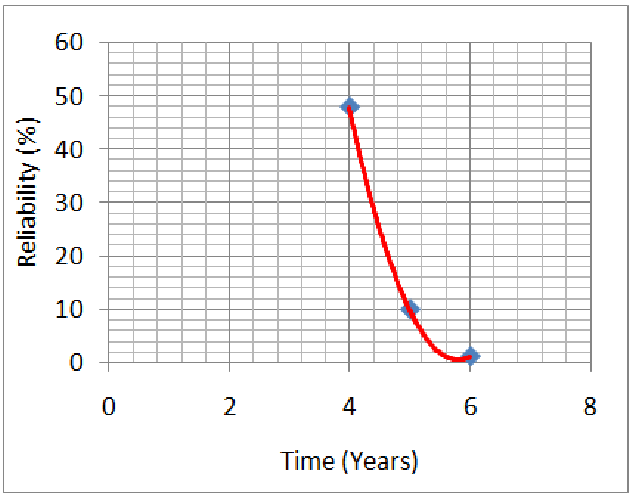

Figure 3. Plotted value of Reliability against Time (years)

Figure 3 show that the reliability of the equipment decreases with operating time. This result therefore provides a guide on the choice of maintenance plan to be adopted to prevent or minimizes system breakdown and failure. Predictive maintenance that is condition based will help to prevent and protect the plant, thereby sustain production and minimize downtime.

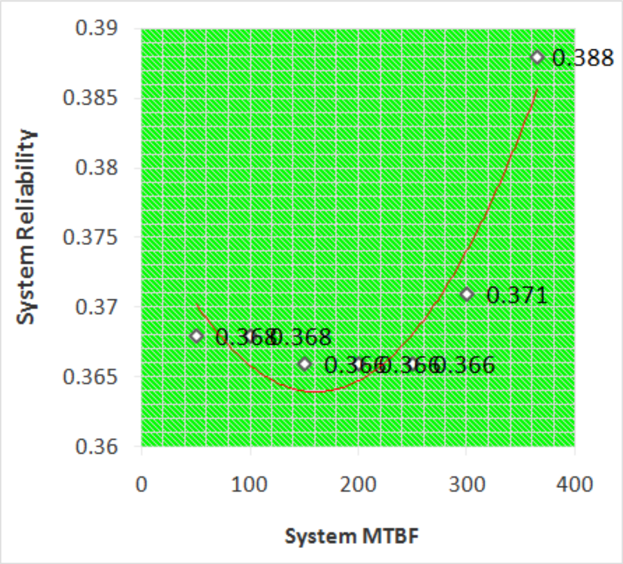

Figure 4. Plot of Reliability with MTBF

4.5. Failure Analysis of the Compressors

A test case was analysed for the systems operating for the period of one year (365days) using equations 16 – 18 we have that the reliability ranges from 0 to 100, and there is gradual increase in failure with time of the plant operation. Figure 4 shows a plot of reliability with the mean time between failures for a process air compressor within 365days of operation. This plot also affirms the fact that failure rate may be influenced by the running hours and maintenance style of the equipment.

The result plotted in Figure 4 shows the reliability of the plant at different MTBF values. This indicates that the reliability of the system for 50days of operation is 36.8%. This increased to 38.8% at the MTBF of 365days. Therefore, there exist a relationship between the system reliability and the failure rate. That is, as the system reliability increases the failure rate gradually decreases.

5. Conclusion

From appropriate equations and statistical tools used in testing the performance and reliability of air compressor. The investigation shows that machinery failures in Indorama Petrochemical Company is as a result of continuous running without inspection, Poor lubrication; and Poor implementation of preventive maintenance programs.

6. Recommendation

The following recommendations were made

i. Adequate preventive maintenance as specified by the manufacturer should be carried out.
ii. Strict adherence to Turn Around Maintenance Schedules (TAM).
iii. Changing of oil as at when due, oil analysis should be carried to determine when lubricants should be changed.
iv. Proper Handling of Lubricants to avoid contamination.
v. The material management department should work hand- in-hand with the user department to ensure that the right spares are supplied.

