iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 10 **Issue:** V **Month of publication:** May 2022

DOI: https://doi.org/10.22214/ijraset.2022.41166

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 10 Issue V May 2022- Available at www.ijraset.com

Improving the Reliability of the Cooling Water System of a Marine Diesel Engine: A Case Study of Caterpillar C32 Diesel Engine

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Abstract: The reliability of a Caterpillar C32 12V marine diesel engine was analyzed in this research using Weibull distribution. The analysis was done with a view to improving the reliability of cooling water system of a marine diesel engine. Weibull parameters such as the Mean Time to Failure (MTTF), Mean Time between Failure (MTBF), Availability, Failure Density of the diesel engine were determined. Data were collected from the maintenance record of a Nigerian Navy Ship logbook for a period of four (4) years. The data were sorted and classified based on sequence of failure and failure time. With this data, key parameters that determine the reliability of the engine were calculated with value of MTBF as 1,279.65hrs, failure rate as 7.8×10^{-4} and operational availability as 0.719. The reliability of the engine was ultimately calculated and was obtained as 95%. The results of the study revealed that the calculated value of failure rate is within the empirical failure rate with the result calculated on the basis of the Weibull distribution for the diesel engine. It is therefore recommended that further studies be carried out to determine the intervals for preventive replacement of the subsystem parts and further study should consider a different method other than Weibull distribution to determine the reliability of the cooling system.

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

I. INTRODUCTION

Diesel engines are used to generate mechanical energy for propulsion of heavy duty machineries like agricultural machineries, vehicles for transportation of goods, and vessels for movement of ships. Diesel engines convert chemical energy to mechanical energy by the connection of the engine to the propellers for ship movement. The engine of a ship is the most critical piece of equipment on the vessel. Therefore, the engine's reliability is paramount in order to optimize safety, life cycle costs and energy of the boat (Dolas & Deshmukh, 2015). Heat produced by diesel engines is primarily from two main sources which include: friction from moving parts of the engine and combustion of liquid fossil fuel (diesel) in the combustion chamber of the engine. Diesel engines are advantageous when compared to other power generating sources such as, solar, wind etc. The advantages of diesel engine are; have very high thermal efficiency when compared to other combustion engine, diesel engines have wide range of speed and also low fuel consumption, thereby making diesel engine one of the widely used combustion engines in the world. It is therefore imperative that the diesel engine should have high reliability for the safety and optimum operation of the vessel. Reliability is the probability that a component or system will perform its required function for a given period of time when used under designed operating conditions (Nitonye, 2017). The role of diesel engine cooling system is principally a process of converting heat energy and transferring the heat generated to other medium. Engine cooling system take away heat fast enough from the engine and keep the engine material temperature well below its melting point thereby increasing the durability of the engine (Umekar & Govindaraj, 2011; Pranita *et al.*, 2018). Diesel engine uses both air and liquid for its cooling operations in modern design. The cooling system of a diesel engine consist of the engine oil, airtight cooling water thermostat, temperature control valve, temperature gauge, temperature sensor and supercharged air cooling equipment, which includes surface heat exchangers (radiators), heat sink, radiator fan units, shutters and the air passage (Wenbin *et al.*, 2017: Sliwinski & Szramowiat, 2018).

These cooling components ofa diesel engine when assembled together are aimed at reducing the high temperature around the engine, as well as maintaining required heat range for proper functioning of the engine according to manufacturers' recommended range. The cooling system of a diesel engine makes use of water in combination with coolant as working fluid that flows through galleries carrying heat away. This cooling system re-circulates cooling water through the engine block, extract the heat from the engine. Only about one – third of the total heat energy generated by the engine is transmitted to the propeller, while the rest flows through tailpipe as exhaust waste (Motey & Essel, 2017).

According to Sliwinski & Szramowiat (2018) there are three basic methods of cooling the engines in most marine diesel engines. They are: the open system (sea-to-sea) which involves taking water from the sea for cooling the engine, and then the water is returned back to the sea after a circle of cooling operation. The second method is the closed systems, which allows for fresh water to circulate around the engine casing with the aid of water pump, pipelines and control sensors. The fresh water is cooled by another open cycle of sea water. The third method is the keel cooling system where engine coolant is circulated through a system of tubing outside the vessel's hull, using the lower temperature of seawater to cool the coolant. The coolant is recirculated through the engine continuously in a circle for the engine cooling.

