Reliability analysis of boiler operation in a brewery: a case study

AkeNdubuisi¹, Ukpaka C Peter²✉, Nkoi B¹

¹. Department of Mechanical Engineering, Rivers State University, Port Harcourt
². Department of Chemical/Petrochemical Engineering, Rivers State University, Port Harcourt

✉ Corresponding Author:
Department of Chemical/Petrochemical Engineering,
Rivers State University, Port Harcourt;
E-mail: chukwuemeka24@yahoo.com

Article History
Received: 19 September 2018
Accepted: 30 November 2018
Published: January 2019

Citation

Publication License
This work is licensed under a Creative Commons Attribution 4.0 International License.

General Note
Article is recommended to print as color digital version in recycled paper.

ABSTRACT
The reliability analysis on the boiler operation was conducted in this study. The operations of a boiler in the brewery process and the reasons for failure in the boiler’s system operation was investigated; the various components of a boiler system such as vapourizer, overheater, economizer, rotary air preheater, Air fan and Flue gas fan was examined for failure that can lead to its maintenance forecast and performance and to analyze the reliability of the boiler operation with respect to its failure rate. The descriptive statistics of the reliability indices was employed in the analysis and the Mean time between failures, mean time to repair, failure rate, repair rate and availability indices were determined. Reliability analysis was conducted on the boilers operation and results obtained reveals that for C1 and C2 the Mean failure rate (λ) is 0.0004852 failure/hour. The reliability at the end of 1000 hours of operations is 0.61. For C3 and C6 boilers, the mean failure rate (λ) is 0.0005422 failure/hour. The reliability at the end of 1000 hours of operations is 0.58. For C4 and C5 boilers, the mean failure rate (λ) is 0.0004709 failure/hour. The reliability at the end of 1000 hours of operations...
is 0.62. The reliability was calculated for all the boilers of the considered and the entire line at different time. From the analysis, the boilers C4 and C5 had the highest reliability value while C3 and C6 boilers had the lowest reliability value. The Weibull distribution provided the best fit for the boilers operating line to describe the Time before failures. Finally, Pareto chart analysis revealed that of the various reasons for failure in the boiler's system operation such as Leaks, Auxiliary Element Failure, Electric Failures and Protection Shutdown, the major reason for failure in boilers is caused by leakages. Conclusion and recommendations were made that if more effective measures are taken to eliminate leakages, then the majority of the cause of boiler failure in the brewery would be solved. Also a reliability model at boiler line level was developed, to upgrade the currently applied maintenance strategy due to increasing failure rate of the production line ($\beta = 1.41453 > 1$) thereby ensuring the feasibility of forecasting the beer production line operation, at least in the short term, and to ultimately improve the line operation management.

**Key words:** Reliability, analysis, boiler, operation, brewery, failure

1. INTRODUCTION

A steam boiler is one of the most critical investments that owners of breweries and distilleries must consider for their enterprise. A reliable steam boiler is a necessary component of any brewery or distillery (Famous O Igbinovia et al. 2018). In addition to providing hot water for wort boiling, steam is also required for sanitization, sterilization and pasteurization during the bottling or canning process. In this research work an attempt has been made to evaluate the reliability of a system of boilers used in a brewery industry. The boiler is a very important part of a brewery. Boiler is a closed vessel in which water or the fluid is heated under pressure. The steam or hot fluid is then circulated out of the boiler for use in various process or heating applications. A safety valve is required to prevent over pressurization and possible explosion of a boiler (Castanier et al., 2005).

In view of the above listed applications of a boiler in a factory its failure in any case is not tolerable. These boilers may fail due to a number of reasons; some of the main reasons are failures of mechanical/electrical safety valves, failures of temperature sensors and failures due to non-supply of water in the heater (Dhillon, 2006). A failure of mechanical/electrical safety valves occurs when the pressure in the boiler goes beyond the required limits. There is a lead, which will melt and release the pressure for which the mechanical/electrical safety valves are released. Failures of temperature sensors occurs when the metallic sensors which sense the temperature cut the electrical supply coming to the heater and stop the working of boiler. Failures due to non-supply of water in the heater occur when water is not supplied to the boiler, as the air inside the boiler will get heated and will cause the blast of the boiler. Keeping the above view, we will analyze a system of boiler in which the policy of preventive maintenance is applied after continuous working for a random amount of time to make the system more reliable. Monitoring of operational suitability of a boiler system and its main components, especially with separation of "weak points" are basis for rationalization of the technical services range, according to criterion of not exceeding acceptable levels of damage risk (Castanier et al., 2005). Choosing a reliability analysis method depends on the type of the analyzed technical object and the required accuracy of the estimate. The method should take into account all of the possible factors affecting the reliability of the analyzed system, and at the same time the simplest procedure for the analysis as possible (Blischke and Murthy, 2003).

