WEIBULL RELIABILITY ANALYSIS AND MAINTENANCE STRATEGIES OF ROTATING EQUIPMENT

BY

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In the Name of Allah, Most Gracious, Most Merciful.

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Contents

Page

Page

Page

List of Illustrations

Fig. #	*Caption*	*Page*

Fig. #	*Caption*	*Page*

List of Tables

Nomenclature

$R(t)$	::	reliability function
$f(t)$	::	probability density function
$F(t)$	::	Cumulative Distribution Function (CDF)
$\lambda(t)$	::	failure rate
μ	::	mean time
$MTBF$	::	mean time between failure
$MTTF$	::	mean time to failure
$MTTR$	::	mean time to repair
σ^2	::	variance
k	::	coefficient of variation
T_m	::	most probable time (mode)
η	::	characteristic life
β	::	shape parameter, $k \approx 1/\beta$
$\Gamma(\bullet)$	::	Gamma function
t_p	::	failure quantile time
$T_{0.5}$	::	median time
$M(t)$	::	maintainability function
$m(t)$	::	maintainability density function
$\nu(t)$	::	instant repair rate
t_{mp}	::	repair time quantile
$A(t)$	::	instantaneous availability function
$A^*(T_o)$	::	intervals availability
N	::	N_{th} maintenance cycle
$R_m(t)$	::	reliability function when maintenance applied
m	::	shape parameter for maintainability
θ	::	characteristic life for maintainability

$E(T)$	::	the expected value of T
T_{pm}	::	time for maintenance
p	::	the probability value
$A(\infty)$	::	steady-state availability
T_o	::	mission time
S_l	::	limit value
S_b	::	breakdown value
S_a	::	alarm value
$H(t)$	::	renewal function
$h(t)$	::	renewal rate function
$V[N(t)]$	::	variance of renewal
$\bar{T}$	::	operation time
$N(t)$	::	number of failures at time t, in a renewal process
$\bar{N}(t)$	::	asymptotic value of the renewal function
$\sigma[N(t)]$	::	standard deviation of number of failures
$\Phi^{-1}(p)$	::	inverse of normal function
$\bar{N}$	::	number of spares needed during a period of time with a probability of shortage $= 1 - p$

Abstract

In this thesis, Weibull reliability analysis have been applied to some rotating equipment in Saudi Aramco's Ras Tanura Refinery. The Weibull reliability analysis is found to be very beneficial to characterize the equipment time to failure in rotating equipment, and to design their appropriate maintenance strategy by knowing the expected number of failures to occur in a given period of time. Through the use of fitted Weibull model as a predictive tool, the operation management can take the appropriate decision in advance to avoid any operational upset. The time-to-failure or time between failure data as well as the time to restore the system for a set of rotating equipment that is stored in Saudi Aramco computer maintenance systems will be utilized to perform both Weibull reliability and maintainability analysis. The data will be derived also from Saudi Aramco on-line monitoring process variables retrieved from Distributed Control System (DCS). After characterizing the reliability and maintainability functions, the steady-state availability of each type of rotating equipment is determined. The proper type of maintenance for each rotating equipment will be identified and the needs of spares for various non-repairable parts used in these equipment will also be determined for a known planning horizon.

الخلاصة

الاسم : دحام مطر العنزي .
عنوان البحث : التحليل الوايبلي للاعتمادية واستراتيجيات الصيانة للآلات الدوارة .
التخصص : الهندسة الميكانيكية
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في هذا البحث تم تطبيق التحليل الوايبلي للاعتمادية على بعض الآلات الدوارة في مصفاة راس تنورة حيث وجد أن هذا التحليل مفيد جداً لوصف أوقات عطل الآلة في المعدات الدوارة وهو عملي أيضا لتصميم استراتيجيات الصيانة المناسبة لكل آلة وذلك عن طريق معرفة عدد الأعطال المتوقعة الحدوث خلال فترة زمنية معينة .

من خلال استخدام أنموذج وايبل كأداة تنبؤ للأعطال تستطيع إدارة عمليات التشغيل اتخاذ القرار المناسب في وقت مناسب أيضا قبل حدوث العطل للآلة وذلك لتفادي أي إخلال بعمليات التشغيل .

أن المعلومات الخاصة بأوقات حدوث الأعطال وأوقات التصليح لأنظمة مجموعة الآلات الدوارة والتي أخذت من نظام الصيانة الحاسوبي في ارامكو السعودية ومن خلال نظام التحكم المستمر الخاص بالآلات الدوارة استخدمت بفاعلية لتحليل الاعتمادية والقدرة الإصلاحية لهذه المعدات .

لقد تم أيضا وصف المستفادية لكل نوع من أنواع الآلات الدوارة المشتمل عليها هذا البحث بعد وصف شامل للاعتمادية والقدرة الإصلاحية . وكذلك تم تحديد أنواع الصيانة المناسبة لكل آلة وعدد قطع الغيار الضروري توفرها لكل آلة خلال فترة زمنية مخطط لها .

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Chapter 1

Introduction and Literature Review

1.1 Introduction

A substantial sum of money is lost each year because of inadequate maintenance procedures. Neglecting to replace or repair a defective part can cause catastrophic system failures which can lead to unscheduled downtime, loss of profits, and even loss of life. Equipment failures can be prevented or minimized, provided we have the right tools to predict them. To predict, prevent, or minimize the system failures, industries increasingly use tools from the area of Reliability, Availability, and Maintainability Engineering (RAM).

Reliability measures are used to predict the probability that a given unit will perform satisfactorily over a specified time. For example, reliability function, $R(t)$, represents the probability of successful operation from time or usage points O to t. Here, time O represents the instant the unit is placed in service, and time t, an arbitrarily selected "*instant*" in its life (in the future). Mathematically if random variable life, T, represents the time to failure of that unit, then the reliability function (or simply reliability) $R(t)$ is defined as

$$R(t) = P(T > t) = \int_t^\infty f(t)dt \tag{1.1}$$

where $f(t)$ = probability density function of T, and is interpreted as

$$f(t)\Delta t = P(t < T < t + \Delta t) \tag{1.2}$$

or

$$f(t) = -\frac{dR(t)}{dt} = \frac{dF(t)}{dt} \tag{1.3}$$

where $F(t) = P(T \leq t) = 1 - P(T > t) = 1 - R(t)$ which is known as Cumulative Distribution Function (CDF).

We can define another important measure of reliability of a unit, known as instantaneous failure rate $\lambda(t)$ also known as failure rate or hazard rate, as follow:

$$\begin{aligned} \lambda(t)\Delta t &= \frac{P[(T < t + \Delta t) \cap (T > t)]}{P(T > t)} \\ &= \frac{P(t < T < t + \Delta t)}{P(T > t)} = \frac{f(t)\Delta t}{R(t)} \end{aligned} \tag{1.4}$$

or

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{1.5}$$

The failure rate and reliability function are related as follows:

$$\lambda(t) = -\frac{1}{R(t)} \frac{dR(t)}{dt} \tag{1.6}$$

or

$$R(t) = \exp\left[-\int_0^t \lambda(t) dt \right] \tag{1.7}$$

Some additional measures of reliability are the Mean Time to Failure (MTTF) which is the expected value of T, $E(T)$ and is given by

$$\mu = MTTF = E(T) = \int_0^\infty t f(t) dt = \int_0^\infty R(t) dt \tag{1.8}$$

It is important to emphasize that MTTF is interpreted as mean time to first failure, and usually referred to as non-repairable items or components. On the other hand, "*mean time between failures*" MTBF is used in cases when we have repair capabilities.

Another useful measure of reliability is failure time quantile (or percentile) t_p, where $0 < p < 1$. The failure time quantile represents the point in time or usage where the cumulative failure probability distribution $F(t_p)$ is equal to p (or $R(t_p)=1-p$).

Hence t_p must satisfy the following relationship

$$F(t_p) = p = \int_0^{t_p} f(t)dt \qquad (1.9)$$

If $p=0.5$, then failure time quantile $T_{0.5}$ is known as median time to failure. At $T_{0.5}$, $F(T_{0.5})=R(T_{0.5})$ and there is 50% chance that life of the unit will be less than $T_{0.5}$ (or 50% chance that the life of the unit will be more than $T_{0.5}$).

The scatter in the time to failure can be expressed by standard deviation, σ of T, and is determined by first determining the variance $\sigma^2 = V(T)$, and then taking a square root of the resulting value. The variance $\sigma^2 = V(T)$ is given by

$$\sigma^2 = \int_0^{\infty} t^2 f(t)dt - \mu^2 \qquad (1.10)$$

The coefficient of variation k is the non-dimensional measure of scatter in data and is given by $k = \frac{\sigma}{\mu}$. The most probable life, T_m, can be determined by solving for $t = T_m$, $\frac{df(t)}{dt} = 0$.

The above reliability measures can be developed for any reliability model. In equipment and machinery component life studies, Weibull model is the most versatile and accepted model. The reliability analysis using Weibull model is also known as Weibull Analysis.

Weibull analysis has been used successfully for years in the aerospace, automotive, and manufacturing industries as one of the decision making tool to identify and eliminate costly and unexpected part failures, and to provide an optimal maintenance strategy. The petroleum and chemical process industries are also discovering the usefulness of these techniques and have begun to apply them in plant and pipeline risk analysis, failure forecasting, maintenance, and other engineering-related decision processes.

Weibull analysis is very helpful to find the following items:

1. Number of failures that may happen to an equipment or a part during a certain period of time.
2. Number of repairs (and/or replacements) to be scheduled during a given duration of time.
3. The modes of the failure as reflected by the shape parameter of the Weibull distribution characterizing the time of failure of the part. These fall into three categories – (a) wear-in, (b) random (non-aging type), and (c) wear-out (aging

type). Wear in mode is reflected by decreasing failure rate (DFR), the random (non-aging type) mode of failure is represented by constant failure rate (CFR), and wear-out failure rate characterized by increasing failure rate (IFR).

4. The optimum replacement interval for components subject to wear-out failure.

1.2 Literature Review

Weibull analysis is found to be used widely in material behavior and many sources were found in this regard when strength, or cycle to failure at a given stress load are represented by a Weibull model [1-5]. However, there are very limited sources which talk about the use of Weibull analysis in petroleum process industries.

Samaha [6] studied the utilizing of Weibull analysis based on failure history that is extracted from maintenance system to give an indication of the component failure mechanism. He has also shown that Weibull analysis can be used to predict the number of failures expected to occur in future for period of time using meantime between failures.

McElroy and Fruchtmans [7] showed a new statistical method which was developed from Reliability Centered Maintenance (RCM) to provide an initial estimate of future component reliability based on small data fields. Their new technique was double-order statistics based on the Weibull distribution function to model equipment failure rate. The application of the advanced statistical model is practical because it can be used with less data and more confidence to relate before-to-after replacement cost ratio to the Weibull shape parameter.

Roberts and Mann [8] proved that a simulation based on Weibull parameters of the major component failure modes is able to duplicate the overall system prediction that the Crow's nonhomogeneous Poisson process model gives. The advantage of his research is that only the major component failure modes of repairable multi-component systems will need to be included in the simulation.

1.2.1 Estimation of Weibull Parameters

Peterlik [9] showed that by analytical solutions and numerical calculations, it has been proven that the maximum likelihood evaluation procedure gives correct results for Weibull parameters determined from a set of experiments.

Pieracci [10] determined a high-quality estimation procedure and the solution of the problem of the determination of the number of experimental data that are necessary to estimate the parameters of the distribution and some related statistics.

From a practical perspective, it is far convenient to use a regression-based analysis, such as shown by Lewis [11], and that will be the main approach which will be used in this work for data analysis.

1.3 Weibull Analysis

The Weibull analysis provide a comprehensive approach in reliability evaluation of products and systems and its renewal characteristics. The time to failure data obtained from industry, such as hydrocarbon plant, can be used for Weibull reliability model, and its parameters can be utilized to understand about the mode of failure. The Weibull fitted model is used to predict number of failure expected to occur in a given period of time. The key indications of reliability are its MTTF (or MTBF), standard deviation, median, mode and quantiles. These models can further be integrated in determining appropriate equipment maintenance and part replacement strategies.

1.3.1 Two Parameter Weibull Model and its Characteristic

The two parameter Weibull Cumulative Distribution Function (CDF) has an explicit equation:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{1.11}$$

and the reliability function is given by [12]

$$R(t) = e^{-(t/\eta)^{\beta}} \tag{1.12}$$

where:

$F(t)$ = fraction failing or probability of failing before time t or unreliability at time t

$R(t)$ = probability of survival or reliability at time t

t = time to failure

η = characteristic life or scale parameter

β = scatter or shape parameter

The shape parameter (β) is a non-dimensional parameter and reflect the type of failure mode, such as infant mortality ($\beta < 1$), random ($\beta = 1$), or wear-out ($\beta > 1$). The other Weibull parameter (η) is a scale parameter having the same unit as of t, and is a function of the mean time to failure (MTTF). For a special case when $\beta = 1$, MTTF $= \eta$.

The general relationship between η and MTTF is given by the following equation: [6]

$$MTTF = E(T) = \mu = \eta \Gamma \left[1 + \frac{1}{\beta} \right]. \tag{1.13}$$

where $\Gamma(\bullet)$ is the gamma function.

Another important characteristic of reliability model is its failure rate $\lambda(t)$, which is defined as

$$\lambda(t) = -\left(\frac{1}{R(t)} \frac{dR(t)}{dt} \right) = \left(\frac{\beta}{\eta} \right) \left(\frac{t}{\eta} \right)^{\beta - 1} \tag{1.14}$$

The following are some other statistical characteristics that should be calculated during a typical Weibull analysis procedure being applied to analyze the machinery time to failure data:

1. Variance

$$\sigma^2 = \eta^2 \left[\Gamma \left(1 + \frac{2}{\beta} \right) - \Gamma^2 \left(1 + \frac{1}{\beta} \right) \right] \tag{1.15}$$

2. Mode

$$T_m = \eta \left[\frac{\beta - 1}{\beta} \right]^{\frac{1}{\beta}} \tag{1.16}$$

3. Co-efficient of Variation

$$k = \frac{\sigma}{\mu} = \frac{\sqrt{\Gamma\left(\frac{2}{\beta} + 1\right) - \Gamma^2\left(1 + \frac{1}{\beta}\right)}}{\Gamma\left(1 + \frac{1}{\beta}\right)} \tag{1.17}$$

4. Quantile t_p is given by

$$t_p = \eta \left(\ln \frac{1}{1-p} \right)^{1/\beta} \tag{1.18}$$

where $F(t_p) = p$.

5. Median $T_{0.5}$

$$T_{0.5} = \eta \, (\ln 2)^{1/\beta} \tag{1.19}$$

1.4 Machinery Failure

The failure of an equipment is a result of one or sequence of events that led the equipment to failure. The downtime and component failure risk can be reduced only if the time is anticipated when the potential problems are expected to occur and avoided.

Failure analysis of machinery is the determination of failure modes and most probable causes of machinery components, and Weibull analysis can assist in the process of determining failure modes.

1.4.1 Definition of Failure

Failure can be defined as any change in a machinery part or component which causes it to become unable to perform its intended function satisfactory [12].

The failure can be caused by one or more of the following:

1. Material defects.

2. Design deficiencies.

3. Processing and manufacturing deficiencies.

4. Assembly errors.

5. Off-design or unexpected service conditions.

6. Maintenance deficiencies.

7. Improper operation.

1.4.2 Metallurgical Failure

Machinery components often fail due to metallurgical problems (corrosion, fatigue fracture, creep, stress level, etc.). These are time-dependent aging processes which leads to wear-out type of failures. The following are the primary failure modes associated with metallurgical failures:

1. Deformation and distortion loss in.

2. Fracture and separation (ductile, brittle, fatigue).

3. Surface and material changes (corrosion, erosion).

4. Elevated temperature failure (creep, stress rupture).

1.4.3 Types of Failure Rate

There could be three main types of failure rates [$\lambda(t)$] for a typical equipment. These are: early failures, random failures, and wear-out failures.

1.4.3.1 Early Failure Rate
(Decreasing Failure Rate - DFR)

It is clear from Figure 1.1 that the failure rate is decreasing with time, i.e., for $t_2 > t_1$, $\lambda(t_2) < \lambda(t_1)$. The early failures of the equipment being carried by either improper repair, use of wrong spare parts, or improper startup or presence of initial defects in the assembly. This is a ***wear-in period*** and may represent initial burn-out period of a new system or product.

1.4.3.2 Random Failure Rate
(Constant Failure Rate - CFR)

The relationship between the failure rate and time is constant as shown in Figure 1.2, i.e., for $t_2 > t_1$, $\lambda(t_2) = \lambda(t_1) = \lambda$. This type of failure usually occurs because of process upsets, human error, or component failure due to some shock, or sudden loading. This period is also referred as ***random failure period***.

1.4.3.3 Wear-out Failure Rate
(Increasing Failure Rate - IFR)

As shown in Figure 1.3, the failure rate is increasing with time, i.e., for $t_2 > t_1$, $\lambda(t_2) > \lambda(t_1)$. This period is known as ***wear-out period*** is mostly influenced by the intensity of time-dependent phenomena, such as corrosion, erosion, creep, and fatigue.

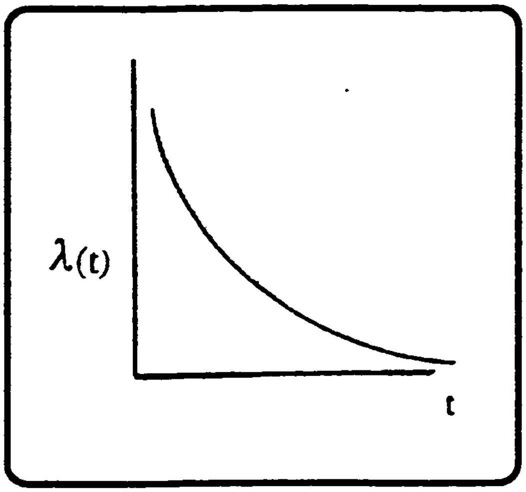


Figure 1.1. Wear-in failure rate.

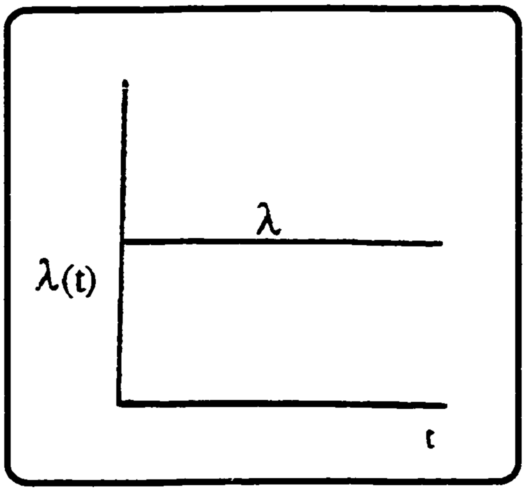


Figure 1.2. Constant failure rate.

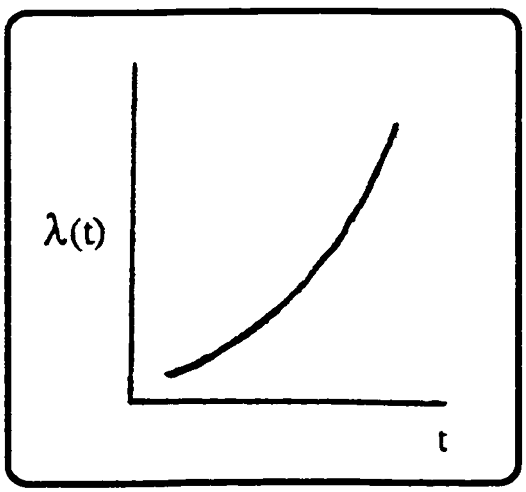


Figure 1.3. Wear-out failure rate.

1.4.4 Bath Tub Curve

The bath tub curve represents a combination of all three types of failure rates, which is experienced by a system in its entire life cycle, is widely used to represent a composite picture of all three types of failure rates acting simultaneously on an equipment as shown in Figure 1.4, well known as a bath tub curve. In this curve, three conditions are clearly distinguished:

1) early failure or wear in (DFR);
2) random failure or constant failure rate (CFR); and
3) wear-out failure (IFR).

When comparing actual equipment failure patterns to the bath tub curve, most equipment follows a portion of the curve, but not the entire curve, it is our desire to operate machinery in the zones which consist of the ***infant mortality*** (wear in) and ***useful life*** (random failure) regions [6]. Some machine parts and systems are so well designed that they don't have infant mortality or wear in failures. The designer wants to have failure rate as small as possible in useful life region. However, in practice, machine parts and systems do age and start experiencing a variety of time-dependent damage process.

1.4.4.1 Interpretation of Bath Tub Curve in Terms of Weibull Shape Parameter β

In each region the failure rate, $\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}$, have its own β and η values.

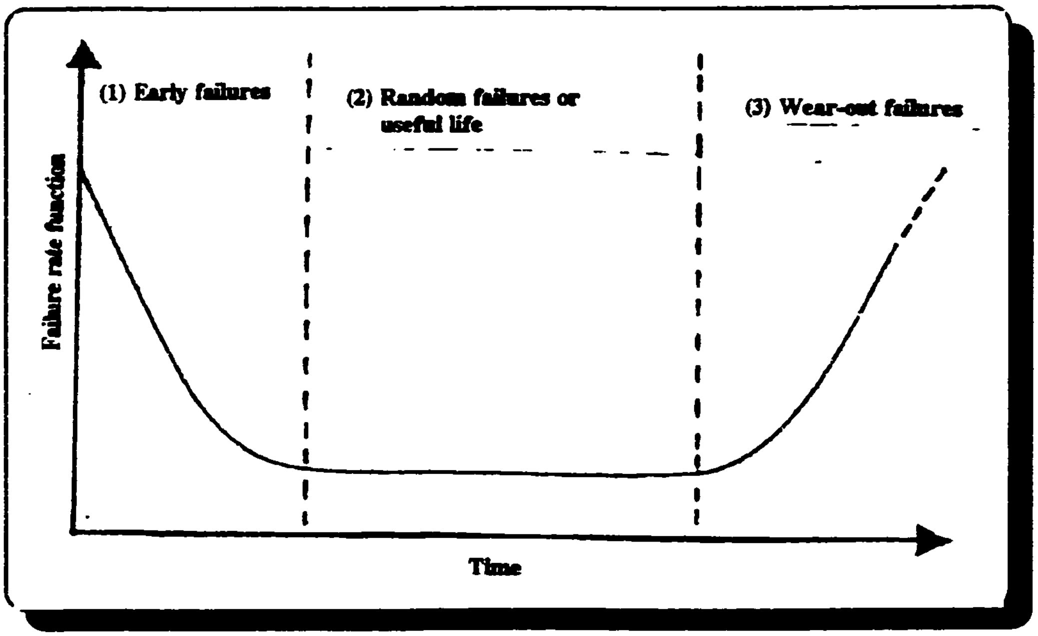


Figure 1.4. Mixed modes of failure leading to a Bath Tub curve.

■ Infant Mortality Region ($\beta < 1$)

This region describes the early time period of the system by showing a decreasing failure rate over time. It is usually assumed that this period of infant mortality is caused by the existence of material and manufacturing flaws together with assembly errors [11]. As time goes on, the failure rate decreases and reliability increases. Overhauling such a component is not appropriate as old parts are better than new [12].

■ Random Failure ($\beta = 1$)

The random failures are independent of time. This period is also termed "***useful life***." An old part is as good as a new one if its failure mode is random. It may be caused by maintenance error, human error, failures due to nature, or foreign object damage [6, 11, 12]. Parts failing in this region do not need any preventive maintenance rather they are candidate for corrective maintenance.

■ Wear-out Failure Region ($\beta > 1$)

This region is characterized by an increasing of failure rate with time. The failure in this region is due to aging effect and old parts are worse than the new ones. The failures tend to be dominated by cumulative time-dependent process, such as corrosion, fatigue cracking, and diffusion of materials. This region is the area of focus in preventive maintenance.

1.5 Maintainability

The maintainability measure $M(t)$ is used to predict the probability that a non-performing unit will be restored to a satisfactory level of performance within a given time frame (0 to t).

We can establish maintainability relationships using the same logic and mathematics that we use for the reliability development. Let $m(t)$ represent the pdf associated with component restoration time. From our definition of maintainability, we have

$$M(t) = \int_0^t m(t)dt \tag{1.20}$$

where $M(0)=0$ and $\lim_{t\to\infty} M(t) = 1$.

If $\upsilon(t)$ represents an instantaneous repair rate [the maintainability counterpart of $\lambda(t)$, the instantaneous failure rate], we have

$$M(t) = 1 - \exp\left[-\int_0^t \upsilon(t)\,dt\right] \qquad t \geq 0 \tag{1.21}$$

where $\upsilon(t) \geq 0$ and $\int_0^t \upsilon(t)dt \rightarrow \infty$ as $t \rightarrow \infty$.

We can also show that

$$\upsilon(t) = \frac{m(t)}{1 - M(t)} \tag{1.22}$$

If MTTR denotes the expected value of the time to repair a system, then

$$MTTR = E[T_{pm}] = \int_0^{\infty} t\, m(t)dt \tag{1.23}$$

We interpret the instantaneous maintainability repair rates (IRR, CRR and DRR) in the same manner as we interpret their failure counterparts.

Thus, if we want to develop a repair time quantile t_{mp}, where $0<p<1$, then t_{mp} must satisfy the following relationship:

$$M(t_{mp}) = p = \int_0^{t_{mp}} m(t)dt \tag{1.24}$$

The t_{mp} value is the direct counterpart to t_p in failure-reliability models. The major distinction is that maintainability focuses on transforming a "*down*" system to an "*up*" state, while reliability focuses on an "*up*" system state transforming to a "*down*" or failure state.

1.6 Machinery Maintenance Strategies

Machinery maintenance strategies can be classified into three types. They are corrective (breakdown maintenance), predictive maintenance using on-line monitoring and preventive maintenance.

1.6.1 Corrective Maintenance

It is applying the necessary repairs for equipment when they are failed because of variety of technical problems like corrosion, erosion, fracture in one or some of its parts.

Even if the preventive maintenance is well organized, still there is a possibility of breakdown failure to happen for the rotating equipment. For this reason, the failure should be repaired as soon as possible to avoid losing the production time.

1.6.2 Predictive Maintenance

It is based on the periodic inspection activities (or continuous inspection activities, i.e., condition monitoring) followed by replacement or overhaul if incipient defects are detected. Predictive maintenance addresses the randomly and suddenly occurring failure modes as far as possible by searching for them and by effecting timely repairs. Predictive maintenance strategy should dictate a continuous search for defects.

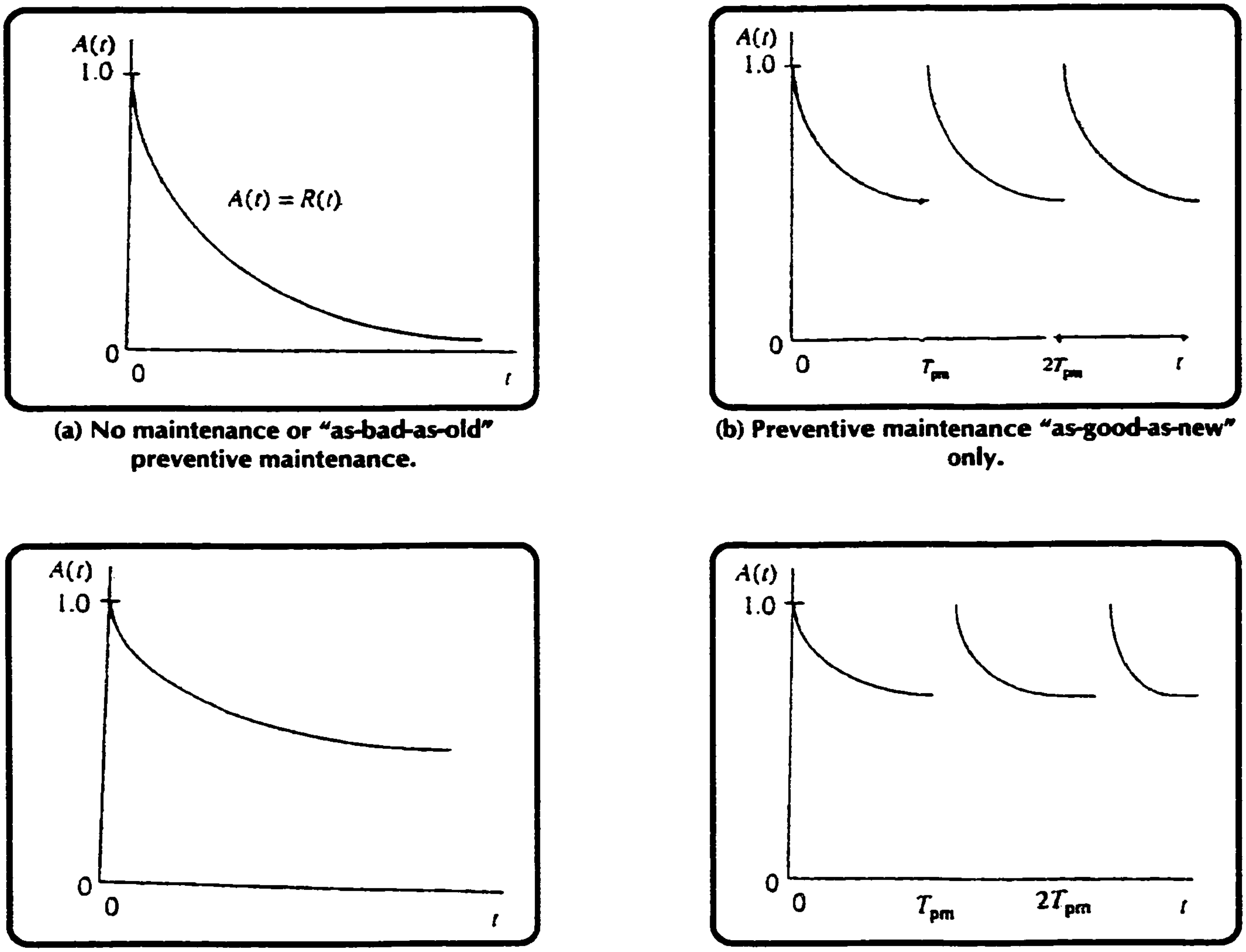
1.6.3 Preventive Maintenance

It is the periodic or the scheduled activities that are applied to an equipment to minimize the damaging effect of various modes of failures. In preventive maintenance, parts are replaced, lubricants changed or adjustments made before failure occurs. The objective of preventive maintenance is to increase the reliability of the system over the long-term by staving off the aging effects of wear.

1.7 Availability

Availability models are useful for studying both preventive and corrective maintenance strategies. They combine reliability and maintainability characteristics simultaneously. Availability, $A(t)$, is defined as the probability that a system, sub-system, or component is available for use at some given time, under given conditions of operation and restoration. In a special case for non-repairable units, where no restoration and corrective or preventive maintenance is possible, availability is identical to reliability [$A(t) \rightarrow 0$ as $t \rightarrow \infty$]. Whereas for repairable systems, the presence of restoration provisions leads to a cyclical or steady-state value where $A(t) \neq 0$ as $t \rightarrow \infty$. A variety of $A(t)$ curves are shown in Figure 1.5. We should note that at this point that the cyclical signatures of $A(t)$ is a result of the assumption or condition that a preventive or corrective maintenance act will always produce an operational system upon re-start (immediately after the maintenance act is completed).

The conceptual of $A(t)$ curves in Figure 1.5 illustrate the performance advantage that restoration provisions offer; we can see that the availability measure of performance clearly is enhanced by both preventive and corrective maintenance. By definition, availability measures a ratio of available state time to available and unavailable state time. Sometimes this ratio is expressed as up time to "*total*" time, where total time includes up time and downtime. Figure 1.6 shows a graphical representation of this relationship. The availability measure by itself is not capable of providing detailed information as to the duration of individual operation and restoration intervals.



(a) No maintenance or "as-bad-as-old" preventive maintenance.

(b) Preventive maintenance "as-good-as-new" only.

(c) Corrective (repair) maintenance only.

(d) Preventive maintenance "almost-as-good-as-new" and corrective (repair) maintenance.

Figure 1.5. Generic availability curves [36].

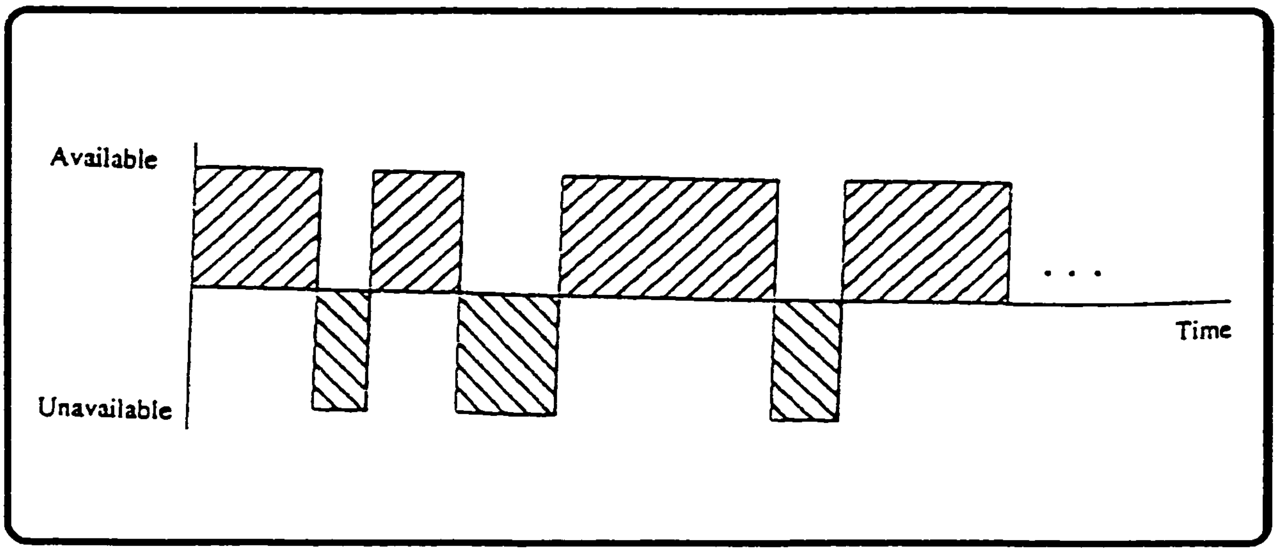


Figure 1.6. Empirical availability performance measure.

1.7.1 Availability with Corrective Maintenance

Figure 1.5(c) depicts a solely corrective maintenance, or repair, case. It is clear that $A(t)$ is initially falling with time and then approaches a steady-state value, which is dependent on the relative failure and repair characteristics. In this case, three primary measures of availability are of interest, according to Lewis [11]:

1. *point availability* as a function of time or usage, defined earlier, $A(t)$,
2. *steady-state availability*, $A(\infty)$, and
3. *average or internal availability*, $A^*(T_0)$. The $A^*(T_0)$ is defined in terms of instantaneous availability, $A(t)$ as

$$A(\infty) = A^*(\infty) = \lim_{t\to\infty} A(t) \tag{1.25}$$

$$A^*(T_o) = \frac{1}{T_o}\int_0^{T_o} A(t)\,dt \quad T_o = \text{mission time} \tag{1.26}$$

These three availability measures hold regardless of the form of the reliability model and corrective maintenance (repair) model. Most analytical treatments of repairable systems are based on exponential (constant hazard) failure-repair model. Various analytical approaches and solution methods have been advocated. We will not attempt to redevelop the detailed solutions which are readily available in Shoman [35], as well as in texts by Lewis [11], Kapur and Lamberson [36]. Here, we will restate availability measures for a single-component system. Cases involving non-exponential failure-repair models as well as multiple-component analyses can be analyzed through simulation techniques, discussed later.

1.7.2 Availability with Preventive Maintenance

In the case of "*as-good-as-new*," the preventive maintenance provided at some time interval T_{pm}, a system that will demonstrate the availability characteristics as shown in Figure 1.5(b). In this case, for the first cycle, $A(t)=R(t)$, $0 \le t \le T_{pm}$. Thereafter, we observe an identical periodical cycle of $A(t)$, beginning immediately after $t=T_{pm}$ and again at each of the following multiples of T_{pm} (provided preventive maintenance restores the system to as-good-as-new condition). The other restoration extreme, "*as-bad-as-old*," produces no change in the system; hence the original reliability curve [Figure 1.5(a)] applies. Here, we assume the maintenance is instantaneous and the system will not fail on re-start. From this comparison, we can see that as-bad-as-old preventive maintenance is pointless, as it requires resources but provides no improvement in $A(t)$:

$$A(t) = R(t) \qquad t \ge 0 \tag{1.26}$$

In the case of as-good-as-new preventive maintenance as in Figure 1.5(b), we see repeated availability cycles. We can calculate the cyclical availability using the reliability measure. For the first cycle and repeating cycles thereafter, $N=0, 1, 2, \ldots$:

$$A(t) = \exp\left[-\int_0^{(t-NT_{pm})} \lambda(t)\,dt\right] \qquad NT_{pm} \le t < (N+1)T_{pm} \tag{1.27}$$

Figure 1.7 shows a generic hazard curve, a corresponding reliability curve and the resulting availability curve for this case. We can observe that the hazard curve here is made up of identical hazard "*cycles*." Hence, we can use Equation (1.27) to model availability and develop a reliability expression:

$$R_m(t) = [R(T_{pm})]^N R(t-NT_{pm}), \qquad NT_{pm} \le t < (N+1)T_{pm} \tag{1.28}$$

Here N represents the number of preventive maintenance cycles we have completed as a function of time or usage, N=0, 1, 2, ...

The as-good-as-new case is of great interest because it can be directly related to a "*replacement*" analysis. For example, Figure 1.7 would correspond to system replacements at T_{pm}, $2T_{pm}$, and so on. Hence, we can use the previous equations to study replacement reliability-availability alternatives.

We can also model the situation where each preventive maintenance operation at T_{pm}, $2T_{pm}$, $3T_{pm}$, and so on, may be imperfect. Here, we assume that a chance p exists of encountering a preventive maintenance operation that is totally faulty (albeit unintentionally) (e.g., the maintenance results in a dead system). Under this assumption,

$$R_m(t) = [R(T_{pm})]^N (1-p)^N R(t-NT_{pm}), \qquad NT_{pm} \le t < (N+1)T_{pm} \tag{1.29}$$

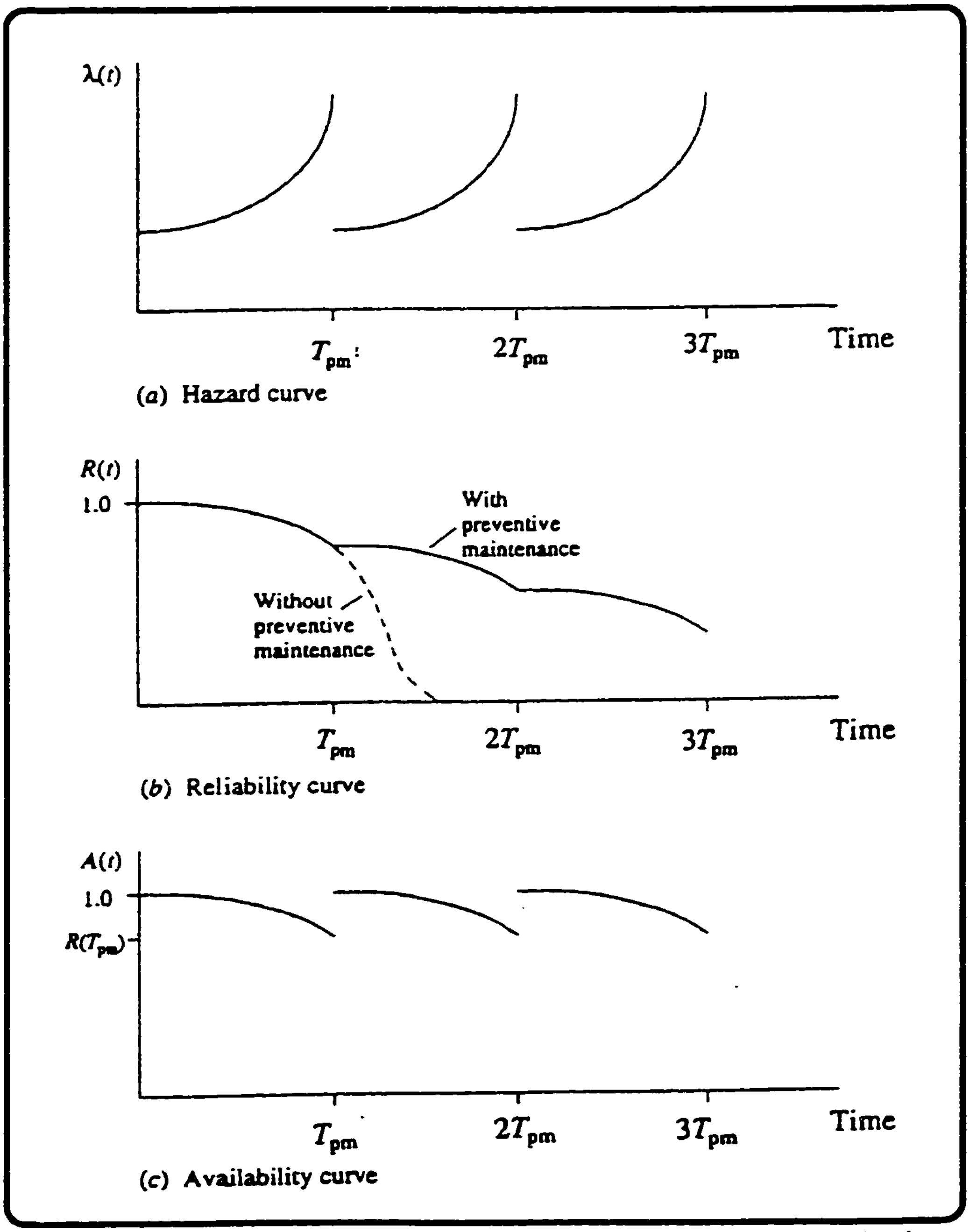


Figure 1.7. Generic hazard curve and corresponding reliability and availability curves [36].