Pranita *et al.* (2018) carried out a simulation study of cooling system for heavy duty diesel engine to know the flow and temperature distribution in the jacket cooling system for 6 cylinder diesel engine. The process was done using a GT-Suite one dimensional simulation software package to study the mass-flow and thermal distribution over the inlet of the cooling package of a selected engine in several steady state operating points. The results obtained suggest that predictive method when used to ascertain failure would successfully capture the thermal effect of recirculation while reducing the necessity for calibration done by prototype testing.

Rafal (2013) designed and built internal combustion engine cooling system using original components of diesel engine 4CT90. The research was aimed at analysing the operations of the cooling control system with varying levels of filling of the coolant and developed a control method of the cooling system before testing the results on the dynamometer. The effects of working conditions on the level of the temperature were also analysed. The model results obtained were close to the exploitation conditions of the engine cooling system of 4CT90. The applied results were checked for the calorific value inside the cylinders of the engine, variable-speed water pump, as well as the temperature uniformity along the cylinder axis. Two values for pressure were selected 0.15 MPa and 0.2 MPa, and two different values of the degree of filling of the cooling liquid were adopted. During the heating of the cylinder and the cylinder head by electrical heaters, temperature and overpressure courses before and after the liquid radiator, temperature before the inlet and outlet of the liquid from the engine and the temperature at selected points inside the engine water jacket were designated.

Marco & Alberto (2012) designed and analyzed a form of a cooling system of a diesel engine. The analysis was primarily focused on reducing the emission of the diesel engine and the fuel consumption of the engine. Findings obtained indicate that the use of a cooling system with electronically controlled diesel engine tends to decrease power consumption of the moving parts of the engine and the temperature of the cylinder walls as a result of friction and the temperature fluctuations. This further resulted in reducing the stresses of the engine and keeping it at a stable temperature for the proper function of the oil film that reduces friction in the sliding components.

Chunhao *et al.* (2018) presented a paper titled 'recent advancement of cooling and heat transfer of diesel engine'. A vast number of reviews by the researchers indicated that primarily, four technology of cooling affects the cooling technology and they include: nanofluid technology, intelligent cooling system technology, LHR engine technology and the optimization of environmental boundary conditions. These four technologies were found to have significant impact on the heat transfer characteristics of diesel engine. The result also showed that the heat dissipation of the diesel engine is reduced and the thermal competence of the engine is improved after using these technologies. Though despite identifying these breakthroughs, there were still several drawbacks encountered in the course of the research some of which include: the lack of defined process to clearly define how the efficiency of engine cooling system is directly affected by the heat load of the engine's thermal efficiency.

A. Components of the Marine Diesel Engine Cooling System

The main engine cooling system consists of four main components:

1) *Piping and Fittings:* The piping distributes coolant in the system and accounts for a significant part of the pressure loss in the system. The size of the main engine and relative spacing of auxiliary machinery requires an extensive network of pipes and fittings in the cooling system. As a result, transport delay occurs in some of the system as it requires more time to pump coolant from one end of the system to the other.
2) *Control Valves:* The main engine cooling system is equipped with two feedback controlled 3-way valves to ensure that temperatures in the Low Temperature (LT) Fresh Water (FW) and High Temperature (HT) FW circuits stay within design limits. The valve in the LT FW circuit controls the amount of coolant that bypasses the heat exchanger such that the temperature of the coolant to the auxiliary machinery stays close to some constant set point. Similarly, the valve in the HT FW circuit controls the ratio coolant and coolant taken from the LT FW circuit to ensure a constant temperature of the coolant flowing to the main engine.