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APPENDICES

APPENDIX I

QUESTIONNAIRE ON MACHINERY FAILURES IN EPCL QUESTIONNAIRE FOR INVESTIGATING EQUIPMENT/COMPONENT FAILURES IN INDORAMA PETROCHEMICALS COMPANY LIMITED, PORT HARCOURT RIVERS STATE, NIGERIA

Instructions

This questionnaire is designed purely for academic purpose and so all information by you will be kept strictly confidential. You are therefore kindly requested to be sincere and objective in your response. To complete this questionnaire, you must be working on the equipment on the equipment either as a maintenance, production, engineering service and maintenance planning staff.

SECTION A
MACHINE DESCRIPTION

1. Machine Tag ☐
2. Function ☐
3. Service Time: Continuous ☐ Intermittent ☐ (Tick (√) where applicable) ☐
4. Area ☐
5. Driver ☐
6. Rated power ☐
7. Rated speed ☐
8. Suction/Discharge pressure
9. Machine orientation: Horizontal ☐ Vertical ☐
10. Type of lubrication: Oil ☐ Grease ☐
11. What is the age of the equipment? ☐

SECTION B
MACHINE REPORT/HISTORY

11. Has there been any record of failure after installation?
Yes ☐ no ☐

12. If “Yes” what is the nature of failure?
Sudden ☐ after repeated symptoms/Alarms ☐

13. Which of these symptoms manifested before failure?
High vibration ☐ Abnormal noise ☐ High amperage ☐
Low discharge pressure ☐ Mechanical seal leakage ☐ Bearing overheating ☐

14. What could be the cause of failure? ☐

a) Maintenance

i) Improper repair ☐ (ii) Lack of preventive maintenance ☐
iii) Inadequate lubrication ☐ (iv) Improper installation ☐

b) Operation

i) Over load ☐ (ii) Improper short down ☐
iii) No lubrication ☐ (iv) Improper operation technology ☐

c) Not suitable for service

i) Faulty design assumption ☐ (ii) End of service life ☐
iii. Lack of spares ☐

SECTION C
COMPONENT FAILURE CONFIRMATION

15. Bearing
What would you say is the cause of failure?
i) Defective bearing seat ☐ (ii) Poor assembly ☐
iii) Misalignment ☐ (iv) Over loading ☐
v) Inadequate lubrication ☐ (vi) What is the machine age? ☐
16. Mechanical
What do you think is the cause of failure?
i) Improper operation ☐ (ii) Misalignment ☐
iii) Improper installation ☐
17. Gears
What is the most common cause of gear failure?
i. Poor lubrication ☐
ii. Vibration ☐
iii. Lack of preventive maintenance ☐
iv. Misalignment ☐
v. What is the age of the machine? ☐
18. In your plant what is the estimated number of failures for the period under review?..
19. Of these, how many are:
i. Lubrication oriented ☐
ii. Non lubrication oriented ☐
20. Is lack of preventive maintenance the cause of failures?
Yes ☐ No ☐
21. What is the equipment age

APPENDIX II

PERCENTILES FOR WEIBULL DISTRIBUTION TEST W

Percentage Point ρ	β_0	β_1	β_2
0.05	0.10102	0.04249	0.005882
0.025	0.11787	0.08550	-0.002048
0.050	0.13200	0.10792	-0.006487
0.950	1.46218	-0.21111	0.012914
0.975	1.64869	-0.26411	0.016840
0.995	1.91146	-0.31361	0.017669
$W\rho = \beta_0 + \beta_1 \ In \ (n) + \beta_2 \ (In \ n)^2$			

Cohen, A. C (1965) Maximum Likelihood Estimation of the Weibull Distribution Based on Complete and Censored Samples, *Technometrics.*

