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Evaluating the Reliability of a Marine Diesel Engine Using the Weibull Distribution

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ABSTRACT:

The reliability analysis of an FBM Model 38 marine diesel engine, using the Weibull distribution was carried out in this paper. The Weibull parameters, Probability Density Function (PDF), Cumulative Distribution Function (CDF) and the Mean Time Between Failure (MTBF) of failed parts of the engine were analyzed and reliability of the system was ultimately determined. It was observed that the reliability of the marine diesel engine is inversely proportional to the service time. Results obtained were used to predict future failures of the observed components. Data from the plots showed a shape factor (β) of 6.17031, characteristic life (η) of 9435.29 for the scavenging blower roller bearing. The blower MTBF is 8766.80. There was no expected blower bearing failure in the next four years of engine operations under normal condition. The Turbocharger ball bearing has a β of 2.88035 and η of 7165.63, the MTBF is 6387.74 while 2 turbocharger bearings are estimated to fail in the next 4 years, if the initial failed bearings were replaced. Furthermore, the Injector nozzles tips have β of 2.78436 and η of 11451 and MTBF of 10194.50 three injector tips were expected to fail in the next four years of engine operations. This research is important as it provides a bases for developing a Weibull library for the marine engine components in other to analyze the failure pattern for an improved maintenance management of the engines.

Keywords: Diesel engine, Failure rate, Maintenance, Reliability, Weibull distribution.

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1. INTRODUCTION:

A mechanical system is a system which has its parts moving in other to perform a particular task. Mechanical systems can either be presented in series or parallel as a chain of connected element. The failure of any part of the system can lead to the failure of the entire system. From the above, a ship can be taken to be a mechanical system with interconnection of components. The engine of a ship is the heart of the ship. The reliability of an engine is the probability of the engine to perform its planned task over a specified period of usage, and under specified operating conditions, in a manner that meets the expectations of the operator (Wasseman, 2002). Unpredicted failure of a marine propulsion engine affects the ship availability and increases operational cost. Re1iability helps to get the product failure distribution model for a particular machine.

Marine diesel engines are mainly used in shipping industries as a major prime mover for vessels. In addition, ship developed recently uses turbine, generator and nuclear energy as their source of energy. Various factors are considered when selecting the engine of a ship, some of these factors include: the reliability and availability of the engine, the repair and installation costs of the engine, the operating costs of the engine, flexible and size of the engine. However, the operating and maintenance cost of every diesel engine are of great important in ship operation. This no doubt is the reason why shipping companies are focusing on ways of developing and improving engine performance to suit operations and optimize engine performance control.

Improving the performance of an engine of a ship is key to ensuring optimum results during usage. It is therefore necessary to focus on ways of improving reliability for the marine propulsion system, and to find the methods or countermeasures to forecast the faults and diagnosis faults on time in the system reasonably so as to prolonging the service life of the ships (Mahesh *et al*., 2018). Over the last few decades, ships have been adjudged to have played important roles in marine transportation and the economy of many nations. Hence, the faults due to marine engine failures and the corresponding losses due to the cost of maintenance and environmental degradation cannot be overlooked. Engine failures in ships may also lead to marine accident and loss of life. This research focuses on evaluating the reliability of an FBM Model 38TD8 marine diesel engine, using the Weibull distribution.

Anantharaman (2018) studied the steady breakdown of components and Weibull failure representation for moving parts to determine the dependability of the propulsion part in an engine. In his sturdy, he analysed the breakdown of the turbocharger and its implication on the main engine. Result obtained indicates that the turbocharger breakdown had the immense effect on the main operation of the engine resulting to restriction of the engine. Hence, harmonizing the operation of the turbocharger and engine is important for safe and dependable running of the main engine.