When preventive maintenance produces a system somewhere between the as-good-as-new and as-bad-as-old cases [almost-as-good-as-new, see Figure 1.5(d)], a determination of the exact hazard curve characteristics from one preventive maintenance cycle to the next must be made. It is suggested that this relationship can be associated with the complexity of the system and the extent of the preventive maintenance operation. In any event, sound engineering judgement is required to establish this relationship. Again, we assume the maintenance is instantaneous and the system will not fail on re-start. Equations (1.27) and (1.28) can be modified and expressed as:

$$R_m(t) = \left[\prod_{i=1}^{N+1} R(T_{pm}) \right] R_{N+1}(t - NT_{pm}) \tag{1.30}$$

where $NT_{pm} \leq t < (N+1)T_{pm}$, $R_0(T_{pm}) = 0$, $N = 0, 1, 2, \ldots.$

Accordingly, the $A(t)$ cycle must correspond to a sequence of hazard curves. The result is a series of unique $A(t)$ segments where

$$A(t) = \exp\left[- \int_0^{(t-NT_{pm})} \lambda_{N+1}(t) d(t) \right] \qquad NT_{pm} \leq t \leq (N+1)T_{pm} \tag{1.31}$$

1.8 Proposed Work

1.8.1 Motivation

In Ras Tanura Refinery (Saudi Aramco), there are several types of rotating equipment, namely pumps, turbines, gas turbines, fans, etc. These rotating equipment are very critical to the operation of the plants. They should work perfectly all the time. When these equipment fail, there will be significant monetary losses due to stoppage of the production and also due to repair or replacement costs. Therefore, appropriate backup or redundant systems are provided to take care of such eventualities.

In this case, the Weibull analysis seems to be very beneficial to predict the equipment time to failure, and other reliability characteristics, as well as to design appropriate maintenance strategy. When operator knows the number of failures expected to occur in future period of time by using mean time between failure of such rotating equipment, they can apply the right decision in advance to avoid any operational upset. With the use of Weibull analysis it is expected to enhance the production activities of Ras Tanura Refinery operation, and will facilitate in reducing the cost of operation.

1.8.1.1 Rotating Equipment to be Investigated

Various equipment have good failure history records in Saudi Aramco system and is available in computerized form for past several years. The following are some rotating equipment whose history will be utilized in this project. These are essentially repairable systems, some of which also have a number of non-repairable parts, such as bearing, mechanical seal, etc.

The three types of rotating equipment (pumps, turbines and motors) are chosen for investigation because they are very common rotating components in every system in Saudi Aramco.

1. PUMPS

The common types of pumps that are used in Saudi Aramco plants are centrifugal pump. These pumps use centrifugal action to convert mechanical energy into pressure in a flowing liquid. The main components of the pump that will be studied in this project are impellers, shafts, seals and bearings as shown in Figure 1.8.

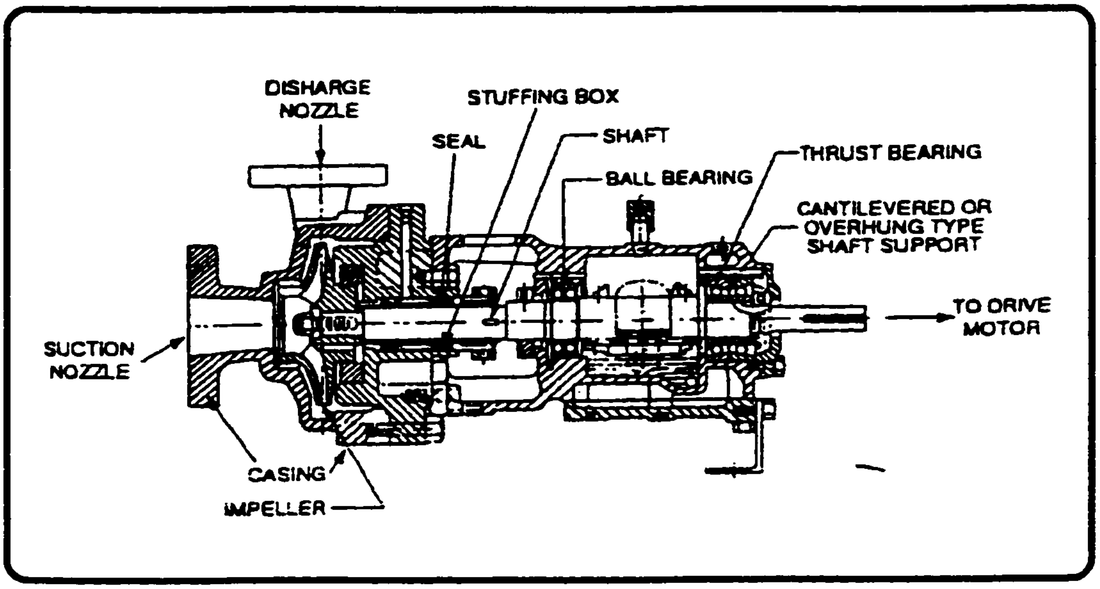


Figure 1.8. Main components of a pump [45].

An important aspect of the impeller is the wear rings. If the impeller is too close to the stationary element, the impeller or the casing will be worn out. The other part is the shaft. It runs through the center of the pump and is connected to the impeller at the left end. Seal(s) is/are very important part(s) in the pump. They are required in the casing area where the liquid under pressure enters the casing. The last main part of the pump is the bearing. The pump housing contains two sets of bearings that support the weight of the shaft.

2. STEAM TURBINES

Steam turbines are the prime movers that are utilized by Saudi Aramco to drive electric generators, compressors and pumps. The steam turbine converts the heat energy in the steam to mechanical energy. The following are the main mechanical aspects of the steam turbine (rotor, bearing, seal, lube oil cooler, throttle valve and governor). The purpose of the rotor, bearings and seals are the same as in the pump. The throttle valve is used to allow the required amount of steam to enter the machine and it is controlled by the governor. The other part is the lubrication oil cooler that is used to cool the oil that lubricate the bearing (see Figure 1.9.).

3. ELECTRIC MOTORS

The electric motor is the prime mover that is used to drive rotating equipment. The main mechanical parts of the motor are bearings, shaft and stator (see Figure 1.10). The proper mounting of a bearing to a shaft and machine frame is a critical factor in the performance of the unit. Bearing are sensitive to shaft deflections, misalignments, distortion and vibration. The shaft is the rotating part and used to transmit the rotation to the driven device by using a coupling.

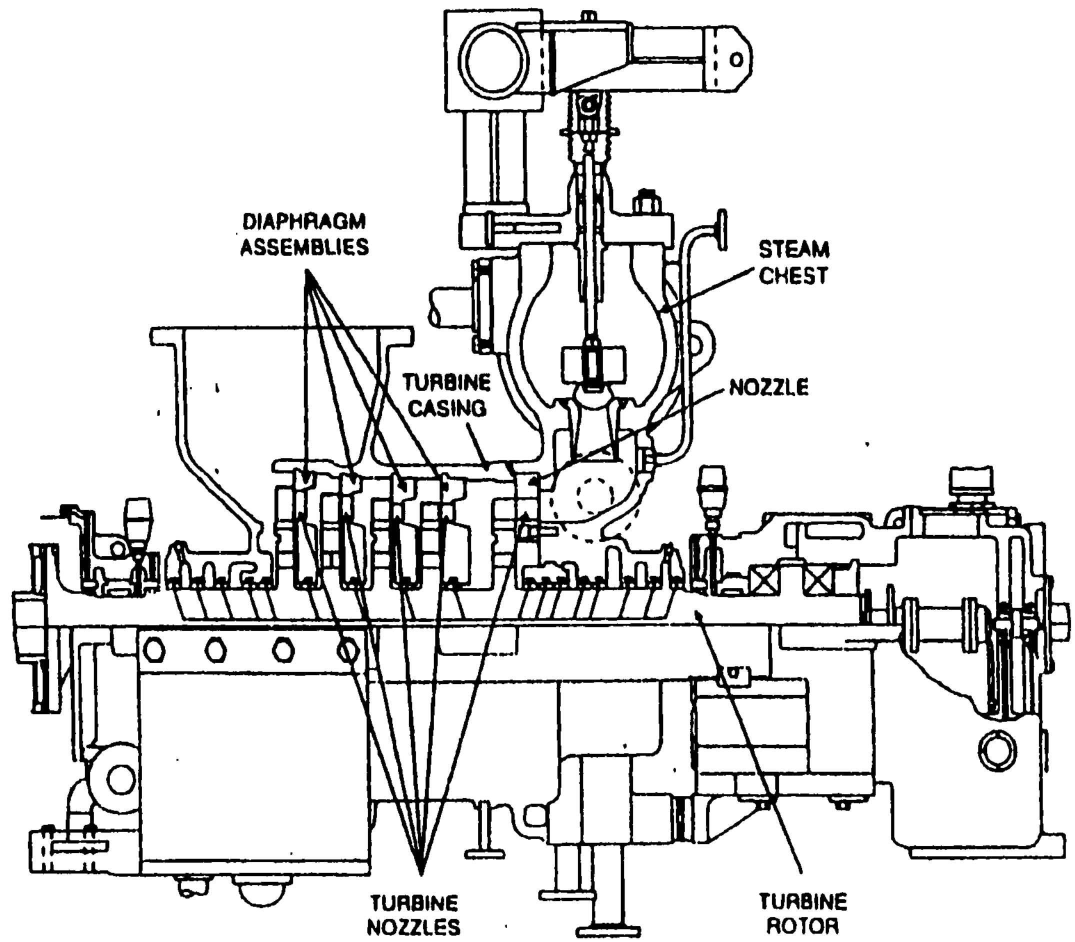


Figure 1.9. Main components of a steam turbine [45].

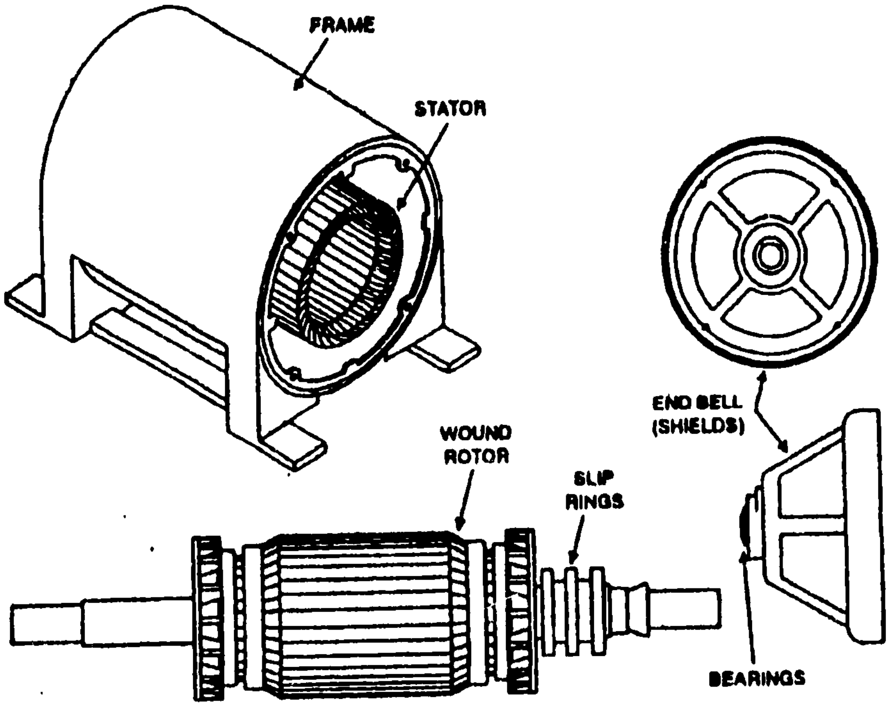


Figure 1.10. Main components of a electric motor [45].

1.8.1.2 Pareto Analysis

Pareto diagrams are important tools in the quality improvement process. Named after the Italian economist Alfredo Pareto, Pareto diagrams were first applied to the area of quality control. Like Pareto, who found that the distribution of wealth was concentrated in a few people, Juran realized that similar principle holds in other fields. For instance, in manufacturing or service, most problems are created by a few causes, even though there are many causes that may influence the occurrence of these problems. These categories of problems were identified as the ***vital few*** and the ***trivial many***, respectively.

The Pareto principle lends support to the 80/20 rule, which states that 80 percent of the problem (non-conformities or defects) are created by 20 percent of the causes. Pareto diagrams help management quickly identify the critical areas (those causing most of the problems) which deserve immediate attention. They identify the important problems, the resolution of which will lead to substantial improvements in quality. They provide guidance in the allocation of limited resources to problem-solving activities. Through the use of Pareto diagrams, problems ;may be arranged in order of importance. "***Importance***" may refer to the financial impact of a problem (which is usually most appropriate) or the relative number of occurrences of the problem.

The steps for constructing a Pareto diagram are as follows:

Step 1: Decide on the means of classifying the data, say by problem causes, type of non-conformity (critical, major, minor), or whatever else seems appropriate.

Step 2: Determine how relative importance is to be judged, that is, whether it should be based on associated dollar values or the frequency of occurrence.

Step 3: Rank the categories from most important to least important.

Step 4: Compute the cumulative frequency of the data categories in their chosen order.

Step 5: Plot a bar graph, showing the relative importance of each problem area in descending order. Identify the vital few that deserve immediate attention.

1.8.1.3 Failure History of Some Rotating Equipment for Five Years (1995-2000)

Failure history of the rotating equipment in Saudi Aramco include valuable information about the repairing cost, number of failures and failure modes. The parts which fail more than three times in five years are defined as ***bad actors***. The Pareto analysis will be utilized for such rotating equipment and sort them based on their repairing cost and mode of failure. Such Pareto analysis of various groups of bad actors equipment will further identify the most critical bad actors, i.e., most frequently failing equipment or parts. Such "***most critical bad actors***" need a careful further analysis for system improvement. To improve the equipment availability, we need to study the history of these equipment and their MTBF (or MTTF) and MTTR. Weibull reliability and maintainability analysis in this case is very helpful. From Weibull reliability analysis, the failure rate behavior can be modeled and the proper type of maintenance can be applied

1.8.2 Proposed Data Sources

The time to failure (or malfunction) data (t_1, t_2, ..., t_n) and time to repair data (t_{m1}, t_{m2}, ..., t_{mn}) for a set of rotating equipment that is stored in Saudi Aramco computer maintenance system will be utilized in this project through Weibull reliability, maintainability and availability analysis. This computerized maintenance management and equipment record systems are common place in many petrochemical plants. The data will be derived also from Saudi Aramco on-line monitoring of process variables data retrieved from Distributed Control System (DCS).

In Saudi Aramco, the computerized maintenance management system is used to store the history of any repair that was applied to any equipment. When an equipment fails, directly a work order will be opened describing the necessary work to be done and the time of opening and closing the work order. However, it is not that simple and direct to find from the computer system the time to failure data and time to repair data for an equipment and apply Weibull analysis, because we have to convert the failure data and repair time from the computer system by tracking each work to the format that we want and this can consume a lot of efforts and time.

1.8.3 Scatter Diagrams for Checking the Underlying Trend in Data

A scatter diagram is a useful device for visually evaluating how two or more variables are related to each other. Sometimes, two variables may not be related to each other, in which case, the measure of association would be small, indicating a non-existent or weak relationship. If there is no general trend that can established from the scatter plots, then the statistical models, such as Weibull distribution can be used to analyze the time between the events of failure and time between repairs. To verify that the the time between the failures and similarly the time between repair do not have an embedded trend, it is necessary to plot the increment of time (time between failure) versus the number of failures in the order they occur.

1.8.4 Validating the Weibull Model (Regression Analysis)

The time to failure (or malfunction) data for items described in Chapter 2 will be used to fit a straight line by regression to the transformation Y and X, where

$$Y = \ln\left[\ln\left(\frac{1}{1 - F(t_i)}\right)\right] \tag{1.31}$$

and

$$X = \ln(t_i),\tag{1.32}$$

where

$$F(t_i) = \frac{i}{N+1}.\tag{1.33}$$

The parameter β is the slope of the line fitted and η is calculated in terms of the slope and the X-intercept of the fitted line. By using these parameters mathematical models for $F(t)$, $R(t)$, and $\lambda(t)$ will be characterized. Similarly, time to repair data will be analyzed to determine $M(t)$, $m(t)$ and $v(t)$.

1.8.5 Developing the Relevant Reliability and Maintainability Indicators

Using these reliability models, various indicators of the rotating equipment reliability, such as mean, variance, median, coefficient of variation, and various percentiles (quantiles) will be determined. This will provide an initial data bank of rotating equipment reliability indications. On similar lines, various maintainability indicators will also be developed.

1.8.6 Utilization of Weibull Analysis in Maintenance Strategies

Based on the Weibull distribution of the failure data of the rotating equipment, the proper maintenance strategy that should be applied to these equipment will be established. Beside the type of maintenance that should be applied (preventive, predictive, or breakdown), the replacement strategies for some non-repairable items and forecasting of the future needs (spare provisioning) and its relative cost will be discussed in this project. To evaluate maintenance strategies certain cost elements need to be determined representing the system under discussion. Such cost will be assessed from Saudi Aramco documentation on costs.

Chapter 2

Failure Modes and Weibull Reliability Analysis

2.1 INTRODUCTION

In this chapter, equipment failure history of some of the equipment at Refinery plants obtained from a computerized Maintenance Management System has been utilized to perform Weibull analysis. The Weibull reliability analysis has been used to provide an indication of the equipment failure modes and to assess the equipment reliability. Such an analysis can help to make the right decision for equipment replacement and a proper selection of equipment maintenance strategy. Analysis results would identify most critical bad actors equipment with highest rate of failure and repairing cost.

The study includes different types of rotating equipment in the Refinery plants. These types of rotating equipment are pumps, turbines and motors. All these equipments are repairable systems. Every action after observing a failure is of corrective nature (corrective maintenance situation). Some parts in these system need replacement rather than repair. The steps of this study are as follows:

1. The equipment that have more than three frequent failures in five years (bad actors) are listed.
2. Pareto analysis is used to identify the most critical bad actors equipment depending on the number of failures and the repairing cost.
3. Percentage of the failure mode of each type of equipment is determined.
4. The most frequent failure mode for the most critical bad actors are highlighted.

5. The reliability parameters from the Weibull analysis are calculated.
6. The reliability curve of some of the most critical bad actor equipment is developed.
7. Repairing costs for the repairable parts and replacement cost for non-repairable parts of the most critical bad actor equipments are analyzed.

2.2 Pumps

In the Maintenance Management System, the time, type of failure and repairing cost of each pump is stored. The data period of our investigation is limited to five years, from January 1995 to January 2000. There are about 300 pumps operating in the plant. Out of these, 44 are those whose history was reviewed. These forty-four (44) pumps as shown in Table 2.1 were determined to be the bad actor (have experienced ≥3 failures) in five years.

2.2.1 Pareto Analysis

The Pareto analysis [44] will be used to identify the most critical bad actors pumps out of these 44 pumps as given in Table 2.1. This group of most critical pumps are the primary target for investigation and reliability improvement. Such Pareto analysis will help to identify the severity of bad actors in the refinery plants.

Table 2.1. Bad Actors Pumps Selected.

Equipment #	*Code #*	*Description*	*No. of Failures in 5 years*	*Total Cost of Failures in US $*
P1	30-2-GGFP11	Glycol Pump B	3	49,000
P2	30-2-G1SEP	Centrifugal Lube Oil Separator	4	33,986
P3	30-2-G58	Salt Water Pump	9	233,429
P4	30-2-G57	Salt Water Pump	4	103,839
P5	30-2-G17	Salt Water Booster Pump	5	49,807
P6	30-2-G13	Salt Water Pump	5	37,259
P7	30-1-G203	Feed Water Pump	6	148,793
P8	30-1-G202	Feed Water Pump	4	146,529
P9	30-1-G214A	Oily Water Pump	4	47,170
P10	30-1-G213B	Oily Water Pump	3	56,435
P11	30-1-G74A	Cooling Water Pump	5	12,615
P12	30-1-G91B	Feed Water Pump	5	109,157
P13	32-1-G92B	Cooling Water Pump	4	18,505
P14	32-1-G112B	Feed Water Pump	4	30,348
P15	32-1-G127A	Super-heater Pump	8	100,849
P16	32-1-G112A	Feed Water Pump	5	75,439
P17	34-1-G866	Booster Pump	4	75,780
P18	34-1-G866A	Booster Pump	7	84,481
P19	34-1-G664	Distillate Pump	6	92,735
P20	34-1-G664B	Distillate Pump	4	29,568
P21	34-1-G55A	Condensate Pump	5	28,465
P22	34-1-G53	Brine Recycle Pump	5	113,789
P23	34-1-G53A	Brine Recycle Pump	4	122,299
P24	34-1-G56	Booster Pump	7	73,060

cont ... Table 2.1. Bad Actors Pumps Selected.

Equipment #	***Code #***	***Description***	***No. of Failures in 5 years***	***Total Cost of failures in US $***
P25	34-1-G863	Brine Recycle Pump	4	40,581
P26	34-1-G664A	Distillate Pump	7	56,327
P27	34-1-G866A	Booster Pump	4	43,935
P28	34-1-G767	Anti-Foam Injection Pump	4	11,982
P29	34-1-G764A	Distillate Pump	6	111,722
P30	34-1-G766	Booster Pump	4	71,462
P31	34-1-G983C	Booster Pump	3	52,226
P32	34-1-G980B	Sump Pump	7	105,965
P33	34-1-G980A	Sump pump	6	48,765
P34	34-1-G963A	Brine Recycle Pump	4	53,747
P35	34-1-G963B	Brine Recycle Pump	5	44,102
P36	34-1-G965	Condensate Pump	5	43,270
P37	34-1-G966	Brine Recycle Pump	5	74,400
P38	35-3-G102A	High Lift Pump	7	240,946
P39	35-3-G102B	High Lift Pump	7	459,617
P40	35-3-G103A	High Lift Pump	8	319,968
P41	35-3-G103B	High Lift Pump	7	488,269
P42	38-G103	Fire Water Pump	10	150,550
P43	38-G102	Fire water Pump	4	87,471
P44	38-G11	Fire Water Pump	4	115,519

Figures 2.1, and 2.2, are the Pareto charts based on number of failures and repairing costs. These figures identify the most critical bad actors pumps based on our criteria of the percentage of repairing cost and number of failures of each pump. Our criteria for both charts (repairing cost chart and number of failures chart) is determined to be 50%, this means, the pumps that have less than 50% of repairing cost and number of failures should be included. In some cases, there are some pumps which have low number of failures, but have high repairing costs and vice versa, therefore, they were also included.

In the number of failure chart based on 50% criteria, we choose 16 pumps and for repairing cost chart we choose also 8 pumps, we found 10 pumps are common in both charts and we choose 7 pumps from each chart based on the severity of either number of failures or repairing costs. These 17 pumps are chosen to be the most critical bad actors and listed in Table 2.2, they will be referred to as "***the most critical bad actors pumps***." The Weibull reliability analysis will be performed on these pumps by using their time between failure data.

2.2.2 Determining Failure Modes

The analysis started by determining the failure modes and the time to failure of each pump as shown in Table 2.3. Figure 2.3 through Figure 2.18 shows the Pie diagrams of the most critical pumps for different modes of failures. Figure 2.19 shows the various

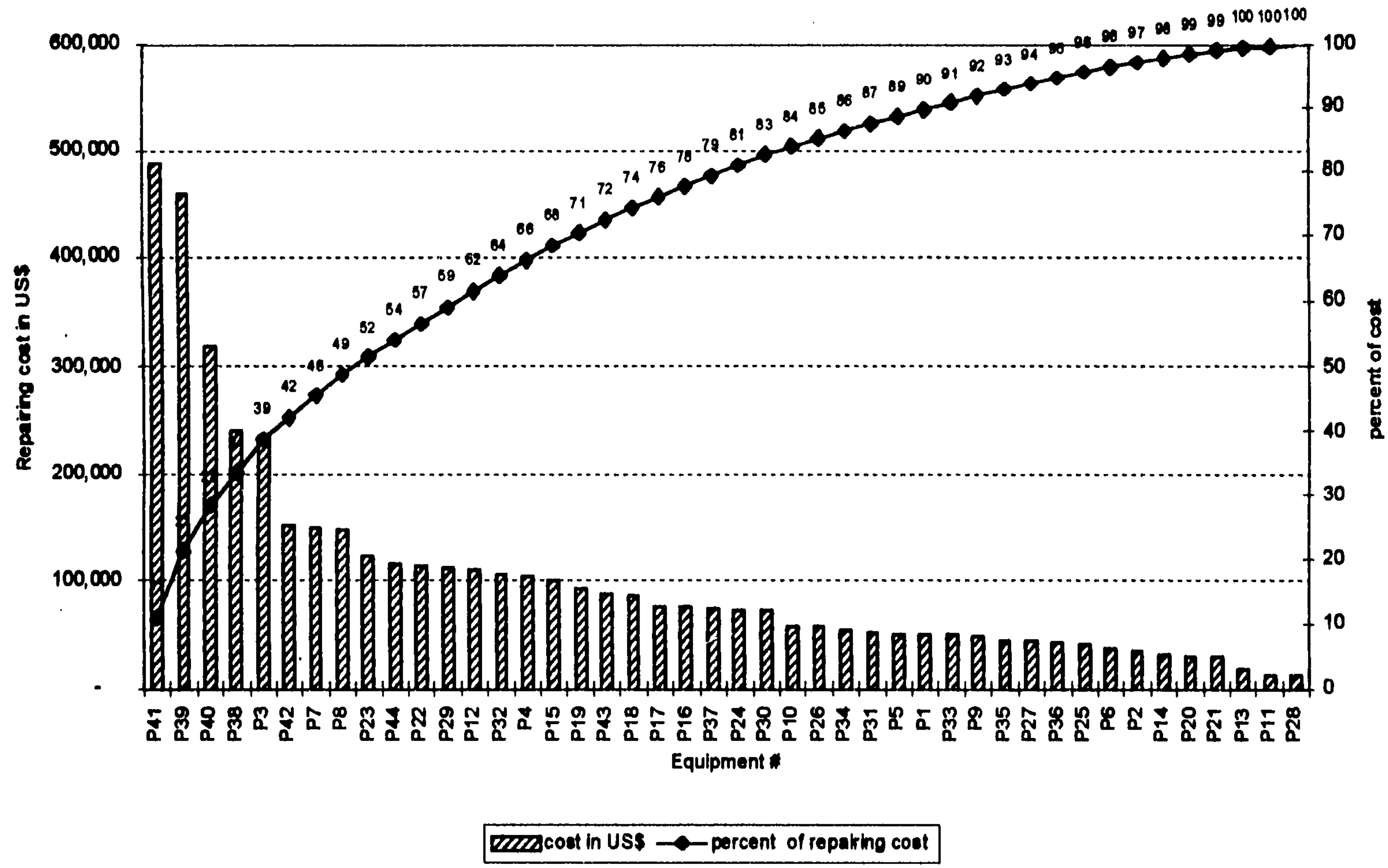


Figure 2.1. Most critical bad actor pumps identified by sorting the bad actor pumps by their repairing cost (Pareto analysis).

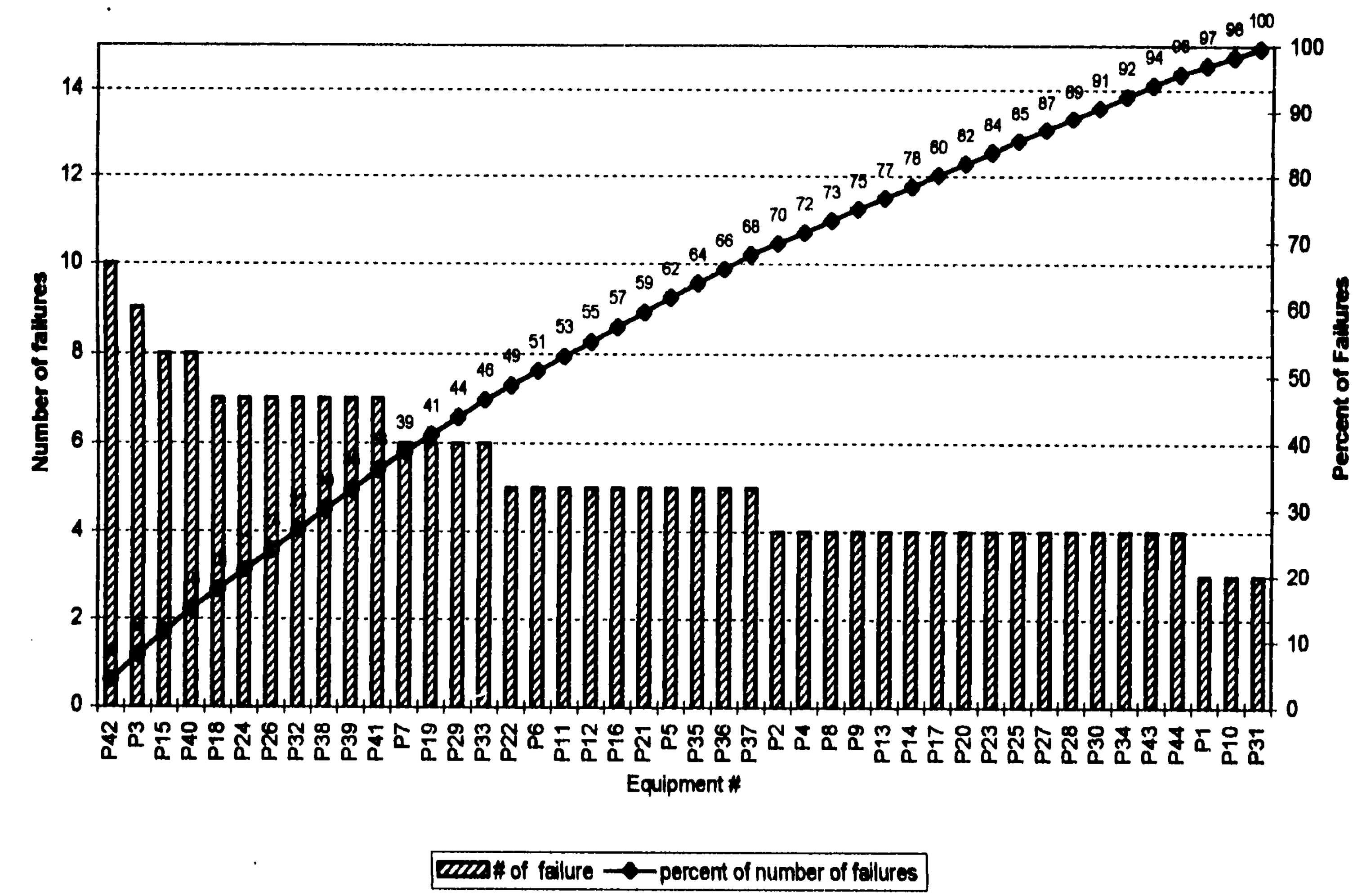


Figure 2.2. Most critical bad actor pumps identified by sorting the bad actor pumps by their number of failures (Pareto analysis).

Table 2.2. Most Critical Pumps among the Bad Actor Pumps.

Equipment #	***Code #***	***Description***	***No. of Failures in 5 years***	***Cost in US $***
P41	35-3-G103B	High Lift Pump	7	488,269
P39	35-3-G102B	High Lift Pump	7	459,617
P40	35-3-G103A	High Lift Pump	8	319,968
P38	35-3-G102A	High Lift Pump	7	240,946
P3	30-2-G58	Salt Water Pump	9	233,429
P42	38-1-G103	Fire Water Pump	10	150,550
P7	30-1-G203	Feed Water Pump	6	148,793
P22	34-1-G53	Brine Recycle Pump	5	113,789
P29	34-1-G764A	Distillate Pump	6	111,722
P8	30-1-G202	Feed Water Pump	4	146,529
P32	34-1-G980B	Sump Pump	7	105,965
P15	32-1-G127A	Super-Heater Pump	8	100,849
P19	34-1-G664	Distillate Pump	6	92,735
P33	34-1-G980A	Sump Pump	6	48,765
P24	34-1-G56	Booster Pump	7	73,060
P26	34-1-G664A	Distillate Pump	7	56,327
P18	34-1-G866A	Booster Pump	7	84,481

modes of failures for all 17 most critical pumps, the highest number of failures are attributed to the failure of pump seals followed by downtime due to overhaul, malfunction of impeller, and their failures. Seals and bearings are essentially non-repairable items and will also be discussed separately. The figure also shows the other types of failures, such as failures of bearings, impellers, shaft, couplings, etc. At this step, all modes of failure for the most frequently failed pumps were determined and sorted by the number of failures associated with their failure modes.

It is found that more than 80% of pump failure is because of seals, overhaul, impellers and bearings. The mechanical seal of pumps have the highest failure mode, which is 36% of the total number of failures (111). The other highest type of failure is the malfunction (23%) due to unknown reasons, so it needs overhaul, this means that the pump should be sent to the Machine Shop for inspection and replacing the defective parts. The other highest of failure modes are due to the impellers (11.7%) and due to bearings (9%).

There are 12 different failure modes for the most critical bad actors pumps. The following is the definition adopted to characterize the various modes of failure:

- ***Mechanical Seal*** .... The pump failed due to a malfunction of the pump's mechanical seal.
- ***Overhaul*** .... The pump failed due to unknown reason. Therefore, it will be sent for overhaul which include inspection and repairing of different parts.

- ***Impeller*** . . . . The pump failed because of its impeller failed due to either corrosion, erosion or cracks.
- ***Bearing*** . . . . The pump failed because of bearing failure.
- ***Shaft*** . . . . The pump failed to operate because of shaft problem, such as misalignment, vibration, etc.
- ***Suction Valve*** . . . . . . A failure due to some thing wrong with the pump suction, such as problems in valve, corroded pipes or slug accumulated in the suction.
- ***Casing*** . . . . A failure due to defective casing, such as misalignment or corrosion.
- ***Operation Upset*** . . . . Failure of a pump due to operational mistakes, such as closing a valve which should not be closed.
- ***Coupling*** . . . . A failure due to coupling distortion or misalignment.
- ***Gaskets*** . . . . A failure due to a gasket rupture or damage caused by leaks.
- ***Control Valve*** . . . . . . A failure due to malfunction of the control valve due to pressure or flow in the line of service.

Table 2.3. Most Critical Pumps among the Bad Actor Pumps: Failure Modes, Time-to-Failure, Time-to-Repair, and Repair Cost.

Equipment #	***Code #***	***Time to Failure*** (Months)	***Failure Mode: Reasons***	***Time to Repair*** (days)	***Repairing Cost in US $***
P41	35-3-G103B	14	Replacing mechanical seal	193	9,183
		28	Replacing mechanical seal	407	22,474
		35	Replacing mechanical seal	116	15,235
		36	Repairing impeller	7	41,348
		39	Repairing impeller	132	24,825
		58	Repairing impeller	227	154,177
		65	Overhaul	68	15,576
P39	35-3-G102B	14	Replacing mechanical seal	248	9,474
		38	Repairing impeller	69	5,861
		42	Overhaul	368	6,793
		47	Repairing impeller	45	12,184
		53	Replacing impeller	80	154,177
		55	Overhaul	65	39,402
		61	Overhaul	71	14,259
P40	35-3-G103A	12	Replacing mechanical seal	122	12,498
		14	Replacing mechanical seal	403	9,835
		18	Replacing mechanical seal	127	15,535
		21	Replacing mechanical seal	250	1,018
		29	Replacing mechanical seal	15	19,753
		34	Replacing mechanical seal	93	11,130
		36	Replacing impeller	72	156,778
		42	Overhaul	205	26,581
P38	35-3-G102A	12	Replacing mechanical seal	426	838
		14	Replacing mechanical seal	404	10,566
		32	Repairing discharge nozzle	146	1,980
		35	Repairing impeller	131	17,372
		41	Repairing impeller	46	7,551
		50	Replacing impeller	69	156,778
		52	Overhaul	14	8,067

cont ... Table 2.3

Equipment #	***Code #***	***Time to Failure*** (Months)	***Failure Mode: Reasons***	***Time to Repair*** (days)	***Repairing Cost in US $***
P7	30-1-G203	8	Repairing control valve	131	5,129
		14	Bearing replacement	383	2,752
		29	Replacing mechanical seal	187	3,191
		38	Replacing mechanical seal	103	18,998
		41	Repairing suction leak	23	26,113
		48	Bearing replacement	173	1,893
P3	30-2-G58	10	Replacing mechanical seal	185	41,498
		18	Repairing shaft	140	14,159
		30	Repairing suction	437	11,053
		38	Repairing shaft	123	19,499
		44	Overhaul	122	26,362
		45	Repairing suction	191	17,728
		47	Overhaul	445	14,646
		53	Operation upset	242	6,832
		57	Operation upset	133	4,960
P42	38-1-G103	6	Repairing shaft	21	7,087
		17	Overhaul	25	3,278
		20	Overhaul	33	9,206
		24	Overhaul	23	5,650
		35	Bearing replacement	14	11,668
		40	Replacing gasket	31	10,284
		42	Repairing shaft	12	8,717
		47	Repairing impeller	17	21,880
		51	Overhaul	43	7,704
		52	Repairing shaft	52	8,434
P22	34-1-G53	30	Overhaul	328	5,410
		42	Replacing mechanical seal	34	54,111
		46	Replacing mechanical seal	116	26,385
		48	Replacing mechanical seal	354	3,800
		53	Replacing mechanical seal	30	11,134

cont ... Table 2.3

Equipment #	***Code #***	***Time to Failure*** (Months)	***Failure Mode: Reasons***	***Time to Repair*** (days)	***Repairing Cost in US $***
P29	34-1-G764A	7	Replacing mechanical seal	139	2,153
		9	Replacing mechanical seal	24	7,820
		31	Repairing coupling	184	3,983
		43	Replacing mechanical seal	202	18,122
		48	Repairing impeller	70	1,500
		55	Overhaul	47	1,211
P33	34-1-G980A	7	Replacing mechanical seal	75	5,848
		10	Bearing replacement	7	575
		17	Bearing replacement	19	932
		18	Repairing coupling	25	905
		40	Replacing mechanical seal	67	9,228
P32	34-1-G980B	10	Overhaul	104	14,262
		16	Overhaul	406	3,447
		23	Bearing replacement	38	5,979
		33	Overhaul	238	6,088
		43	Overhaul	37	4,230
		50	Overhaul	52	2,364
		53	Overhaul	125	17,535
P15	32-G127A	17	Bearing replacement	20	446
		24	Replacing mechanical seal	362	14,095
		35	Overhaul	86	5,057
		39	Repairing impeller	2	2,350
		43	Replacing mechanical seal	30	4,608
		46	Replacing mechanical seal	358	5,445
		51	Overhaul	123	1,305
		57	Replacing mechanical seal	35	3,672
P8	30-1-G202	11	Bearing replacement	25	19,448
		14	Replacing mechanical seal	180	1,256
		26	Casing leak	95	4,683
		56	Bearing repair	12	4,192

cont ... Table 2.3

Equipment #	***Code #***	***Time to Failure*** (Months)	***Failure Modes: Reasons***	***Time to Repair*** (days)	***Repairing Cost in US $***
P19	34-1-G664	11	Replacing mechanical seal	171	4,570
		17	Replacing mechanical seal	30	7,679
		19	Bearing replacing	154	1,250
		31	Overhaul	60	10,687
		39	Overhaul	77	2,410
		46	Casing repair	49	8,417
P18	34-1-G866A	13	Repairing suction valve	91	577
		15	Replacing mechanical seal	276	7,024
		17	Overhaul	120	3,564
		20	Replacing mechanical seal	56	9,240
		30	Overhaul	65	2,560
		33	Replacing mechanical seal	99	10,148
		46	Overhaul	34	13,570
P24	34-1-G56	3	Replacing mechanical seal	231	5,189
		12	Replacing mechanical seal	23	6,619
		23	Replacing mechanical seal	107	9,377
		37	Repairing suction valve	101	2,419
		41	Shaft repair	178	16,018
		43	Overhaul	54	3,949
		53	Bearing replacement	39	11,145
P26	34-1-G664A	5	Replacing mechanical seal	242	5,561
		9	Replacing mechanical seal	161	6,222
		13	Replacing mechanical seal	157	5,169
		18	Bearing replacement	30	2,405
		38	Replacing mechanical seal	84	4,477
		58	Casing repair	56	995
		61	Casing repair	30	1,561

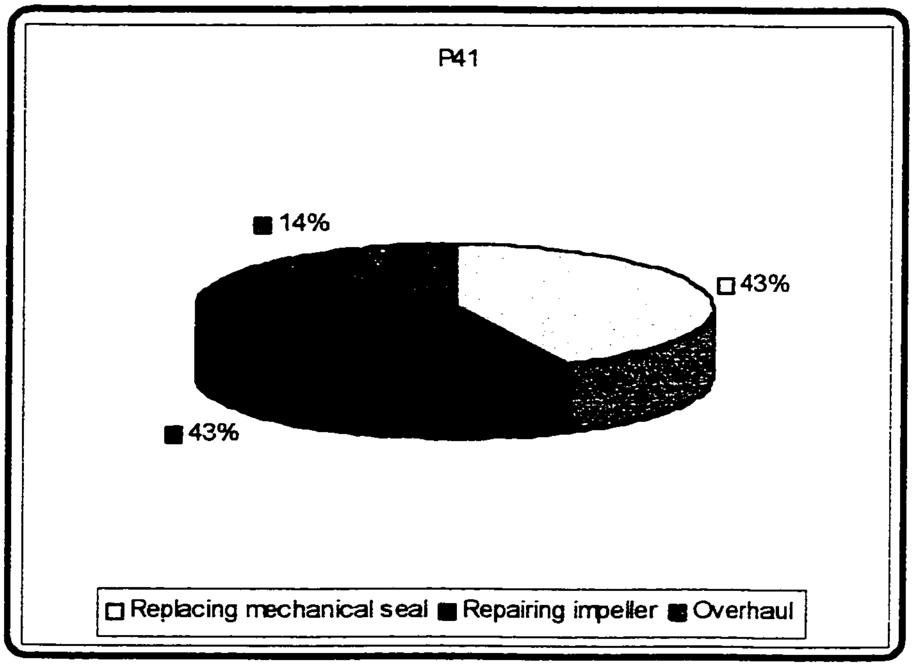


Figure 2.3. Modes of failure of most critical bad actor pump P41.