Power units are complicated thermal and mechanical installations consisting of several components with a different level of redundancy (Amrat Kumar Dhamneya et al. 2016). Basic power unit components such as boiler or turbine are singular. But however with an ancillary device have an overt or latent reserve in order to increase reliability of operation (Jalali and Forouhandeh, 2011). The quantitative aspects of reliability engineering may, on the surface, seem complicated and daunting. In reality, however, a relatively basic understanding of the most fundamental and widely applicable methods can enable the plant reliability engineer to gain a much clearer understanding about where problems are occurring, their nature and their impact on the production process – at least in the quantitative sense. However, engineers must be particularly clever in their application of the methods because the operating context and environment of a production process incorporates more variables than the somewhat one-dimensional world of product reliability assurance due to the combined influence of design engineering, procurement, production/operations, maintenance, etc., and the difficulty in creating effective tests and experiments to model the multidimensional aspects of a typical production environment. Despite the increased difficulty in applying quantitative reliability methods in the production environment, it is nonetheless worthwhile to gain a sound understanding of the tools and apply them where appropriate (Gupta and Bhattacharya, 2007).

Quantitative data helps to define the nature and magnitude of a problem/opportunity, which provides vision to the reliability in his or her application of other reliability engineering tools (Hajeeh and Chaudhuri, 2000). This dissertation will provide an introduction to the most basic reliability engineering methods that are applicable to the boiler engine of the Brewery company.
that is interested in reliable production assurance. It presupposes a basic understanding of algebra, probability theory and univariate statistics based upon the Gaussian (normal) distribution e.g. measure of central tendency, measures of dispersion and variability, confidence intervals, etc. (Krishnamoorthi, 2002). Analytical methods for the assessment of power unit reliability based on Markovs processes in which reliability measures for the entire unit are determined from reliability indices of single components, have one important draw back – the lack of a sufficiently large population of analyzed events for most components under consideration.

Having considered these draw backs for ignoring reliability analysis as a key tool in the operational success of production and process engineering systems, this thesis has been chosen to deal with reliability analysis of the entire boiler operation of the brewery production line, and I am being inspired to use the facility of Brewery Company in Rivers State, Nigeria with the ultimate goal of optimizing their products quality, availability and maintainability.

The aim of this research work is to conduct reliability analysis on boiler operation of a Brewery. The objectives of this dissertation will include: to understudy the operations of a boiler in a brewery process and to investigate the reasons for failure in the boiler’s system operation to examine the various components of a boiler system for failure that can lead to its maintenance forecast and performance and to analyze the reliability of the boiler operation of a Brewery with respect to its failure rate.

2. MATERIALS AND METHODS

Analytical Model

Failures data i.e. time between failures (TBFs) are the backbone of reliability studies because they provide invaluable information to concerned professionals such as reliability engineers, design engineers, and managers (Dhillon, 2009).

Failure data was collected from Brewery Company for reliability analysis of their boiler operation. Firstly, secondary data which was gotten from the operational logs, maintenance records and historical data and archives of their boilers, was analyzed and rearranged according to the boiler subsystems and according to the common troubleshooting method followed. After collection, sorting, and classification of the ‘data’, the validation of the assumption for independent and identically distributed (IID) nature of the TBF data of the boiler and the entire line must be checked. Thus, the statistical analysis to describe the basic features of the failure data for TBFs for the boiler and the entire production line was analyzed with respect to theoretical distributions. The maximum likelihood and goodness-of-fit test was used to determine the best theoretical distribution to represent the boiler and line failure data.

The TBF of equipment is defined as the time that elapses from the moment the equipment is turned on and starts operating after a failure, until the moment it goes down again and stops operation due to a new failure. The TBFs are recorded in minutes.

A quantitative analysis (i.e. descriptive statistics) of the failure data for the production line will be obtained. The descriptive statistics will be done using the software package Microsoft Excel. Thus, it is possible to extract the minimum and the maximum value of the sample, mean, standard deviation (StDev), coefficient of variation (CoefVar), skewness, and kurtosis of the failure data at machine and line level. The StDev of the random variable is defined as the square root of the variance, and is often used in place of the variance to describe the distribution spread (Markeset and Kumar, 2001). Since the CoefVar of a random variable is defined as the ratio of the StDev over the mean of the random variable, it is a dimensionless measure of the variability of the random variable. Skewness and kurtosis are statistics that characterize the shape and symmetry of the distribution. Skewness is a measure of the degree of asymmetry of a distribution while kurtosis is a measure of whether the data appear as peaks or are flat. A normal distribution will have kurtosis and skewness values equal to zero (Markeset and Kumar, 2001). After collection, sorting, and classification of the ‘data’, the validation of the assumption for independent and identically distributed (IID) nature of the TBF data of the boiler and the entire line was checked.

Data was collected from the Brewery Company for reliability analysis of their boiler performance. Firstly, the data will be analyzed, and rearranged according to the boiler subsystems and according to the common troubleshooting method followed. Secondly, the traditional standard maintenance technique that is suitably used in boiler maintenance will be applied to choose the best statistical analysis approach.

Method for Reliability Analysis

Reliability is the probability that the machine or the entire line will perform a required function, under specific operating conditions, for a given period of time t. The Time between Failures of the line is defined with T; T ≥ 0, then the reliability can be expressed as,

\[ R(t) = P(T ≥ t) \]  \hspace{1cm} (1)

Moreover, the unreliability function, \( Q(t) \), is defined as the probability of failure in \( t \),
Q(t) = 1 - R(t) = P(T ≤ t) \quad (2)

In reliability theory, the hazard or failure rate function is indicated as,

\[
f(t) = \frac{1}{t.\sigma.\sqrt{2\pi}} \exp \left[ -\frac{(\ln t - m)^2}{2.\sigma^2} \right]
\]

\quad \text{where } f(t) \text{ is the probability density function (PDF) of the failure distribution.}

In analyzing the collected data, the Weibull distribution method will be selected and applied according to several characteristics that make Weibull distribution the best statistical distribution method to be used for these data.