APPENDIX III

PROBABILITY CHART FOR DISTRIBUTION

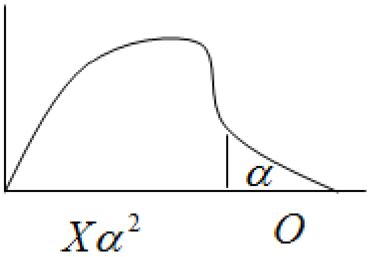
N	0.005	0.01	0.025	0.05	0.10	0.50	0.00	0.95	0.975	0.99	0.995
3.	0.2510	0.2518	0.2506	0.2607	0.2915	0.5214	0.0102	0.9926	0.9281	0.9297	0.00003
4.	0.1211	0.1302	0.1111	0.1601	0.1521	0.1768	0.7514	08581	0.9236	0.9650	0.0817
5	0.0915	0.0205	0.1018	0.1187	0.1412	0.2825	0.5547	0.6682	0.7590	0.0800	0.0102
6	0.0610	0.0665	0.0802	0.0256	0.1123	0.2226	0.4202	0.5082	0.5812	0.3501	0.2501
7	0.0511	0.0521	0.0700	0.0810	0.0286	0.1871	0.3474	0.4162	0.4952	0.5786	0.0000
8	0.0151	0.0512	0.0611	0.0000	0.0852	0.1625	0.2034	0.3427	0.4033	0.4813	0.0000
9	0.0101	0.0112	0.0517	0.0633	0.0151	0.1415	0.2553	0.3005	0.2095	0.4125	0.0000
10	0.0162	0.0101	0.0132	0.0568	0.0678	0.1225	0.2178	0.2525	0.2619	0.3391	0.0000
11	0.0000	0.0350	0.0117	0.0528	0.0616	0.1112	0.1911	0.2265	0.2162	0.2619	0.0000
12	0.0011	0.0358	0.0110	0.0121	0.0567	0.1000	0.1723	0.2018	0.2164	0.2716	0.2078
13	0.0287	0.0007	0.0182	0.0160	0.0528	0.0220	0.3563	0.1820	0.2421	0.2421	0.2612
14	0.0265	0.0017	0.0062	0.0128	0.0106	0.0817	0.1417	0.1617	0.2131	0.2134	0.115