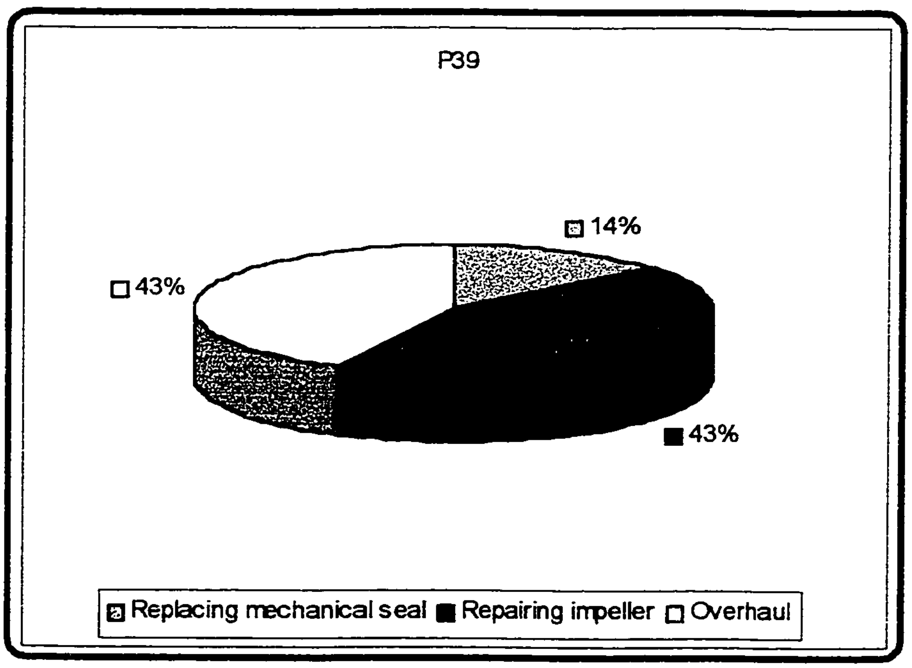


Figure 2.4. Modes of failure of most critical bad actor pump P39.

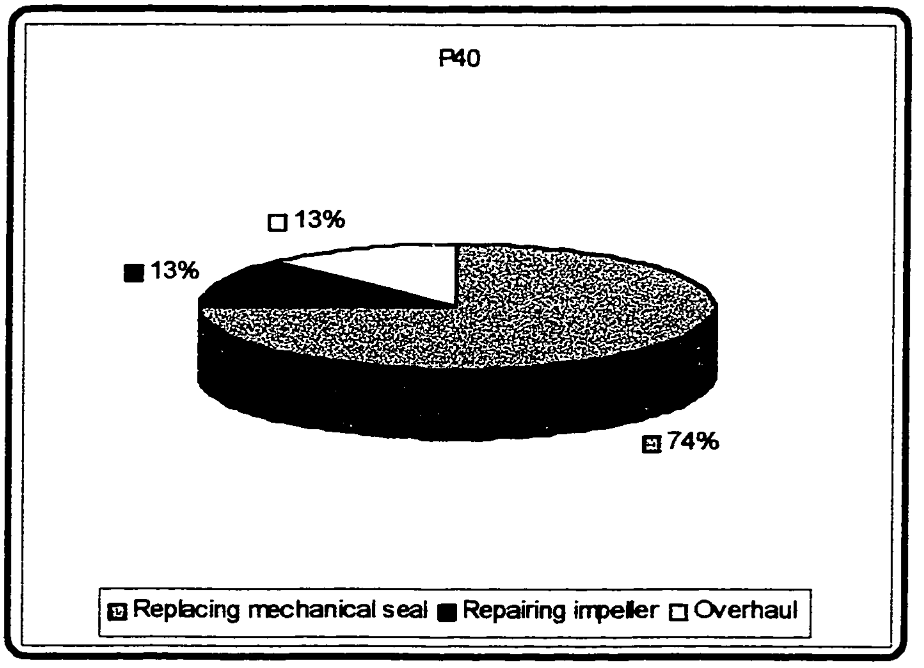


Figure 2.5. Modes of failure of most critical bad actor pump P40.

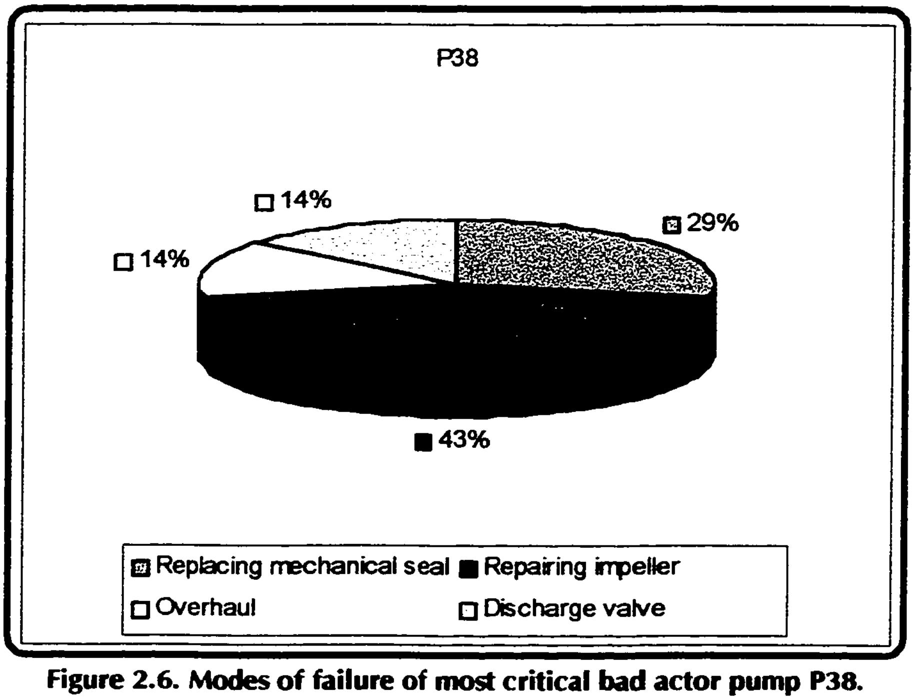


Figure 2.6. Modes of failure of most critical bad actor pump P38.

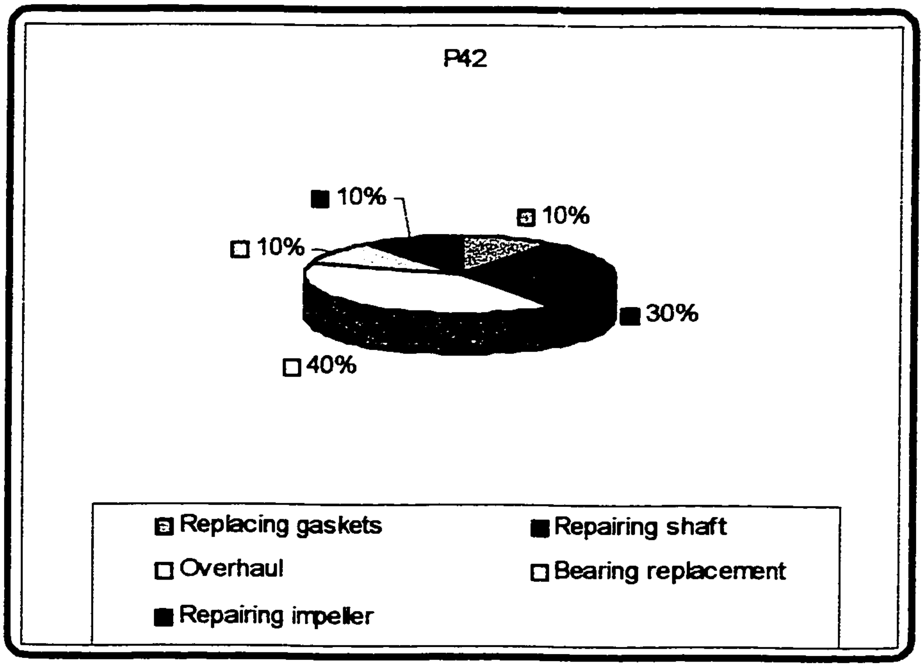


Figure 2.7. Modes of failure of most critical bad actor pump P42.

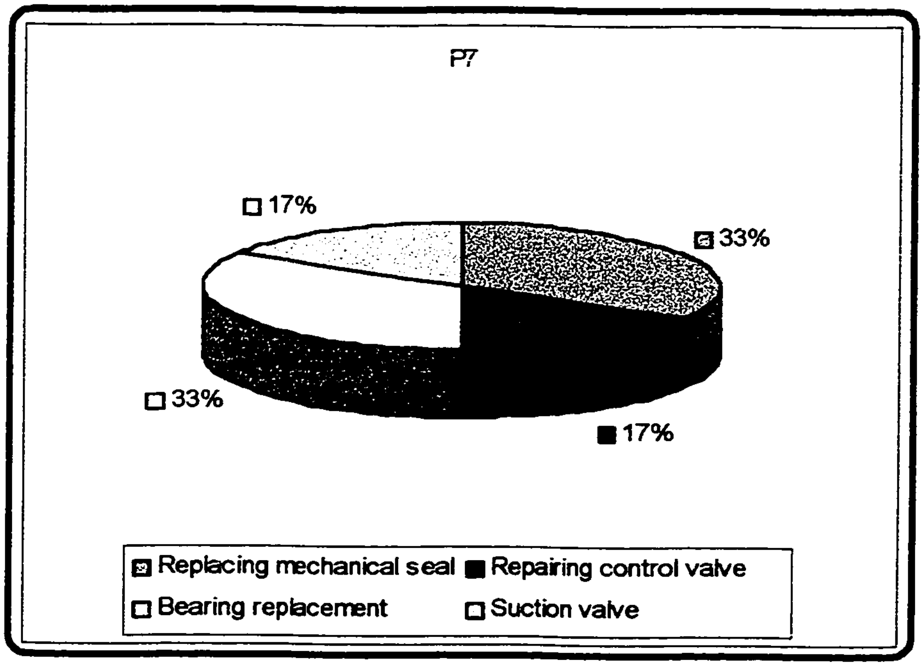


Figure 2.8. Modes of failure of most critical bad actor pump P7.

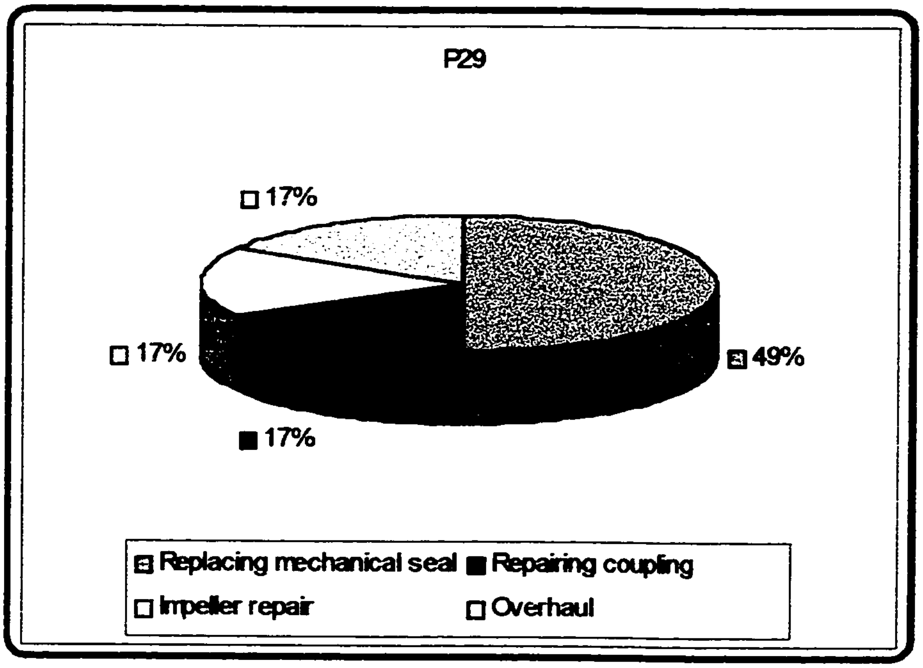


Figure 2.9. Modes of failure of most critical bad actor pump P29.

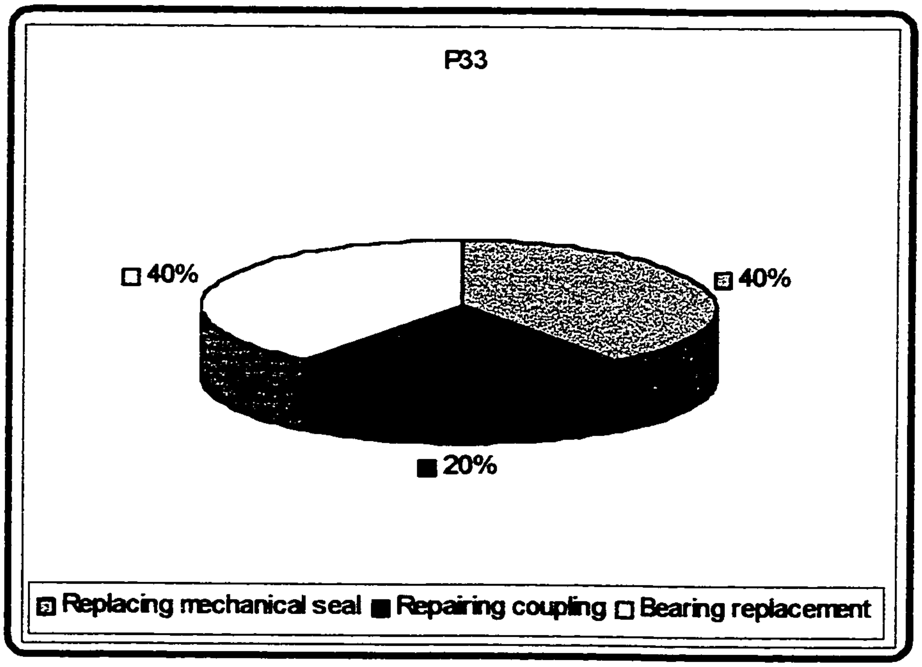


Figure 2.10. Modes of failure of most critical bad actor pump P33.

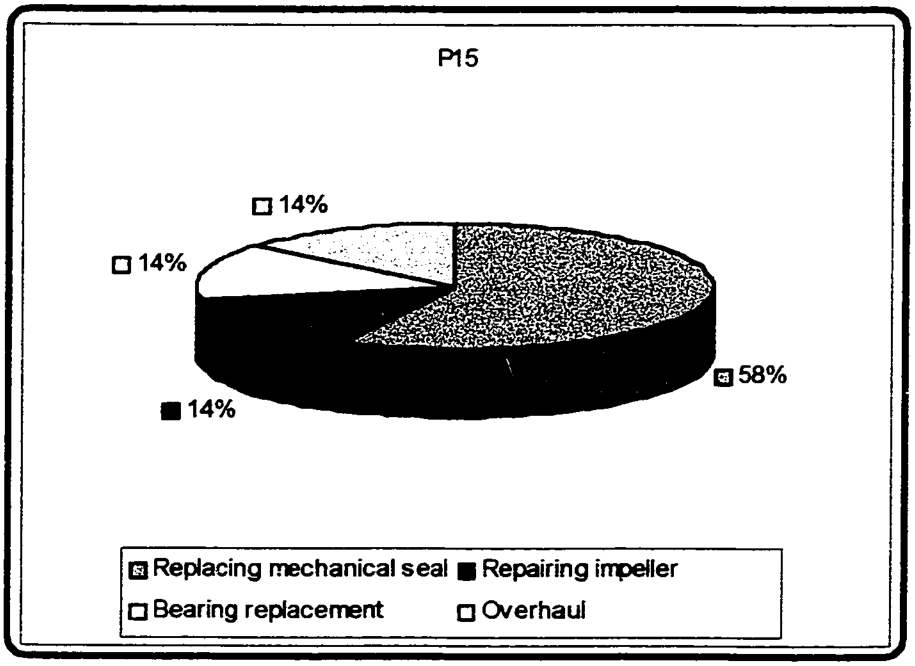


Figure 2.11. Modes of failure of most critical bad actor pump P15.

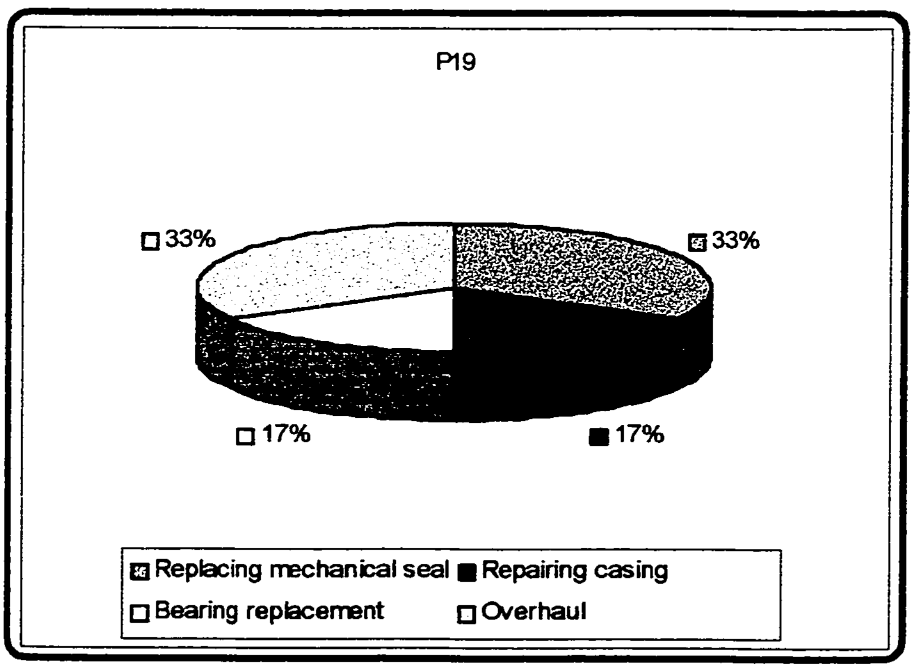


Figure 2.12. Modes of failure of most critical bad actor pump P19.

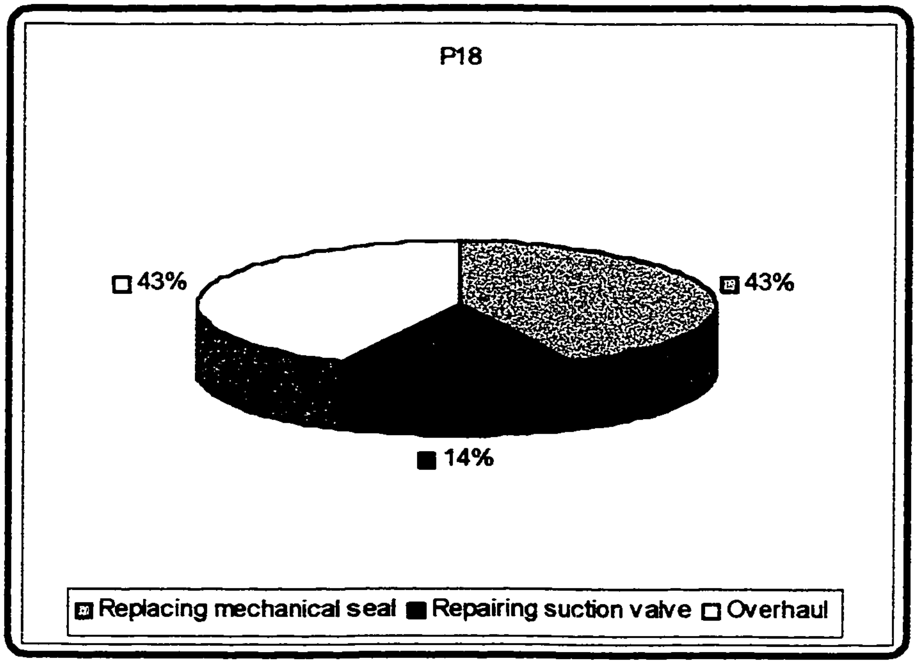


Figure 2.13. Modes of failure of most critical bad actor pump P18.

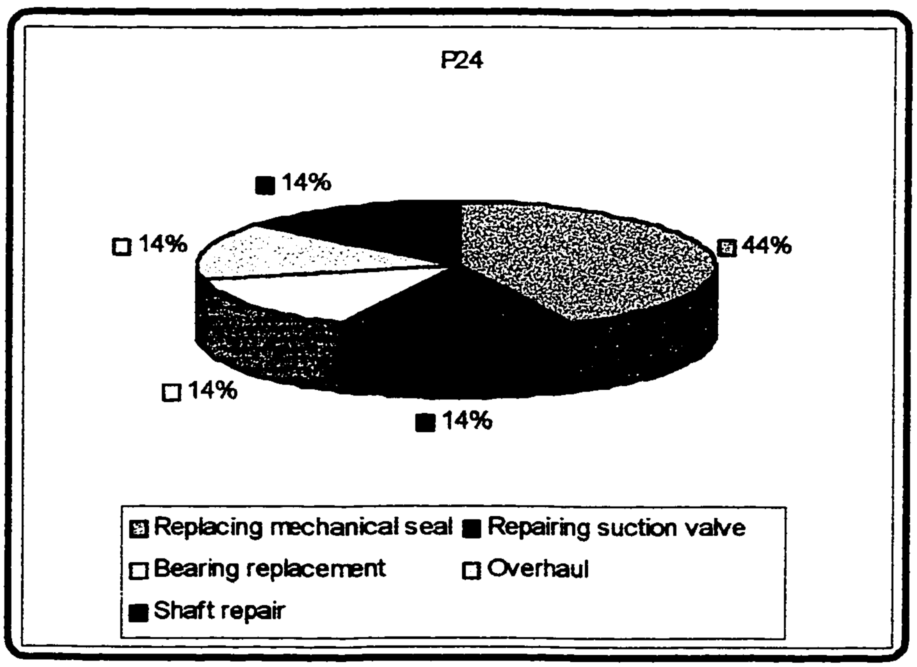


Figure 2.14. Modes of failure of most critical bad actor pump P24.

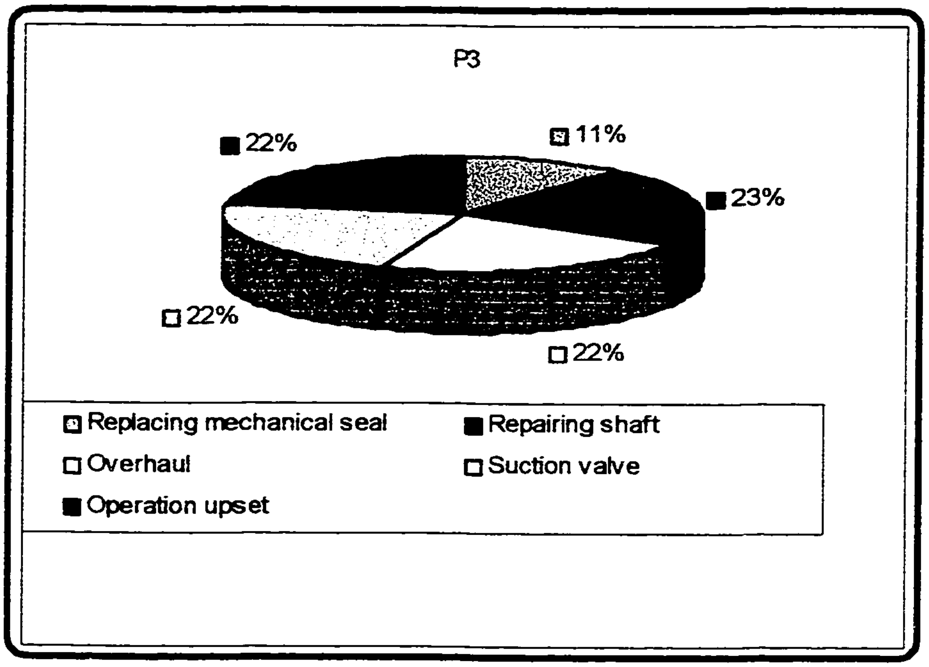


Figure 2.15. Modes of failure of most critical bad actor pump P3.

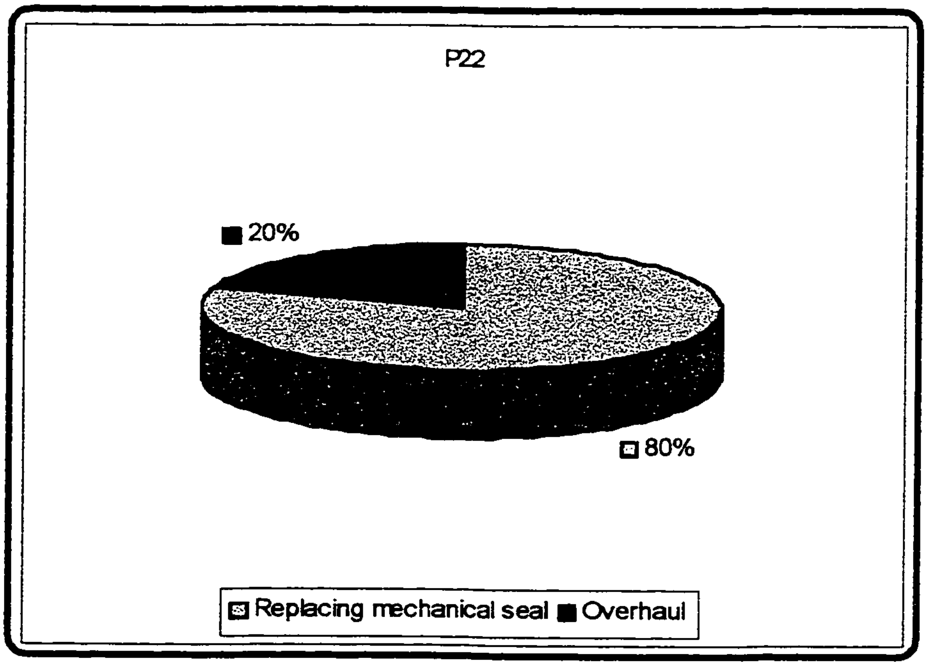


Figure 2.16. Modes of failure of most critical bad actor pump P22.

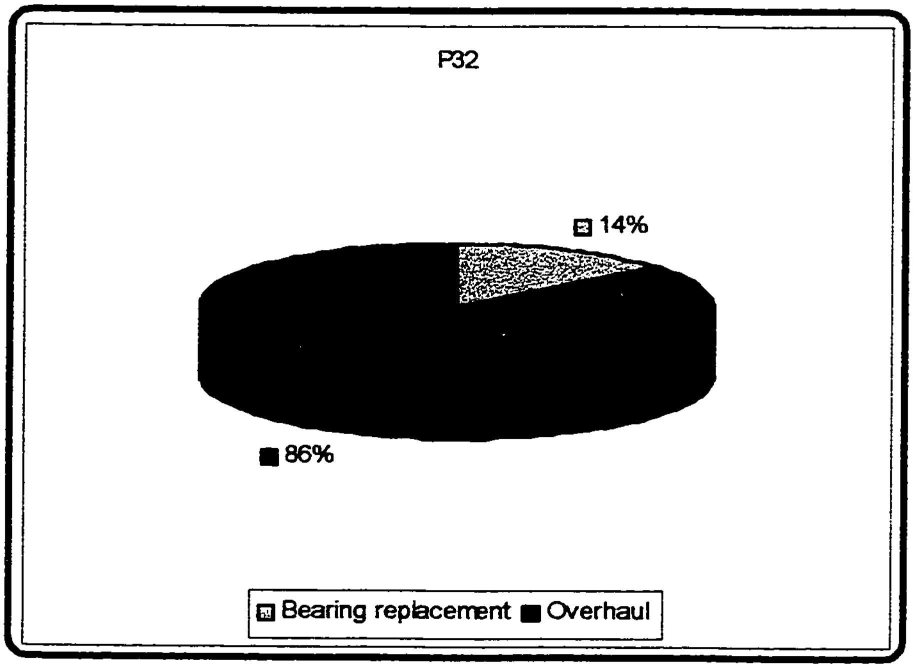


Figure 2.17. Modes of failure of most critical bad actor pump P32.

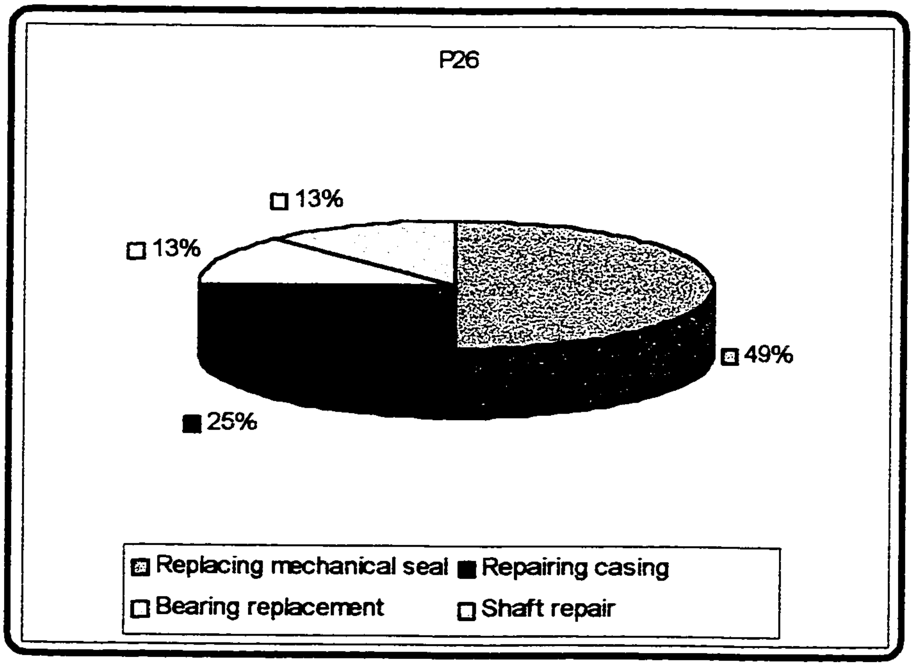


Figure 2.18. Modes of failure of most critical bad actor pump P26.

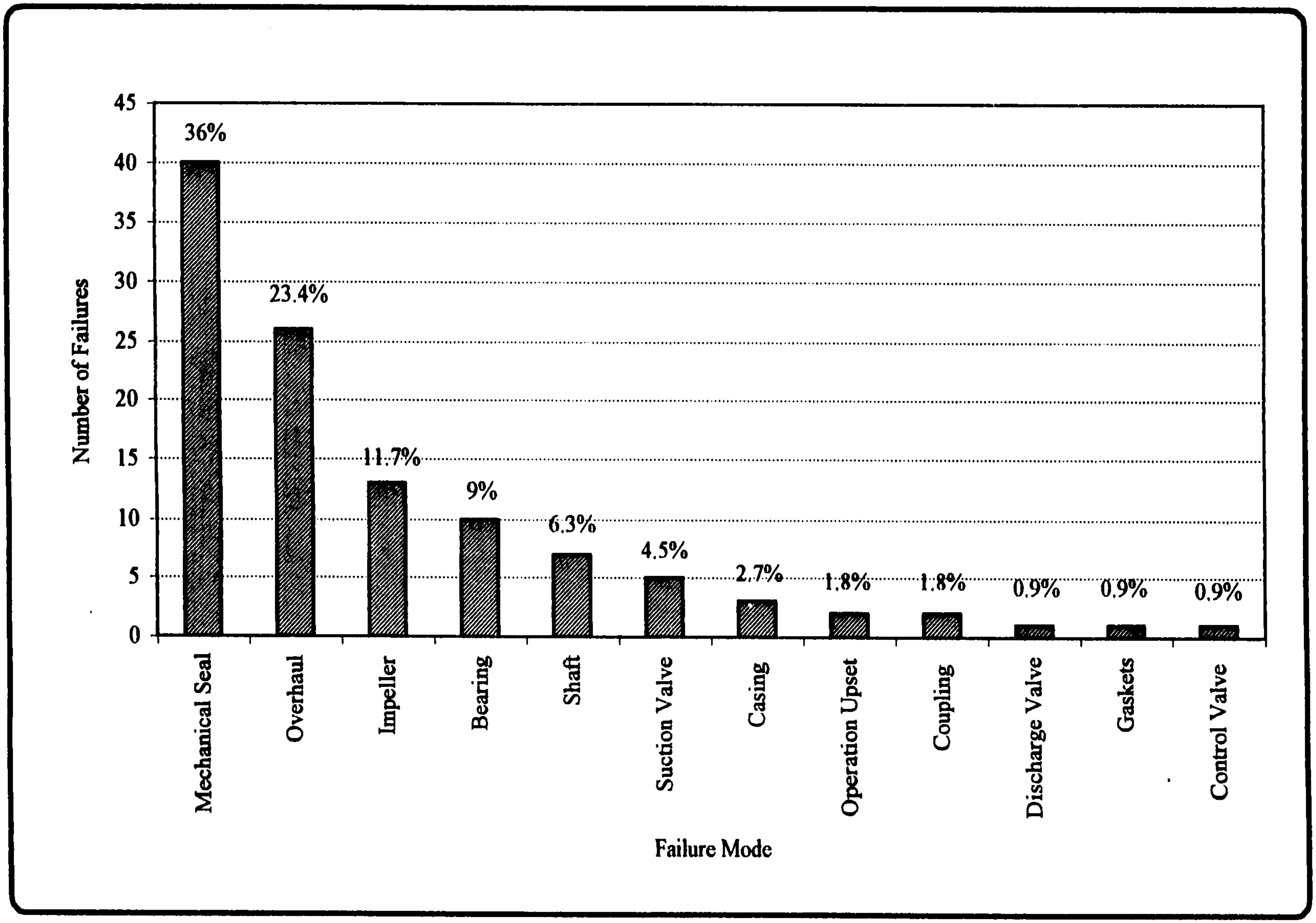


Figure 2.19. Failure modes for the most critical bad actor pumps.

2.2.3 Reliability Parameters

The Weibull analysis helps to determine the reliability function, $R(t)=\exp[-(t/\eta)^{\beta}]$ and its parameters (β, η, MTBF, etc.). From Eq. 1.17, $\beta=\phi(\sigma/\mu)$, where μ and σ^2 are the mean and variance of life, respectively. The other parameter, η, is the characteristic life. As shown in the scatter diagrams (Appendix A, Figures A-1 through A-4), for some selected pumps, there is no need for the time between fialures so the Weibull model is very helpful.

By utilizing Excel spreadsheet, each pump was analyzed and their related reliability parameters were determined. In this analysis each pump is considered to be one repairable system including all types of failures/ malfunctions. Figure 2.20 through Figure 2.35 show the linearized Weibull plots for the time between failure data of most critical bad actor pumps; whereas Figure 2.36 through Figure 2.39 are the reliability curves for some of the most critical bad actor pumps that have different β values ($\beta>1$, $\beta=1$, $\beta<1$). Table 2.4 shows the reliability parameters for the most critical bad actor pumps.

The reliability parameters of the bad actors are very important to study its reliability and availability. These parameters are β, η, MTBF, standard deviation, mode T_m, and median time $T_{0.5}$. The shape parameter β is important to determine the type of failure of the equipment and type of maintenance that should be applied. Ten (10) pumps are found to have $\beta \geq 1$. The mean time between failure (MTBF) is also calculated for each pump. From the MTBF, we can predict the failure time of the pump to plan ahead of time the right action to minimize the plant downtime. The lowest MTBF of the pump is for P40, P42 and P15 (4.5 months, 5.5 months and 5.8 months, respectively), the highest MTBF is for P12, P29, P26 and P41 (12.9, 11.6, 11.5 and 11.1 months, respectively).

Table 2.4. Reliability Parameters for the Most Critical Bad Actor Pumps.

Equipment #	***Code #***	β	η (months)	***MTBF*** (months)	***Standard Deviation*** (months)	***Variation Coefficient***	***Mode,*** T_m (months)	$T_{0.5}$ (months)
P41	35-3-G103B	0.84	10.17	11.10	13.30	1.19		6.58
P39	35-3-G102B	1.02	9.03	9.00	8.80	0.98	0.21	6.31
P40	35-3-G103A	1.71	5.03	4.50	2.70	0.60	3.01	4.06
P38	35-3-G102A	0.97	7.72	7.80	8.10	1.03		5.29
P3	30-2-G58	1.15	7.09	6.70	5.90	0.87	1.21	5.16
P42	38-1-G103	1.26	5.96	5.50	4.40	0.80	1.73	4.46
P7	30-1-G203	1.48	9.56	8.60	5.90	0.69	4.49	7.47
P22	34-1-G53	1.11	6.98	6.70	6.00	0.90	0.89	5.02
P29	34-1-G764A	0.97	11.43	11.60	11.90	1.03		7.84
P33	34-1-G980A	0.64	9.28	12.90	20.80	1.62		5.25
P32	34-1-G980B	1.97	8.47	7.50	4.00	0.53	5.91	7.03
P15	32-1-G127A	2.09	6.60	5.80	2.90	0.50	4.84	5.54
P19	34-1-G664	1.26	8.70	8.10	6.50	0.80	2.49	6.50
P18	34-1-G866A	0.99	6.57	6.60	6.70	1.01		4.54
P24	34-1-G56	1.19	10.28	9.70	8.20	0.84	2.21	7.55
P26	34-1-G664A	0.93	11.17	11.50	12.30	1.07		7.54
P8	30-1-G202	0.86	17.67	19.10	22.30	1.17		11.54

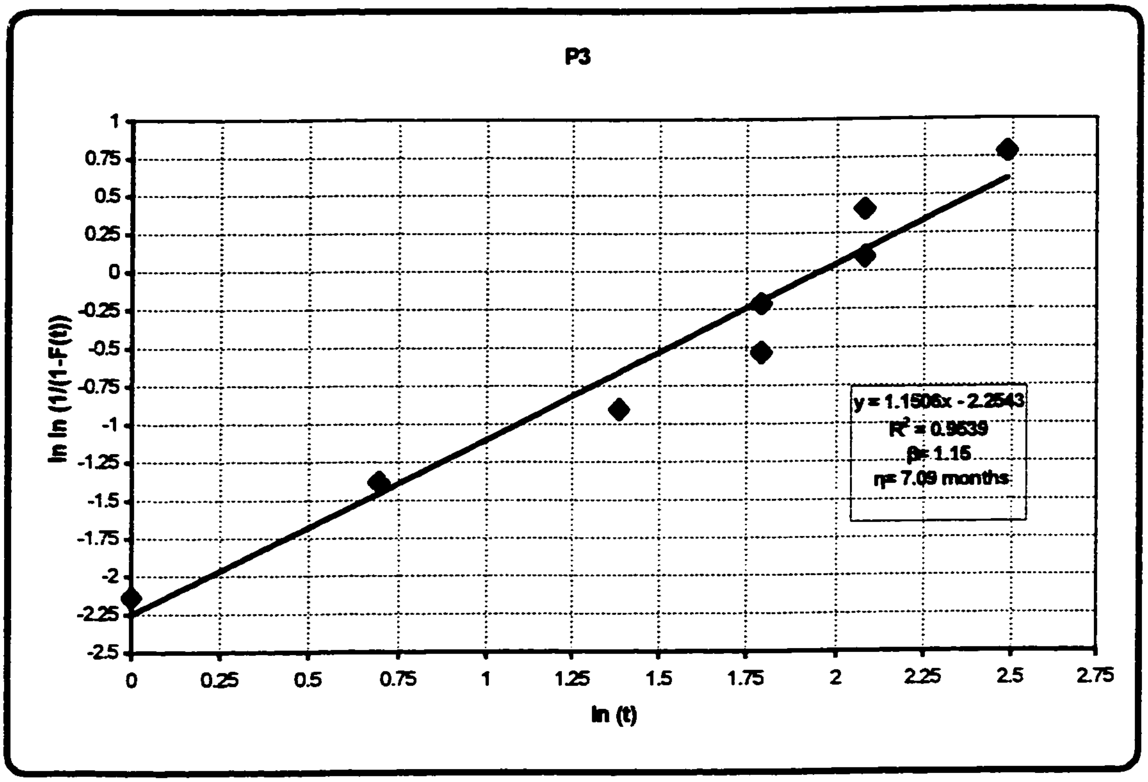


Figure 2.20. Weibull plot for most critical bad actor pump P3.

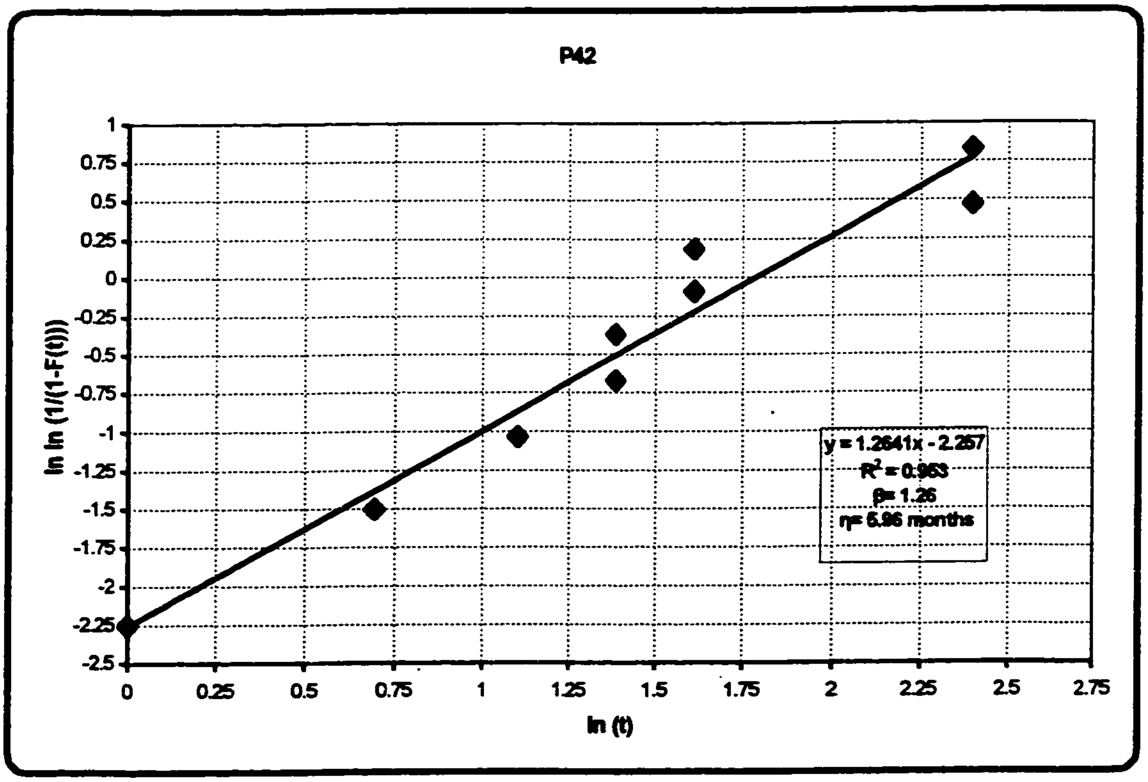


Figure 2.21. Weibull plot for most critical bad actor pump P42.