3) *Heat Exchangers or Coolers:* Heat exchangers are used for transferring heat from one medium to another with- out mixing the two, and are usually configured as two heat exchangers in parallel for redundancy. In this context, heat exchangers are used in several places, Central Fresh Water Coolers (CFWC) is used when referring to the heat exchangers that separate the Sea Water (SW) circuit from the LT FW circuit, while specific names are used for individual consumers.
4) *Pumps:* Pumps in the LT FW, HT FW and SW circuits are usually grouped as two or three centrifugal pumps in parallel with one pump working as stand-by. Pumps play an essential role in the main engine cooling system as they generate the flow that transfers heat from engine to the seawater. They are also the main power consumers in the main engine cooling system, and at least one pump in each circuit is always running, even when the vessel is in port and the main engine is stopped.

B. Key Performance Indicators in Reliability Analysis in Diesel Engine.

Engine failure exists in varying degrees (total failure or partial failure). But failure is said to have occurred in a machine when a system or component can no longer produce the desired result, even if the engine is working, but have failed to produce the desired result. Engine performance metrics like Mean Time to Repair (MTTR), Mean Time Between Failures (MTBF), Mean Time to Failure and Availability are essential for any engineering operation. By tracking these key performance indicators effectively, engineers can optimize machine performance and minimize failure rate, thereby keeping breakdown of the engine at minimum. Even the most efficient maintenance engineering team experience equipment failures, for effective utilization of these performance metrics, maintenance engineers must have sound knowledge of these key performance indicators. Figure 1 illustrates the various components in the analysis of the diesel engine cooling water system as stated by Tran *et al.* (2007).

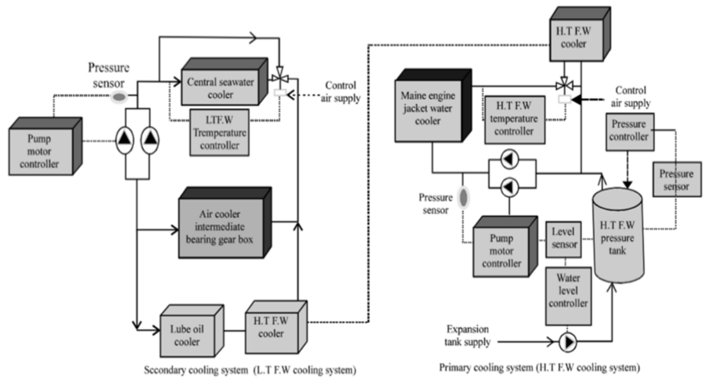

Figure 1: Components included in the analysis of jacket water cooling system

II. MATERIALS AND METHODS

This work was carried out through descriptive analysis of a cooling system of a marine diesel engine and analytical models that include: exponential reliability model, maintainability and historical data collection. Failure data were collected from the engine logbook and original equipment manufacturers manual onboard and used to determine the reliability of diesel engine. Every failure of the engine is kept in the ship's logbook, and especially in the logbook of engine failures. The data of the marine diesel engines of NNS ANDONI was employed to analyze the reliability of the engine's cooling system. This is because the ship uses the Caterpillar C32 diesel engines for its propulsion. Firstly, the secondary data which were obtained from the operational logbook, maintenance records and archives were analyzed and rearranged according to the components (subsystems) of the cooling water system. After collection, sorting, and classification of the data, the validation of the assumption for Independent and Identically Distributed (IID) nature of the Time Between Failures (TBF) data of the engine's cooling system and the entire line were checked.

Secondly, the traditional standard maintenance technique that is suitably used for the cooling water system maintenance was applied to choose the best statistical analysis approach. In analyzing the collected data, Weibull distribution method was selected and applied according to several characteristics of reliability engineering and failure analysis. The primary advantage of Weibull distribution is the ability to provide reasonably accurate failure analysis and failure forecasts with extremely small or large data samples. Another advantage of the method is that it provides a simple and useful graphical plot. The data plot is extremely important to the operators, engineers and managers. Finally, Weibull distribution technique is very useful for Maintenance Management (MM) of machines and equipment and was applied to improve the reliability of the cooling system by using the model not only to predict the MTTF of the system components but also to predict the remaining life of the identified components of the system.