Dutta *et al*. (2010) studied the reliability of defense vehicles gearbox assembly using Weibull distribution. The result proved that Weibull is an effective method of reliability analysis. Dhananjay and Sudhir (2015) studied the dependability of cooling organism of a diesel engine. They asserted that the working process of the diesel engine is a function of the engine systems and sub-system. The cooling system is an essential part of the marine diesel engine, and failure of the system is highly connected to the performance of the cooling system and its sub-system. In other to determine the time to breakdown of the cooling component, two parameter Weibull distribution was adopted using least square method with Minitab 16.1R software used in determining the effects of these parameters. The result obtained showed the dependability, availability, average time between failure, the failure rate and the failure density were adversely affected by the various selected parameter.

Khaeroman *et al.* (2016) examined the breakdown of a six cylinders crankshaft for diesel generator. The study discussed the breakdown of a marine engine crankshaft of 4-stroke 6-cylinder marine diesel engine. They postulated that a good examination and assessment of the size of the crankshaft used in a diesel engine was fundamental to reduce the failure of the crankshaft of an engine as a result of fatigue which could result in formation of fracture and cracks in the cylinder crankshaft. Saranga *et al.* (2000) conducted a research on reliability test using multiple relevant state parameters. The arithmetical models for reliability forecast under multiple condition parameters was used, the model was presented based on the continuous time Markov chain, and it was established that the rate of degradation of the system depends on the condition of the system and the fact that various parameters are the reason for system degradation can be dependent.

Kang *et al*. (2010) conducted a research on improvement of matrix-based system dependability method and applications to structural plants. Dunnett-Sobel model of correlation was used to determine the dependability using matrix-based system reliability method of analysis. Results obtained proved that matrix-based system dependability method is produced a better result when compared to other developed method.

Dario and Luka (2010) examined the reliability of a high diesel engine. The empirical reliability functions, the rate of breakdown and the density of breakdown of the diesel engine were ascertained using information of the average failure rate. Results obtained indicate that the Weibull distribution with parameters of $\beta = 2.613$ and $\eta = 400$ produced a good result for a light high-speed diesel engine. The rate at which faulty parts are to be replaced were determined based on data obtained from the empirical parameters. The recommendations of the findings were also highlighted for manufacturers of marine diesel engines.

It is very obvious from the survey that, most of the researchers are focused on reliability analysis using quantitative and qualitative methods as well as estimating parameters using analytical methods. They often ended their research at these reliability values. In this Study however, the Weibull parameters will be estimated from the probability plot of Minitab 16 software and the results obtained will be used to predict the future failures of the observed components of a marine diesel engine in the same failure mode.

2. MATERIALS AND METHODS:

A marine diesel engine FBM Model 38TD8 onboard a vessel was used as a case study in this research. The engine is a 2-stroke medium speed engine designed to provide propulsion power for ships, electrical plants and submarines. The engine has a design capacity for continuous power loading. Its main components include fuel injector pumps, injector nozzles, pistons, turbocharger, scavenging blower and tube type heat exchanger. The engine is straight shaped with a total of 12 cylinders and 24 pistons vertically opposing each other.

Due to the fact that the engine is a two stroke opposed-piston, it features no cylinder head. The camshafts on the engine cylinder provide appropriate timing for two injection pumps for each cylinder. The engine's bore is 206.4mm, stroke is 210mm and the cylinder height is 970mm. The engine piston displacement is 200 liters with firing pressure of 91.35bar. The maximum exhaust temperature at the exhaust port is 599^{o}C. These specifications were used from the FBM model 38 instructions manual 1990. Figure 1 shows the various parts of a diesel engine.