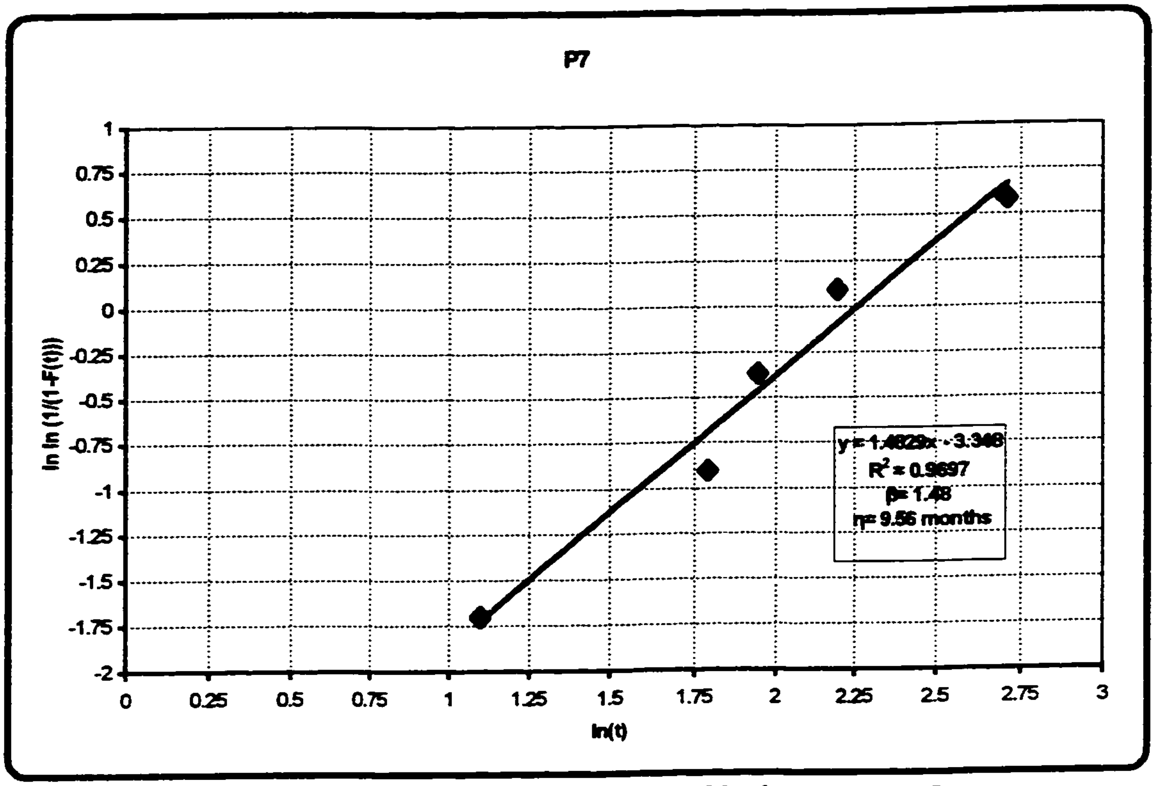


Figure 2.22. Weibull plot for most critical bad actor pump P7.

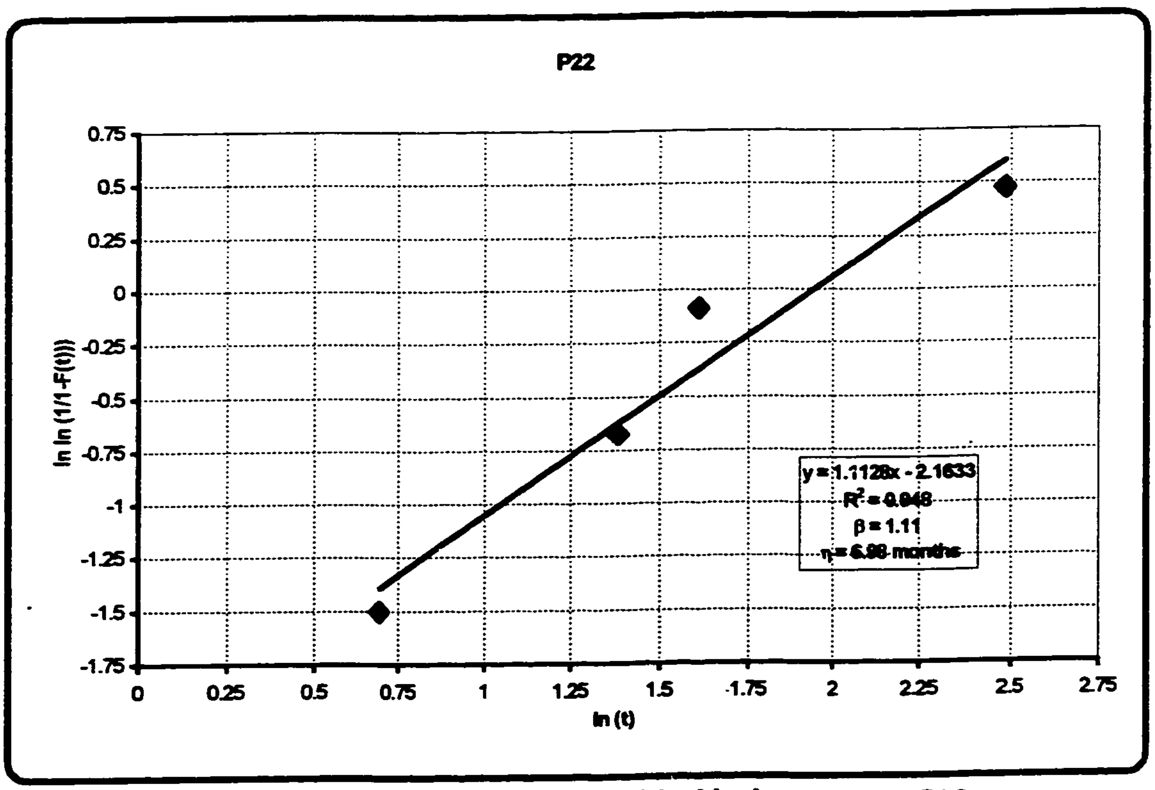


Figure 2.23. Weibull plot for most critical bad actor pump P22.

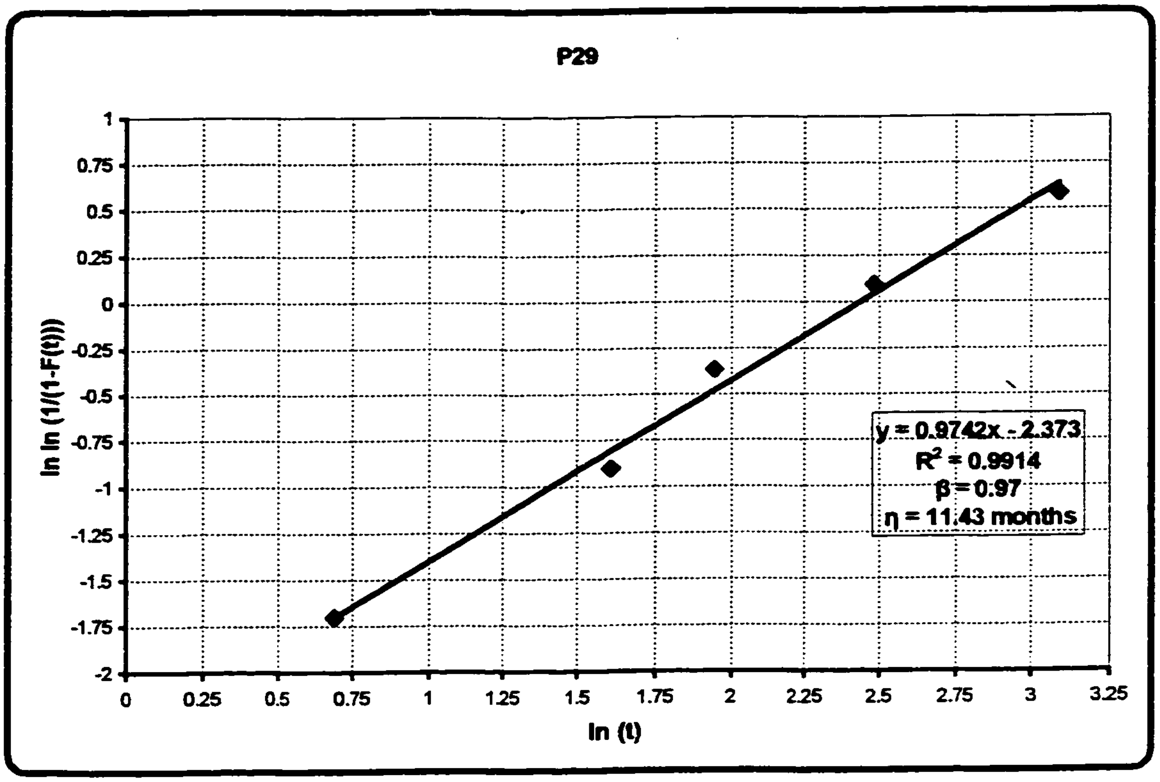


Figure 2.24. Weibull plot for most critical bad actor pump P29.

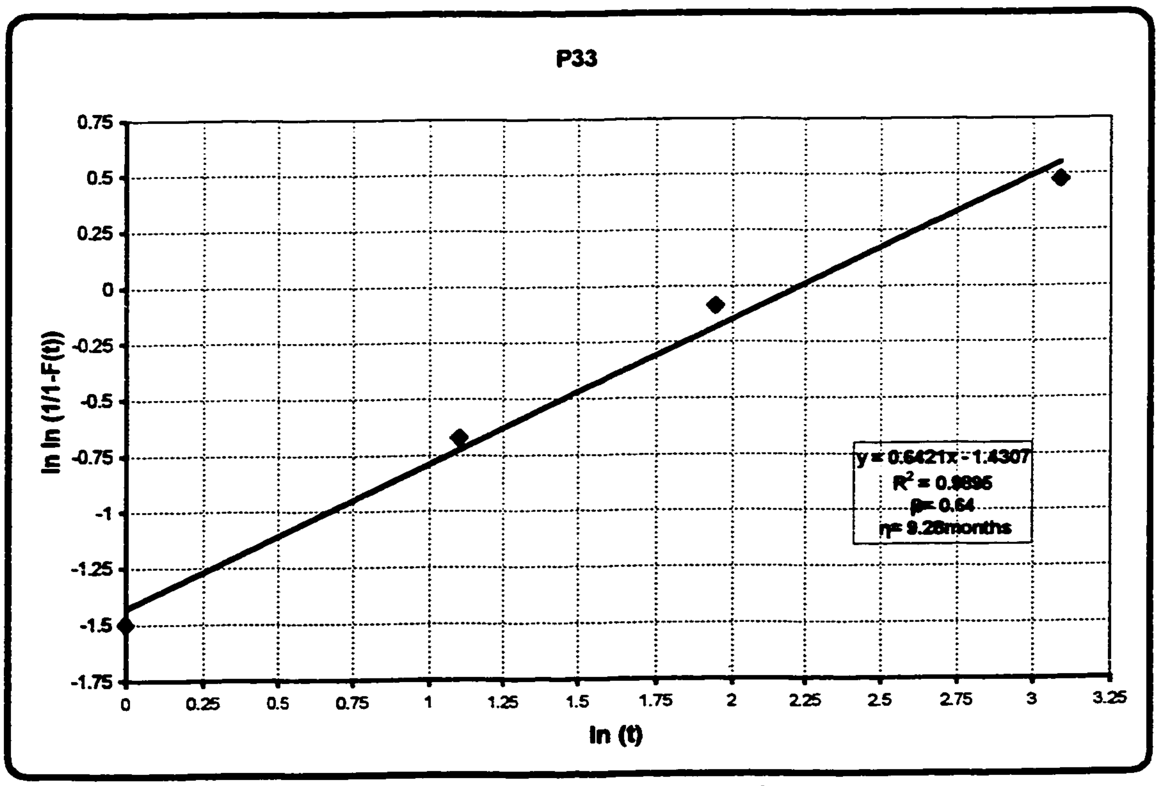


Figure 2.25. Weibull plot for most critical bad actor pump P33.

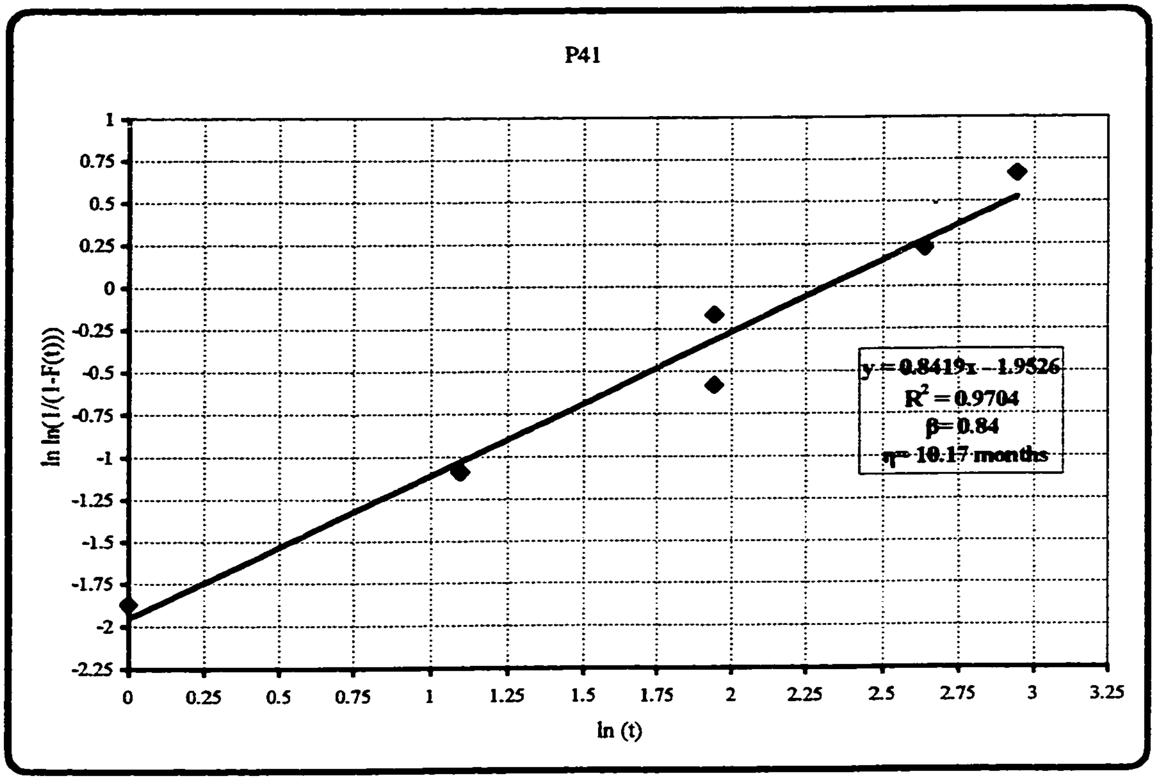


Figure 2.26. Weibull plot for most critical bad actor pump P41.

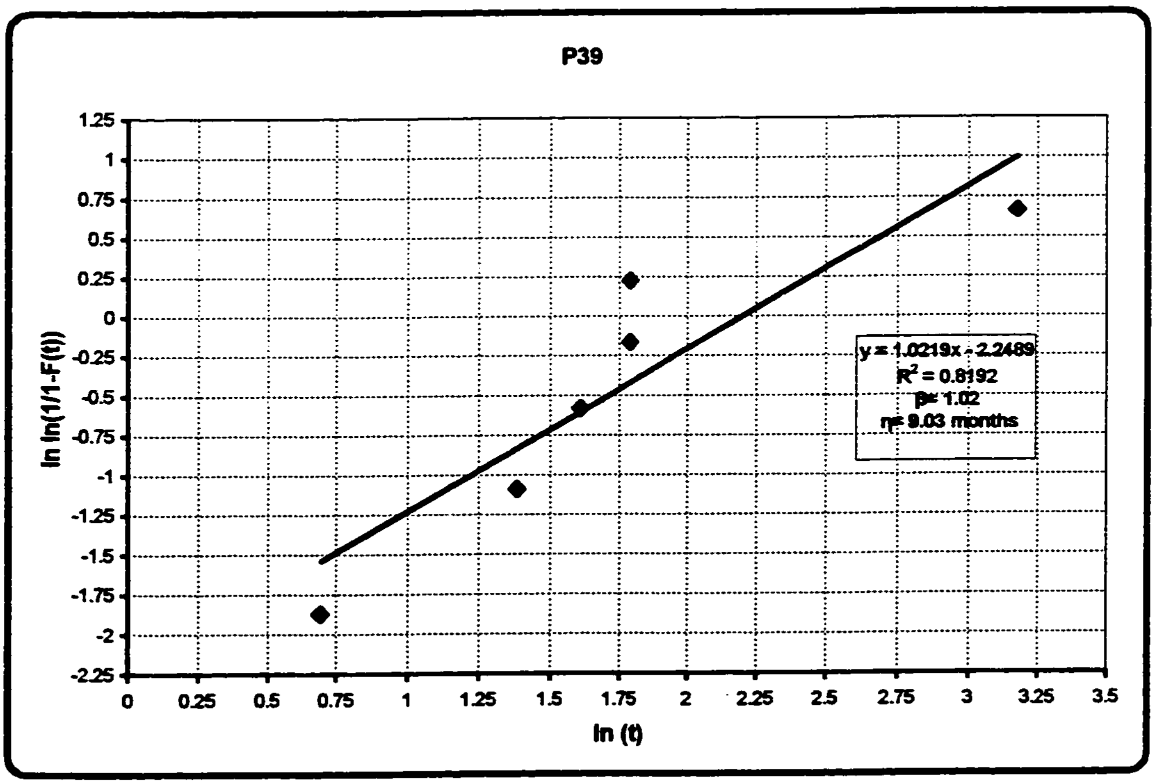


Figure 2.27. Weibull plot for most critical bad actor pump P39.

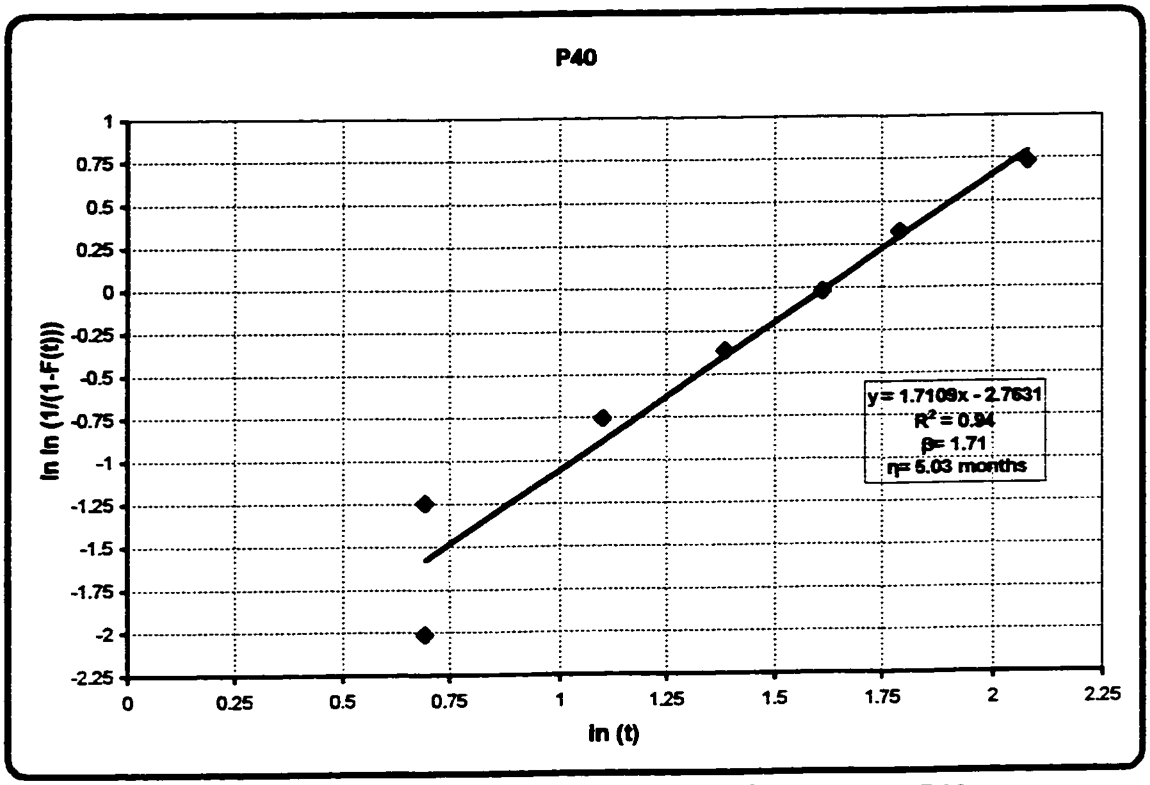


Figure 2.28. Weibull plot for most critical bad actor pump P40.

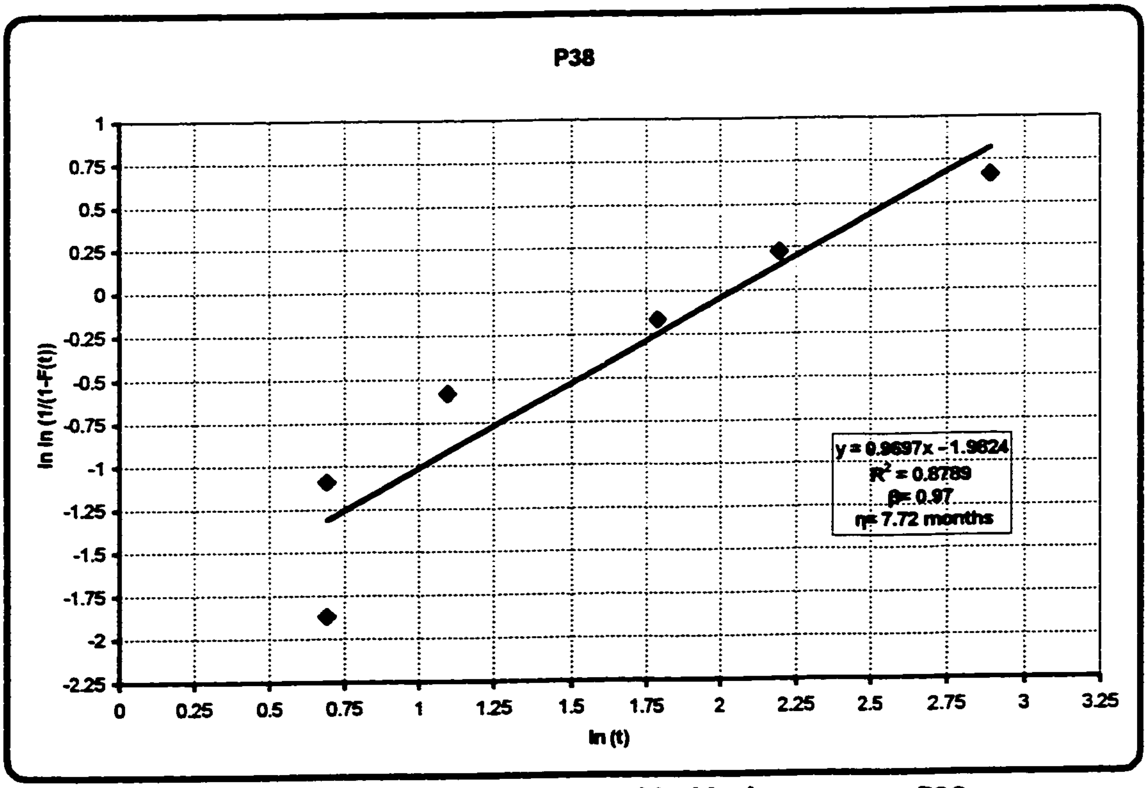


Figure 2.29. Weibull plot for most critical bad actor pump P38.

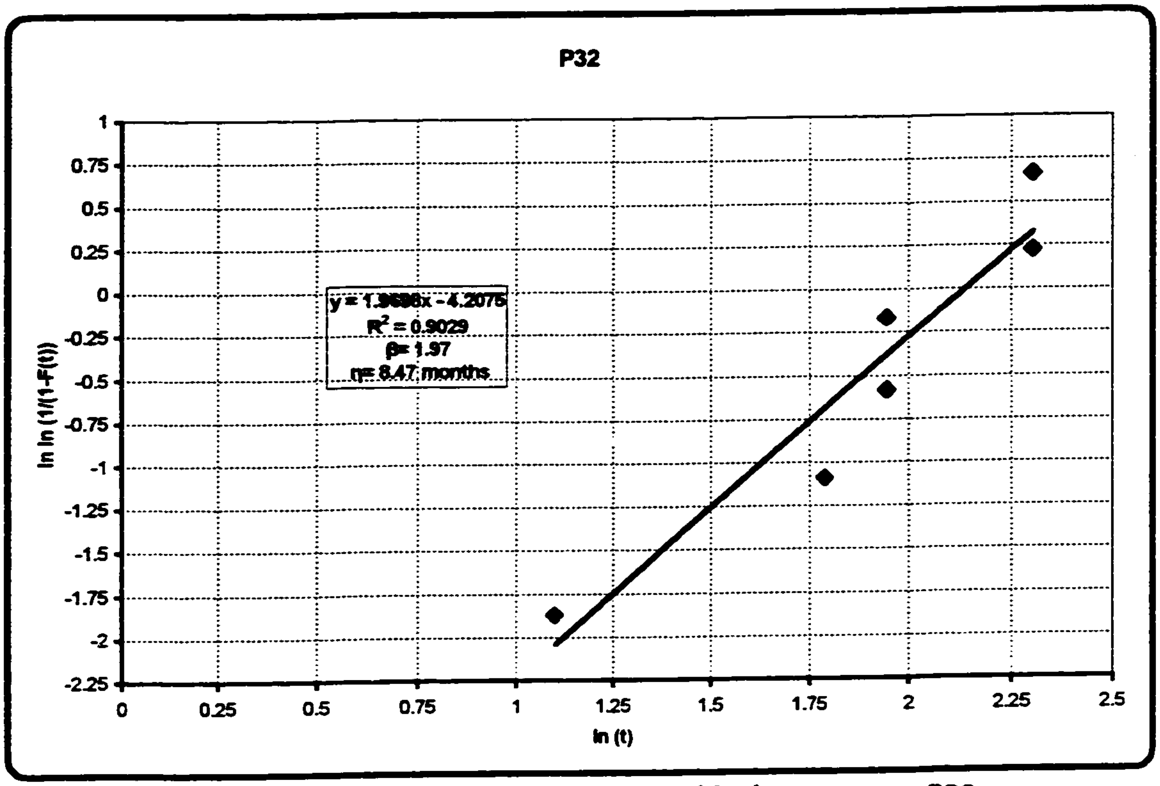


Figure 2.30. Weibull plot for most critical bad actor pump P32.

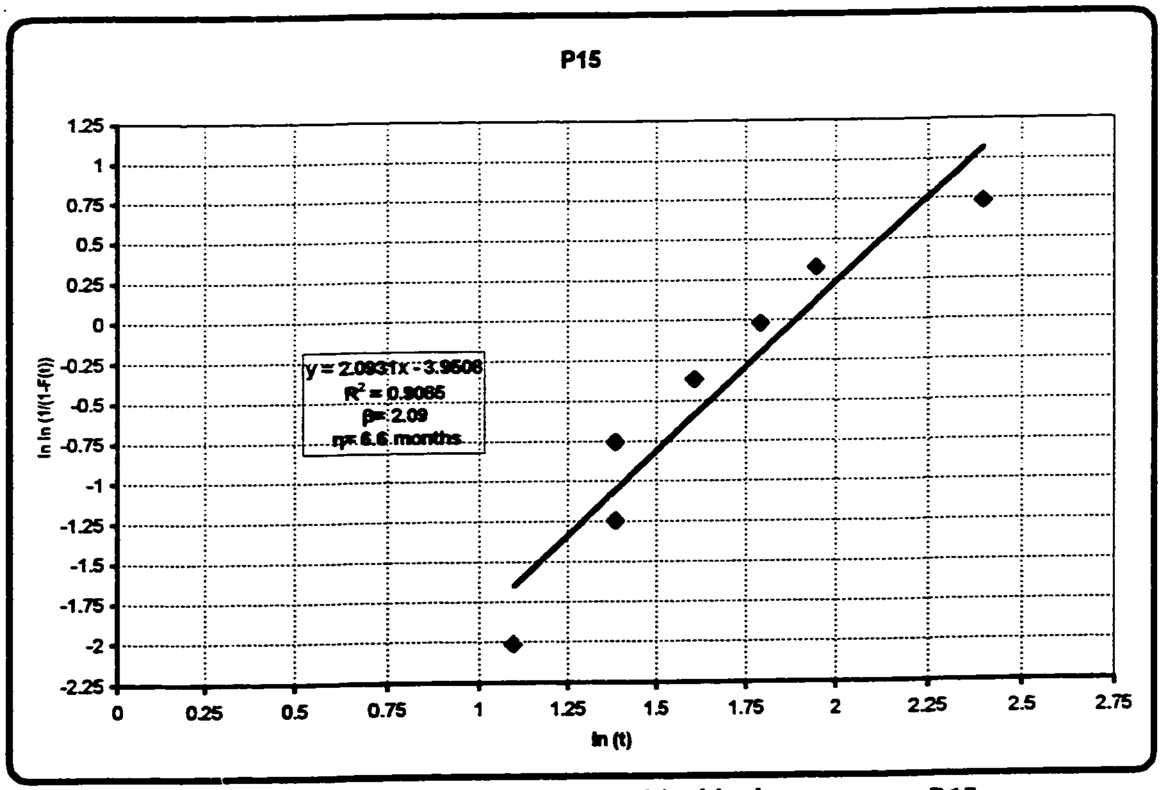


Figure 2.31. Weibull plot for most critical bad actor pump P15.

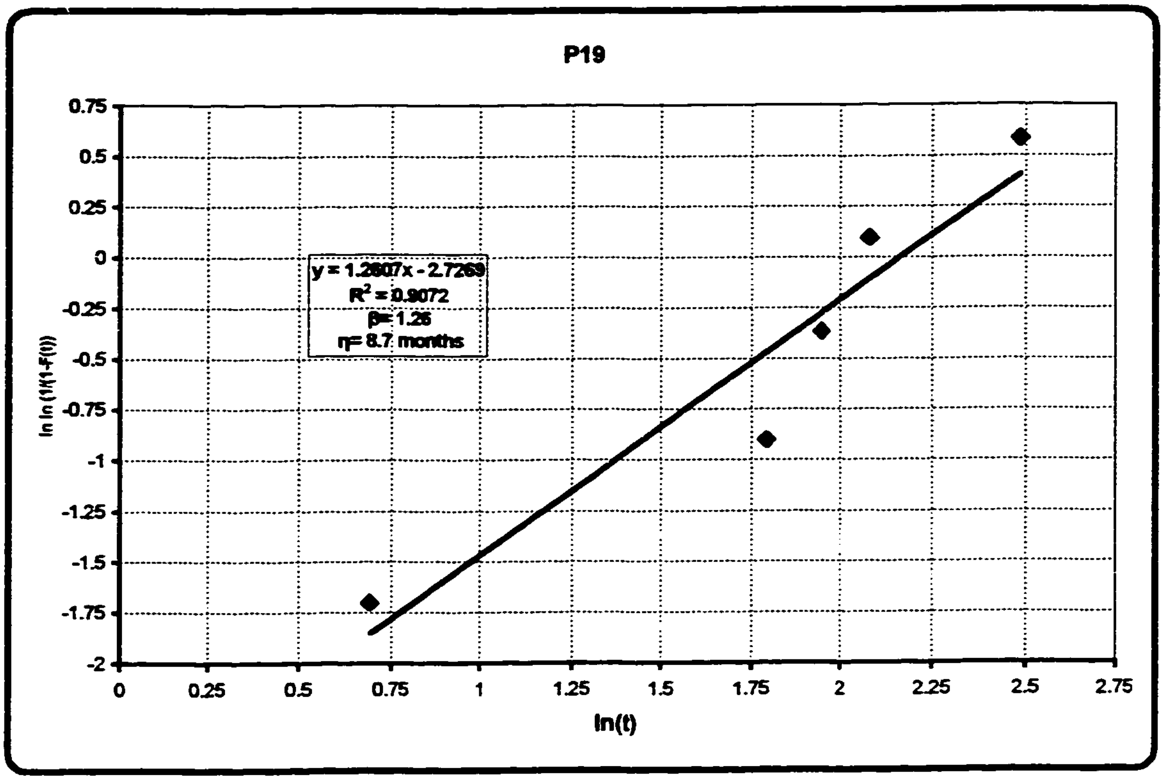


Figure 2.32. Weibull plot for most critical bad actor pump P19.

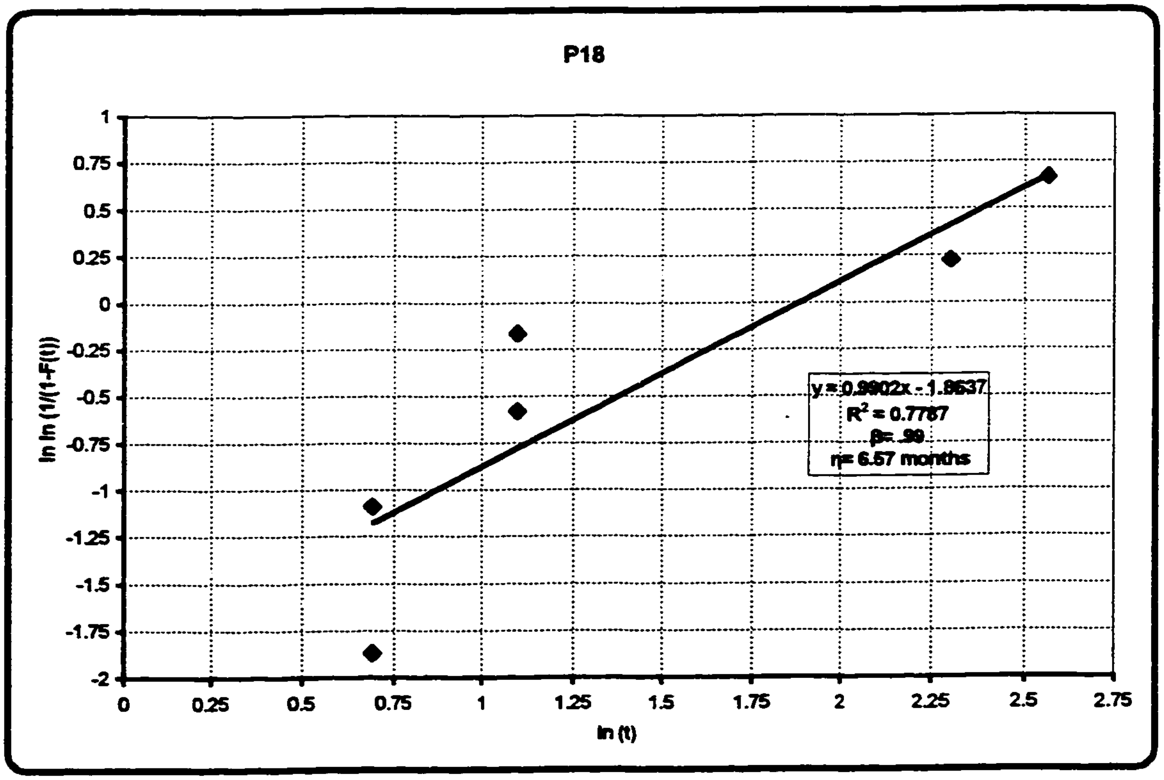


Figure 2.33. Weibull plot for most critical bad actor pump P18.

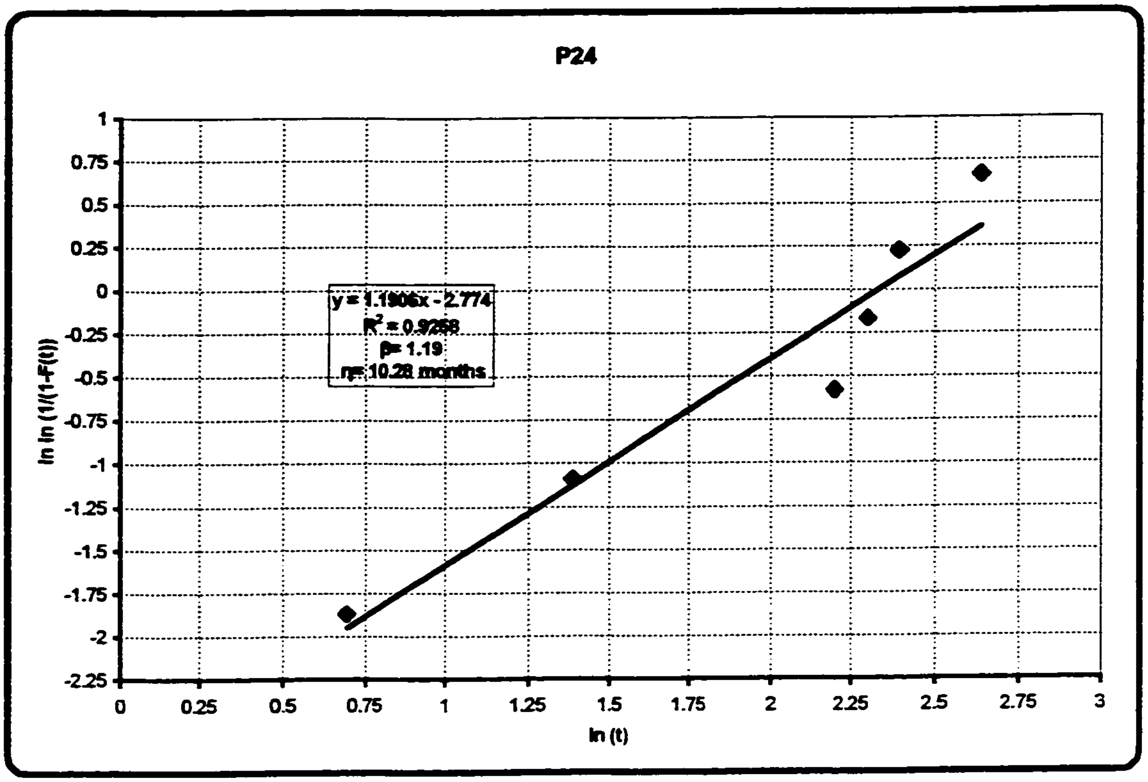


Figure 2.34. Weibull plot for most critical bad actor pump P24.

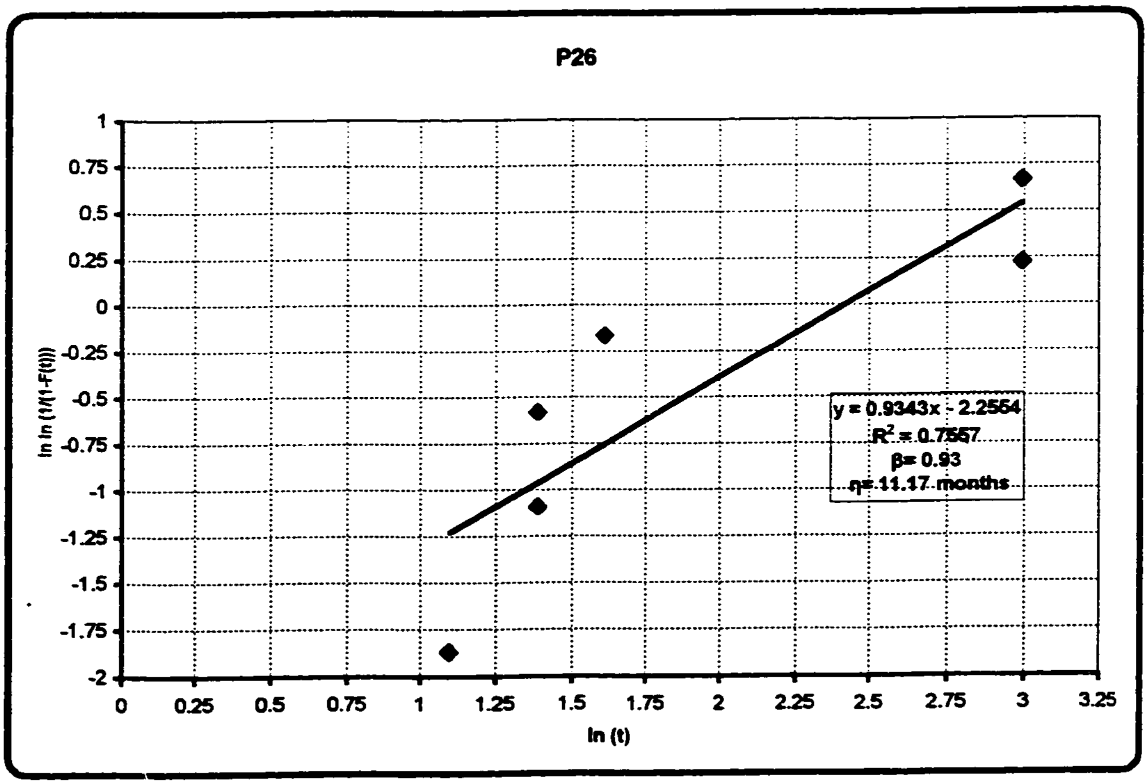


Figure 2.35. Weibull plot for most critical bad actor pump P26.