A. *Reliability-Centered Maintenance Methodology*

The RCM steps are as highlighted below. The steps describe the systematic approach used to implement the system function, identify failure mode, prioritise failure modes and perform PM tasks (Samuel *et al.* 2018). The RCM steps are as follows:

1) Step 1: System selection and data collection.
2) Step 2: System boundary definition.
3) Step 3:System description and functional block.
4) Step 4: System function functional failures.
5) Step 5: Failure mode effect analysis
6) Step 6: Logic tree diagram.
7) Step 7: Task selection.

B. *System Selection and Data Collection*

Determining the list of the system components is one of the first steps in RCM. The criticality analysis requires different kind of data of each component that build up the system. The effect of failure of the system main components may affect system productivity and maintenance cost. The factors effecting selection of critical system are as follows:

1) Mean-time between failures (MTBF).
2) Total maintenance cost.
3) Mean time to repair (MTTR).
4) Availability.

C. *Mean Time between Failures (MTBF)*

The MTBF is a basic measure of reliability for reparable items and is estimated by the total time in operation of a system and its subsystems used by the vessel divided by the total number of failures (breakdowns) recorded within a specific investigation period.

$$\text{MTBF} = \frac{\sum t_I}{n} \qquad (1)$$

where:

$\sum t_I$ = the total running time in operation of the system during an investigation period for both failed and non-failed items.

n = number of failures (breakdowns) of system or its parts occurring during a certain investigation period.

D. *Mean Time to Repair (MTTR)*

Mean time to repair MTTR is the average time required to troubleshoot and repair failed system or sub-system and return it to normal operating conditions. It is a basic technical measure of the maintainability of system and repairable parts. Maintenance time is defined as the time between the start of the incident and the moment the system is returned to operation (i.e., how long the equipment is out of production). This includes notification time, diagnostic time, fix time, wait time (cool down), reassembly, alignment, calibration, test time, back to operation, etc. *Total maintenance cost* = cost of downtime X total number of maintenance done.

Mean time to repair ultimately reflects how well the system can respond to a problem and repair it. It is suitable for all kinds of system or subsystems and it is given by:

$$MTTR = \frac{Total\ repair\ \ time}{Total\ number\ of\ \ repairs}$$

$$MTTR = \frac{\sum t_1}{n} \qquad (2)$$

where:

t_1 = total accumulative time of system or its parts to repair or maintain in statistical time.

n = number of repair actions in the population of system during the specified investigation time period.

E. Failure Rate (λ)

Failure rate is the probability of failure per unit time. It is the rate of occurrence of failures. A degraded failure rate is used for systems with repairable parts; a critical failure rate is used for non-reparable parts. It is the reciprocal of the MTTF /MTBF function and is given by:

$$\lambda = \frac{1}{MTBF} = \frac{n}{\sum t_1} \qquad (3)$$

where:

$\sum t_I$ = the total running time in operation of the system during an investigation period for both failed and non-failed items.

n = number of failures (breakdowns) of system or its parts occurring during a certain investigation period.

F. Availability

The availability measure is used for system when failure consequences only lead to economic losses. The "availability" of a system is, mathematically, MTBF / (MTBF + MTTR) for scheduled working time. It is given by:

$$A = \frac{MTBF}{(MTBF + MTTR)}$$

Or

$$A = \frac{T_O}{T_O + T_1} \qquad (4)$$

where:

T_0 = Time that system works.

T_1 = Time that system do not work, including repair and maintenance time.

G. Reliability

Reliability is defined as the probability of a system to perform its intended function without failure under stated condition within a specified period of time. To determine the reliability (R_t) of a system, the mathematical expression is given as:

$$R(t) = e^{-\lambda t} \qquad (5)$$

where:

λ = Failure rate.

t = Expected time.

Reliability emphasizes dependability in the lifecycle management of a system or equipment. Dependability, or reliability, describes the ability of a system or component to function under stated conditions for a specified period of time. Reliability is closely related to availability, which is typically described as the ability of a component or system to function at a specified moment or interval of time. Reliability plays a key role in the cost-effectiveness of systems.

H. Weibull Distribution

The Weibull distribution most frequently provides the best fit of life data. Beta (β) and Scale (η) are the two crucial parameters of Weibull line.