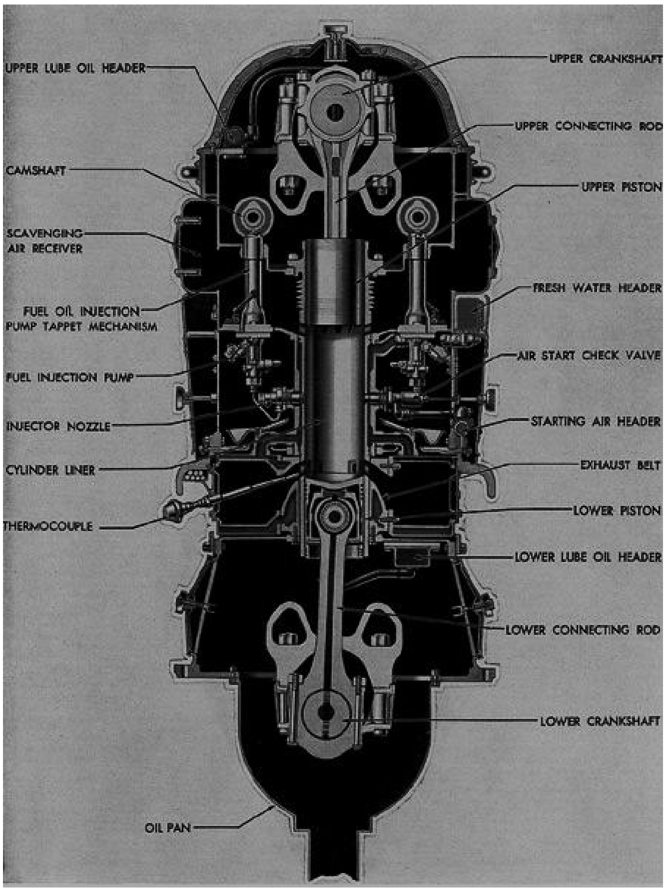

Figure 1: Components of a Diesel Engine (Retrieved from: Maritime.org/doc/fleet sub/diesel/chap 3 html)

2.1 Weibull Distribution

The Weibull distribution method is used to develop models in devices with declining, steady, or increasing failure rates. The versatility of this method is one reason for its wide use in reliability analysis. The Weibull distribution is usually described by the shape, scale and threshold parameters. These parameters are known as the 3 - Parameter Weibull distribution. The 2 - parameter Weibull distribution consists of characteristic life (η) and shape factor (β) values. β determines the shape of the distribution. If β is $<$ 1, then the failure rate of the engine is increasing. If $\beta > 1$, the failure rate of the engine is decreasing. If $\beta = 1$, then the failure rate of the engine is constant.

2.2 The 3-Parameter Weibull

The 3 - parameter Weibull probability density function (PDF) is given by:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad (1)$$

where:

$$f(t) \geq 0, t \geq \gamma \quad (2)$$
$$\beta > 0$$
$$\eta > 0$$
$$-\infty < \gamma < +\infty$$

and:

f = Dependent variable
t = Lifetime of engine
η = Scale parameter
β = Shape parameter
γ = Location parameter
e = 2.71828 is the base for natural logarithms

2.2 Mean Time Between Failures (MTBF)

This is the measure of reliability for repairable machines. It is the average time anticipated until the first failure of a machine. MTBF is an arithmetical value and is the mean over a long period of time with a large number of units. The mean, $\bar{x}$ (also called MTBF) of the Weibull PDF is given by:

$$\bar{x} = \gamma + \eta . \Gamma\left(\frac{1}{\beta} + 1\right) \quad (3)$$

Where:

$\Gamma(n) = \int_0^{\infty} e^{-x} x^{n-1}$ is the gamma function.

2.3 The Weibull Cumulative Distribution Function

The cumulative distribution function (CDF) are functions whose values are the probability that an equivalent random variable has a value less than or equal to the argument of the function. CDF defines the proportion of parts that will fail up to age (t) i.e. the probability of breakdown up to time (t). This is usually referred to as unreliability. The equation for the 2 - parameter Weibull CDF is given as:

$$f(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (4)$$

2.4 The Weibull Reliability Function

The re1iability of marine engines refers to the number of hours of which the engine performs before failing during its operations. The complement of the CDF is reliability (R), which is described as the probability that the machine will not fail until a given time (t).