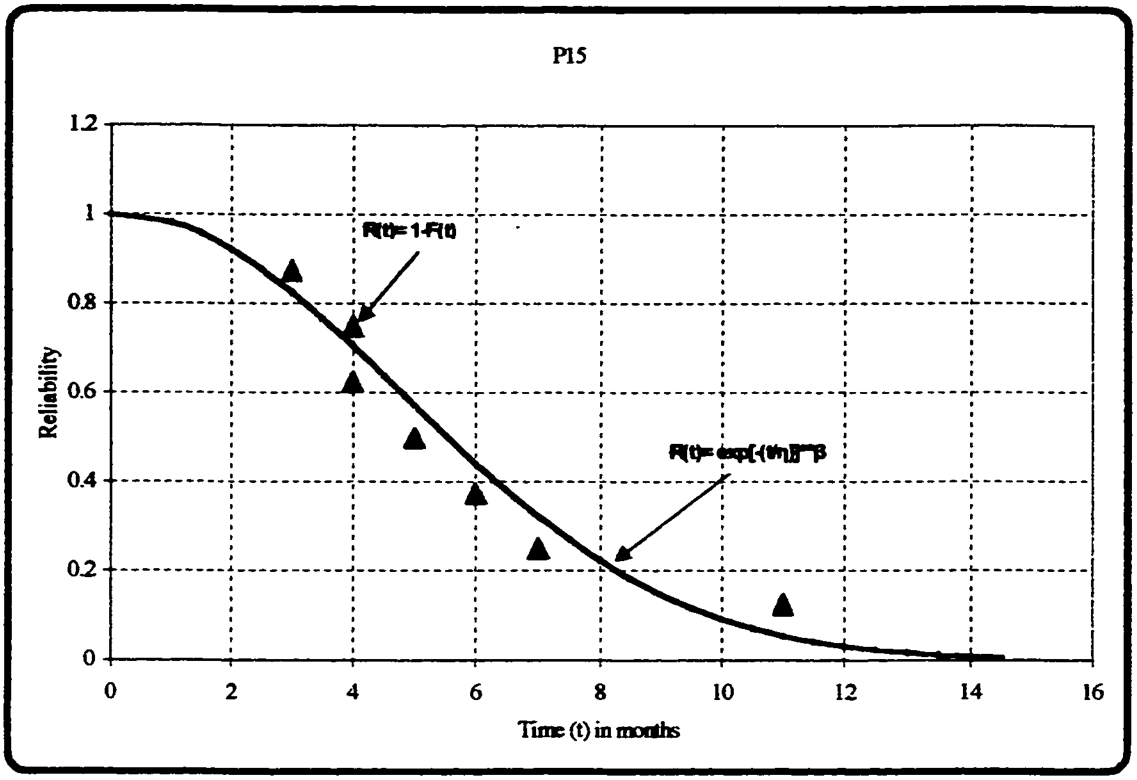


Figure 2.36. Reliability chart for most critical bad actor pump P15.

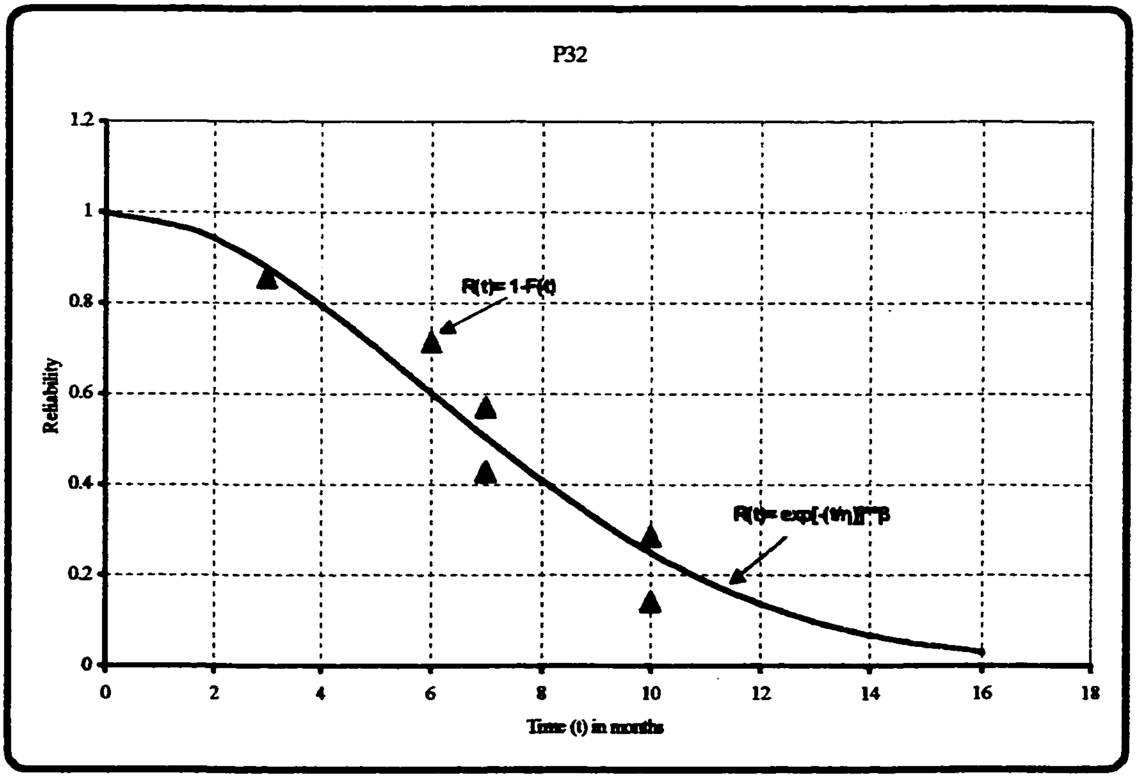


Figure 2.37. Reliability chart for most critical bad actor pump P32.

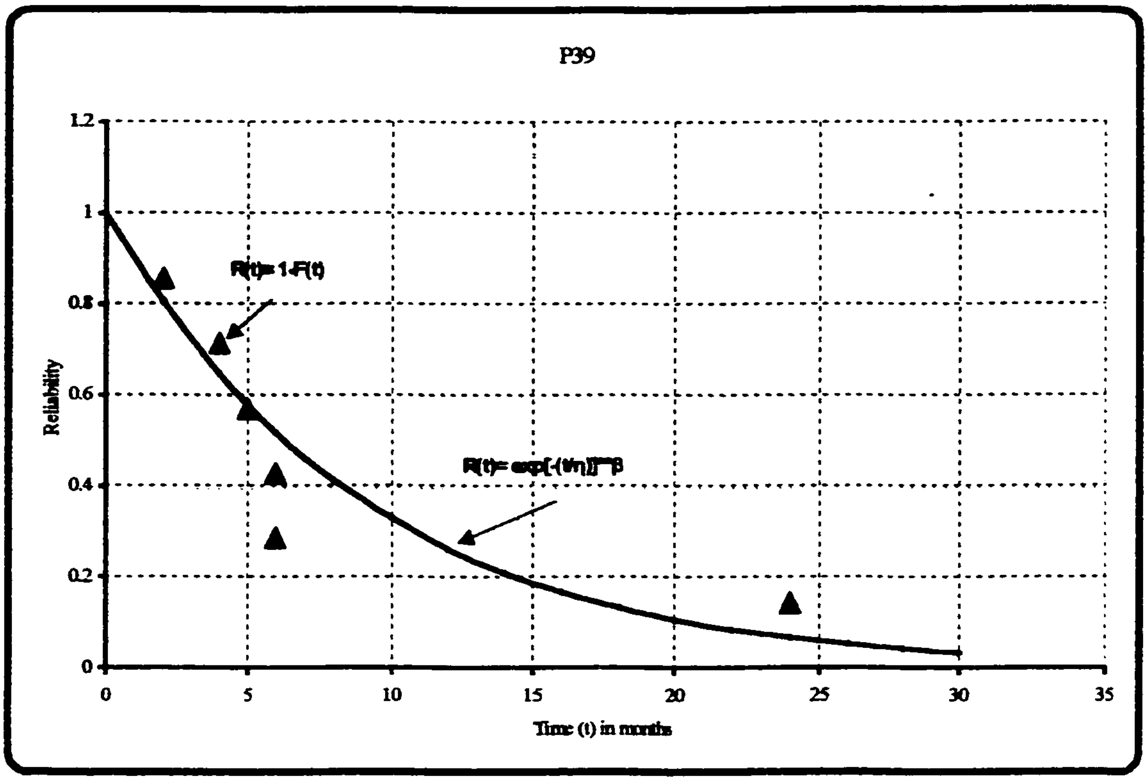


Figure 2.38. Reliability chart for most critical bad actor pump P39.

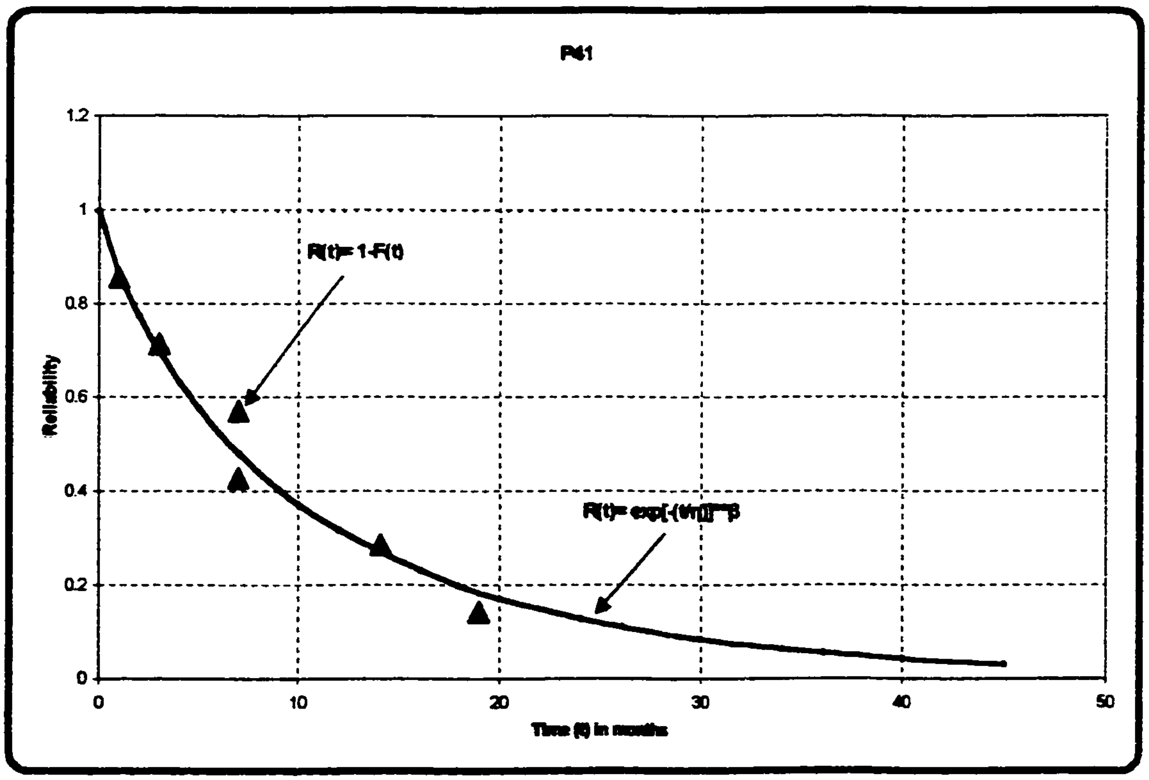


Figure 2.39. Reliability chart for most critical bad actor pump P41.

2.2.4 Weibull Reliability Analysis for Non-Repairable Parts of the Most Critical Bad Actor Pumps

The most common non-repairable parts of the most critical bad actor pumps are found to be seals and bearings. The common practice of maintenance of these parts are replacing them with new one when they failed. In this analysis, as shown in Table 2.5, the most critical bad actor pumps are segregated based on their process (for example, seawater pumps, distillate pumps). As shown in Figures 2.40 and 2.41, the time to failure data of the seals and bearings of all the distillate pumps, and seawater pumps is pooled together. The Weibull analysis on seals and bearings are performed to find the shape parameter and the characteristic life.

It is found that the behavior of the failure of seals for both seawater pumps and distillate pumps are same. So, the time to failure of the of the pumps seals are combined together and plotted in one figure (Figure 2.40). From this figure, we calculated the characteristic life of pump seals and found it to be 27.5 months, which is around two-and-a-half year. The other type of non-repairable parts of the pump are bearings. As shown in Figure 2.41, the bearings last little bit longer than seals in service. The characteristic life of the pump bearings are 29.4 months. The shape parameter for both pump seals and pump bearings are greater than one ($\beta = 1.76$ for seals and $\beta = 1.74$ for bearings).

Table 2.5. List of Most Critical Bad Actor Pumps Based on their Process.

Equipment #	*Code #*	*Description*	*Process Type*
P41	35-3-G103B	High lift pump	Seawater pump
P39	35-3-G102B	High lift pump	Seawater pump
P40	35-3-G103A	High lift pump	Seawater pump
P38	35-3-G102A	High lift pump	Seawater pump
P3	30-2-G58	Salt water pump	Seawater pump
P22	34-1-G53	Brine recycle pump	Seawater pump
P18	34-1-G866A	Booster pump	Seawater pump
P24	34-1-G56	Booster pump	Seawater pump
P7	30-1-G203	Feedwater pump	Distillate pump
P15	32-1-G127A	Super-heater pump	Distillate pump
P19	34-1-G664	Distillate pump	Distillate pump
P29	34-1-G764A	Distillate pump	Distillate pump
P26	34-1-G664A	Distillate pump	Distillate pump
P32	34-1-G980B	Sump pump	Distillate water pump
P42	38-5-103	Firewater pump	Distillate water pump
P8	30-1-G202	Feedwater pump	Seawater pump
P33	34-1-G980A	Sump pump	Distillate water pump

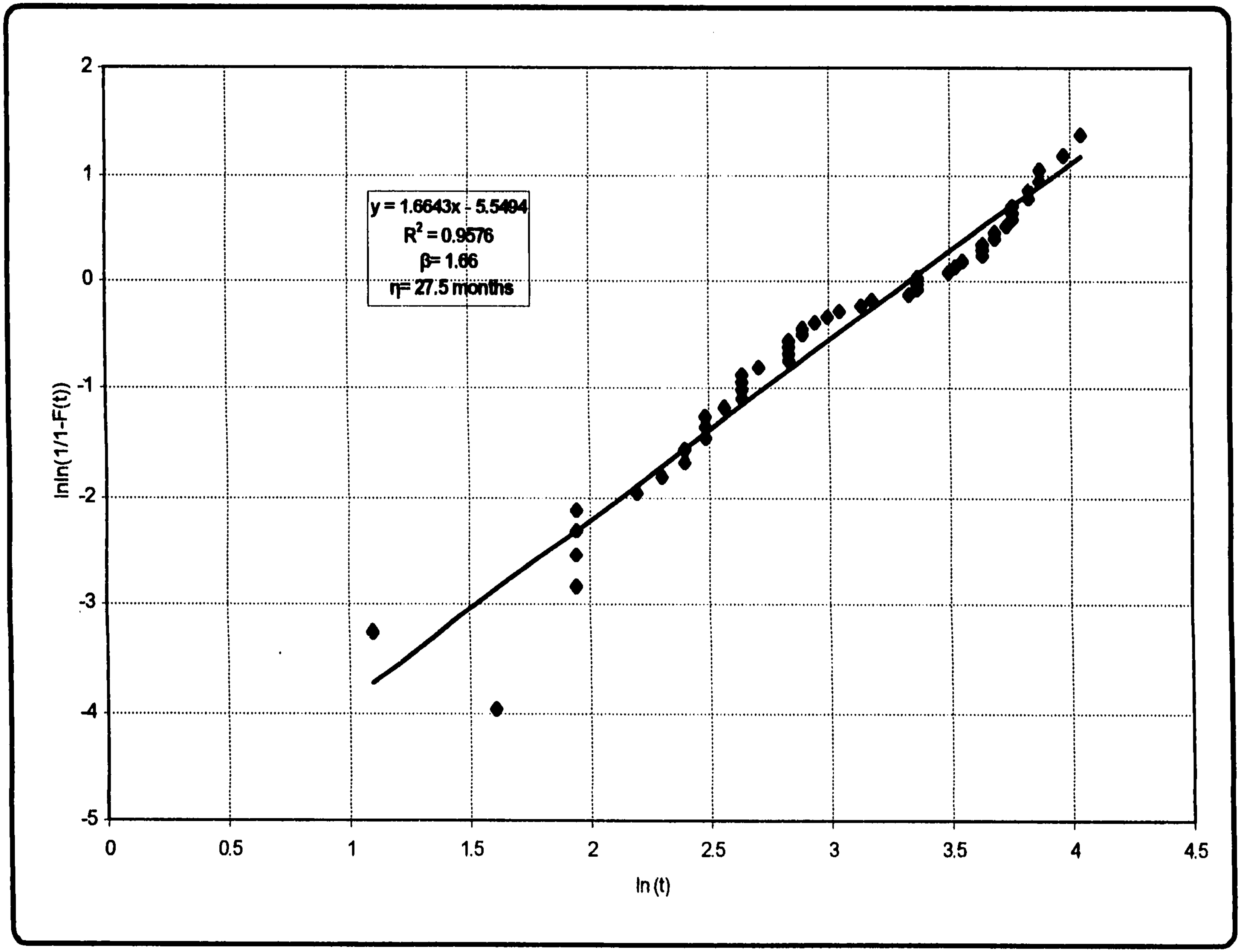


Figure 2.40. Weibull analysis of seal for all types of most critical bad actors pumps.

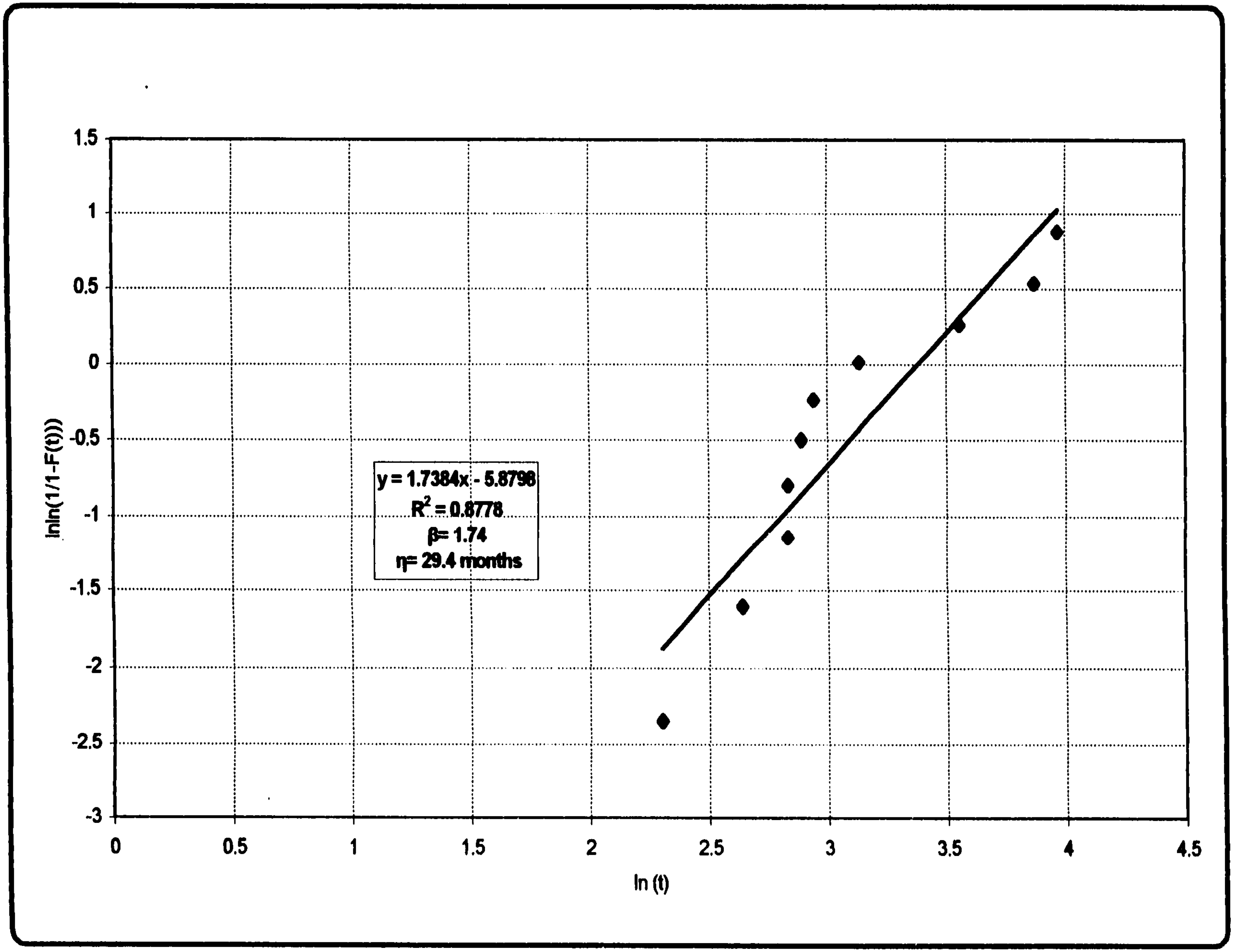


Figure 2.41. Weibull analysis of bearings for all types of most critical bad actors pumps.

2.2.5 Cost Analysis

2.2.5.1 Cost of All Modes of Failures

The cumulative repairing cost for all modes of failure for each pump versus the five years of operation were plotted. This type of cost analysis can help in deciding if we have to continue to repair the equipment or we have to purchase new one because of the repairing cost is becoming much higher than the cost of new pump. This analysis is shown in Figures 2.42 and 2.43.

The cost analysis is conducted for both repairable parts (all modes of failures) and non-repairable parts. The accumulative repairing costs for all modes of failure for the 17 pumps versus the time of operation for the five years of study are plotted. Also, the average accumulative repairing costs versus the operation time of each pump is estimated and plotted. However, for non-repairable parts, the repairing costs versus the time between failure is plotted for both seals and bearings. For the analysis cost of all modes of failures of pumps, we can see that there is an increasing of repairing cost from 1997 until 1999. However, from the year 1995 to 1997 and from 1999 to 2000, there is a constant amount of money which was spent for repairing.

2.2.5.2 Non-Repairable Parts

Money is a very critical factor in failure analysis and maintenance strategies and from this point the cumulative cost of the non-repairable part of the bad actor pumps which are found to be seals are investigated through the operational. The repairing costs for seals of all of the most critical bad actor pumps are plotted versus the operation time as shown in Figure 2.44.

For the seals of all pumps (non-repairable parts), it is found that the maintenance cost is increasing significantly after 10 months of operation. The accumulative cost of the non-repairable parts is including also the cost of repairing auxiliaries that is related to the pump seal and the seal will not work if this is failed. So, after the expected life of the seal (27.5 months), the old seals should be replaced with new ones and the related auxiliaries (tubes, fittings, drains, etc.,) should be inspected and replaced if it is necessary.

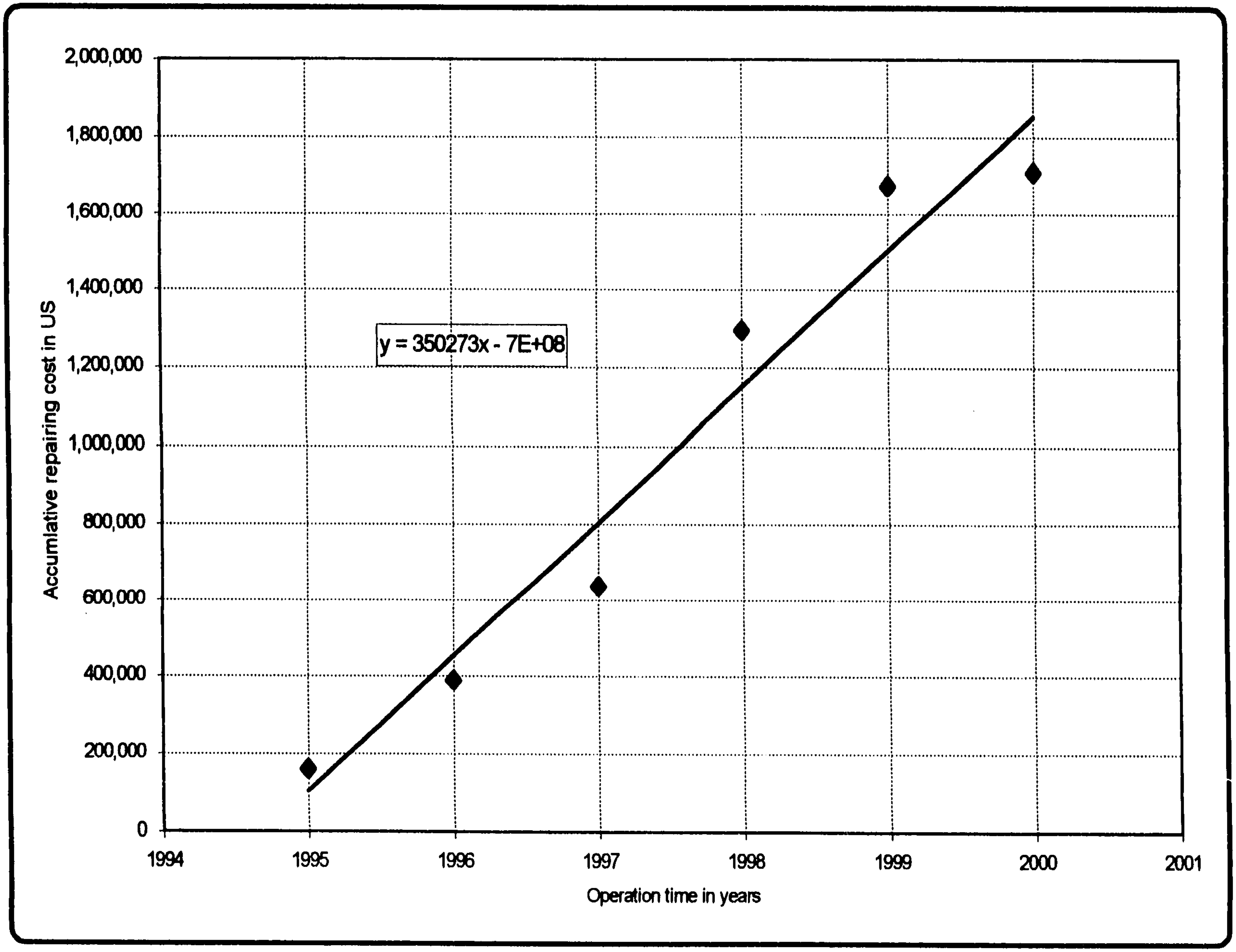


Figure 2.42. Accumulative repair costs versus time of operation for the most critical bad actors pumps (all failure modes).

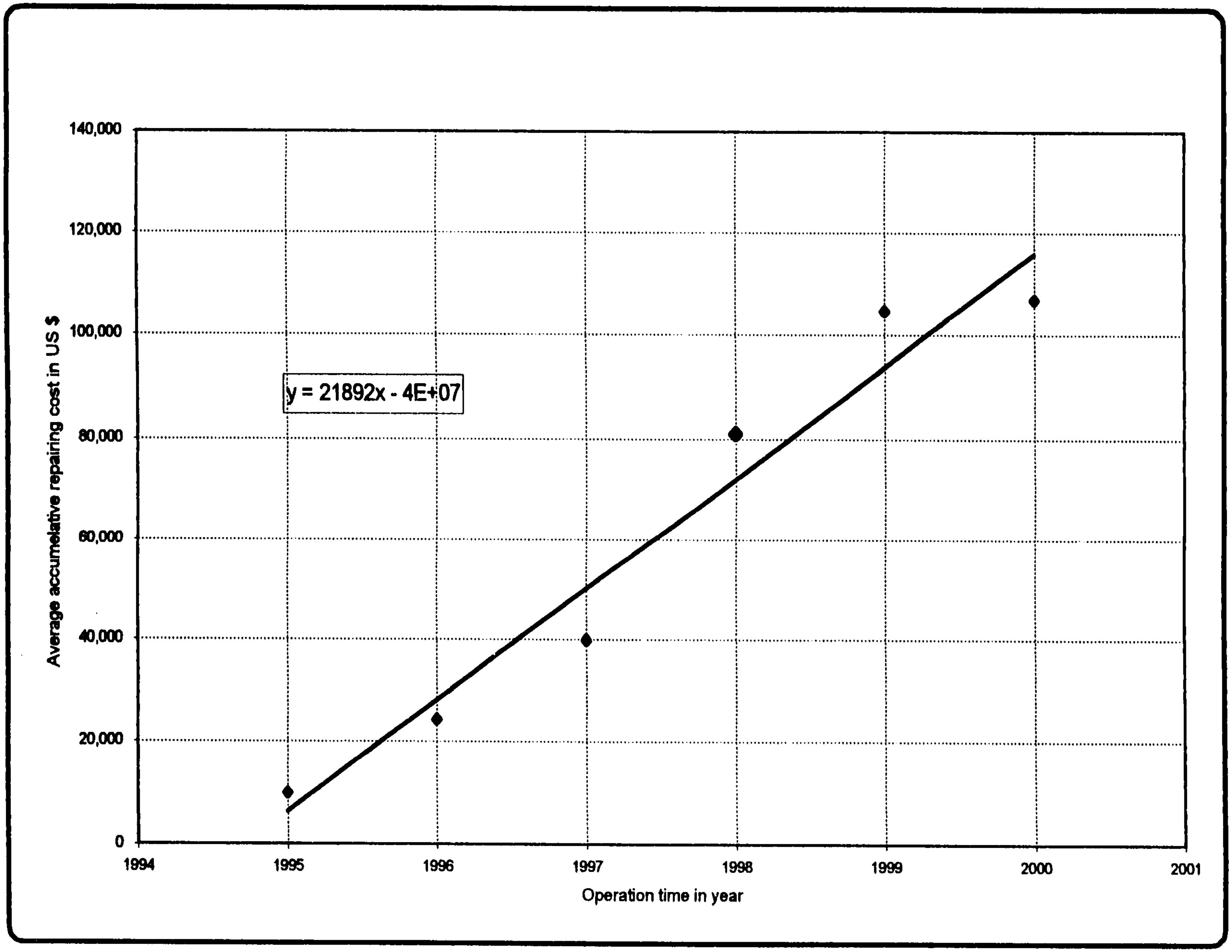


Figure 2.43. Average accumulative repairing cost for each bad actor pump (all failure modes).

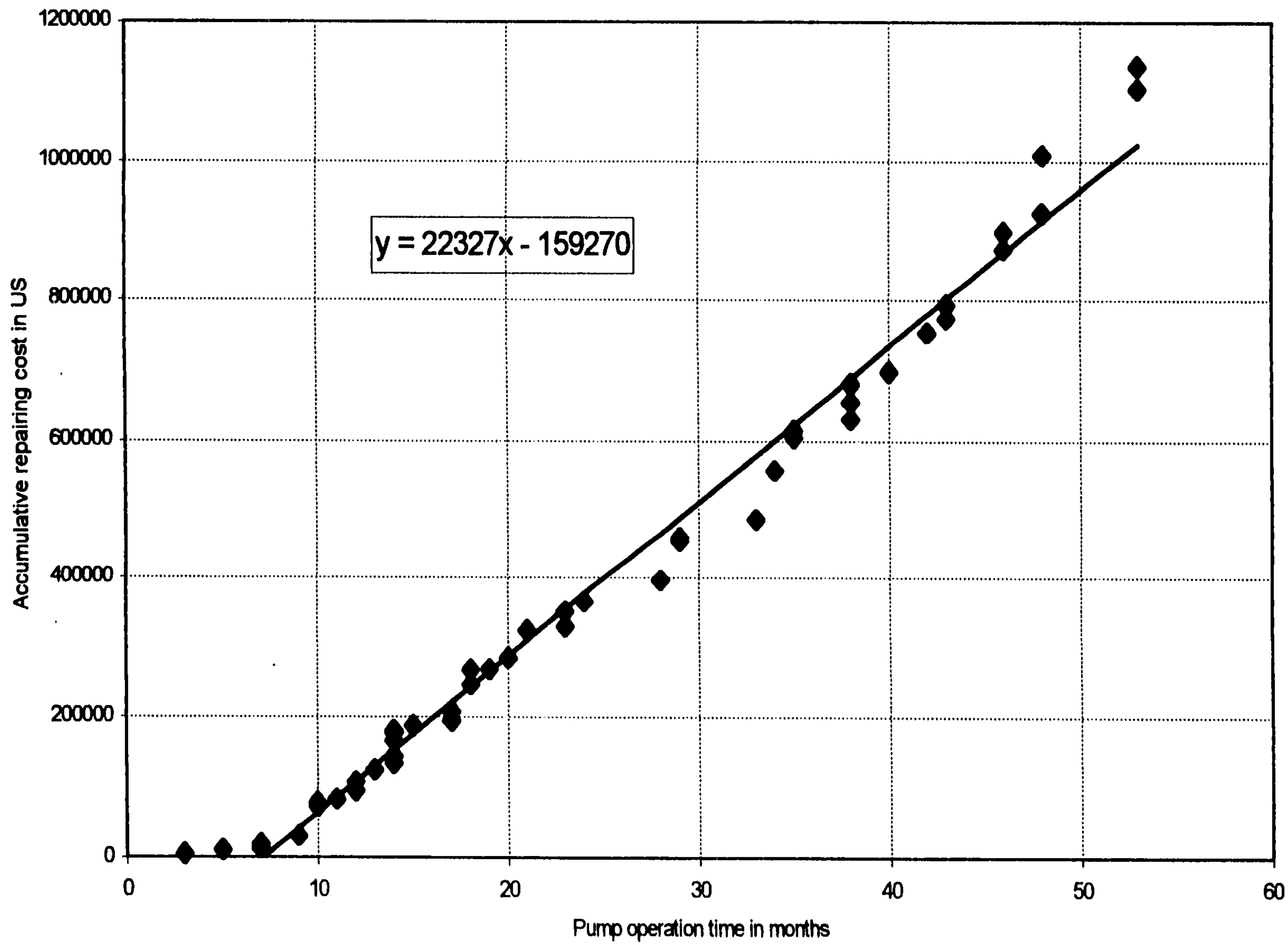


Figure 2.44. Accumulative repairing cost for seals of all pumps versus operation time.

2.3 Turbines

The other type of rotating equipment that was studied is steam turbines. A total of 50 steam turbines are in operation in the Refinery plants. Out of this, 13 steam turbines have been found to have suffered frequent failures and incurred high repairing cost (bad actors) as shown in Table 2.6.

2.3.1 Pareto Analysis

The Pareto analysis as shown in Figures 2.45 and 2.46 is utilized to identify the most critical bad actors steam turbines based on ranking the number of failures and their associated repairing cost. The Pareto analysis criteria for steam turbines is 75% of the accumulative percentage of number of failures and repairing cost. This means the turbines that have 75% of the accumulative repairing cost and 75% of accumulative number of failures should be included as the most critical bad actors steam turbines. Based on that, ten (10) steam turbines, as shown in Table 2.7, were determined to be the most critical bad actors steam turbines and the Weibull reliability analysis will be applied to them.

2.3.2 Determining Failure Modes

As shown in Table 2.8, with the utilization of the Maintenance Management System, the time to failure (trip-off), failure modes and repair cost were gathered for each turbine. As a part of failure analysis, the failure mode should be determined at each

Table 2.6. Bad Actors Steam Turbines.

Equipment #	*Code #*	*Description*	*No. of Failures*	*Cost in US $*
T4	32-KT106	Turbine of D. F. in LPB # 6	15	107,926
T7	32-GT111D	Turbine for Feed Water Pump	12	105,461
T13	30-1-GT91A	Turbine for Feed Water Pump	11	214,082
T5	32-KT107	Turbine for F. D. Fan in LPB # 7	10	153,859
T6	32-GT111C	Turbine for Feed Water Pump	8	124,780
T10	32-KT108	Turbine of F. D. Fan in LPB # 8	8	40,766
T1	35-3-GT104A	Turbine of High Lift Pump	7	23,835
T8	30-1-GT91B	Turbine for Feed Water Pump	7	314,782
T9	30-1-GT90B	Turbine for Circulating Pump	7	102,933
T3	35-3-GT103B	Turbine for High Lift Pump	6	152,498
T12	30-1-KT707	Turbine for F. D. Fan	5	92,688
T2	35-3-GT103A	Turbine of High Lift Pump	4	34,148
T11	30-1-GT202	turbine for Feed Water Pump	4	61,786

Table 2.7. Most Critical Bad Actors Steam Turbines: Failure Modes, Time-to-Failure, Time-to-Repair, and Repair Cost.

Equipment #	*Code #*	*Description*	*No. of Failures*	*Cost in US $*
T4	32-KT106	Turbine of D. F. in LPB # 6	15	107,926
T7	32-GT111D	Turbine for Feed Water Pump	12	105,461
T13	30-1-GT91A	Turbine for Feed Water Pump	11	214,082
T5	32-KT107	Turbine for F. D. Fan in LPB # 7	10	153,859
T6	32-GT111C	Turbine for Feed Water Pump	8	124,780
T10	32-KT108	Turbine of F. D. Fan in LPB # 8	8	40,766
T1	35-3-GT104A	Turbine of High Lift Pump	7	23,835
T8	30-1-GT91B	Turbine for Feed Water Pump	7	314,782
T9	30-1-GT90B	Turbine for Circulating Pump	7	102,933
T3	35-3-GT103B	Turbine for High Lift Pump	6	152,498

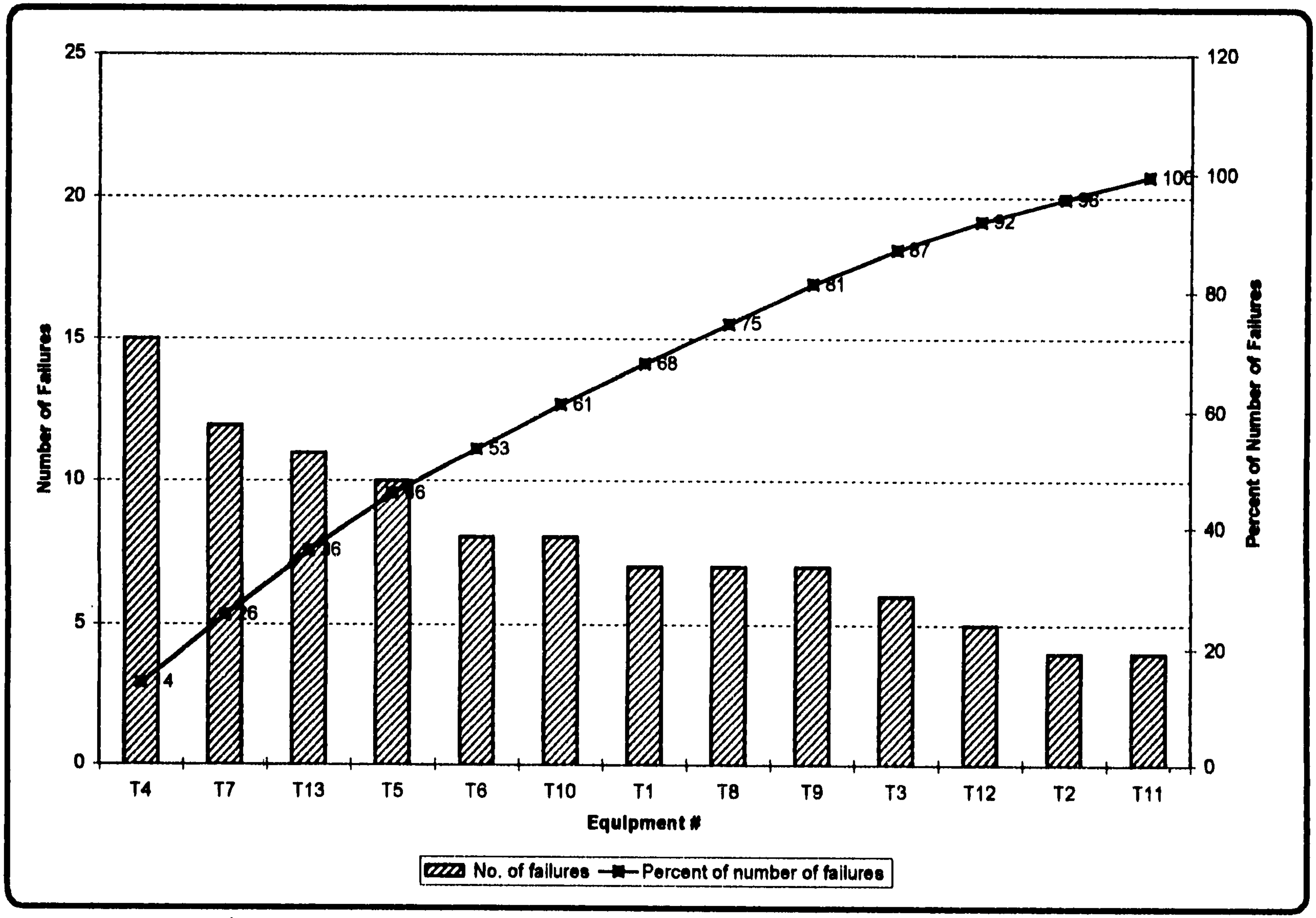


Figure 2.45. Pareto chart and analysis for number of failures of the bad actors steam turbines.