The slope of the line, β is principally significant and may provide a trace to the physics of failure. The characteristic life η is the typical time to failure in Weibull analysis (Abernethy Robert, 2002).

The slope β also indicates which class of failures is present. B< 1.0 indicates infant mortality, β = 1.0 means random failures (independent of age) and β > 1.0 indicates wear out failures. The effect of different values of shape parameter β, on the shape of the pdf is assessed (while keeping η constant). The shape of the pdf can take on a variety of forms based on the value of β. Weibull probability plot specifies the Weibull shape parameter.

I. Data Collection

Secondary data were collected from the engine log book and original equipment manufacturers manual onboard and used to analyze the reliability of the cooling water system for the marine diesel engine. Every failure of the engine is kept in the ship's log, and especially in the log book of engine failures. The record of failure data of the cooling water system of marine diesel engines of NNS ANDONI (with Caterpillar C32 Diesel Engine) were employed to analyze and improve the reliability of the engine's cooling water system.

J. Source of Data Collection

The sources of data for the calculations of this work included:

1) Ship's corrective maintenance logbooks.
2) Ship's annual report sheets.
3) Diesel engine manufacture's manual and data sheet.

III. RESULTS AND DISCUSSION

The diesel engine considered in this research is that of a Caterpillar C32 12VEngine onboard NNS ANDONI and analysis carried out were based on the cooling system of the vessel. First, phase data collection from the maintenance record of service station logbook of the ship for a period of four (4) years was taken. The data were sorted and classified based on part number and failure hours. The cooling system failure data obtained from the log book are shown in Table 4.1. Each failed part of the diesel engine is given a serial number as the failure occur as documented in the logbook. This was primarily to avoid clumsy write-ups in the logbook.

Table 2: Operation Time Derived From Logbook

Number of Parts	Time of Failure (hrs)
1	1123
2	968
3	1056
4	1269
5	1134
6	936
7	1321
8	1647
9	1086
10	2040
11	1168
12	1266
13	1072
14	1479
15	1782
16	1376
17	1165
18	1455
19	1166
20	1084

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A. Estimation of Mean Time Between Failure

The MTBF of the various parts were estimated. For the cooling system of a marine diesel engine, the cooling subsystems experienced various levels of failure in the vessel and corrective maintenance were applied in most cases. Since the time of failure, free work of the pump was recorded in the ship logbook, it can be used to determine the MTTF. The MTBF can be calculated from Equation 3.1 as:

$$MTBF = \frac{\sum t_i}{n}$$

$$MTBF = \frac{25{,}593}{20}$$

$$= 1{,}279.65 \text{hrs}$$

B. Failure Rate (λ)

Failure rate is the probability of failure per unit time. It is the reciprocal of the MTBF function and is given by Equation 3.3 as:

$$\lambda = \frac{1}{MTBF} = \frac{n}{\sum t_1}$$

where:

$\sum t_I$ = the total running time in operation of the system during an investigation period for both failed and non-failed items.

n = number of failures (breakdowns) of system or its parts occurring during a certain investigation period.

$$\lambda = \frac{1}{MTBF} = \frac{n}{\sum t_1}$$

$$\lambda = \frac{1}{1{,}279.65}$$

$$= 7.8 \times 10^{-4}$$

C. Reliability

Reliability is very essential in determining the performance of an engine. To determine the reliability (R_t) of a system, the mathematical expression is given in Equation 3.5 as:

$$R(t) = e^{-\lambda t}$$

$$R(t) = e^{-7.8 \times 10^{-4}(2{,}251)}$$

$$R(t) = 0.96$$

D. Estimation of Operational Availability

Operational availability of a marine diesel engine cooling system is the probability that the engine, when used under specified conditions, will function satisfactorily at any point in time. The observed time comprises the uptime and down time. The operational availability is given by:

$$Operational\ Availability\ (Ao) = \frac{Uptime}{Uptime + Downtime}$$

$$Ao = \frac{25{,}593}{25{,}593 + 10{,}009}$$

$$Ao = 0.719$$

E. Calculated Values of Empirical Functions

Table 3.2 contains data collected from the engine logbook and calculated to determine the density function, failure rate and reliability of the vessel for various time intervals.