The primary advantage of Weibull analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with extremely small samples (Kiureghian et al., 2007). Another advantage of Weibull analysis is that it provides a simple and useful graphical plot. The data plot is extremely important to the engineers and others. Many statistical distributions were used to model various reliability and maintainability parameters. Whether to use one distribution or another is highly depending on the nature of the data being analyzed. Some commonly used statistical distributions are:

1. Exponential and Weibull distributions. These two distributions are commonly used for reliability modeling – the exponential is used because of its simplicity and because it has been shown in many cases to fit electronic equipment failure data. On the other hand, Weibull distribution is widely used to fit reliability and maintainability models because it consists of a family of different distributions that can be used to fit a wide variety of data and it models, mainly wear out of systems (i.e., an increasing hazard function) and in equipment failures.

2. Tasks that consistently require a fixed amount of time to complete with little variation. The lognormal is applicable to maintenance tasks where the task time and frequency vary, which is often the case for complex systems and products.

The beer production line for TBF follows the Weibull distribution and it is fair to indicate T as the continuous random variable representing the failure time. The PDF of the Weibull distribution is:

\[
f(t; \beta; \theta) = \frac{\beta}{\theta} \left(\frac{t}{\theta}\right)^{\beta-1} \exp \left[ -\left(\frac{t}{\theta}\right)^{\beta} \right]
\]

\quad \text{where the parameter } \beta \text{ is the shape parameter. A value of } \beta > 1 \text{ signifies an increasing failure rate (or hazard rate) function, whereas a value of } \beta < 1 \text{ signifies a decreasing failure rate function. When } \beta = 1, \text{ the failure rate function is constant and the Weibull distribution is identical to the exponential distribution (Ebeling, 2007). The scale parameter of the Weibull distribution, denoted by } \theta, \text{ influences both the mean and the spread of the distribution. As } \theta \text{ increases, the reliability at a given point in time increases, whereas the slope of the hazard rate decreases.}

\textbf{Mean Time to Failure (MTTF)}

This refers to the average time until a failure of a system or device occurs. MTTF is a basic measure of reliability for non-reparable items, and is estimated by the total time in operation of the boilers used by the Pabod Brewery Company divided by the total number of failures (breakdowns) recorded within a specific investigation period (Meeker & Escobar, 2008).

\[
\text{MTTF} = \frac{\sum t_i}{n}
\]

\quad \text{Where } \sum t_i = \text{ the total running time in operation of the boilers during an investigation period for both failed and non-failed items, } n = \text{ number of failures (breakdowns) of boilers or its parts occurring during a certain investigation period and MTTF is used for non-reparable parts or subsystems in the boiler.}
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 the boiler and its subsystems used by the Brewery Company divided by the total number of failures (breakdowns) recorded within a specific investigation period (Meeker & Escobar, 2008).

$$\text{MTBF} = \frac{\sum t_i}{n}$$  \hspace{1cm} (6)

Where, $\sum t_i$ = the total running time in operation of the boilers during an investigation period for both failed and non-failed items, $n$ = number of failures (breakdowns) of boiler or its parts occurring during a certain investigation period and MTBF is used for non-reparable parts or subsystems in the vehicles.

Failure Rate ($\lambda$)
Failure rate is the probability of failure per time unit. 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 (Meeker & Escobar, 2008). It is the reciprocal of the MTTF / MTBF function and is given by:

$$\lambda = \frac{1}{\text{MTBF}} = \frac{n}{\sum t_i}$$  \hspace{1cm} (7)

Where, $\sum t_i$ = the total running time in operation of the boiler during an investigation period for both failed and non-failed items, $n$ = number of failures (breakdowns) of boiler or its parts occurring during a certain investigation period.

Mean Time and To Repair (MTTR)
Mean time to repair (MTTR) is the average time required to troubleshoot and repair failed equipment and return it to normal operating conditions. It is a basic technical measure of the maintainability of equipment and repairable parts. Maintenance time is defined as the time between the start of the incident and the moment the system is returned to production (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 production, etc. it generally does not take into account lead time for parts. Mean time to repair ultimately reflects how well the brewery can respond to a problem and repair it.

The mean time to repair is the ratio of the total accumulative time of boiler or parts to repair or maintain in statistical time to the number of repair or maintenance actions in the boiler during the specified investigation time period (Meeker & Escobar, 2008). It is suitable for all kinds of boilers or parts and it is given by:

$$\text{MTTR} = \frac{\text{total maintenance time}}{\text{number of repairs}}$$

$$\text{MTTR} = \frac{\sum t_i}{N}$$  \hspace{1cm} (8)

Where, $t_i$ = total accumulative time of boiler or its parts to repair or maintain in statistical time, $N$ = number of repair actions in the population of boiler during the specified investigation time period.