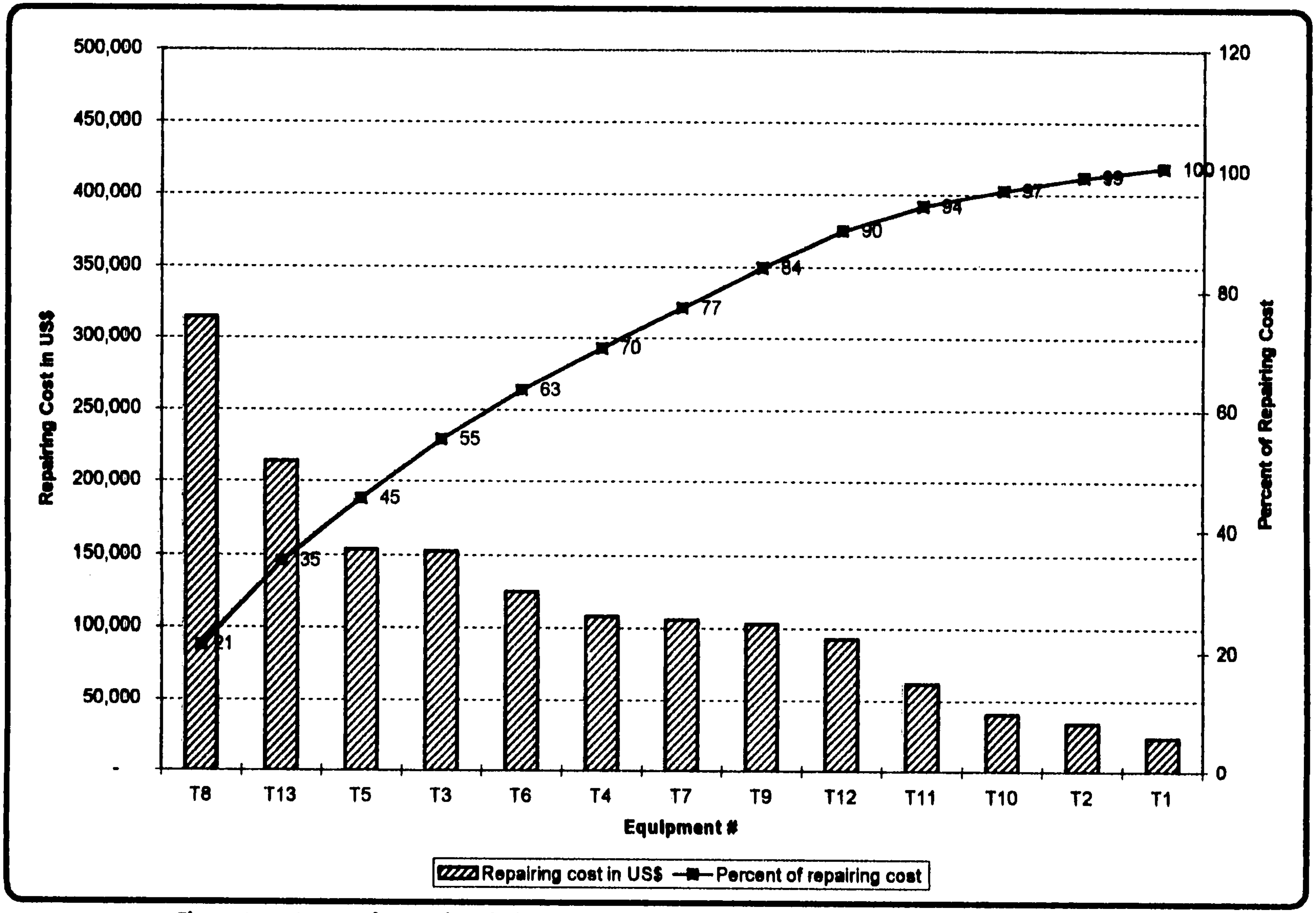


Figure 2.46. Pareto chart and analysis for maintenance repairing cost of the bad actors steam turbines.

Table 2.8. Determining the Failure Modes of all Most Critical Bad Actor Turbines.

Equipment #	***Code #***	***Time to Failure in Months***	***Failure Mode***	***Time to Repair*** (days)	***Repairing Cost in US $***
T1	35-3-GT104A	49	Coupling replacement	19	4,682
		51	Cooler leak	178	2,133
		55	Retube cooler	82	2,671
		56	Retube cooler	14	968
		64	Oil cooler	7	238
		65	Throttle valve repair	16	8,999
		66	Retube ejector	27	3,646
T3	35-3-GT103B	31	Governor repair	267	8,673
		44	Overhaul	111	12,456
		47	Rotor repair	175	2,721
		49	Governor repair	8	2,200
		63	Overhaul	26	11,864
		64	Overhaul	51	51,568
T4	032-KT106	8	Governor repair	15	1,231
		12	Lube oil leak	15	571
		13	Carbon seal	160	1,506
		15	Isolation valve repair	8	689
		17	Governor	30	583
		18	Trip valve repair	7	545
		34	Carbon seal	15	1,619
		35	Carbon seal	108	20,990
		41	Trip valve repair	14	2,953
		47	Oil leak	14	1,036
		48	Overhaul	64	12,460
		50	Oil leak	40	1,362
		51	Oil leak	149	2,447
		54	Overhaul	15	28,931
		61	Oil leak	123	1,131

cont ... Table 2.8

Equipment #	***Code #***	***Time to Failure in Months***	***Failure Mode***	***Time to Repair*** (days)	***Repairing Cost in US $***
T5	032-KT107	11	Governor repair	46	4,040
		12	Throttle valve	80	3,272
		26	Lube oil leak	20	4,483
		28	Governor	65	638
		30	Governor	31	2,320
		32	Throttle valve	35	1,201
		46	Governor	4	2,160
		54	Lube oil leak	71	4,229
		55	Cooler repair	314	1,302
		63	Governor	95	6,952
T6	32-GT111C	6	Throttle valve	32	1,540
		12	Oil level indicator	33	272
		15	Casing repair	175	10,026
		32	Bearing repair	32	6,647
		33	Governor	69	360
		44	Bearing	90	18,189
		49	Governor	175	9,756
		51	Governor	33	1,102
T7	32-GT111D	9	Throttle valve	34	1,325
		11	Governor	30	222
		12	Governor	33	136
		16	Governor	15	5,325
		27	Lube oil leak	87	926
		29	Overhaul	51	14,071
		37	Throttle valve	36	6,535
		47	Lube oil leak	41	5,632
		48	Governor	69	731
		51	Linkage repair	51	7,725
		52	Lube oil leak	250	1,230
		57	Throttle valve	35	2,347

cont ... Table 2.8

Equipment #	***Code #***	***Time to Failure in Months***	***Failure Mode***	***Time to Repair*** (days)	***Repairing Cost in US $***
T8	30-1-GT91B	5	Trip valve repair	70	2,320
		10	Throttle valve	41	3,369
		12	Governor	299	3,121
		32	Replace the lube oil motor	35	2,162
		49	Overhaul	80	107,194
		51	Casing steam leak	22	47,313
		58	Over-speed trip valve	25	6,465
T9	30-1-GT90B	5	Steam leak	230	540
		9	Governor	33	1,235
		10	Carbon seal	81	10,119
		11	Governor	75	446
		16	Trip valve repair	68	10,153
		18	Throttle valve	30	5,231
		28	Carbon seal	56	11,935
T10	32-KT108	8	Repair water line	30	531
		31	Water leak	1	825
		32	Carbon seal	26	6,114
		44	Control valve	3	530
		45	Oil leak	95	3,211
		46	Oil leak	72	4,095
		48	Linkage repair	51	450
		49	Linkage repair	217	2,432
T13	30-1-GT91A	4	Packing seal	100	6,220
		6	Bearing repair	56	5,230
		9	Governor	103	8,359
		15	Bearing	32	349
		16	Steam leak	57	9,035
		20	Steam leak	46	9,996
		24	Throttle valve	257	9,332

cont ... Table 2.8

Equipment #	***Code #***	***Time to Failure in Months***	***Failure Mode***	***Time to Repair*** (days)	***Repairing Cost in US $***
T13	30-1-GT91A (cont...)	30	Governor	7	272
		33	Casing leak	67	18,655
		42	Lube oil leak	35	1,381
		59	Throttle valve	33	2,625

trip-off for these steam turbines. The failure modes and its percentage compare to other failure modes are plotted in Pie chart, as shown in Figure 2.47 through Figure 2.56.

The failure mode versus total number of failures of the most critical steam turbines are also plotted to see what is the highest type of failures in steam turbine bad actors and this is shown in Figure 2.57.

It is found that the highest number of failures in turbines are due to repairable parts (78%). These are governors (28%), lubrication oil coolers (25.7%) and throttle valves (24.3%). Figure 2.57 shows also that the non-repairable parts have low number of failures compared with repairable parts (11.6%). The non-repairable parts of the most critical bad actors steam turbines are found to be 9.5% for seals and 4.1% for bearings.

There are four different failure modes for the most critical steam turbines, which are defined as follows:

- ***Governor*** . . . . A failure of a turbine due to malfunction of the governor.
- ***Lube Oil Cooler*** . . . . A failure due to repairing the lubrication oil cooler of the turbine which some times become corroded.
- ***Throttle Valve*** . . . . . . A failure of the turbine due to the malfunction of the throttle valve.
- ***Seal*** . . . . A failure due to the malfunction of the turbine seal.

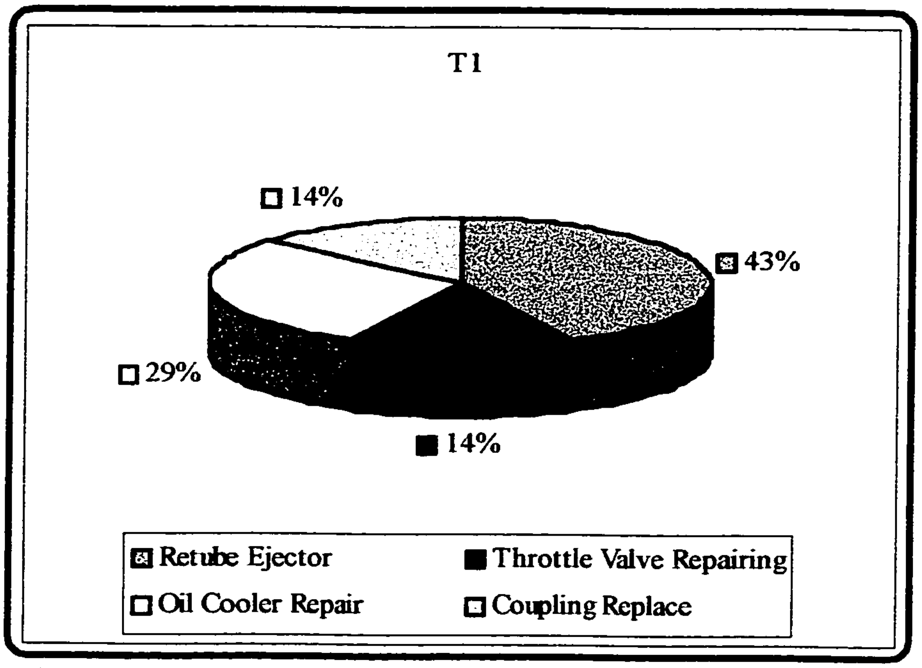


Figure 2.47. Comparison of failure modes and its percentage to other failure modes for turbine T1.

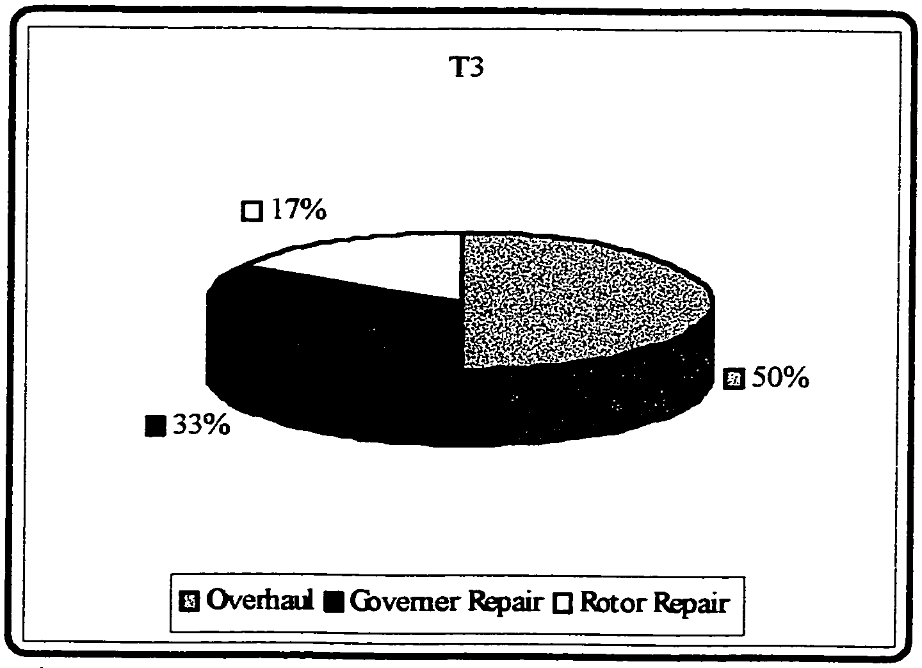


Figure 2.48. Comparison of failure modes and its percentage to other failure modes for turbine T3.

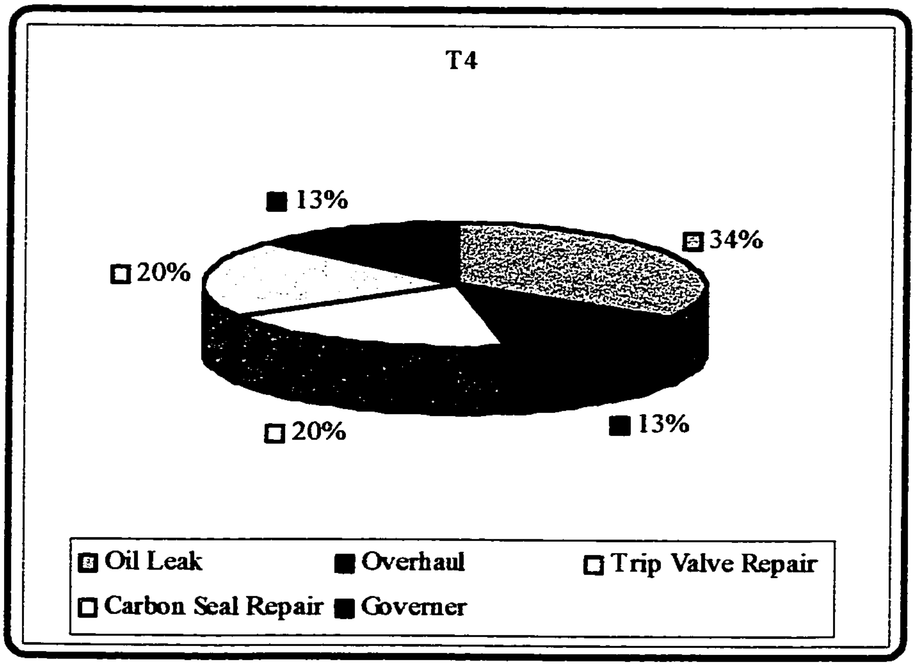


Figure 2.49. Comparison of failure modes and its percentage to other failure modes for turbine T4.

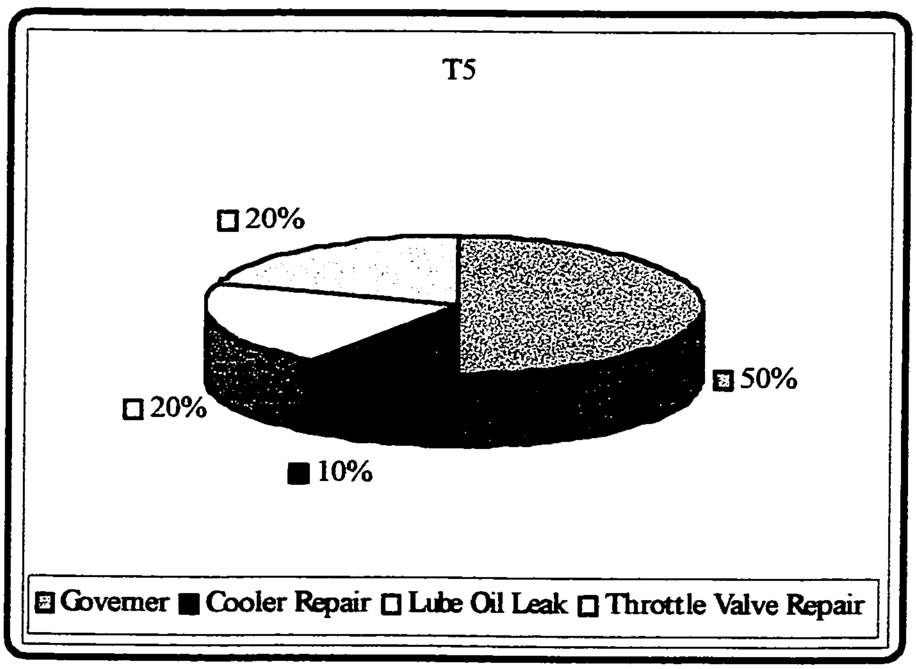


Figure 2.50. Comparison of failure modes and its percentage to other failure modes for turbine T5.

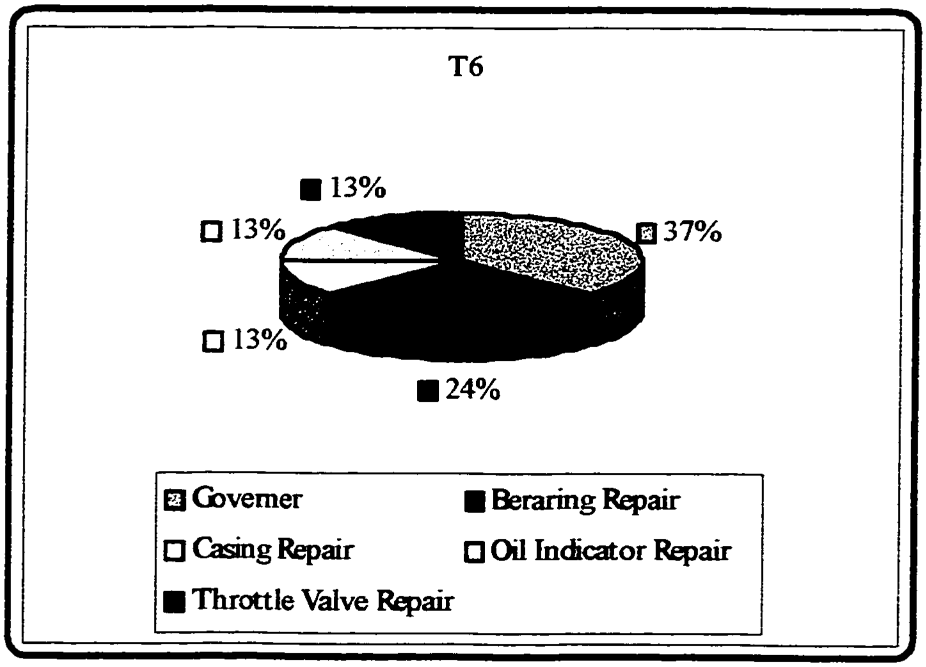


Figure 2.51. Comparison of failure modes and its percentage to other failure modes for turbine T6.

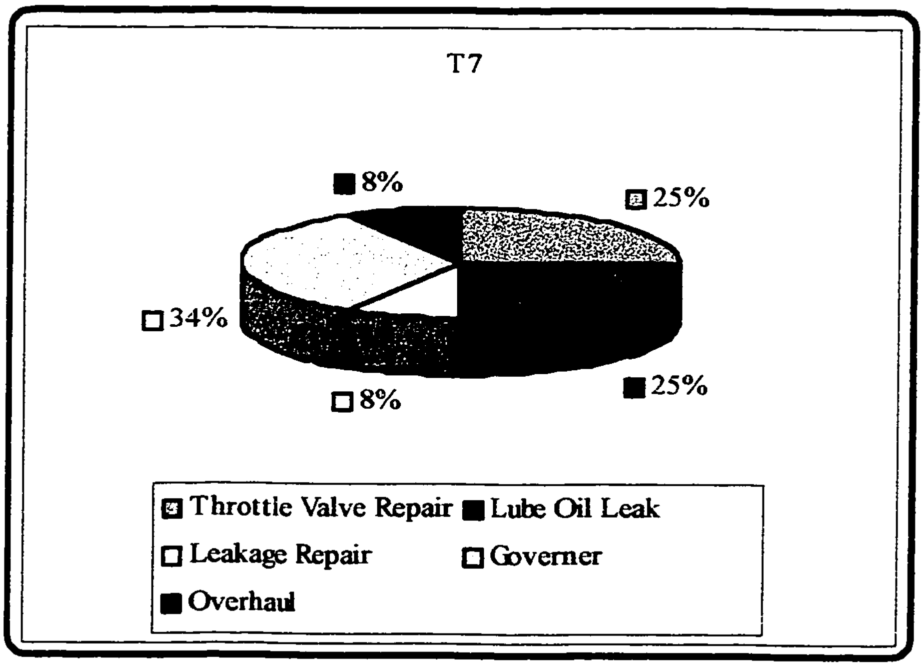


Figure 2.52. Comparison of failure modes and its percentage to other failure modes for turbine T7.

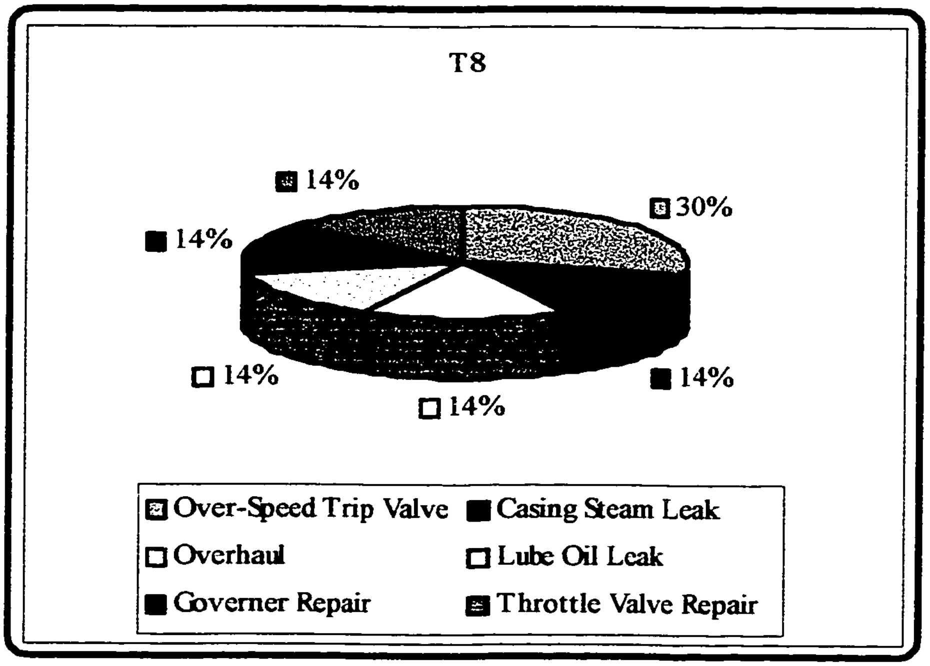


Figure 2.53. Comparison of failure modes and its percentage to other failure modes for turbine T8.

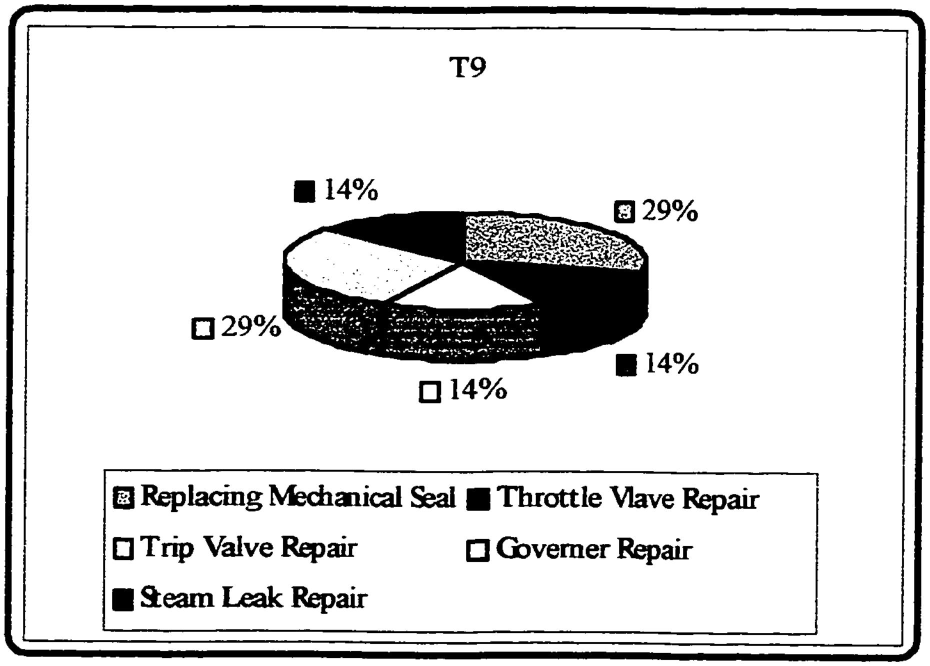


Figure 2.54. Comparison of failure modes and its percentage to other failure modes for turbine T9.

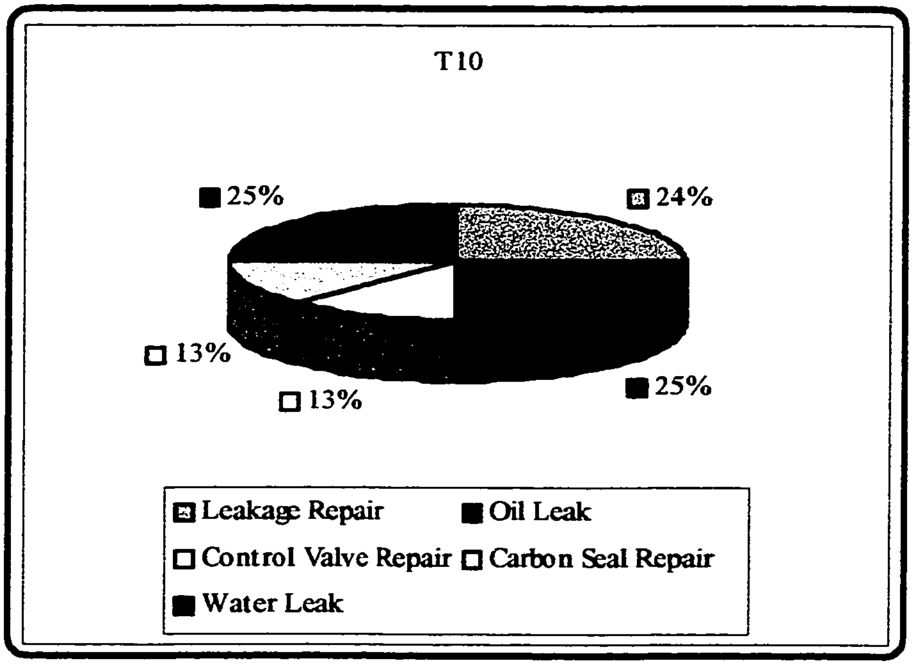


Figure 2.55. Comparison of failure modes and its percentage to other failure modes for turbine T10.

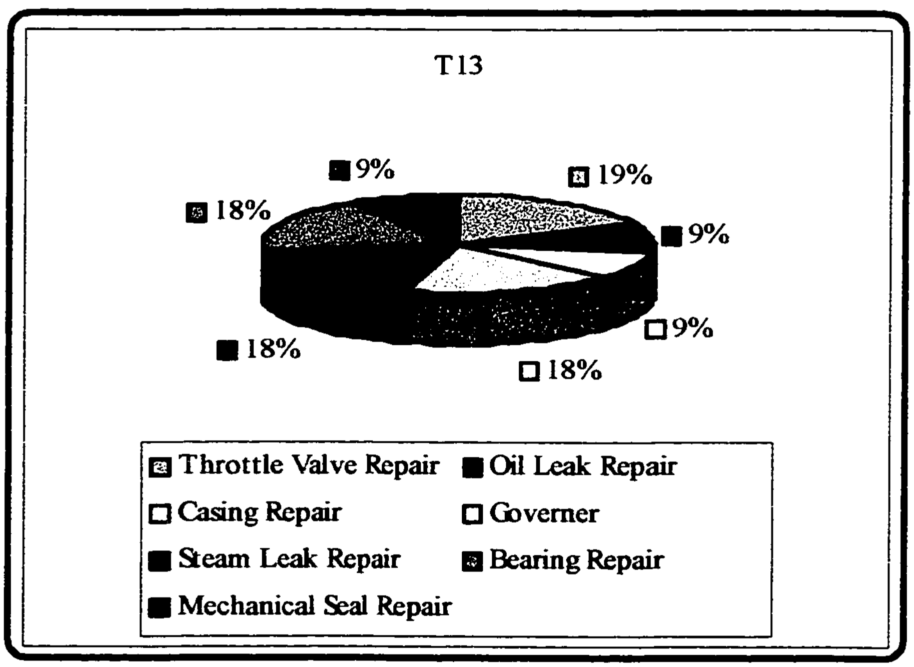


Figure 2.56. Comparison of failure modes and its percentage to other failure modes for turbine T13.

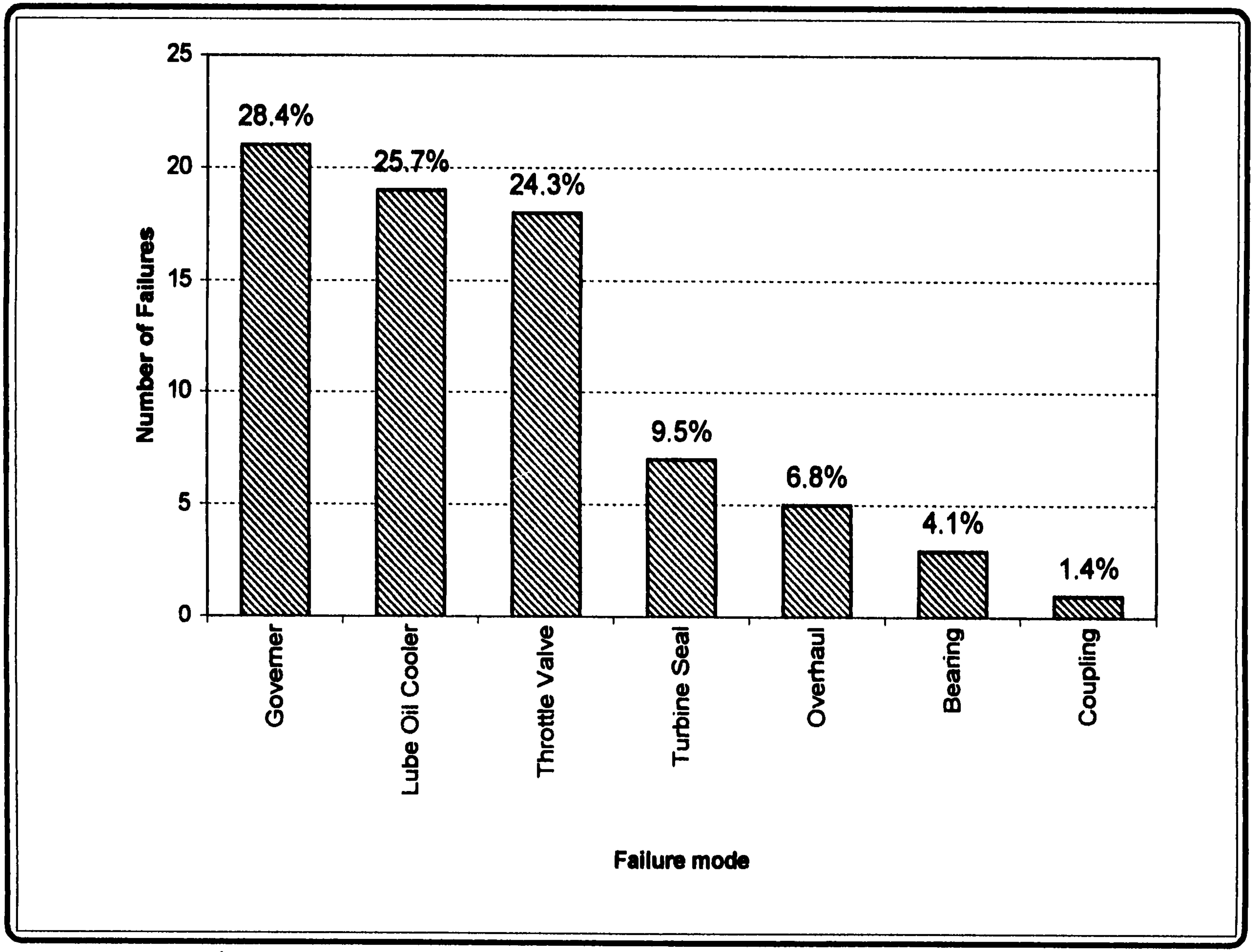


Figure 2.57. The failure modes versus number of failures for most critical bad actors turbines.

2.3.3 Reliability Parameters

Since there is no trend for the time between failure data of the most critical bad actors steam turbines as shown in Appendix A, Figures A-5 through A-8, Weibull model should be used for reliability analysis.

As a part of reliability analysis, each bad actor steam turbine time between failure for all modes of failures were gathered and with utilization of Weibull analysis, the shape parameter, β, and the characteristic life, η, were determined as shown in Figure 2.58 through Figure 2.67.

Also, the reliability charts for some selected bad actor steam turbines were plotted in Figure 2.68 through Figure 2.70. The reliability parameters are summarized in Table 2.9 for the most critical bad actors steam turbines.

Table 2.9. Reliability Parameters for the Most Critical Steam Turbines.

Equipment #	*Code #*	β	η (months)	*MTBF* (months)	*Standard Deviation*	*Variation Coefficient*	$T_{0.5}$ (months)
T1	35-3-GT104A	0.91	3.33	3.46	3.77	1.08	2.24
T3	35-3-GT103B	0.72	7.61	9.29	13.00	1.39	4.60
T4	32-KT106	1.04	4.08	4.01	3.85	0.95	2.88
T5	32-KT107	0.84	6.40	6.98	8.27	1.18	4.16
T6	32-GT111C	0.96	7.28	7.41	7.72	1.04	4.98
T7	32-GT111D	1.05	4.89	4.79	4.55	0.94	3.46
T8	30-1-GT91B	0.87	10.30	17.50	28.52	1.63	7.07
T9	30-1-GT90B	0.94	4.45	4.57	4.84	1.05	3.03
T10	32-KT108	0.56	5.72	9.34	17.69	1.89	3.00
T13	30-1-GT91A	1.23	6.22	5.82	4.74	0.81	4.63

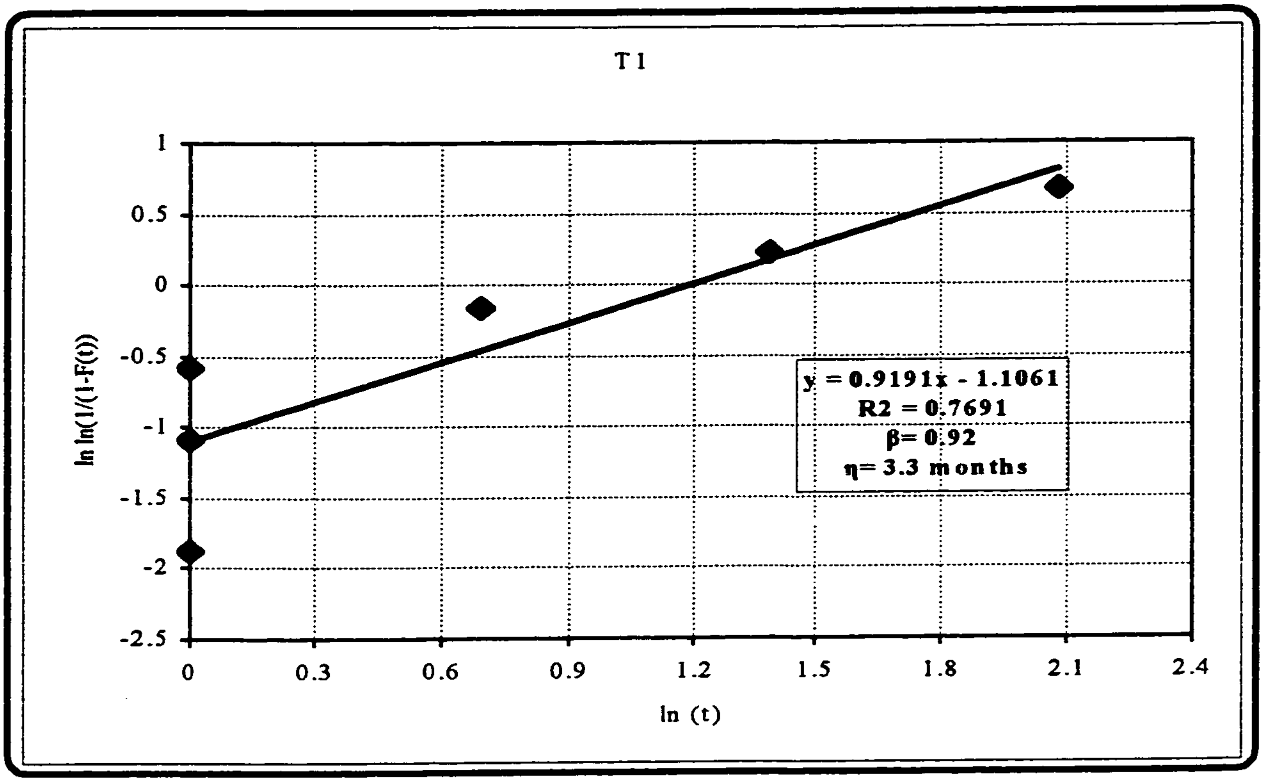


Figure 2.58. Weibull plot for the most critical bad actor steam turbine T1.

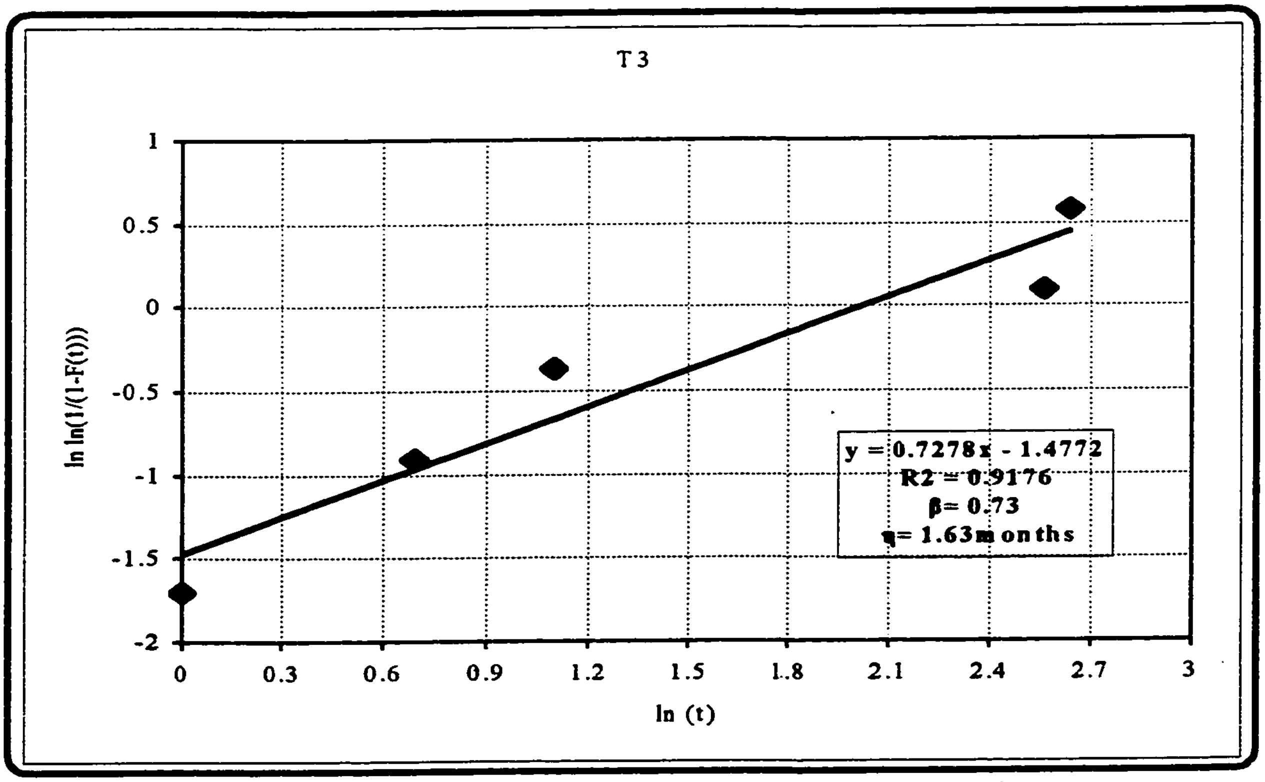


Figure 2.59. Weibull plot for the most critical bad actor steam turbine T3.

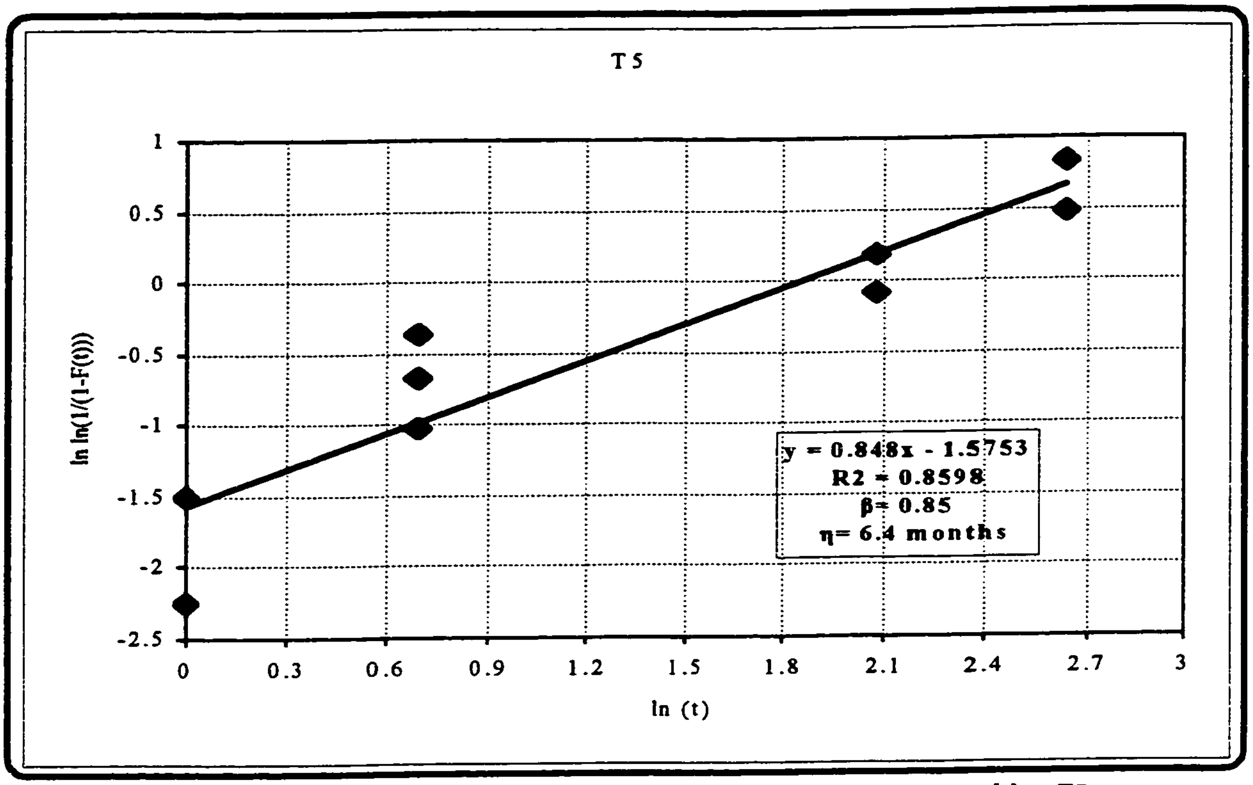


Figure 2.60. Weibull plot for the most critical bad actor steam turbine T5.