Table 3: Calculated values of Empirical Functions

Time Interval (hr)	Number of Failures	Failure Density 10^{-4}	Failure Rate 10^{-4}	Reliability
000 – 1,460	2	1.4	2.5	0.91
1,461 - 2,920	3	2.1	3.2	0.80
2,921 – 4,460	5	3.5	5.6	0.66
4,461 – 5,840	8	5.6	12.8	0.44
5,841 – 7,300	7	4.9	15.1	0.21
7,301 – 8,760	9	6.3	15.2	0.01

Figure 1 shows the failure density of the diesel engine at various intervals. From the graph it is observed that as the time of usage of the cooling system of the vessel increase the number of failure increases. Although, there was a slight reduction in the rate of failure between 4,461 – 5,840hrs, this reduction could be as a result of proactive checks and repairs of the cooling system.

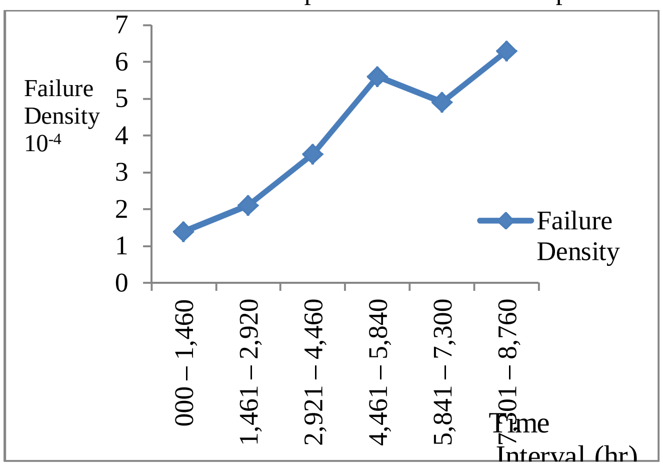

Figure 1: Failure Density Analyses for Different Time Intervals.

Figure 2 shows the failure rate of the diesel engine at various intervals. From the graph it is observed that as the time of usage of the cooling system of the vessel increase the number of failure rate increases rapidly, this could be as a result of constant repair of the subsystems of the cooling system. Between 7,301 and 8,760 when it was observed that the failure rate increased drastically, there was a total overhaul of the entire cooling system to increase the reliability of the cooling system and the reliability of the marine diesel engine.

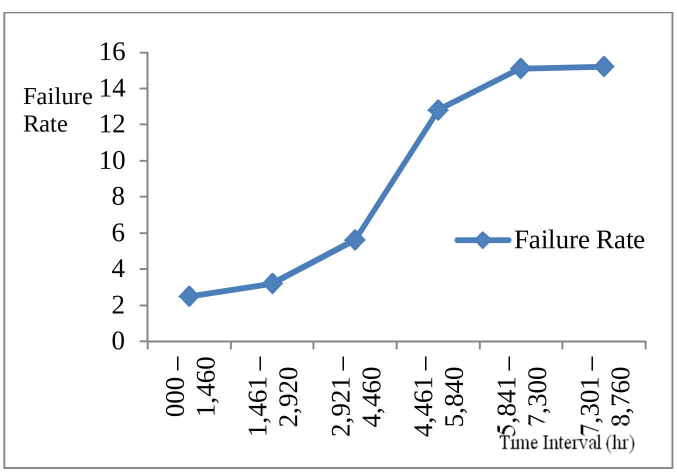

Figure 2: Failure Rate Analyses for Different Time Intervals

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
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From Figure 3, which shows the reliability of the cooling system of the diesel engine, it is observed that the reliability of the cooling system decreases rapidly as the time increase. This could be as a result of higher number of failed part in the cooling system of the diesel engine.