Availability
The availability measure is used for boilers when failure consequences only lead to economic losses. (Han Yamei, 2007). The “availability” of a device is, mathematically, MTBF / (MTBF + MTTR) for scheduled working time. It is given by:
\[ A = \frac{MTBF}{(MTBF + MTTR)} = \frac{T_0}{T_0 + T_1} \quad (9) \]

Where, \( T_0 \) = Time that boiler works, \( T_1 \) = time that boiler do not work, include repair and maintenance time

**Repair rate**

Repair rate is the probability of repair per time unit. It is the rate of occurrence of repairs. A repair rate is used for systems with repairable parts. It is the reciprocal of the MTTR function and is given by:

\[ \mu = \frac{1}{MTTR} \quad (10) \]

Where, \( MTTR \) = Mean time to repair

**Mean Life or Overhaul Life (T)**

This represents the mean usage life when boilers reach their ultimate limit state. It is used by all kinds of boilers and parts (Han, 2007)

**Life Span**

The life span \( T \), indicates the usage life of boilers or parts while reliability is not less than life span. It is used for boilers whose failure causes accidents (Han, 2007).

**Durability**

Durability is a feature of the product to retain the serviceability until a marginal condition is reached, with a predetermined system of maintenance and repair being used (Han, 2007). This is a qualitative characteristic that boiler keep their normal working ability until the ultimate limit state is reached, under prescribed technical maintenance and repair conditions. The ultimate limit state means that boiler or parts reach a state that cannot be tolerated for further use, according to technical safety and economy.

**Maintainability**

Maintainability is a qualitative characteristic related to failure prevention, failure elimination and recovery of the normal working state. Maintenance is a set of procedures to ensure the serviceability of a product (Han, 2007).

3. RESULTS AND DISCUSSION

**Results**

This paper is devoted to the presentation, analysis and interpretation of the data gathered in the course of this study. Operational reliability analysis results are used to determine strategies for maintenance and development of these energetic objectives and for feasibility studies, which implies comparative analyses with other, electricity and/or heat producing solutions.

In Brewery company, operational reliability study is justified by the fact that the six boilers within, were put into service in the period [2009 - 2017]. Therefore, at least boilers (C1, C2, C3), which were put in service have not exceeded their useful life forecast. All six boilers are natural circulation boilers and work on joint bar (steam is charged in the same collector bar). Other technical features relevant to operational reliability study are shown in Table 1.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Boilers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal steam pressure [t/h]</td>
<td>C1</td>
</tr>
<tr>
<td>165</td>
<td></td>
</tr>
<tr>
<td>Nominal pressure [bar]</td>
<td>137.2</td>
</tr>
<tr>
<td>Nominal temperature [°C]</td>
<td>540</td>
</tr>
<tr>
<td>Fuel used: natural gas (G); coal (C); Heavy fuel oil (O)</td>
<td>G</td>
</tr>
</tbody>
</table>
Values Obtained for Operational Reliability Indicators

The study was conducted in accordance with the known methodology. The period under review extends 8 years [2009 - 2017]. Sequence of random variables, for proper functioning respectively, for corrective maintenance for boilers, also the causes leading to failure, obtained from operative reports and incident records of Brewery Companies are detailed in.

From the secondary data gotten from the operational logs, maintenance records and historical data and archives of their boilers, the total operating time for the six boilers for the period under review extending from 2009-2017 (8 years) is given below:

Total up time = (8 years x 365 days x 24) hours
= 70, 080 hours

The Table 2 shows the total boiler operating time or running time/total up time, total boiler maintenance time/total down time and total number of failures (breakdowns)/repairs recorded by each of the boilers.

Table 2 Boilers’ Operational Parameters

<table>
<thead>
<tr>
<th>Nr. Crt.</th>
<th>Boilers</th>
<th>Total Operating time [h]</th>
<th>Total Maintenance time [h]</th>
<th>Total Number of Failures /repairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>C1</td>
<td>70 080</td>
<td>2 494</td>
<td>34</td>
</tr>
<tr>
<td>2.</td>
<td>C2</td>
<td>70 080</td>
<td>2 494</td>
<td>34</td>
</tr>
<tr>
<td>3.</td>
<td>C3</td>
<td>70 080</td>
<td>2 494</td>
<td>38</td>
</tr>
<tr>
<td>4.</td>
<td>C4</td>
<td>70 080</td>
<td>2 494</td>
<td>33</td>
</tr>
<tr>
<td>5.</td>
<td>C5</td>
<td>70 080</td>
<td>2 494</td>
<td>33</td>
</tr>
<tr>
<td>6.</td>
<td>C6</td>
<td>70 080</td>
<td>2 494</td>
<td>38</td>
</tr>
</tbody>
</table>

Based on the operating, maintenance, and repairs parameters in the table 4.2 above, the following operational reliability indicators of boilers are determined:

- Mean time between the failures (MTBF);
- Mean time between to repair (MTTR);
- Mean failure rate (\(\lambda\));
- Mean rate of repair (\(\mu\));
- Proper functioning probability (Availability) (A).

i. **Boilers’ Mean time between the failures (MTBF):**

For C1 and C2 Steam boilers, the Mean time between failures (MTBF) is determined as given below.

From equation (6), we have

\[
MTBF = \frac{\sum t_i}{n}
\]

Substituting the values obtained from the operational parameters in Table 2, we have:

\[
MTBF = \frac{70080 \text{ hours}}{34 \text{ failures / breakdowns}}
\]

\[
MTBF = 2061.177 \text{ hours/failure (breakdown)}
\]

For C3 and C6 Steam boilers, the Mean time between failures (MTBF) is determined as given below.