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (5)$$

2.5 The Weibull Failure Rate Function

Failure rate is the rate at which an engine fails over a specified period of time; it is usually expressed as failures per unit of time and denoted by λ. The Weibull failure rate of an engine depends on time of performance, with the rate varying over the life cycle of the engine. The Weibull failure rate function λ(t), which could also be taken as the hazard function is expressed as:

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \quad (6)$$

3. RESULTS AND DISCUSSION:

The major failures and failure modes observed include failure of roller bearings in a scavenging blower leading to a catastrophic destruction of the blower lobes, housing and gears and subsequent seizure of the engine. Another failure observed was the failure of the turbocharger ball bearing which affected the seals, turbine and compressor blades leading to passage of lube oil into the air chamber and engine noisy operations.

The four engines have a total of 48 injector nozzles and fuel pumps in which individual nozzles and fuel pumps failed at various times leading to excessive smoking of the affected units. Defective nozzles tips and fuel valve seats were replaced to solve the problem. Other recorded failures include mechanical seals of freshwater and seawater pumps, failure of air shaft and corrosion of more than 20% of heat exchanger elements. It is important to state that these failed components were subsequently replaced with new ones or repaired.

Table 1 contains the component failure times and censored data while Table 2 shows the failure data of the FBM Model 38TD8 marine diesel engine component and the number of failures for the period May 2012 to August 2019. The Censored times shows the period when no failures occurred. It also showed failures that occurred that were not the type of failure under observation. Censored units are those units which have not failed by the failure mode that are under investigation. Early censored means the unit's age is less than the initial failure age while right censored means the age is greater than the oldest failure. They are commonly referred to as suspensions.

Table 1: FBM Model 38TD8 Marine Diesel Engine Components' Failure Data

Unit No	Component	Quantity	No of Failure	Failure Type
1	Scavenging Blower Roller Bearing	16	2	Roller Bearing Failure
2	Turbo Charger Ball bearing	8	2	Ball Bearing Failure
3	Injector Nozzles tips	48	7	Worn out injector tips
4	Injector Pump valve seats	48	6	Worn out valve seat
5	Air Distributor shaft	4	1	Worn Shaft Rocker arm
6	Water Pump mechanical seal	8	3	Failed mechanical seals
7	Tube Heat Exchanger tube elements	4	1	Corroded Tube Elements

Using the MINITAB 16 statistics tool for the reliability distribution Analysis for right censoring, the overview of the individual probability density, cumulative distribution, reliability and hazard plot functions of the components are shown in Figures 2 to 13.

3.1 Distribution Overview for the Failed Blower Roller Bearings

Figures 2 to 5 show the distribution overview plot of the failed roller bearing in the scavenging blower. The table of statistics shows the failed roller bearing and scale factors as well as the number of failures and censored units. The graphs are the PDF, CDF, reliability and failure rate plots.