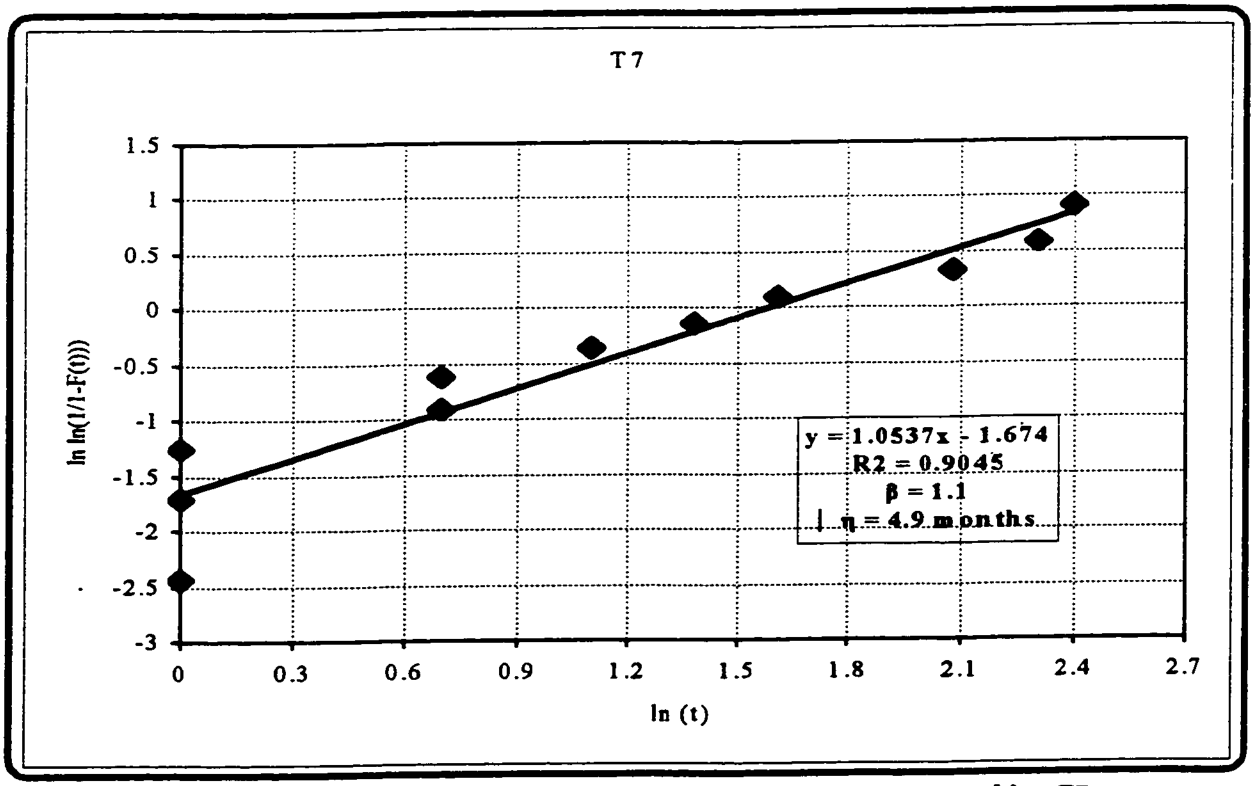


Figure 2.61. Weibull plot for the most critical bad actor steam turbine T7.

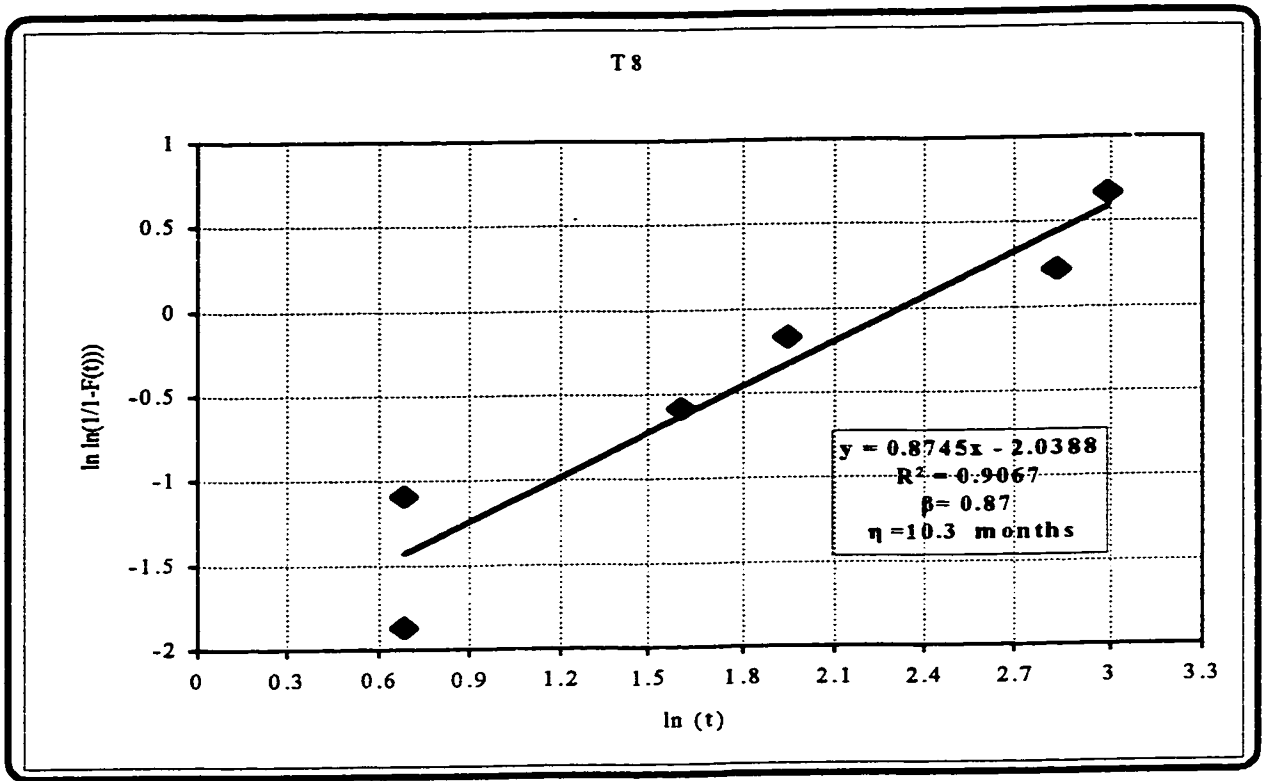


Figure 2.62. Weibull plot for the most critical bad actor steam turbine T8.

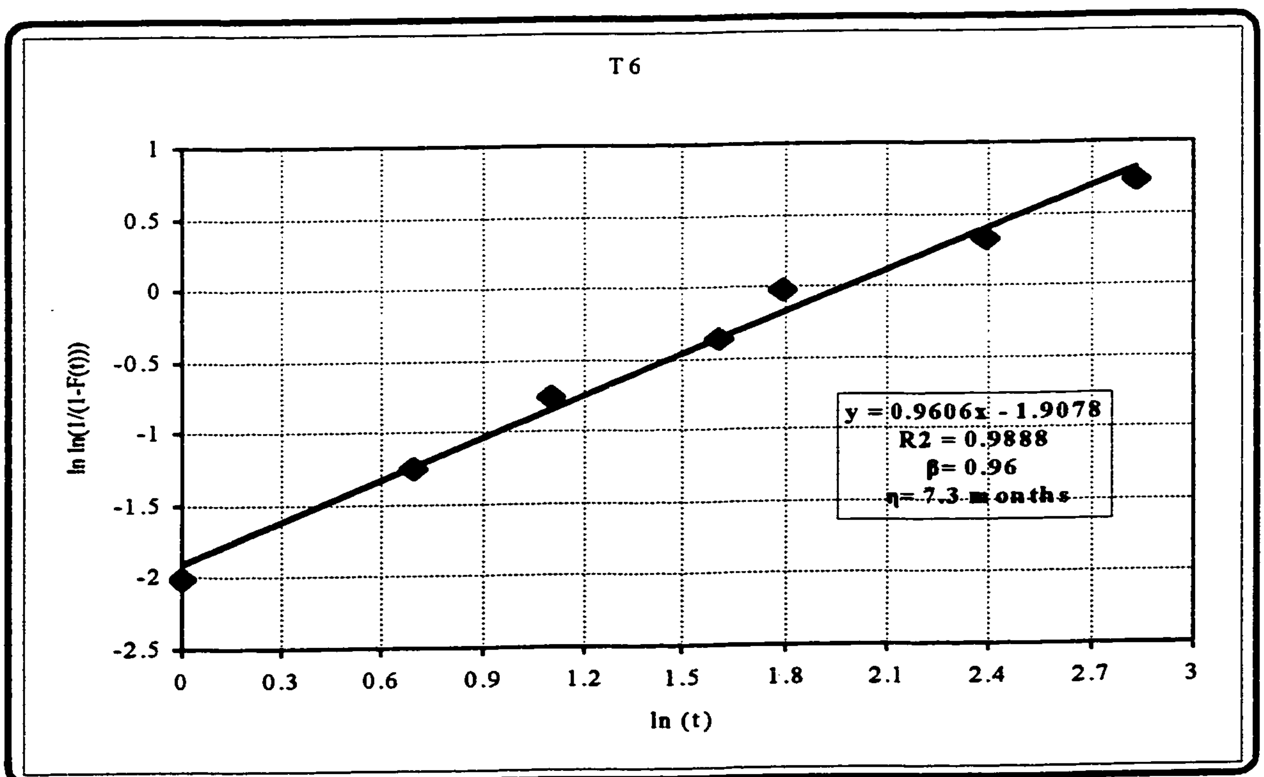


Figure 2.63. Weibull plot for the most critical bad actor steam turbine T6.

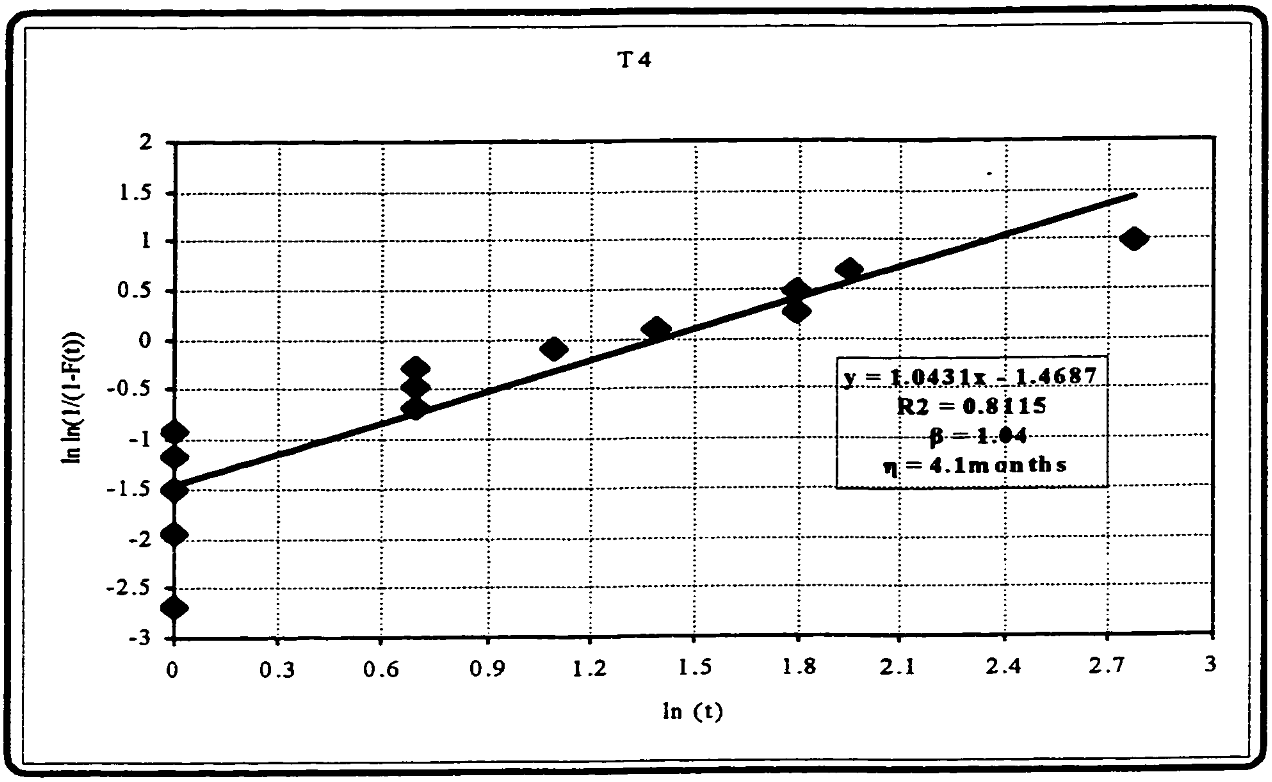


Figure 2.64. Weibull plot for the most critical bad actor steam turbine T4.

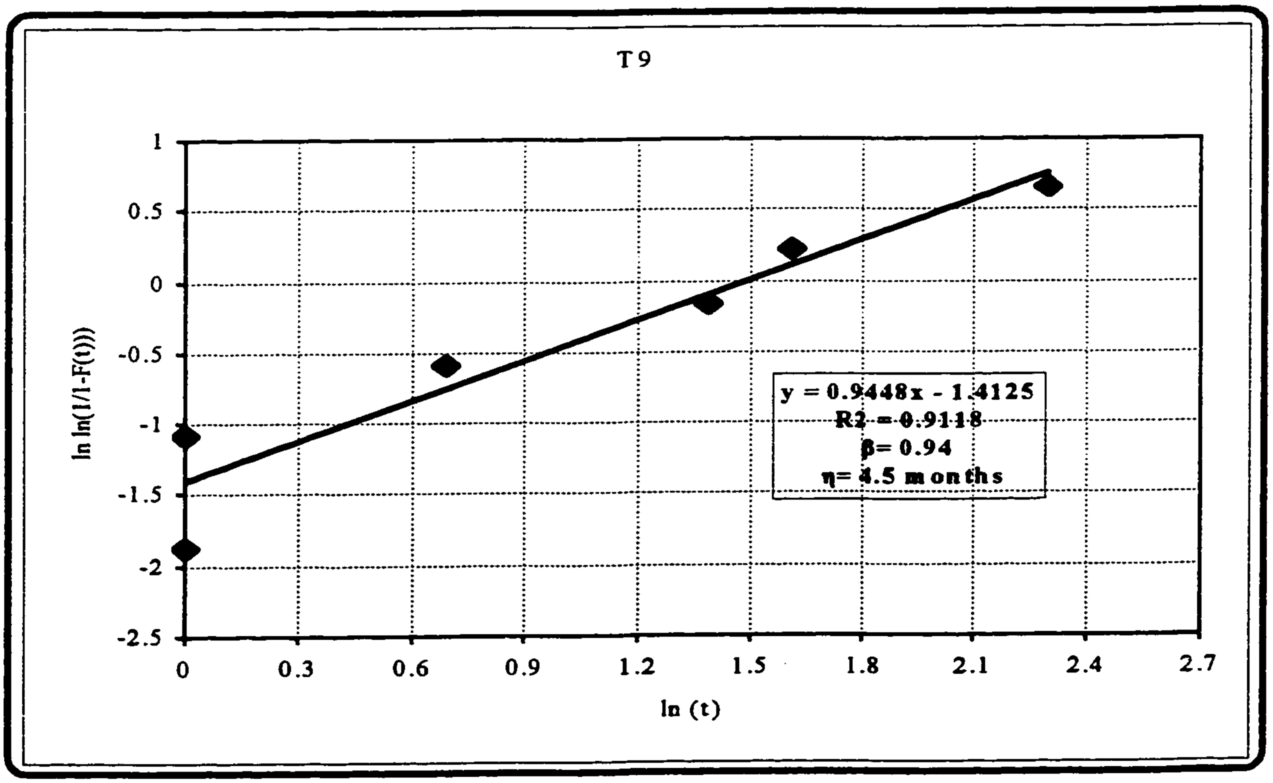


Figure 2.65. Weibull plot for the most critical bad actor steam turbine T9.

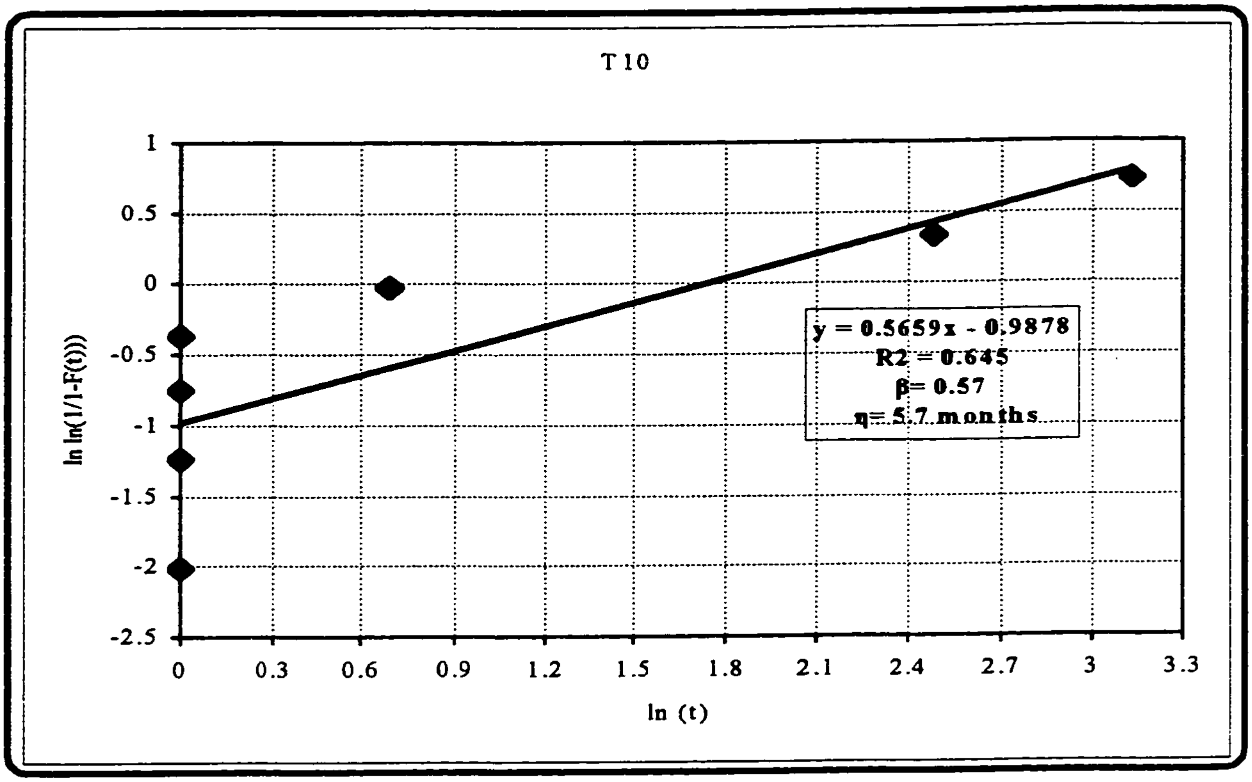


Figure 2.66. Weibull plot for the most critical bad actor steam turbine T10.

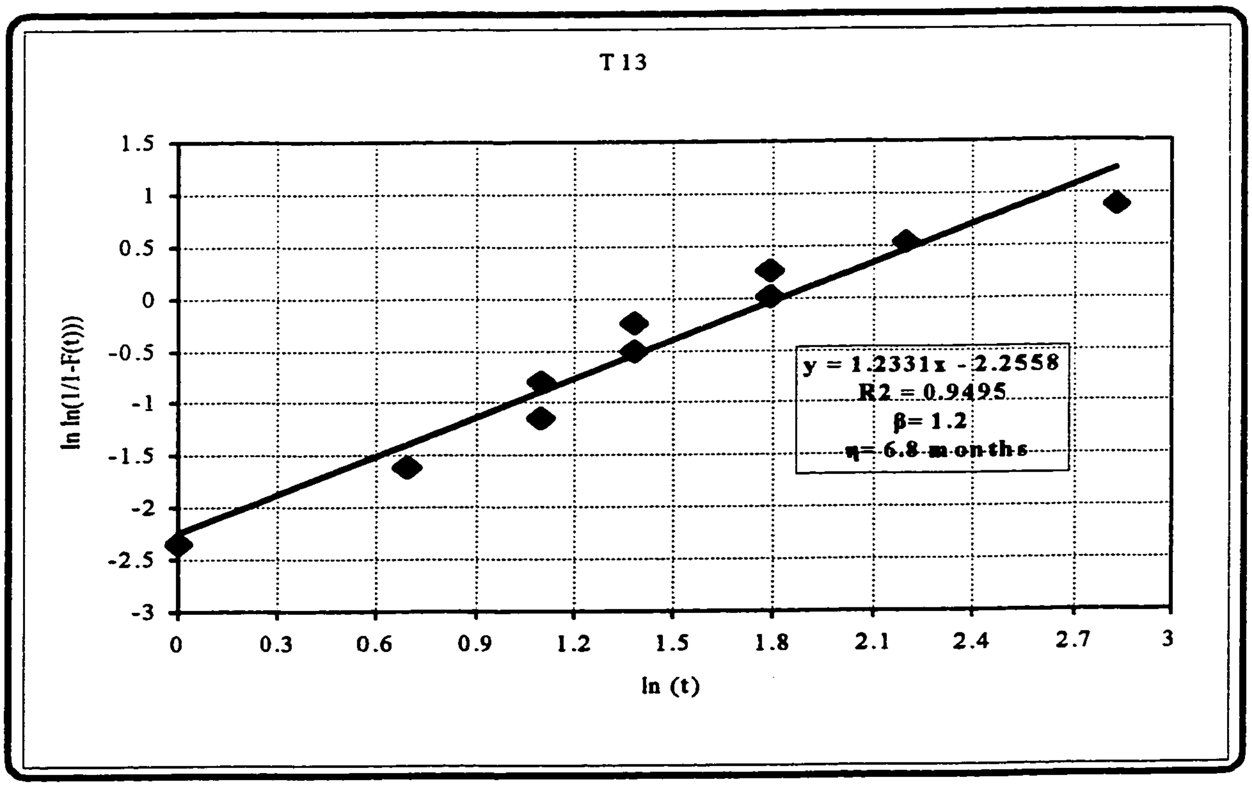


Figure 2.67. Weibull plot for the most critical bad actor steam turbine T13.

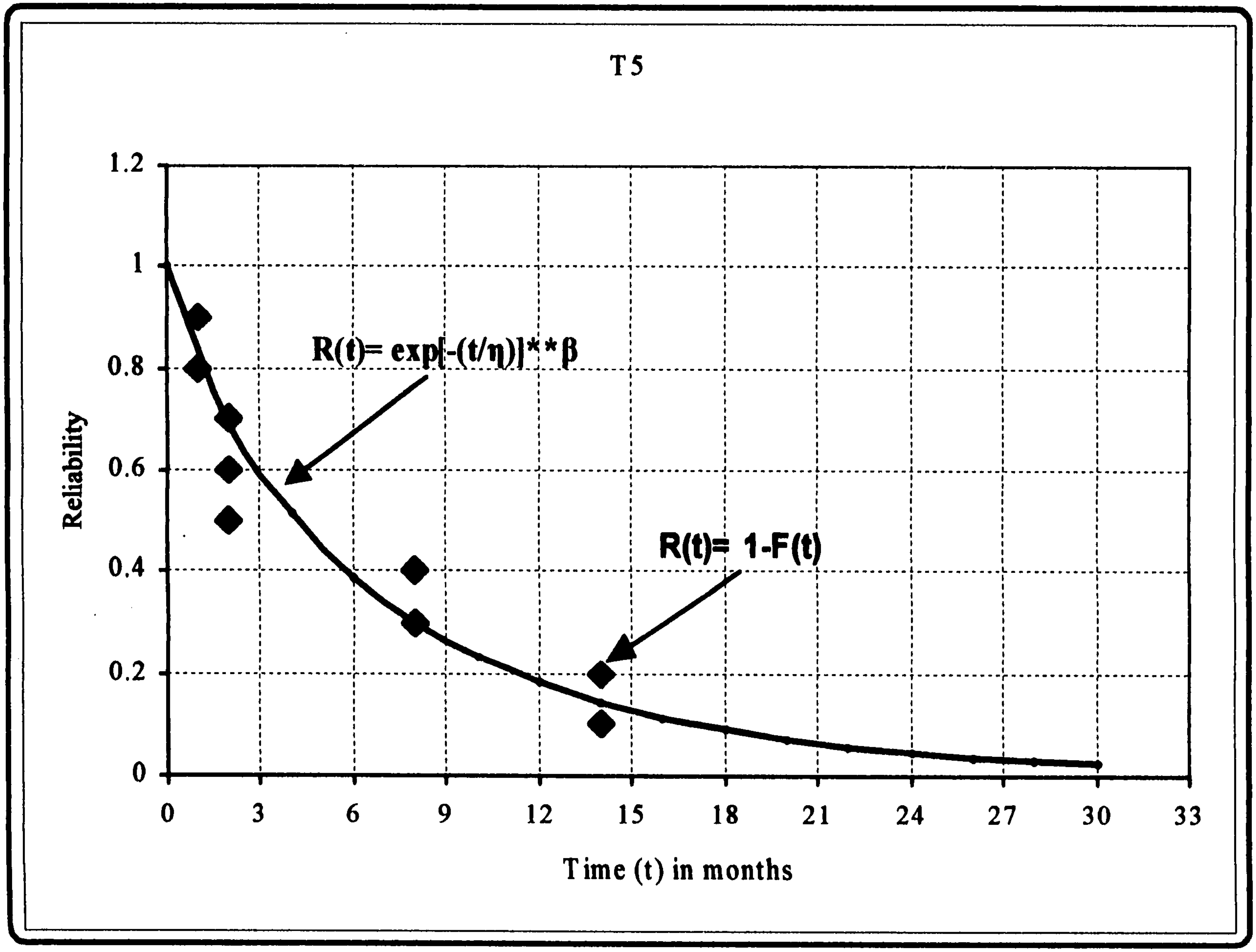


Figure 2.68. Reliability chart for bad actor steam turbine T5.

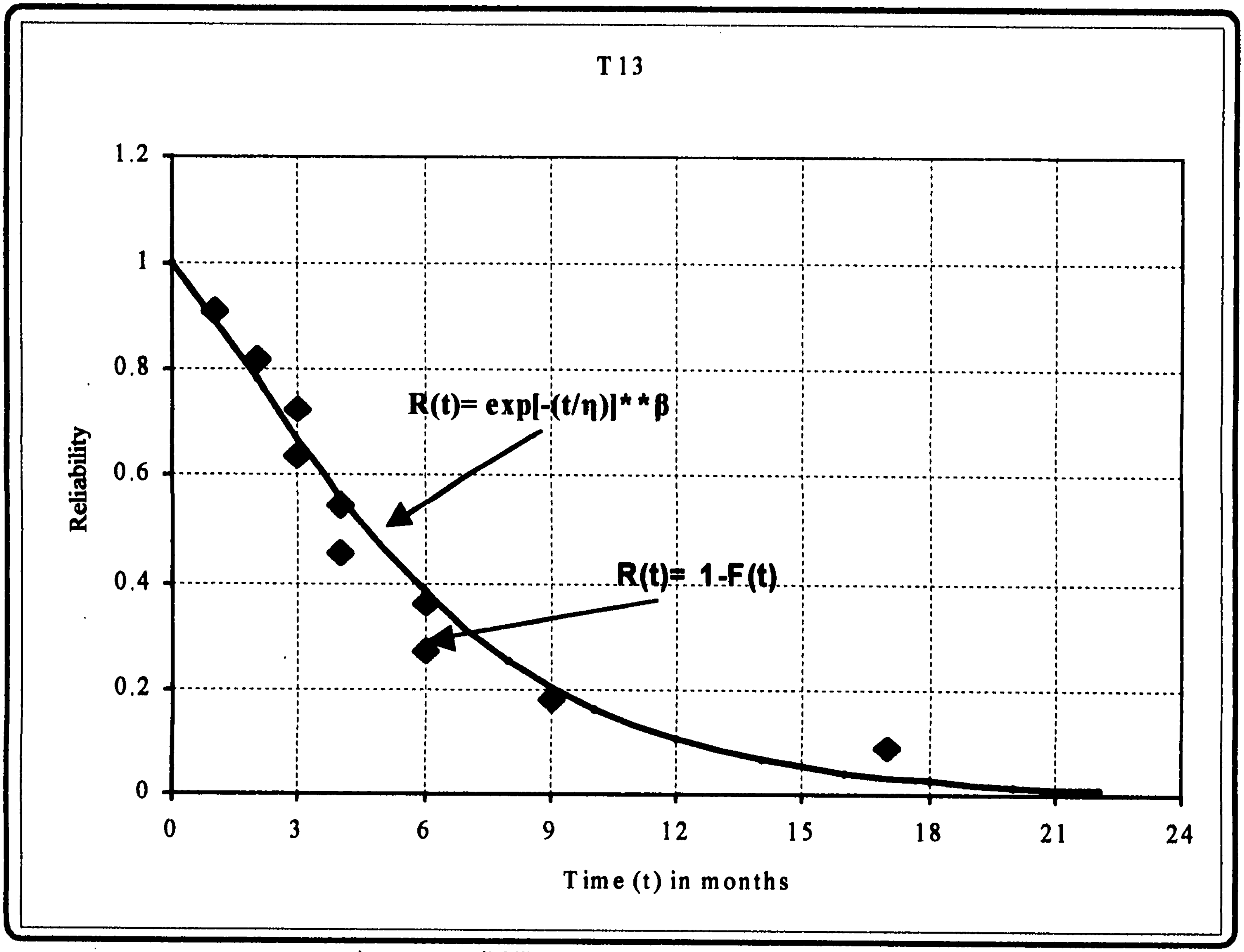


Figure 2.69. Reliability chart for bad actor steam turbine T13.

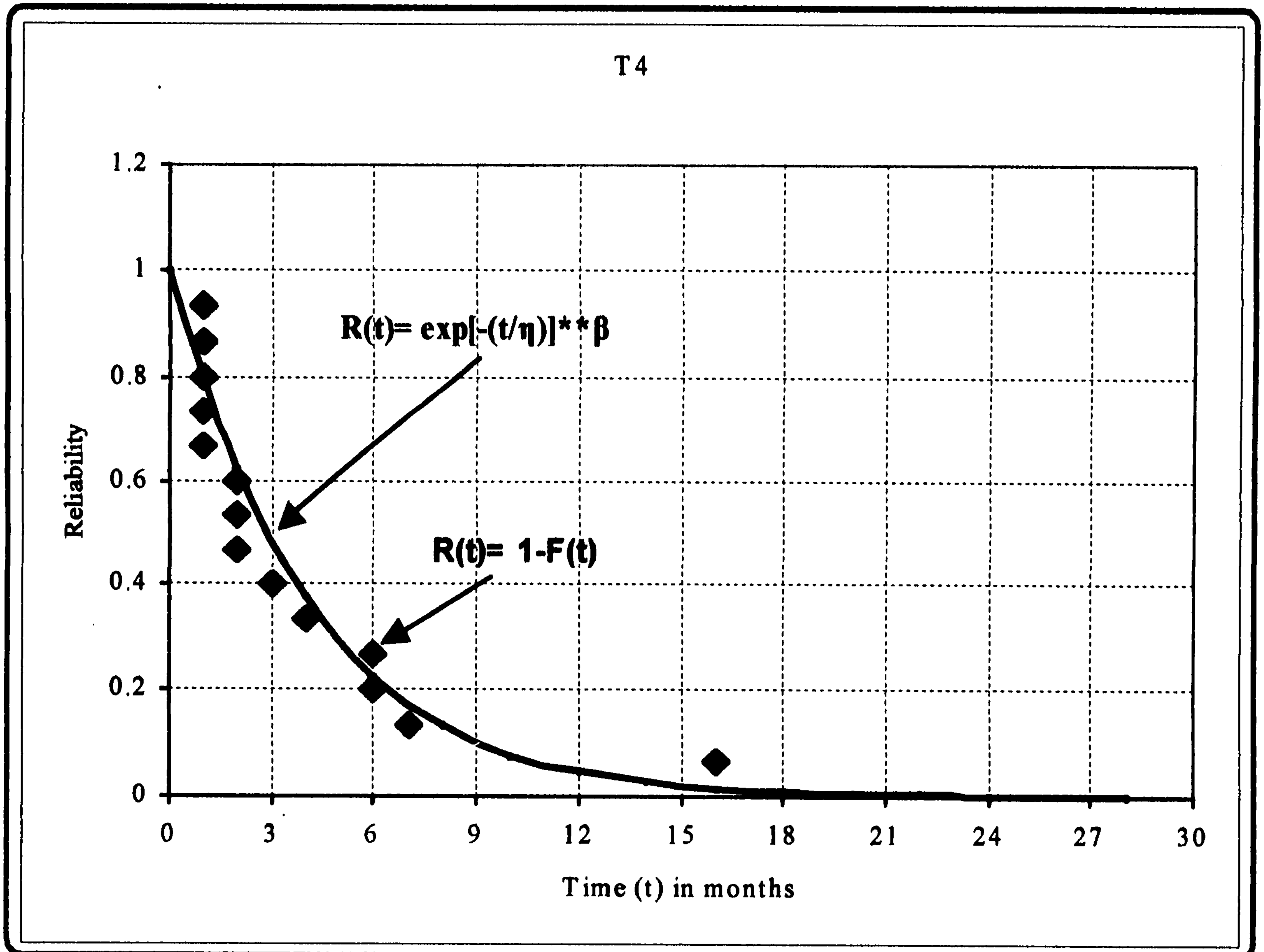


Figure 2.70. Reliability chart for bad actor steam turbine T4.

2.3.4 Weibull Analysis for Non-Repairable Parts

The frequent non-repairable failed parts of the most critical steam turbines are seals. As shown in the Weibull plot of the steam turbine seals (Figure 2.71), the shape parameter $\beta = 1.1$ and the characteristic life $\eta = 26.4$ months, which gives us an indication that these seals can last for approximately 26 months before they failed and they should be put under on-line monitoring and report immediately any abnormal operation.

2.3.5 Cost Analysis

2.3.5.1 Repairable Parts

It was found from Figure 2.57 that the highest modes of failures of the repairable parts of the most critical bad actors steam turbines are governor, lube oil cooler and throttle valve. The cost analysis for these parts are shown in Figure 2.72 through Figure 2.74. In these figures, the repairing cost versus the five years of operation are plotted to show that is it worth from economic point of view to continue repairing these parts or it is better to do modification repair on them.

The cost analysis of the repairable parts of the turbines include the mechanical governors, lubrication oil coolers and throttle valves. For steam turbines mechanical governor, the repairing cost period is repeated each 20 months and is getting increased. So, it is recommended to retrofit the mechanical governor to electronic governors to eliminate the frequent failures of the mechanical parts. Most of the lubrication oil coolers repairing cost was spent in the last 10 months of our investigation period which is five years. To minimize the spending maintenance cost on these coolers, we recommend to replace them with new coolers. By referring to their history, they have a severe corrosion and cannot be repaired. The throttle valves repairing cost figure shows a high amount of money was spent in the first 20 months but still it shows continuous spending of money. Since the throttle valve is very important from the safety point of view, it is recommended to be replaced by new valves.

2.3.5.2 Non-Repairable Parts

The non-repairable parts of the bad actors steam turbines found to be seals. Here we pooled together all bad actors steam turbines seals. Figure 2.75 shows the time between failures and the accumulative cost of the steam turbine seals. The non-repairable parts of turbines which is seal do not have a significant problem. It last 15 months with no spending of money and it is logic when you know that the seal characteristic life is around 27 months.

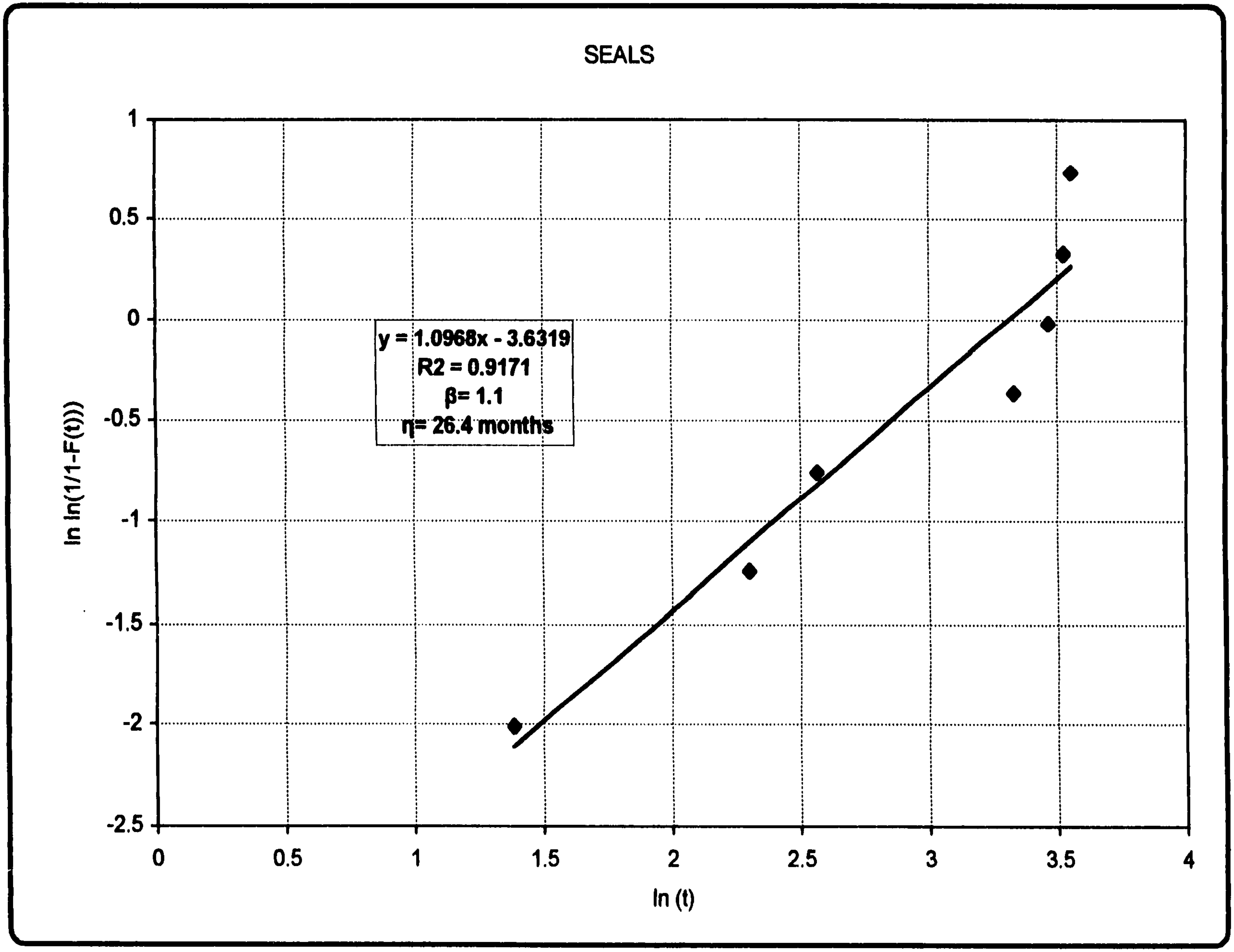


Figure 2.71. Weibull plot for the most critical bad actors turbine seals.