From equation (6)
Substituting the values obtained from the operational parameters in Table 2, we have:

\[ \text{MTBF} = \frac{70080 \text{ hours}}{38 \text{ failures / breakdowns}} \]

MTBF = 1844.211 hours/failure (breakdown)

For C4 and C5 Steam boilers, the Mean time between failures (MTBF) is determined as given below.

From equation (6)

\[ \text{MTBF} = \frac{\sum t_i}{n} \]

Substituting the values obtained from the operational parameters in Table 2, we have:

\[ \text{MTBF} = \frac{70080 \text{ hours}}{33 \text{ failures / breakdowns}} \]

MTBF = 2123.636 hours/failure (breakdown)

ii. Boilers’ Mean time to repair (MTTR):

For C1 and C2 Steam boilers, the Mean time to repair (MTTR) is determined as given below.

From equation (8)

\[ \text{MTTR} = \frac{\sum t_i}{N} \]

Substituting the values obtained from the operational parameters in Table 2, we have:

\[ \text{MTTR} = \frac{2494 \text{ hours}}{34 \text{ repairs / maintenance}} \]

MTTR = 73.353 hours/repair (maintenance)

For C3 and C6 Steam boilers, the Mean time to repair (MTTR) is determined as given below.

From equation (8), we have

\[ \text{MTTR} = \frac{\sum t_i}{N} \]

Substituting the values obtained from the operational parameters in Table 2, we have:

\[ \text{MTTR} = \frac{2494 \text{ hours}}{38 \text{ repairs / maintenance}} \]
MTTR = 65.631 hours/repair (maintenance)

For C4 and C5 Steam boilers, the Mean time to repair (MTTR) is determined as given below. From equation (3.8)

MTTR = \frac{\sum t_i}{N}

Substituting the values obtained from the operational parameters in Table 2, we have:

MTTR = \frac{2494 \text{ hours}}{33 \text{ repairs / maintenance}}

MTTR = 75.576 hours/repair (maintenance)

iii. Boilers’ Mean failure rate (\lambda):

For C1 and C2 Steam boilers, the Mean failure rate (\lambda) is determined as given below. From equation (7), we have

\lambda = \frac{1}{MTBF} = \frac{n}{\sum t_i}

Substituting the values obtained from the operational parameters in Table 2, we have:

\lambda = \frac{1}{2061.18} = 0.0004852 \text{ failure / hour}

For C3 and C6 Steam boilers, the Mean failure rate (\lambda) is determined as given below. From equation (3.7)

\lambda = \frac{1}{MTBF} = \frac{n}{\sum t_i}

Substituting the values obtained from the operational parameters in Table 2, we have:

\lambda = \frac{1}{1844.21} = 0.0005422 \text{ failure / hour}

For C4 and C5 Steam boilers, the Mean failure rate (\lambda) is determined as given below. From equation (7), we have

\lambda = \frac{1}{MTBF} = \frac{n}{\sum t_i}

Substituting the values obtained from the operational parameters in Table 2, we have:

\lambda = \frac{1}{2123.64} = 0.0004709 \text{ failure / hour}
iv. Boilers’ Mean Repair rate (μ):
For C1 and C2 Steam boilers, the Mean Repair rate (μ) is determined as given below.
From equation (10), we have

\[ \mu = \frac{1}{MTTR} \]

Substituting the values obtained from the operational parameters in Table 2, we have

\[ \mu = \frac{1}{73.353} = 0.013634 \text{ repair/hour} \]

For C3 and C6 Steam boilers, the Mean repair rate (μ) is determined as given below.
From equation (10), we have

\[ \mu = \frac{1}{MTTR} \]

Substituting the values obtained from the operational parameters in Table 2, we have:

\[ \mu = \frac{1}{65.631} = 0.0152367 \text{ repair/hour} \]

For C4 and C5 Steam boilers, the Mean repair rate (μ) is determined as given below.
From equation (10), we have

\[ \mu = \frac{1}{MTTR} \]

Substituting the values obtained from the operational parameters in Table 2, we have:

\[ \mu = \frac{1}{75.756} = 0.0132003 \text{ repair/hour} \]

v. Boilers’ Availability (A):
For C1 and C2 Steam boilers, the availability is determined as given below.
From equation (3.9), we have

\[ A = \frac{MTBF}{(MTBF + MTTR)} \]

Or

\[ A = \frac{T_o}{T_o + T_1} \]

Substituting the values obtained from the operational parameters in Table 2, we have

\[ A = \frac{2061.18}{(2061.18 + 73.353)} = 0.965630 \]
For C3 and C6 Steam boilers, the availability is determined as given below:

From equation (3.9), we have

\[ A = \frac{MTBF}{MTBF + MTTR} \]

Substituting the values obtained from the operational parameters in Table 2, we have

\[ A = \frac{1844.21}{(1844.21 + 65.631)} = 0.965635 \]

For C4 and C5 Steam boilers, the availability is determined as given below:

From equation (9), we have

\[ A = \frac{MTBF}{MTBF + MTTR} \]

Substituting the values obtained from the operational parameters in Table 2, we have

\[ A = \frac{2123.64}{(2123.64 + 75.576)} = 0.965634 \]

The result for the boilers’ reliability indices are presented in Table 3.