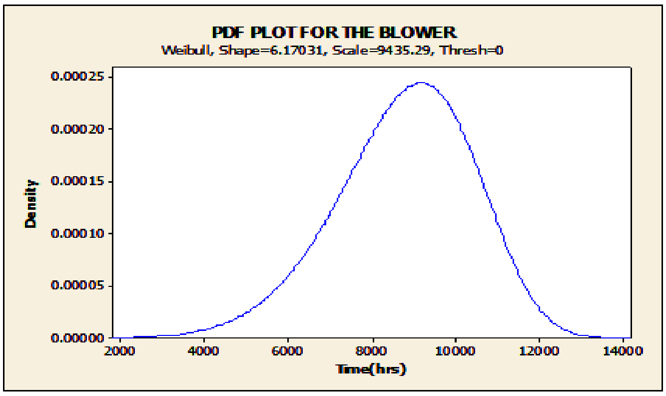

Figure 2: PDF Plot for Blower

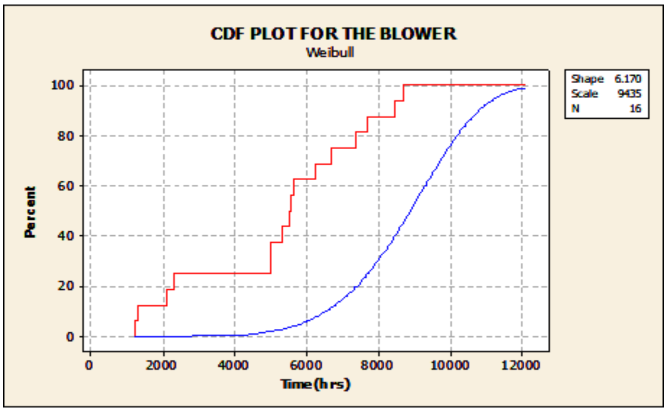

Figure 3: CDF Plot for Blower

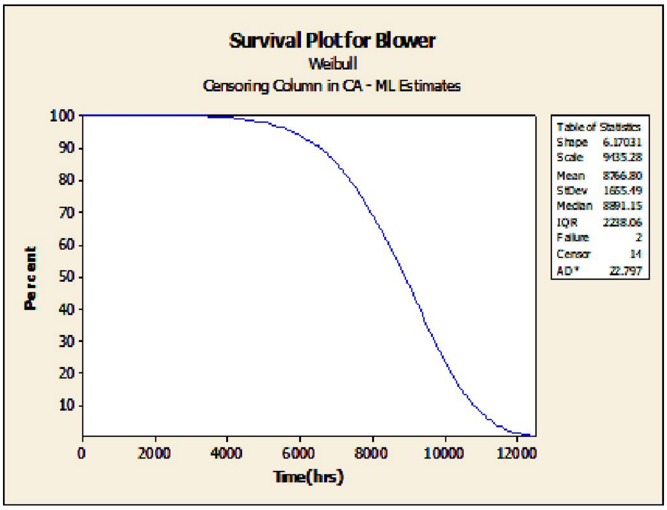

Figure 4: Survival Plot for Blower

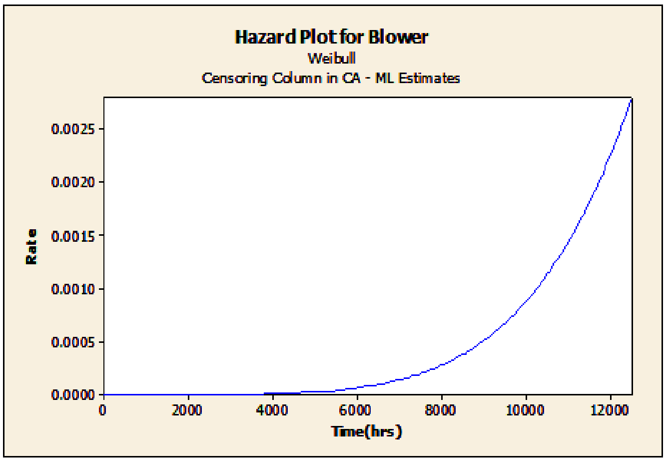

Figure 5: Hazard Plot for Blower

From Figure 2, it was observed that the PDF plot is left skewed, the β took a quadratic shape indicating that the density of the failed blower roller bearing will increase gradually from 3,000 – 9,000hrs. At 9000hrs, there is a decrease in the density of the failed roller bearing to 13,000hrs indicating that it followed the Weibull distribution. Figure 3 is the CDF graph which is a plot of random variables and from the CDF plot it is observed that 90% of the bearing life would not survive up to 12,500hrs of operations. Figure 4 is the survival plot of the blower which is a percentage plot of survival with respect to time at which the blower would fail. From the figure 4 it can be seen that the blower may likely fail after 12,000hrs of use, and as such it is advisable that maintenance of the blower should be carried out to avoid sudden failure. Figure 5 is the hazard plot which shows that the downtime rate increases over time. The reliability of the bearing reduces while the failure increases with time.