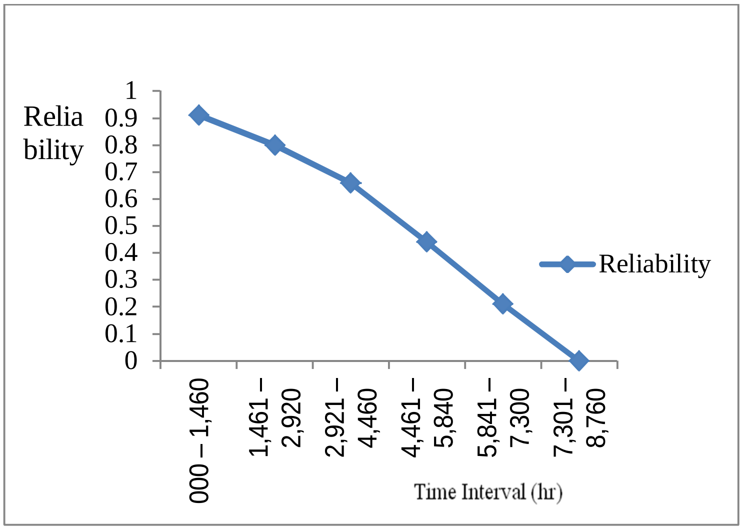

Figure 3: Reliability Analyses for Different Time Intervals

F. Discussion of Results

From the data obtained from the logbook of the vessel containing the failure of the engine, it was observed that a total number of twenty failures occurred in the engine related to the cooling operation of the engine. An aggregate of 25,593hrs is the total running time in operation of the system during the investigation period for both failed and non-failed parts. This time simply represents the time in which the engine was required for use and was available, including time the engine was not available due to failure of the cooling system.

1) *Mean Time Between Failure:* The MTBF which is used to measure the average time elapsed between breakdowns of the cooling system was calculated from the logbook as 1,279.65hrs. This indicates that the cooling system was functional for over 97% of the total time for which the engine was needed for its operation.
2) *Failure Rate (λ):* The failure rate is the probability of failure per unit time. The failure rate was calculated as 0.00078. This figure clearly shows that the failure rate of the cooling system was very low, and as such the cooling system could perform optimally. From the calculated values of the empirical functions, it is found that the failure rate of the cooling system increases as the time increases (failure rate is directly proportional to the operation time). This could be as a result of wear and tear resulting from usage of the engine, therefore reducing the efficiency of the cooling system.
3) *Reliability:* The reliability of the cooling system of the diesel engine was calculated as 96% from the log book. Therefore, the cooling system can be said to be very reliable during the operation of the vessel. The reliability of the cooling system decreases as the operating time increase. It was observed that between 7,301 and 8,760hrs, the cooling had the lowest reliability and at this point it is advised that the whole cooling system be overhauled to improve the reliability of the cooling system.

IV. CONCLUSION

The duty of the cooling system of a diesel engine is dissipate the heat flow from the parts of the engine exposed directly to high temperature, thereby preventing overheating, rapid corrosion and expansion of the parts of the engine. The cooling system of the engine is also responsible for maintaining the optimal operating temperature of the internal diesel engine, which a basic requirement for proper functioning of the engine with optimal temperature requirement. The improvement of diesel engine cooling water system for marine diesel engine and heat transfer can improve thermal efficiency and reduce exhaust emissions. With the improvement of marine diesel engine, there is an increase of the power density and the stricter regulations within the marine sector on release of non-environmental friendly emissions.

Tracking and analyzing the reliability of cooling system of a diesel engine is a major challenge faced by maintenance engineers onboard a vessel on daily basis. For an effective tracking of a diesel engine cooling system, critical key performance indicators such as the MTTF, MTTR, MTBF, etc are essential in analyzing the performance of the engine cooling system. Only by tracking these key performance indicators can the engineers on board the vessel minimize downtime and keep performance of the engine at optimum.

The calculated value of failure rate is within the empirical failure rate and the one calculated on the basis of the Weibull distribution for the diesel engine. In the process of estimating certain technical system reliability, it is common to assume that the failure rate varies. In this case, it is expected that random failures will occur in the system and thus, the failure rate is therefore time dependent. The reliability of the cooling system shows continuous increase in failure rate function and the fact that the reliability of the system can be well approximated by the Weibull distribution. From the results obtained, it is observed that the failure rate increases as the time increases and thus, the reliability decreases as the time increases.