N	0.005	0.01	0.025	0.05	0.10	0.50	0.00	0.95	0.975	0.99	0.995
15	0.0247	0.0208	0.0111	0.0123	0.0166	0.0118	0.1285	0.1485	0.1926	0.1926	0.2123
16	0.0233	0.0280	0.0126	0.0174	0.0118	0.0228	0.1187	0.1355	0.1542	0.1270	0.1211
17	0.0222	0.0261	0.0110	0.0352	0.0112	0.0081	0.1000	0.1257	0.1423	0.1614	0.1201
18	0.0212	0.0250	0.0201	0.0332	0.0388	0.0642	0.1015	0.1161	0.1311	0.1483	0.1668
19	0.0203	0.0218	0.0278	0.0311	0.0368	0.0000	0.0915	0.1071	0.1192	0.1371	0.1152
20	0.0196	0.0027	0.0263	0.0302	0.0352	0.0570	08811	0.1002	0.1286	0.1286	0.1369
21	0.0100	0.0217	0.0250	0.0200	0.0337	0.0510	0.0800	0.0018	0.1051	0.0198	0.1288
22	0.0185	0.0208	0.0218	0.0278	0.0123	0.0516	0.0701	0.0894	0.0288	0.1118	0.1213
23	0.0181	0.0201	0.0210	0.0266	0.0010	0.0102	0.0742	0.0836	0.0233	0.1043	0.1112
24	0.0177	0.0194	0.0224	0.0256	0.0206	0.0168	0.0701	0.0788	0.6882	0.0284	0.1011
25	0.0173	0.0188	0.0218	0.0218	0.0236	0.0111	0.0668	0.0749	0.0836	0.0927	0.1000
26	0.0162	0.0182	0.0211	0.0210	0.0271	0.0126	0.0636	0.0712	0.0813	0.0985	0.0018
27	0.0165	0.0177	0.0208	0.0232	0.0261	0.0407	0.0606	0.0678	00747	00813	0.0006
28	0.0161	0.0172	0.0203	0.0225	0.0256	0.0101	0.0576	0.0649	0.0706	0.0015	0.0000
29	0.0157	0.0168	0.0186	0.0212	0.0212	0.0177	0.0555	0.0621	0.0752	0.0259	0.0000
30	0.0153	0.0161	0.0188	0.0210	0.0242	0.0061	0.0536	0.0593	0.0712	0.0712	0.0000
31	0.0142	0.0000	0.0183	0.0207	0.0215	0.0152	0.0518	0.0560	0.0615	0.0656	0.0000
32	0.0145	0.0156	0.0178	0.0201	0.0222	0.0000	0.0121	0.0517	0.0561	0.0561	0.0000
33	0.0141	0.0152	0.0173	0.0125	0.0221	0.0120	0.0125	0.0577	0.0573	0.0636	0.0000
34	0.0137	0.0148	0.0168	0.0100	0.0217	0.0119	0.0159	0.0507	0.0555	0.0611	0.0621
35	0.0133	0.0141	0.0161	0.0185	0.0211	0.0100	0.0444	0.0188	0.0537	0.0585	0.0000
36	0.0129	0.0141	0.0160	0.1010	0.0205	0.0100	0.0129	0.0170	00519	00567	0.0630
37	0.0125	0.0138	0.0156	0.0176	0.0200	0.0291	0.0114	0.0154	0.0501	0.0546	0.0603
38	0.0122	0.0135	0.0152	0.0172	0.0105	0.0263	0.0100	0.0140	0.0163	0.0525	0.0578
39	0.0120	0.0133	0.0148	0.0168	0.0190	0.0275	0.0186	0.0126	0.0165	0.0542	0.0553
40	0.0118	0.0131	0.0141	0.0161	0.0186	0.0267	0.0375	0.0114	0.0147	0.0192	0.0553
41	0.0116	0.0129	0.0140	0.0161	0.0182	0.0260	0.0361	0.0102	0.0130	0.0126	0.0510
42	0.0114	0.0127	0.0137	0.0158	0.0178	0.0251	0.0355	0.0389	0.0117	0.0164	0.0123
43	0.0112	0.0125	0.0134	0.0155	0.0174	0.0215	0.0346	0.0379	0.0105	0.0452	0.0162
44	0.0110	0.0123	0.0131	0.0152	0.0170	0.0243	0.0338	0.0369	0.0224	0.0119	0.0171
45	0.0108	0.0121	0.0129	0.0142	0.0166	0.0238	0.0329	0.0359	0.0185	0.0423	0.0160
46	0.0106	0.0118	0.0122	0.0146	0.0162	0.0233	0.0120	0.0349	0.0376	0.0436	0.0112
47	0.0101	0.0117	0.0125	0.0141	0.0158	0.0228	0.0011	0.0340	0.0367	0.0324	0.0138
48	0.0103	0.0115	0.0123	0.0111	0.0155	0.0223	0.0000	0.0332	0.0355	0.0352	0.0000
49	0.0102	0.0113	0.0122	0.0139	0.0155	0.0218	0.0205	0.0324	0.0312	0.0321	0.0000
50	0.0101	0.0111	0.0120	0.0137	0.0152	0.0211	0.0288	0.0317	0.0310	0.0360	0.0105
51	0.0100	0.0100	0.0112	0.0135	0.0142	0.0200	0.0282	0.0310	0.0331	0.0349	0.0301
52	0.0000	0.0107	0.0112	0.0133	0.0145	0.0250	0.0776	0.0001	0.0323	0.0341	0.0123
53	0.0007	0.0106	0.0118	0.0131	0.0113	0.0001	0.0210	0.0296	0.0315	0.0332	0.0161

Bain, L. J. (1978) Statistical Analysis of Reliability and Life-Testing Models, Marcel Dekker Inc, New York.