3.2 Distribution Overview for the Failed Turbocharger Ball Bearings

Figures 6 to 9 show the distribution overview plot of the failed ball bearing in the turbocharger. The table of statistics shows the bearing shape and scale factors as well as the number of failures and censored units. The graphs shown are the PDF, CDF, reliability and failure rate plots.

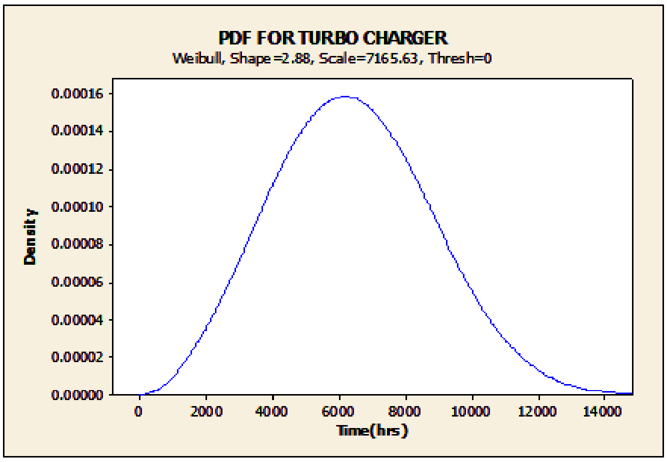

Figure 6: PDF Plot for Turbocharger

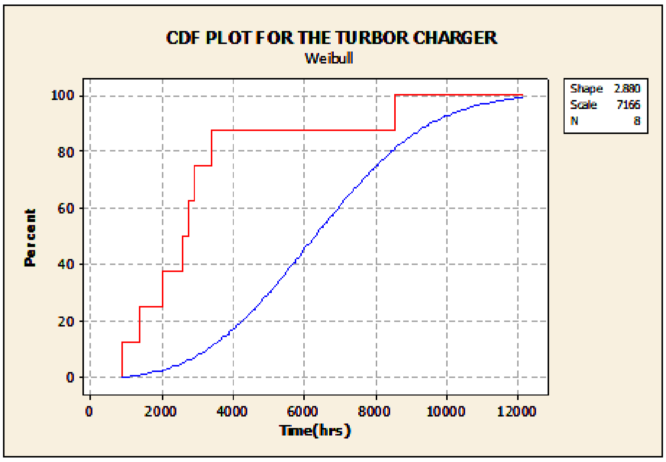

Figure 7: CDF Plot for Turbocharger

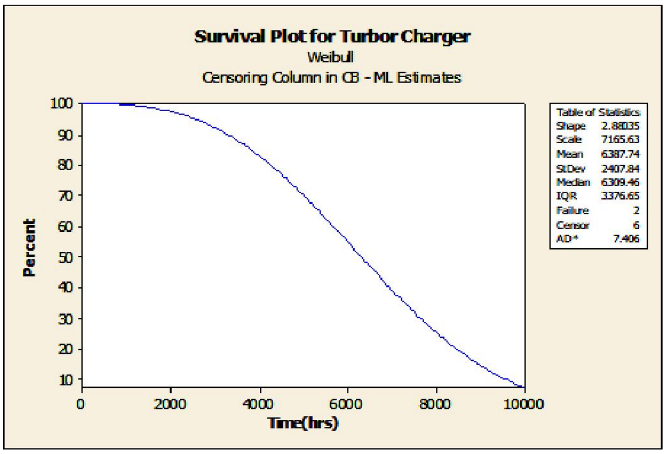

Figure 8: Survival Plot for Turbocharger

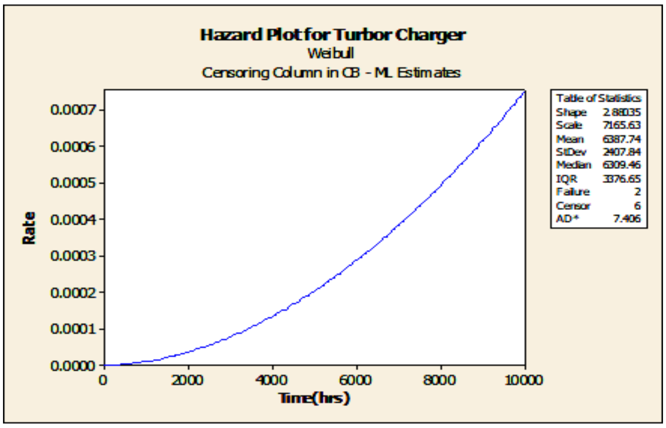

Figure 9: Hazard Plot for Turbocharger

From Figure 6, it was observed that the PDF plot is left skewed while the Weibull shape parameter (β) took a quadratic shape indicating that the density of the failed turbocharger ball bearing will increase gradually from 0 – 6,000hrs. At 6,000hrs, there is a decrease in the density of the failed turbocharger ball bearing to 14,000hrs indicating that it followed a Weibull distribution. Figure 7 is the CDF, which is a plot of random variables and from the CDF plot it is observed than 90% of the turbocharger ball bearing life would not survive up to 10,000hrs of operations. The reliability of the turbocharger ball bearing decreases while the failure increases with time. Figure 8 is the survival plot of the blower which is a percentage plot of survival with respect to time at which the blower would fail. From the figure it can be seen that the turbocharger ball bearing may likely fail after 10,000hrs of use, and as such it is advisable that maintenance of the turbocharger ball bearing should be carried out to avoid sudden failure. Figure 9 is the hazard plot which shows the failure rate of the turbocharger ball bearing increases with time.

3.3 Distribution Overview for the Failed Injector Nozzle Tips

Figures 10 to 13 shows the distribution overview plot of the failed injector nozzle tips. The table of statistics shows the bearing shape and scale factors as well as the number of failures and censored units. The graphs are the PDF, CDF, reliability and failure rate plots.