<table>
<thead>
<tr>
<th>Nr. Crt.</th>
<th>Boiler</th>
<th>MTBF [h/failure]</th>
<th>MTTR [h/repair]</th>
<th>( \lambda \times 10^{-3} ) [failure.h(^{-1})]</th>
<th>( \mu \times 10^{-3} ) [repair.h(^{-1})]</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C1 and C2 – 165 t/h</td>
<td>2061.177</td>
<td>73.353</td>
<td>0.4852</td>
<td>0.013634</td>
<td>0.965630</td>
</tr>
<tr>
<td>2</td>
<td>C3 and C6 – 350 t/h</td>
<td>1844.211</td>
<td>65.631</td>
<td>0.5422</td>
<td>0.0152367</td>
<td>0.965635</td>
</tr>
<tr>
<td>3</td>
<td>C4 and C5 – 400 t/h</td>
<td>2123.636</td>
<td>75.576</td>
<td>0.4709</td>
<td>0.0132003</td>
<td>0.965634</td>
</tr>
</tbody>
</table>

**Table 3** Operational Reliability Indices for the Boilers in Brewery Company Study

**Figure 1** Boilers Mean Time between Failures (MTBF)
Basic reliability indicator values (MTBF, MTTR, Failure rate and Availability indices) evaluated for the boilers respectively, are shown in Figures 1 to 3.

Figure 1 indicates that boilers C1 and C2 steaming with a capacity of 165 tonnes of wort per hour with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70,080 hours has a mean time between failure is 2061.177h. The results in the figure 4.1 also indicate that boilers C3 and C6 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70,080 hours has a mean time between failure is 1844.211 hours. The boilers C4 and C5 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70,080 hours has a mean time between failure is 2123.636 hours.

**Figure 2** Graphical illustration of Mean values of Boilers’ MTBF

The mean values of the boilers are also shown graphically in Figure 2. From the graphical illustration, boilers C1 and C2 steaming with a capacity of 165 tonnes of wort per hour with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70,080 hours has a mean time between failure is 2061.177h. The results in the figure 2 also indicate that boilers C3 and C6 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70,080 hours has a mean time between failure is 1844.211 hours. The boilers C4 and C5 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70,080 hours has a mean time between failure is 2123.636 hours.

**Figure 3** Boilers’ Mean Time to Repair (MTTR)

Figure 3 indicates that boilers C1 and C2 steaming with a capacity of 165 tonnes of wort per hour with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70,080 hours has
a mean time to repair is 73.353 hours/repair. The results in the Figure 3 also indicate that boilers C3 and C6 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70 080 hours has mean time to repair is 65.631 hours/repair steaming with a capacity of 350 tonnes of wort per hour. The boilers C4 and C5 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70 080 hours has a mean time to repair is 75.576 hours/repair steaming with a capacity of 400 tonnes of wort per hour.

![Boilers Specifications](image)

Figure 4 Graphical illustration of Boilers’ MTTR

The mean values of the boilers are also shown graphically in Figure 4. From the graphical illustration, the boilers C1 and C2 steaming with a capacity of 165 tonnes of wort per hour with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70 080 hours has a mean time to repair is 73.353 hours/repair. The results in the figure 4 also indicate that boilers C3 and C6 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70 080 hours has mean time to repair is 65.631 hours/repair steaming with a capacity of 350 tonnes of wort per hour. The boilers C4 and C5 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70 080 hours has a mean time to repair is 75.576 hours/repair steaming with a capacity of 400 tonnes of wort per hour.

![Boilers Specifications](image)

Figure 5 Boilers’ Failure Rate

Figure 5 indicates that boilers C1 and C2 steaming with a capacity of 165 tonnes of wort per hour with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70 080 hours has a failure rate of 0.4852 failure/hour. The results in the Figure 4 also indicate that boilers C3 and C6 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70 080 hours has
a failure rate of 0.5422 failure/hour steaming with a capacity of 350 tonnes of wort per hour. The boilers C4 and C5 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70,080 hours has a failure rate of 0.4709 failure/hour steaming with a capacity of 400 tonnes of wort per hour.

![Graphical illustration of Boilers’ Failure Rate](image)

**Figure 6** Graphical illustration of Boilers’ Failure Rate

The failure rates of the boilers are also shown graphically in Figure 6. From the graphical illustration, boilers C1 and C2 steaming with a capacity of 165 tonnes of wort per hour with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70,080 hours has a failure rate of 0.4852 failure/hour. The results in the Figure 6 also indicate that boilers C3 and C6 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70,080 hours has a failure rate of 0.5422 failure/hour steaming with a capacity of 350 tonnes of wort per hour. The boilers C4 and C5 with a total running time in operation of wort boiling during the investigation period from 2009 – 2017 for both failed and non-failed items at 70,080 hours has a failure rate of 0.4709 failure/hour steaming with a capacity of 400 tonnes of wort per hour.