APPENDIX IV

VALUES OF CHI-SQUARE



α df	.100	.050	.025	.010	.005	.001
1	2.71	3.84	5.02	6.63	7.88	10.8
2	4.61	5.99	7.38	9.21	10.6	13.8
3	6.25	7.81	9.35	11.3	12.8	16.3
4	7.78	9.49	11.1	13.3	14.9	18.5
5	9.24	11.1	12.8	15.1	16.7	20.5
6	10.6	12.6	14.4	16.8	18.5	22.5
7	12.0	14.1	16.0	18.5	20.3	24.3
8	13.0	15.5	17.5	20.1	22.0	26.1
9	14.7	16.9	19.0	21.7	23.6	27.9
10	16.0	18.3	20.5	23.2	25.2	29.6
11	17.3	19.7	21.9	24.7	26.8	31.3
12	18.5	21.0	23.3	26.2	28.3	32.9
13	19.8	22.4	24.7	27.7	29.8	34.5
14	21.1	23.7	26.1	29.1	31.3	36.1
15	22.3	25.0	27.5	30.6	32.8	37.7
16	23.5	26.3	28.8	32.0	34.3	39.3
17	24.8	27.6	30.2	33.4	35.7	40.8
18	26.0	28.9	31.5	34.8	37.2	42.3
19	27.2	30.1	32.9	36.2	38.6	43.8
20	28.4	31.4	34.2	37.6	40.0	45.3
21	29.6	32.7	35.5	38.9	41.4	46.8
22	30.8	33.9	36.8	40.3	42.8	48.3
23	32.0	35.2	38.1	41.6	44.2	49.7
25	34.4	37.7	40.6	44.3	46.9	52.6
26	35.6	38.9	41.9	45.6	48.3	54.1
27	36.7	40.1	43.2	47.0	49.6	55.5
28	37.9	41.3	44.5	48.3	51.0	56.9
29	39.1	42.6	45.7	49.6	52.3	58.3
30	40.3	43.8	47.0	50.9	53.7	59.7
35	46.1	49.8	53.2	57.3	60.3	66.6
40	51.8	55.8	59.3	63.7	66.8	73.4
45	57.5	61.7	65.4	70.0	73.2	80.1
50	63.2	67.5	71.4	76.2	79.5	86.7
55	68.8	73.3	77.4	82.3	85.7	93.2
60	74.4	79.1	83.3	88.4	92.0	99.6
65	80.0	84.8	89.2	94.4	98.1	106.0
70	85.5	90.5	95.0	100.4	104.0	112.3
75	91.1	96.2	100.8	106.4	110.3	118.6
80	96.6	101.9	106.6	112.3	116.3	124.8
85	102.1	107.5	112.4	118.2	122.3	131.0
90	107.6	113.1	118.1	124.1	128.3	137.2
95	113.0	118.8	123.9	130.0	134.2	143.3
100	118.5	124.3	129.6	135.8	140.2	149.4

Lewis, E.E. (1987), *Introduction to Reliability Engineering*. John Wiley and Sons, 81-165.

APPENDIX V

STANDARD NORMAL CUMULATIVE FUNCTION Φ(U)

n	**00**	**01**	**02**	**05**	**01**	**05**	**06**	**07**	**08**	**09**
0	5000	5010	5080	5120	5160	5100	5210	5270	5319	5350
1.	5388	5188	5178	5517	5557	5506	5656	5675	5714	5753
2.	5705	5882	5871	5010	5018	5087	6026	6064	6105	6141
3.	6120	6217	6255	6293	6331	6168	6106	6112	6180	6817
4.	6551	6501	0628	6661	6700	6756	6772	6808	6811	6879
5.	6015	6050	6885	2010	7051	7088	7125	7157	7100	7224
6.	7257	7201	7521	7557	7580	7422	7154	7186	7517	0000
7.	7580	7611	7612	7675	7705	7711	7761	7701	7000	0852
8.	7881	7010	7030	7067	7005	8025	8051	8078	8000	0433