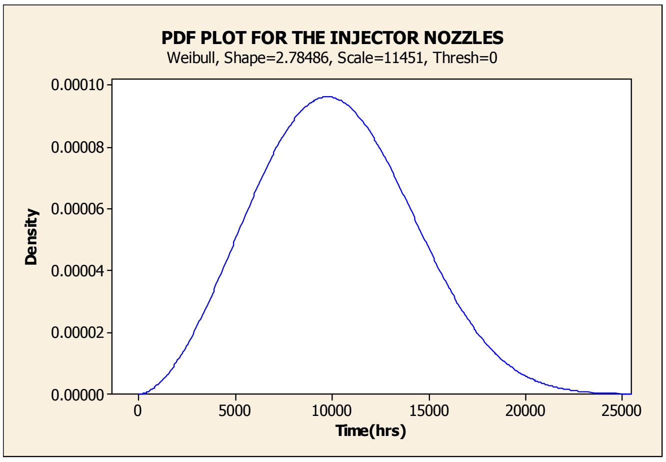

Figure 10: PDF Plot for Injector Nozzle Tips

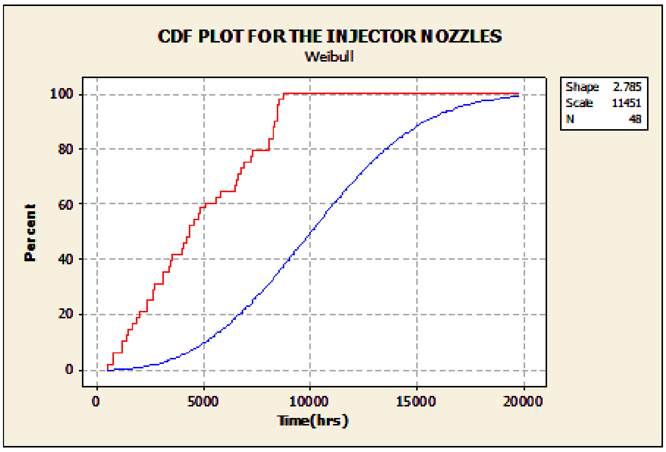

Figure 11: CDF Plot for Injector Nozzle Tips

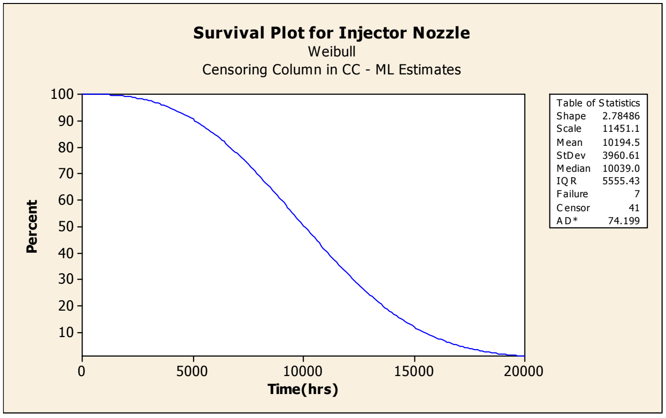

Figure 12: Survival Plot for Injector Nozzle Tips

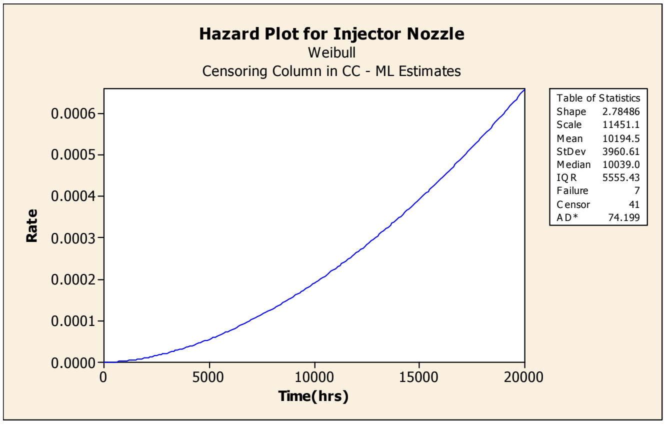

Figure 13: Hazard Plot for Injector Nozzle Tips

From Figure 10 it is observed that the PDF plot is left skewed, the Weibull shape parameter (β) took a quadratic shape indicating that the density of the failed turbocharger ball bearing will increase gradually from 0 – 10,000hrs. At 10,000hrs, there is a decrease in the density of the failed injection nozzle to 22,500hrs indicating that it followed a Weibull distribution with shape parameter (β). Figure 11 is the CDF, which is a plot of random variables and from the CDF plot it is observed than 90% of the failed injector nozzle tips life would not survive up to 15,449hrs of operations. The reliability of the injector tips decreases while the failure rates increases with time. Figure 12 is the survival plot of the failed injector nozzle tips which is a percentage plot of survival with respect to time at which the injector nozzle tips would fail. From the figure it can be seen that the injector nozzle tips may likely fail after 20,000hrs of use, and as such it is advisable that maintenances of the blower should be carried out to avoid sudden failure. Figure 13 is the hazard plot which shows that rate of failure of the injector nozzle tips increase.

4. CONCLUSION:

Engine breakdown is simply due to the presence of conditions that cause the engine to function out of order according to set parameters. In this research, failure records of the engine of an FBM Model 38TD8 diesel engine onboard a ship was obtained.

The failure data collected were used to determine the Weibull parameters of the failed components. This was achieved by analysing empirical data on failures of the marine engine derived from the engine log book, and calculating the observed individual failed components of the engines. From the Weibull data it was possible to predict the future failures of the engine components.

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