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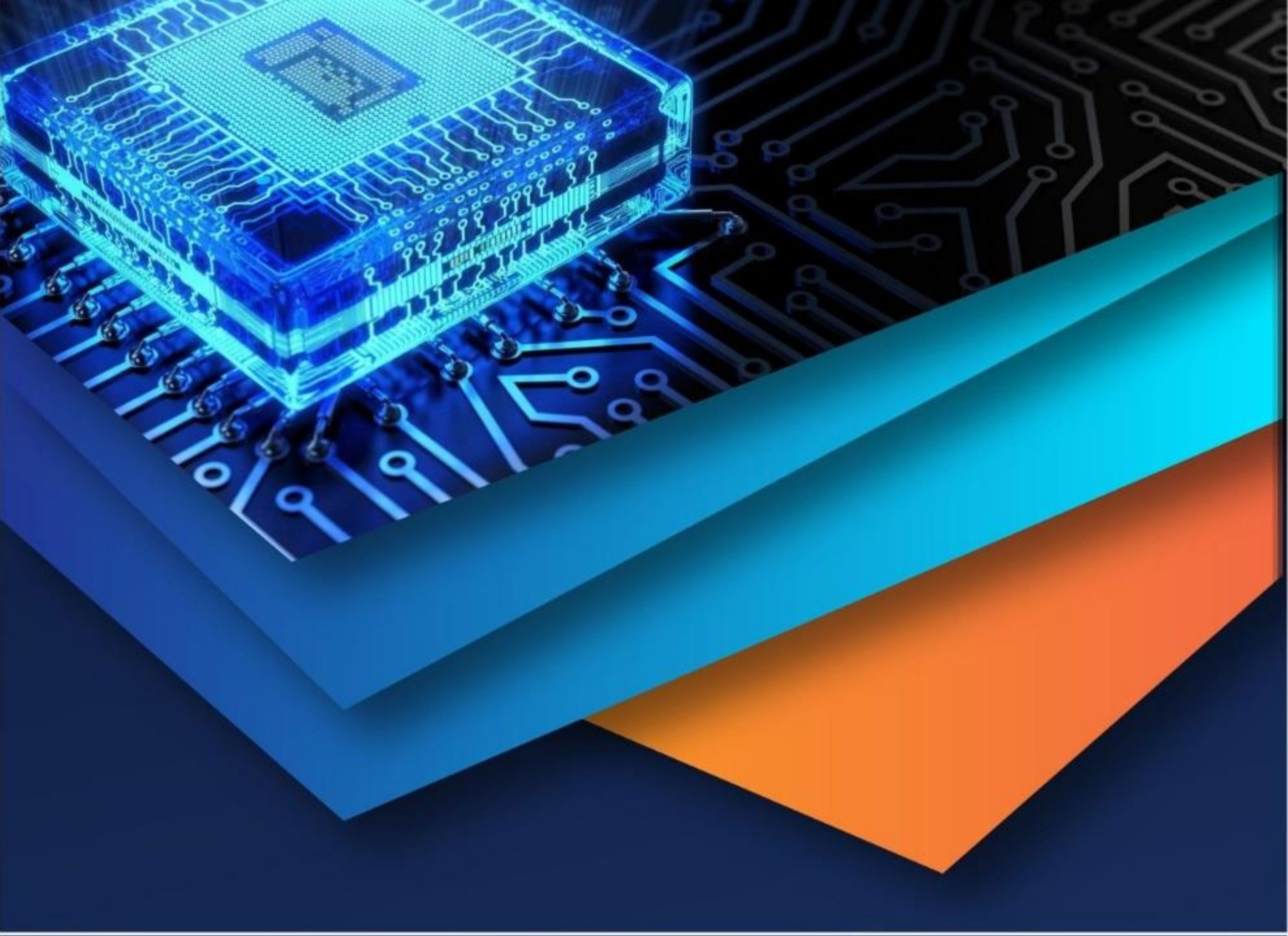

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