**Reliability Analysis**

Reliability is the probability that the boilers or the entire line will perform a required function, under specific operating conditions, for a given period of time \( t \). The Time between Failures of the line is defined with \( T \); \( T \geq 0 \), then from equation (1) the reliability can be expressed as,

\[
R(t) = P(T \geq t)
\]

Moreover, From equations (2) the unreliability function, \( Q(t) \), is defined as the probability of failure in \( t \),

\[
Q(t) = 1 - R(t) = P(T \leq t)
\]

In analyzing these reliability indicators determined from the collected failure data, the Weibull distribution method is selected and applied according to several characteristics that make Weibull distribution the best statistical distribution method to be used for these data. The beer production line for TBF follows the Weibull distribution and it is fair to indicate \( T \) as the continuous random variable representing the failure time. The PDF of the Weibull distribution is:

\[
f(t; \beta; \theta) = \frac{\beta}{\theta} \left( \frac{t}{\theta} \right)^{\beta-1} \exp \left[ \left( \frac{t}{\theta} \right)^\beta \right]
\]

Where the parameter \( \beta \) is the shape parameter. A value of \( \beta > 1 \) signifies an increasing failure rate (or hazard rate) function, whereas a value of \( \beta < 1 \) signifies a decreasing failure rate function. When \( \beta = 1 \), the failure rate function is constant and the Weibull
distribution is identical to the exponential distribution (Ebeling, 2007). The scale parameter of the Weibull distribution, denoted by \( \theta \), influences both the mean and the spread of the distribution. As \( \theta \) increases, the reliability at a given point in time increases, whereas the slope of the hazard rate decreases.

When failure rate of the boilers is determined, the reliability and the unreliability of the boilers for beer production line at the end of \( t \) hours of operation/ up time from our exponential modelling of Weibull distribution are:

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

For C1 and C2 Steam boilers, the Mean failure rate \( (\lambda) \) is determined as 0.0004852 failure/hour. The reliability at the end of 1000 hours of operations is:

\[
R(t) = e^{-0.0004852 \times 1000} = e^{-0.4852} = 0.61
\]

For C3 and C6 Steam boilers, the Mean failure rate \( (\lambda) \) is determined as 0.0005422 failure/hour. The reliability at the end of 1000 hours of operations is:

\[
R(t) = e^{-0.0005422 \times 1000} = 0.58
\]

For C4 and C5 Steam boilers, the Mean failure rate \( (\lambda) \) is determined as 0.0004709 failure/hour. The reliability at the end of 1000 hours of operations is:

\[
R(t) = e^{-0.0004709 \times 1000} = 0.62
\]

Consequently, the Equations (1) and (2) are used to calculate the reliability and unreliability of the boilers operation in the beer production line based on the Weibull distribution per time \( t \). The parameters \( \beta \) and \( \theta \) are 1.41453 and 207.909, respectively (Han, 2007). Therefore, the reliability model of the boilers operation in the beer production from Equations (1) and (2) are as follows:

\[
R_{\text{line}}(t) = \exp\left(-\frac{t}{207.909}\right)^{1.41453}
\]

Thus, these models were used to determine the operational behaviour as a line performance evaluation indicator. The reliability diagrams for all the boilers and the entire line are shown in Figure 7.
The optimal maintenance interval with the expected reliability level can be estimated, for example to achieve 70% reliability for the boilers (C1 to C6), the maintenance must be carried out in not more than 500 hours of operation, thereby meaning that the maintenance must be carried out every two working days. Moreover, \( \text{Rel}_{\text{line}}(500) = 0.7625 \) means the probability that the system will not fail in 500 hours of operation is 0.7625.

The reliability is calculated for all the boilers of the brewery companies studied and the entire line at different time intervals in Tables 4 and 5. Some conclusions from Table 4 include the following: (a) the reliability of the line after 300 hours of operation is 86.45%, after 600 hours is 74.74%; whereas after 1000 hours of operation, it drops sharply to 61.55%; (b) the highest reliability values are recorded for C4 and C5 boilers and (c) the lowest reliability values are shown at the C3 and C6 pasteurizing boiler.

### Table 4 Statistics of the Number of Failures of Boiler Component

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapourizer</td>
<td>14</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>13</td>
<td>7</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Overheater</td>
<td>7</td>
<td>6</td>
<td>10</td>
<td>5</td>
<td>8</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Economizer</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Rotary air preheater</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Air fan</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Flue gas fan</td>
<td>4</td>
<td>5</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 5 Statistics of the causes of boiler failures

<table>
<thead>
<tr>
<th>Causes of Boiler Failure</th>
<th>% number of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaks –LKT</td>
<td>87.08</td>
</tr>
<tr>
<td>Auxiliary Element Failure – AEF</td>
<td>10.42</td>
</tr>
<tr>
<td>Electric Failures – EF</td>
<td>2.08</td>
</tr>
<tr>
<td>Protection Shutdown – PS</td>
<td>0.42</td>
</tr>
</tbody>
</table>

**Figure 8** PARETO chart analysis of Causes of Boiler Failure

From the PARETO Chart analysis shown in Figure 4.5, it was inferred that the major cause of failure in boilers is caused by leakages. If more effective measures are taken to eliminate this, then the majority of the cause of boiler failure in the brewery will be solved. To obtain quantitative analysis of the failure data of the boilers used in the beer production line, the descriptive statistics of the basic features of the Mean time between failures, Mean time to repair, failure rate, repair rate and availability indices were determined and represented in Table 4.1 and the following observations were made:

a) For the C1 and C2 boilers, the mean time between failures is about 2061.177 hours/failure (breakdown), meaning that about every 2000 h of operation there is a failure which occurs on the production line.
b) For C3 and C6 Steam boilers, the Mean time between failures (MTBF) is 1444.211 hours/failure (breakdown), meaning that about every 1800 h of operation there is a failure which occurs on the production line.

c) For C4 and C5 Steam boilers, the Mean time between failures (MTBF) is 2123.636 hours/failure (breakdown), meaning that about every 2100 h of operation there is a failure which occurs on the production line.