n	00	01	02	05	01	05	06	07	08	09
9.	8150	8186	8212	8288	8261	8280	8015	8310	8363	0389
10.	8111	8118	8161	8185	8508	8551	8551	8377	8500	8621
11.	8615	8665	8686	8708	8220	8710	8770	8700	8810	8800
12.	8818	8860	8888	8007	8025	8011	8062	8080	8007	00147
13.	00520	00100	00658	00821	00088	01110	91500	01166	61621	01771
14.	91921	02075	02220	02061	02507	02617	02785	02922	08056	00189
15.	93319	00148	03571	00000	08822	00013	01062	01170	01205	01108
16.	91720	01830	01718	01815	01050	05053	05151	05254	05352	00149
17.	95515	05637	05728	00818	0500	05001	06080	06164	06246	06327
18.	96107	06185	06662	06638	06712	06781	06856	06026	00005	07062
19.	79128	01793	07257	01120	07581	07111	07500	07558	00015	07670
20.	07125	07778	07811	01882	07032	02082	08000	08077	08121	08160
21.	98211	08257	08100	08011	08382	08122	08161	08500	08537	08574
22.	98610	08615	08670	08715	08715	0778	08800	08810	08010	08800
23.	08018	08056	08085	00007	00358	00613	00861	00106	00011	01576
24.	01802	02021	02210	02151	02656	00857	03053	00211	00131	08613
25.	00700	00863	01152	01207	01157	01611	01766	01010	00000	05201
26.	05110	00123	00411	05731	05855	00075	06003	06207	00000	06127
27.	06511	06636	06786	06833	06028	07020	07110	07107	08002	07365
28.	07115	07523	07500	07675	07741	007811	0788	07018	0850	08071
29.	08131	08193	08250	08505	08359	08111	08162	08511	08005	08605
30.	08650	08691	08736	08777	08810	08866	08895	08030	02636	08000
31.	00321	00616	00057	01260	01553	01836	02112	02378	01810	02886
32.	00120	03363	00500	03810	01021	01230	01120	04620	06376	0101
33.	00166	00335	05400	05658	05611	00059	06105	06212	02408	06505
34.	06631	06752	06860	06082	07001	07197	07299	07308	08282	97585
35.	07671	07750	07812	07022	07000	08071	08116	08215	08821	08347
36.	08100	08160	08527	08583	08637	08680	08730	08787	02150	08870
37.	08022	08800	00030	00126	00700	00158	00501	01888	01777	00168
38.	00765	00052	00127	00593	00818	00100	01581	01558	06551	01088
39.	00100	00385	00571	05751	00126	006000	06253	06406	07718	06606
10.	06833	06064	07000	07211	02327	071000	07116	07610	08512	02815
11.	00981	08022	08100	08186	08261	08338	08100	08177	00655	08005
12.	08165	08723	08778	08832	08882	08031	08078	00226	01000	01006
13.	01150	01837	02100	02515	02876	03193	00107	00788	00268	04332
11.	01587	01831	05065	06288	05502	05706	00002	02080	07620	06430
15.	06602	06700	06008	02051	07187	07318	07112	07561	0.000	07781
16.	07888	07087	08081	08172	00258	08310	08112	08101	01215	00631
17.	08600	08761	08821	08877	08031	080123	00320	00780	00000	01661
18.	02067	00153	00002	00174	00000	00822	01131	01120	00000	01058
19.	00208	00116	05675	00880	00001	00200	061256	00000	00000	06880

Loner, P. D.T. (1991) *Practical Reliability Engineering*, Third Edition, 64-93.