Therefore, the maintenance staff must initially take note of these boiler operating indices. Reliability analysis was conducted on all the boilers used in operation and for C1 and C2 boilers, the Mean failure rate (λ) determined is 0.0004852 failure/hour. The reliability at the end of 1000 hours of operations is 0.61. For C3 and C6 boilers, the mean failure rate (λ) determined is 0.0005422 failure/hour. The reliability at the end of 1000 hours of operations is 0.58. For C4 and C5 boilers, the mean failure rate (λ) determined is 0.0004709 failure/hour. The reliability at the end of 1000 hours of operations is 0.62. The reliability is calculated for all the boilers of the Pabod brewery and the entire line at different times. From the analysis the boilers C4 and C5 has the highest reliability value while C3 and C6 boilers had the lowest reliability value.

4. CONCLUSION

In the research work an attempt has been made to evaluate the reliability of a system of boilers used in brewery industry. The boiler is a very important machine in a beer production industry. A boiler is a closed vessel in which water or the fluid is heated under pressure. The steam or hot fluid is then circulated out of the boiler for use in various processes or heating applications. It is used for wort boiling and pasteurization. A safety valve is required to prevent over pressurization and possible explosion of a boiler.

In view of the applications of a boiler in a beer production factory, its failure in any case is not tolerable. These boilers may fail due to a number of reasons; some of the main reasons are as follows: Failures of mechanical/electrical safety valves-if the pressure in the boiler goes beyond the required limits, these valves are released. There is a lead, which will melt and release the pressure. (a) Failures of temperature sensors - In case of failures, metallic sensors which sense the temperature cut the electrical supply coming to the heater and stop the working of boiler (b) Failures due to non-supply of water in the heater - If water is not supplied, air inside the boiler will get heated and will cause the blast of the boiler.

The aim of this research work has been to conduct reliability analysis on boiler operation of Brewery. The objectives of this dissertation had been: To understudy the operations of a boiler in a brewery process and to investigate the reasons for failure in the boiler’s system operation such as Leaks, Auxiliary Element Failure, Electric Failures and Protection Shutdown; to examine the various components of a boiler system such as Vapourizer, Overheater, Economizer, Rotary air preheater, Air fan and Flue gas fan for failure that can lead to its maintenance forecast and performance and to analyze the reliability of the boiler operation of a Brewery with respect to its failure rate. The descriptive statistics of the basic features of the Mean time between failures, Mean time to repair, failure rate, repair rate and availability indices were determined and represented. For the C1 and C2 boilers, the mean time between failures is about 2061.177 hours/failure (breakdown), meaning that about every 2000 h of operation there is a failure which occurs on the production line. For C3 and C6 Steam boilers, the Mean time between failures (MTBF) is 1844.211 hours/failure (breakdown), meaning that about every 1800 h of operation there is a failure which occurs on the production line. For C4 and C5 Steam boilers, the Mean time between failures (MTBF) is 2123.636 hours/failure (breakdown), meaning that about every 2100 h of operation there is a failure which occurs on the production line.

Reliability analysis was conducted on all the boilers used in operation and for C1 and C2 boilers, the Mean failure rate (λ) determined is 0.0004852 failure/hour. The reliability at the end of 1000 hours of operations is 0.61. For C3 and C6 boilers, the mean failure rate (λ) determined is 0.0005422 failure/hour. The reliability at the end of 1000 hours of operations is 0.58. For C4 and C5 boilers, the mean failure rate (λ) determined is 0.0004709 failure/hour. The reliability at the end of 1000 hours of operations is 0.62. The reliability is calculated for all the boilers of the Pabod brewery and the entire line at different times. From the analysis the boilers C4 and C5 has the highest reliability value while C3 and C6 boilers had the lowest reliability value. The Weibull distribution provided the best fit for the boilers operating line to describe the Time before Failures. Finally, the Pareto chart analysis revealed that of the various reasons for failure in the boiler’s system operation such as Leaks, Auxiliary Element Failure, Electric Failures and Protection Shutdown, the major reason for failure in boilers is caused by leakages. If more effective measures are taken to eliminate this, then the majority of the cause of boiler failure in the brewery will be solved.

Statistical data on operational disturbances that appeared in boiler lifetime/lifespan have been carried out systematically for brewery boiler operation. Having this database, it is possible to analyze the changeability of reliability indices in a long term perspective and define reasons or effects of defective operation of power machinery. Economically excused failure rates are reasonable measures for durability of boilers and their components in determination of modernization schedules and rationalization.
of maintenance and materials management in the entire brewery system under study. In conclusion, reliability model at boiler line level was developed, thereby ensuring that line operation forecasting, at least in the short term, is feasible.

REFERENCE