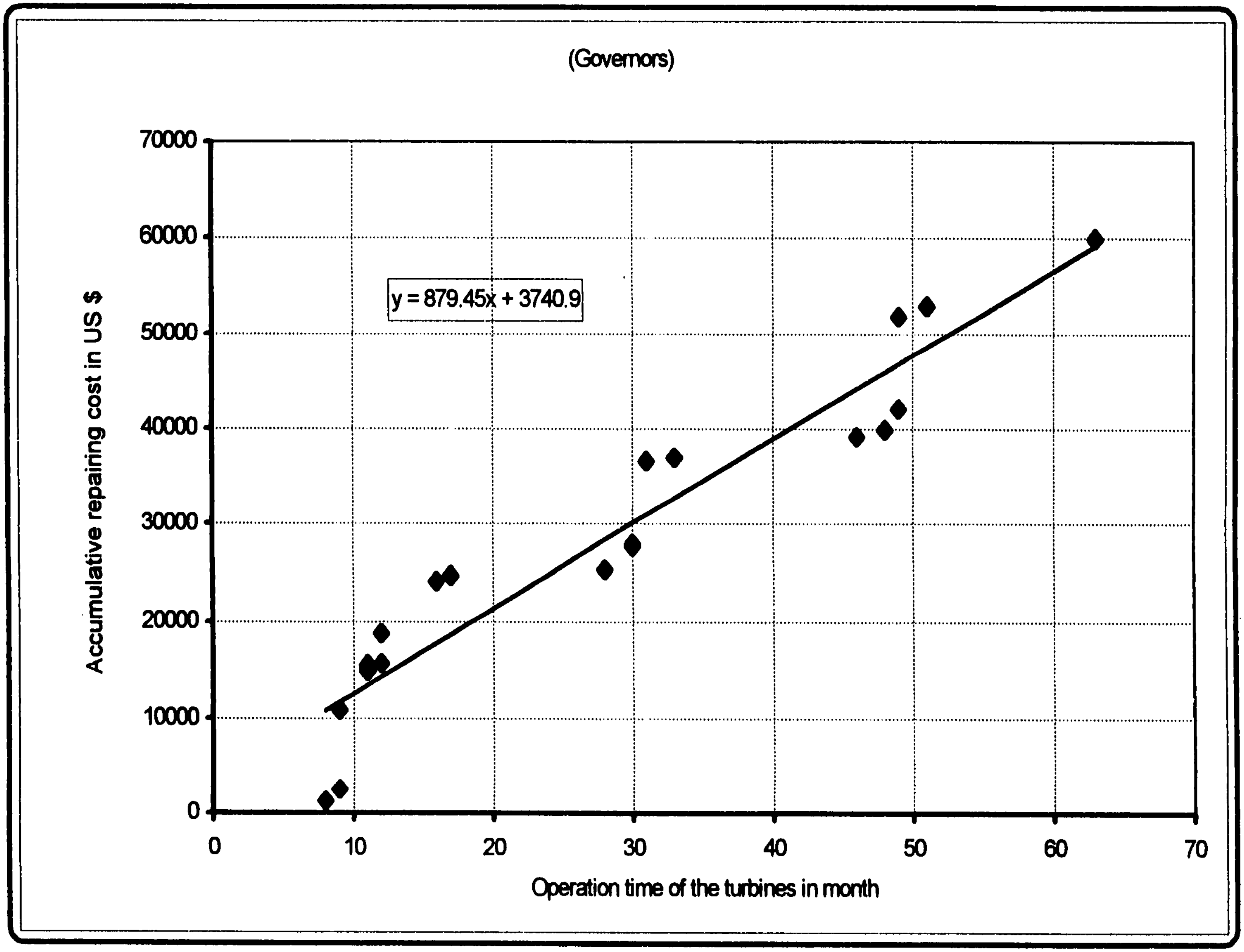


Figure 2.72. Accumulative repairing cost for bad actor steam turbines, governors (repairable parts).

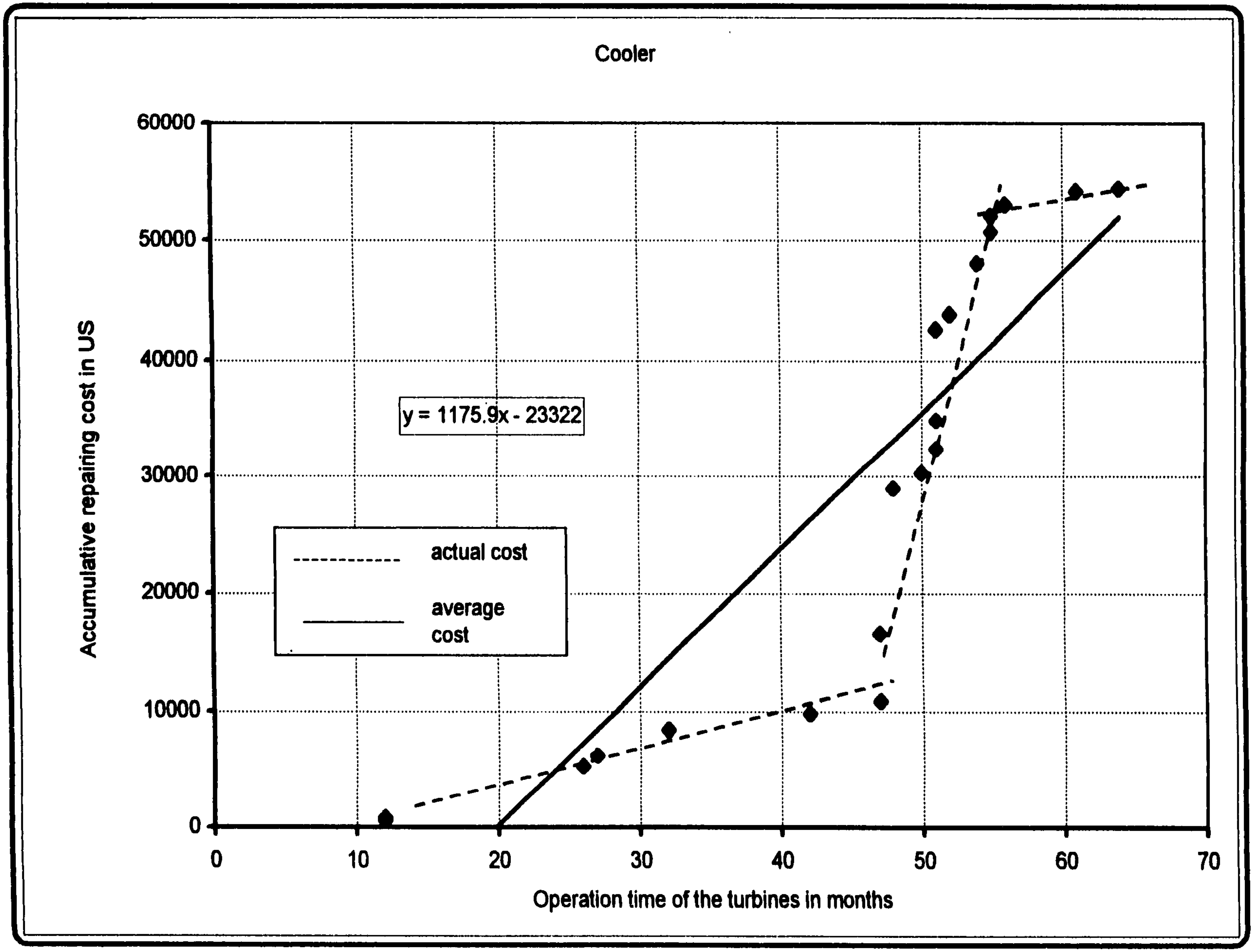


Figure 2.73. Accumulative repairing cost for bad actors steam turbines, coolers (repairable parts).

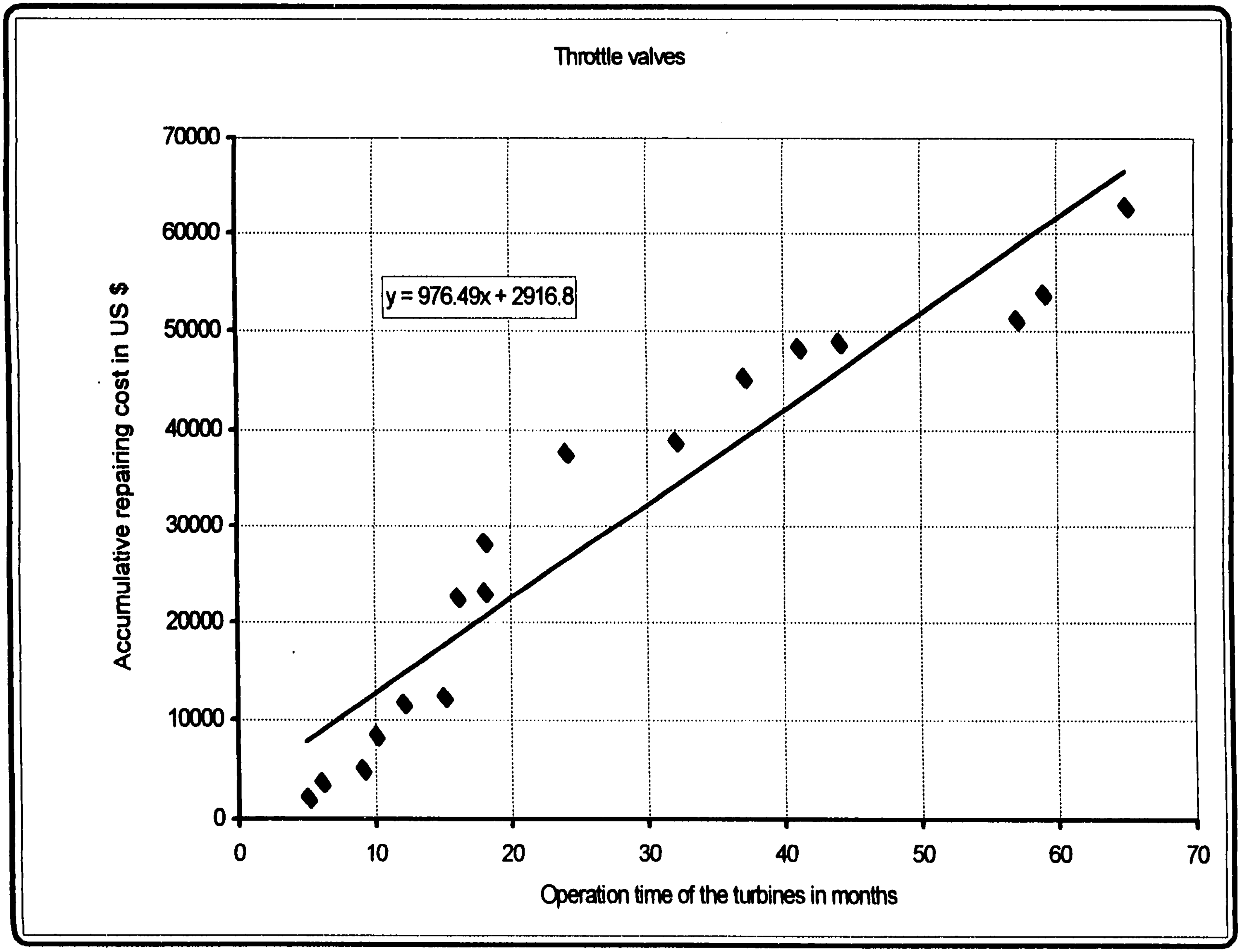


Figure 2.74. Accumulative repairing cost for bad actors steam turbines, throttle valves (repairable parts).

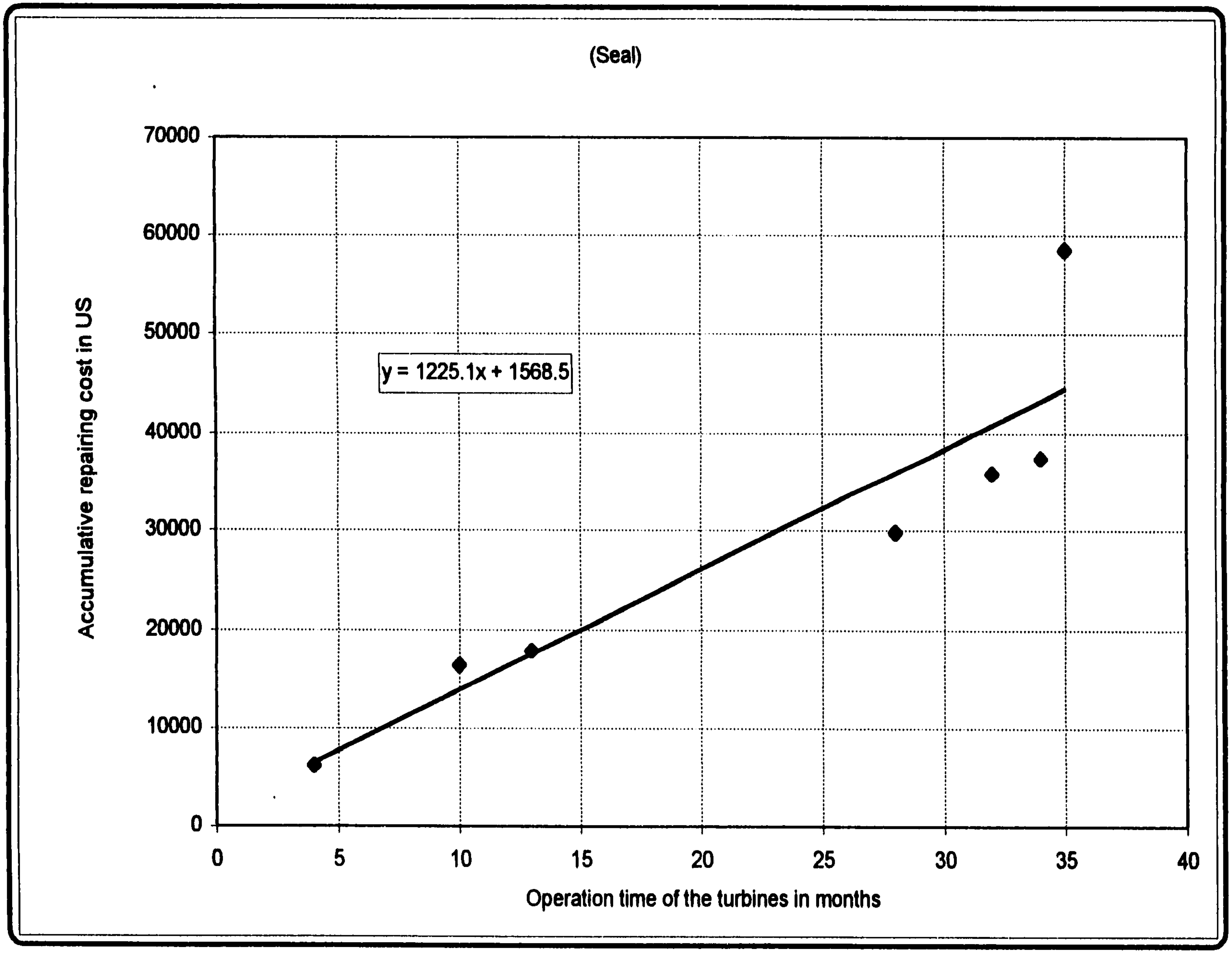


Figure 2.75. Accumulative repairing cost for bad actors steam turbines, seals (non-repairable parts).

2.4 Motors

The survey covered 342 motors and found that only 12 motors are bad actors, as shown in Table 2.10. To determine the most critical bad actors motors, we sorted the bad actors motors by the number of failure and repairing cost as shown in the Pareto charts (Figures 2.76 and 2.77). From these figure, seven (7) motors were chosen to be the most critical bad actors as shown in Table 2.11.

The Pareto criterion is to study and resolve the 60% of failure problems and 60% of the repairing cost problems of the motors. There are six motors under the number of failures curve which is below 60% as shown in Figure 2.76, and there are three motors in the repairing cost chart as shown in Figure 2.77. From these two figures, there are two common motors, so we choose them as the most critical bad actors motors and the other five are chosen because they are either under the number of failures chart or under the repairing cost chart.

Table 2.10. Bad Actors Motors.

Equipment #	*Code #*	*Description*	*Failures in 5 years*	*Cost in US $*
M4	34-1-GM983D	Motor for booster pump	5	22,610
M2	38-GM12	Motor for fire water pump	5	14,624
M12	30-2-GM241D	Motor for pump	5	13,171
M5	34-1-GM56	Motor for pump	4	9,585
M7	30-2-GM42	Motor for pump	4	5,480
M11	38-GM103	Motor for fire water pump	3	20,879
M9	38-GM11	Motor for fire water pump	3	18,786
M1	32-FM102	Motor for F. D. Fan	3	12,272
M10	33-K13LOP	Motor for L. O. pump	3	12,186
M8	30-2-GM17	Motor for pump	3	8,486
M6	30-2-GM18	Motor for pump	3	8,455
M3	30-2-GM25	Motor for pump	3	5,947

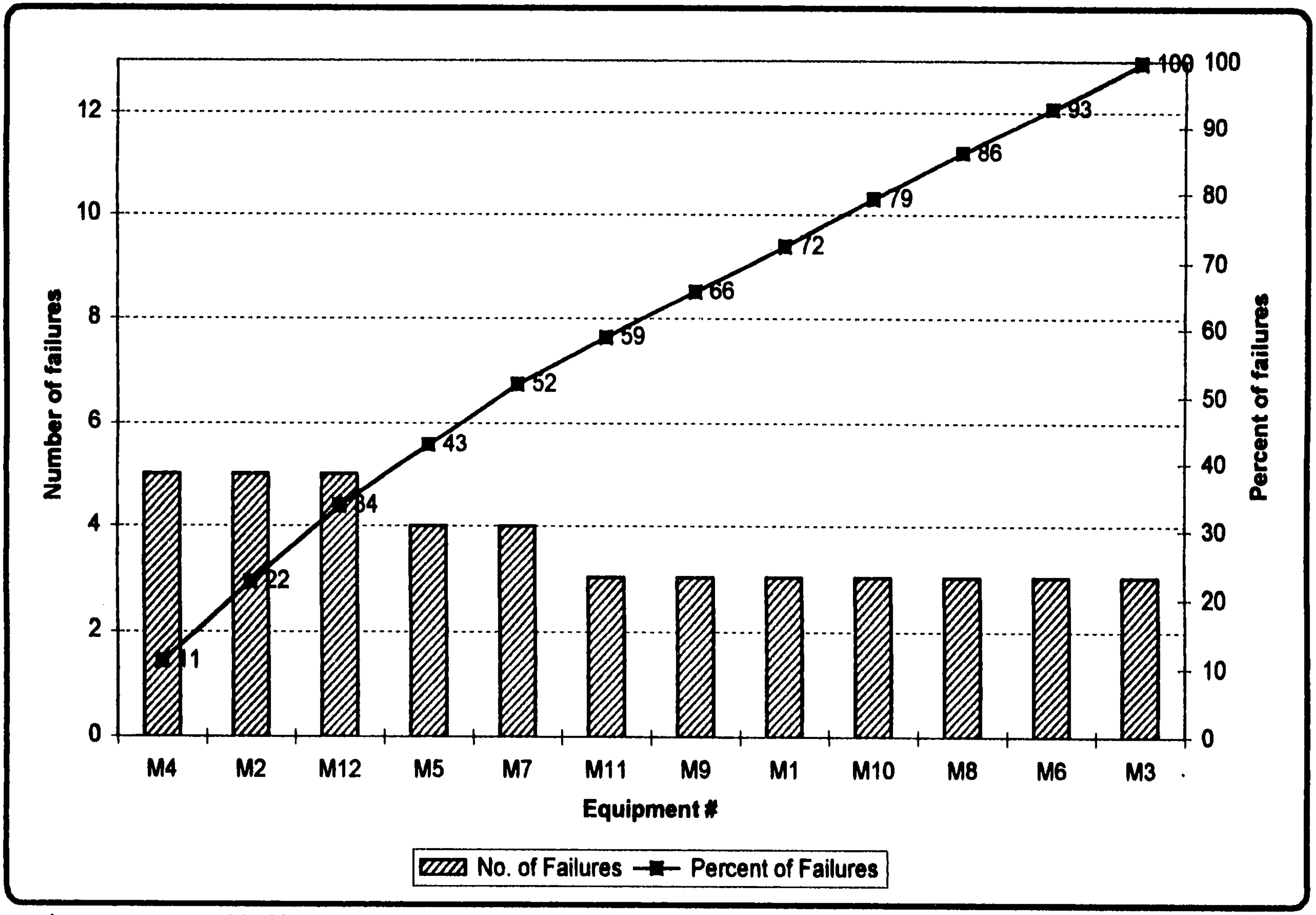


Figure 2.76. Most critical bad actors motors identified by sorting the bad actors motors by their number of failures (Pareto analysis).

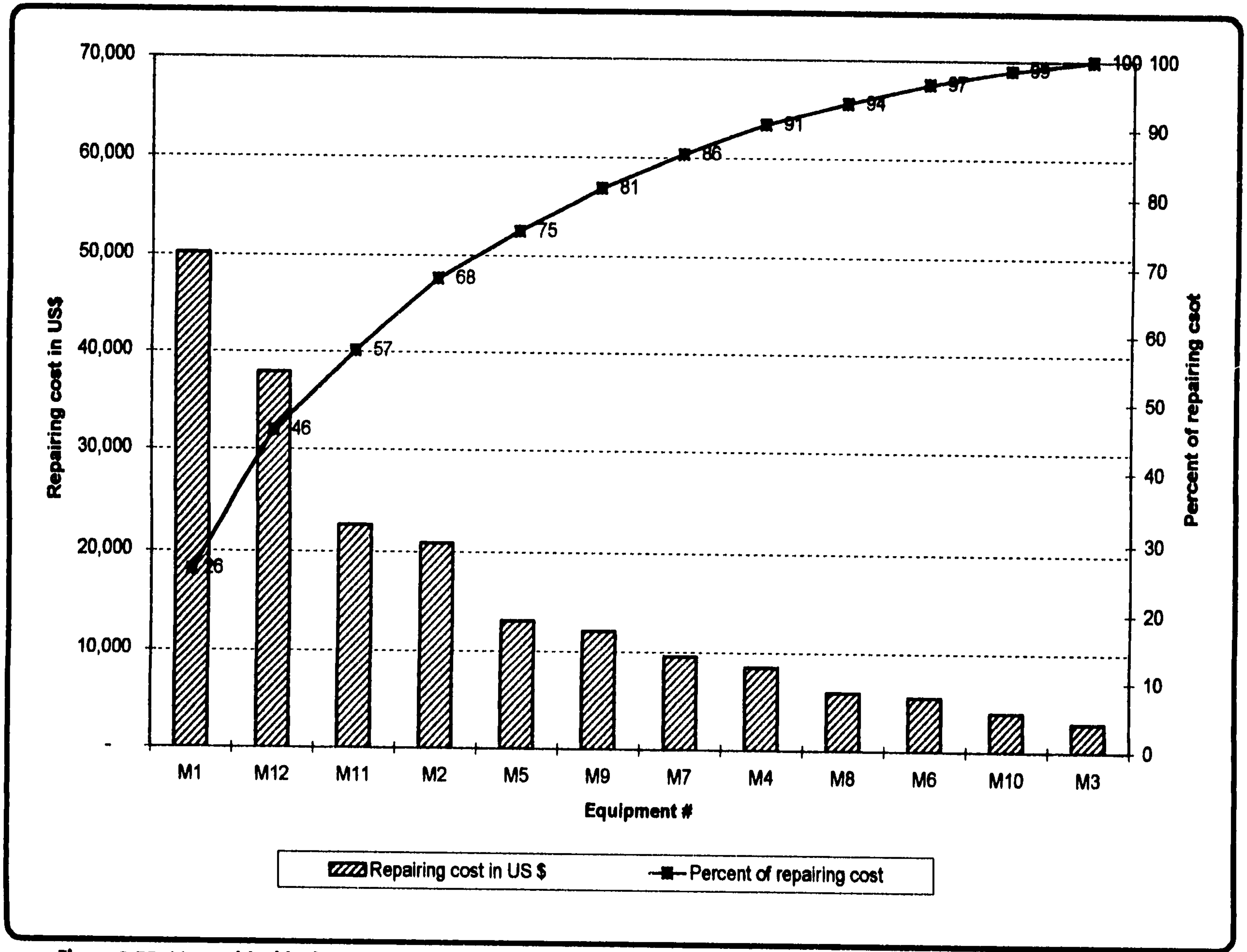


Figure 2.77. Most critical bad actors motors identified by sorting the bad actors motors by their repairing cost (Pareto analysis).

Table 2.11. Most Critical Bad Actor Motors: Failure Modes, Time-to-Failure, Time-to-Repair, and Repairing Cost.

Equipment #	***Code #***	***Time to Failure*** (in months)	***Failure Mode***	***Time to Repair*** (days)	***Repairing Cost*** (in US $)
M4	34-1-GM983D	9	Coupling	117	970
		38	Grounded	62	1,151
		44	Bearing	108	4,520
		47	Bearing	384	4,300
		50	Bearing	257	5,400
M2	38-GM12	13	Bearing	31	2,865
		15	Bearing	128	2,310
		22	Bearing	40	5,209
		50	Grounded	27	3,210
		60	Bearing	39	699
M12	30-2-GM241D	11	Bearing	199	1,681
		12	Bearing	29	1,709
		26	Grounded	261	6,322
		45	Overhaul	42	985
		55	Overhaul	46	4,594
M5	34-1-GM56	28	Bearing	214	2,136
		31	Rewinding	40	2,075
		33	Rewinding	226	3,319
		47	Overhaul	26	4,052
M7	30-2-GM42	6	Overhaul	135	2,296
		11	Vibration	73	3,195
		34	Bearing	248	4,596
		36	Bearing	99	882
M11	38-GM103	36	Grounded	140	3,652
		46	Bearing	69	7,072
		51	Bearing	59	1,634
M1	32-FM102	8	Rewinding	48	2,201
		23	Base repair	25	6,731
		27	Base repair	75	1,266

2.4.1 Determining Failure Modes

As shown in Table 2.11, the time to failure, failure modes and repairing cost for each most critical bad actor motor were gathered from Aramco Management Material System and from the Data Control System. The failure modes are plotted in PI charts, as shown in Figure 2.78 through 2.83, to make the comparison easy.

The failure modes versus number of failures are plotted in Figure 2.84 to determine the highest failure modes to investigate the root cause of the failure and try to prevent it.

Motors are found to have variety of failure modes. It is not like pumps and turbines where there are common failure modes. In motors only non-repairable parts (bearings) is the highest failure percentage out of the total number of failures (44%). The other highest failure modes are grounding (12.5%), overhaul (12.5%) and rewinding (9.4%). The mechanical parts of the motor is very few (bearings, shafts, etc.,) and most of failures are due to electric parts (wires, breakers) which are the motor auxiliaries.

There are seven different failure modes for the most critical motors, and they are defined as follows:

- ***Grounded*** .... A motor failed to operate due to a grounded cable which has caused a short circuit.
- ***Rewinding*** .... A motor failed due to the stator problem which needs to be rewinded.

- ***Base Repair*** .... A motor failure due to defective base or corrosion occur to the motor base.
- ***Vibration*** .... A motor failure due to high vibration.
- ***Inspection*** .... A motor shutdown to inspect some defected parts to recommend the necessary repairs.
- ***Breaker Repair*** ..... A motor failure due to repairing its breaker.
- ***Cable Replacement*** .. A motor failure due to replacement of a defective cable.

2.4.2 Weibull Reliability Analysis

As shown in Appendix A, Figures A-9 through A-12, there is no trend for the time between failures data so the Weibull model can be used effectively. By utilizing Excel Spreadsheet, the Weibull analysis was applied to the most critical bad actor motors, as shown in Figure 2.85 through Figure 2.91, to determine the shape parameter and characteristic life for each motor and the other reliability parameters. Also, the reliability charts for some selected motors are figured out in Figures 2.92 and 2.93. Other reliability parameters were also calculated and summarized in Table 2.12.

It is found from the reliability parameters analysis of the most critical bad actors motors that the characteristic lives are higher than pump and turbines (from 11 months to 21 months) but the shape parameters are less than one. The MTBF for the motors are also high, some of them are 73 months, 25 months and 20 months. The lowest MTBF is 12.5 months, which is considered to be high compared with pumps and steam turbines.

Table 2.12. Reliability Parameters of Most Critical Bad Actors Motors.

Equipment #	***Code #***	β	η (months)	***MTBF*** (months)	***Standard Deviation***	***Variation Coefficient***	$T_{0.5}$ (months)
M4	34-1-GM983D	0.86	11.50	12.47	14.59	1.16	7.23
M2	38-GM12	0.90	14.60	15.33	17.08	1.11	9.68
M12	30-2-GM241D	0.67	15.50	20.34	31.11	1.52	8.97
M5	34-1-GM56	0.65	13.80	18.98	30.38	1.60	7.86
M1	32-FM102	1.20	11.00	10.40	8.70	0.84	8.10
M7	30-2-GM42	0.65	24.20	32.94	52.43	1.59	13.75
M11	38-GM103	0.76	21.30	24.97	33.08	1.32	13.19

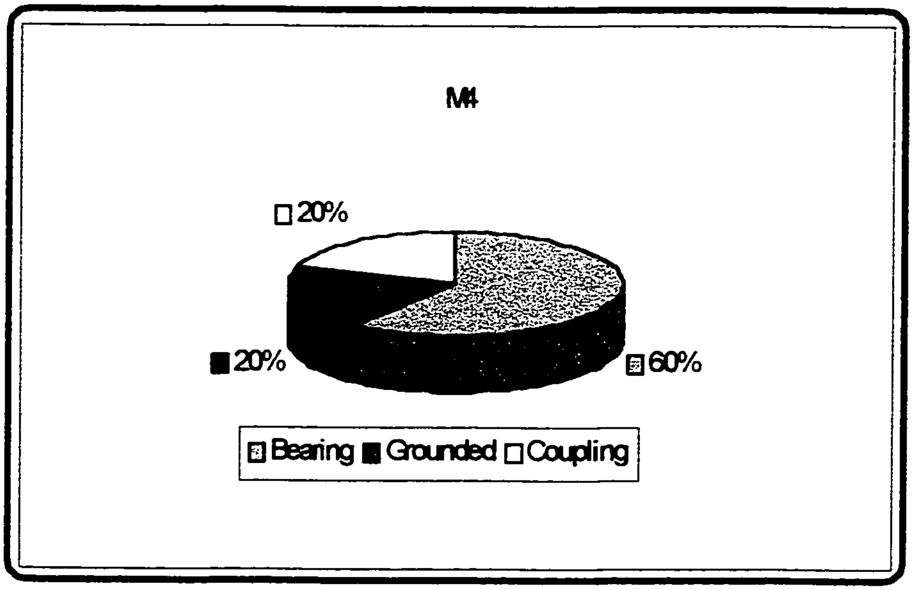


Figure 2.78. Failure mode of bad actor motor M4.

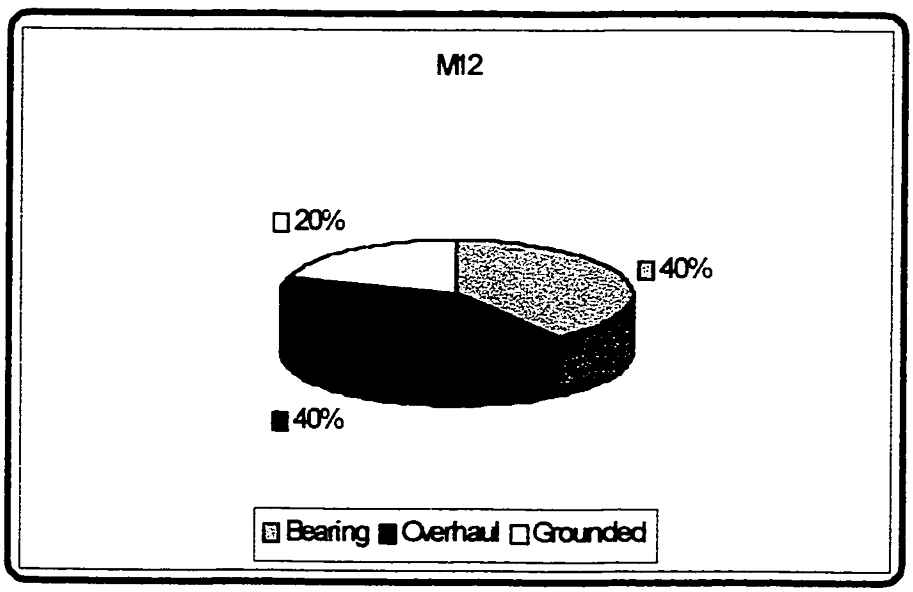


Figure 2.79. Failure mode of bad actor motor M12.

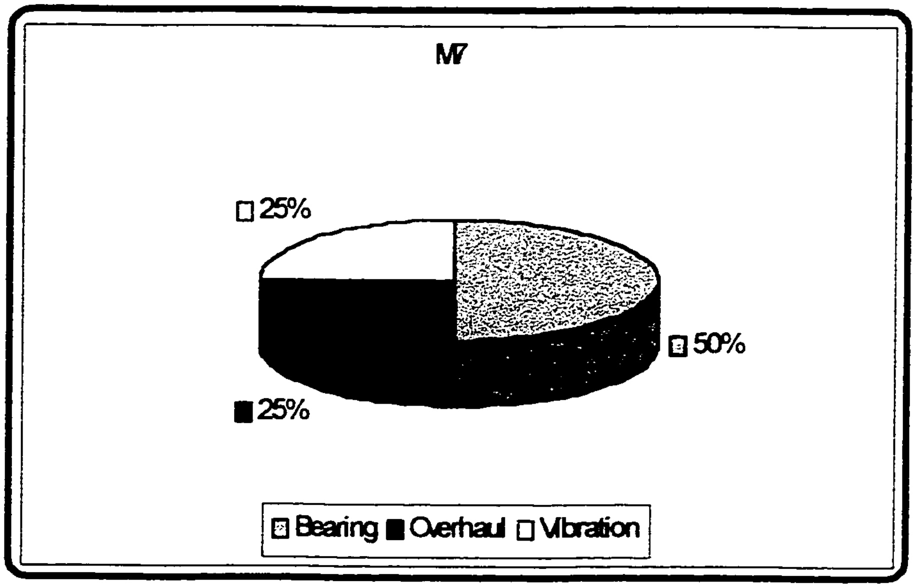


Figure 2.80. Failure mode of bad actor motor M7.

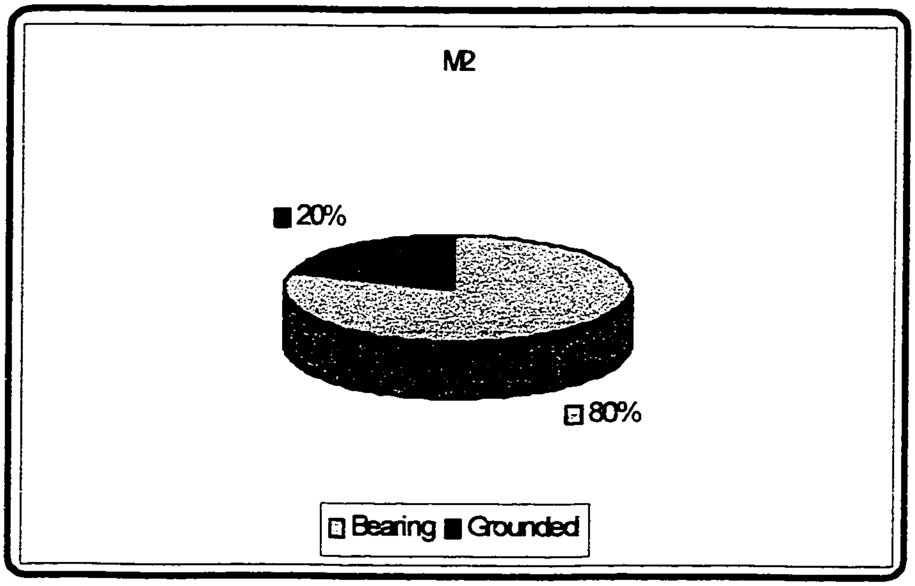


Figure 2.81. Failure mode of bad actor motor M2.

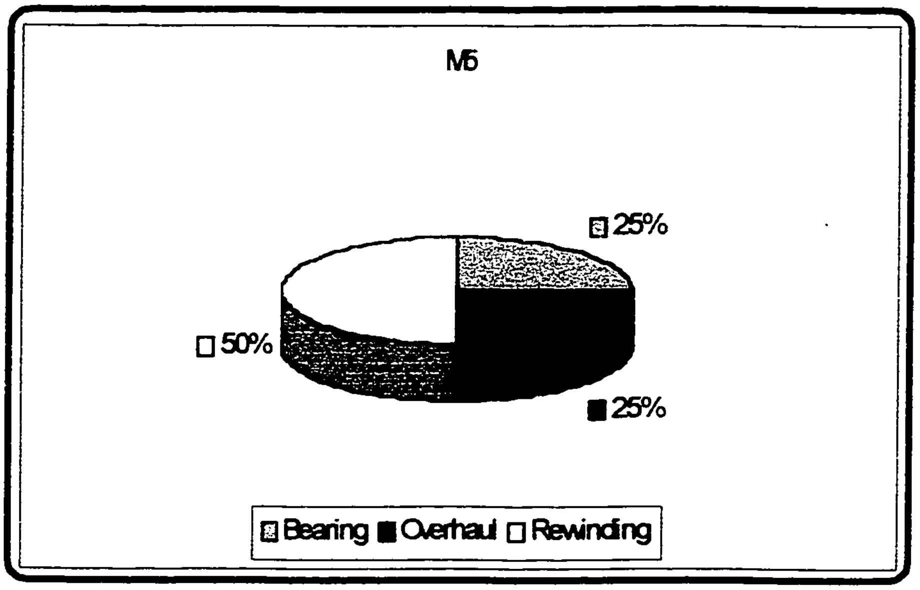


Figure 2.82. Failure mode of bad actor motor M5.

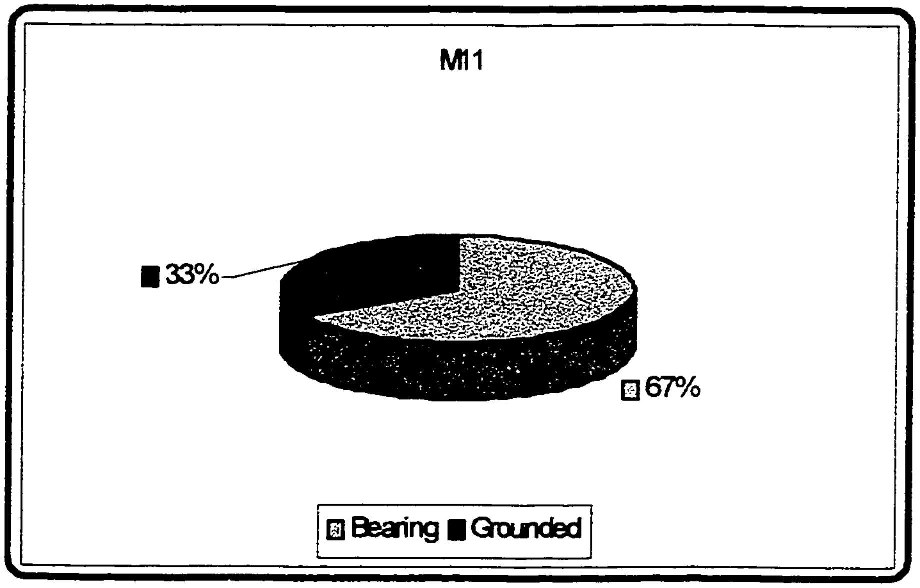


Figure 2.83. Failure mode of bad actor motor M11.

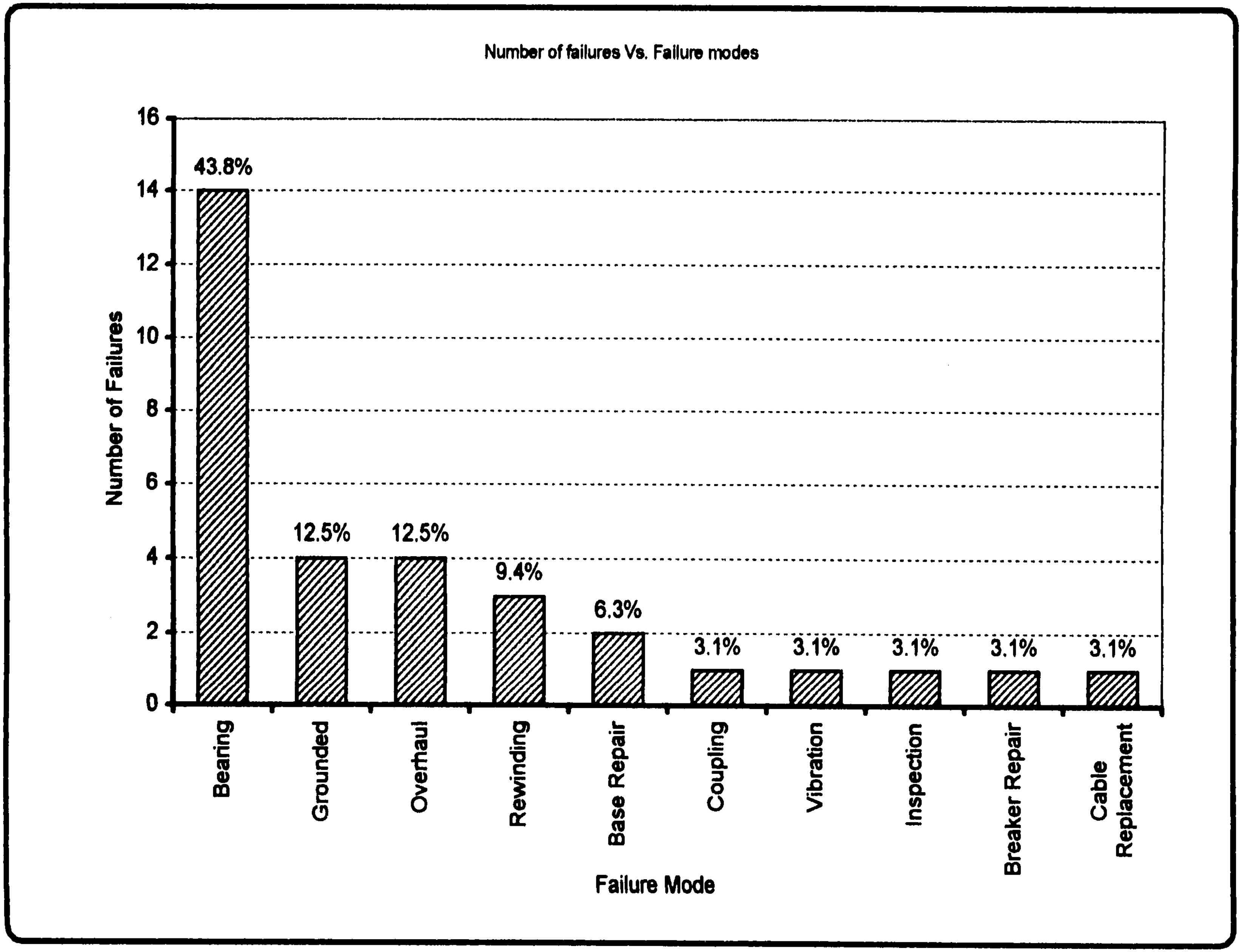


Figure 2.84. Number of failures versus failure modes.

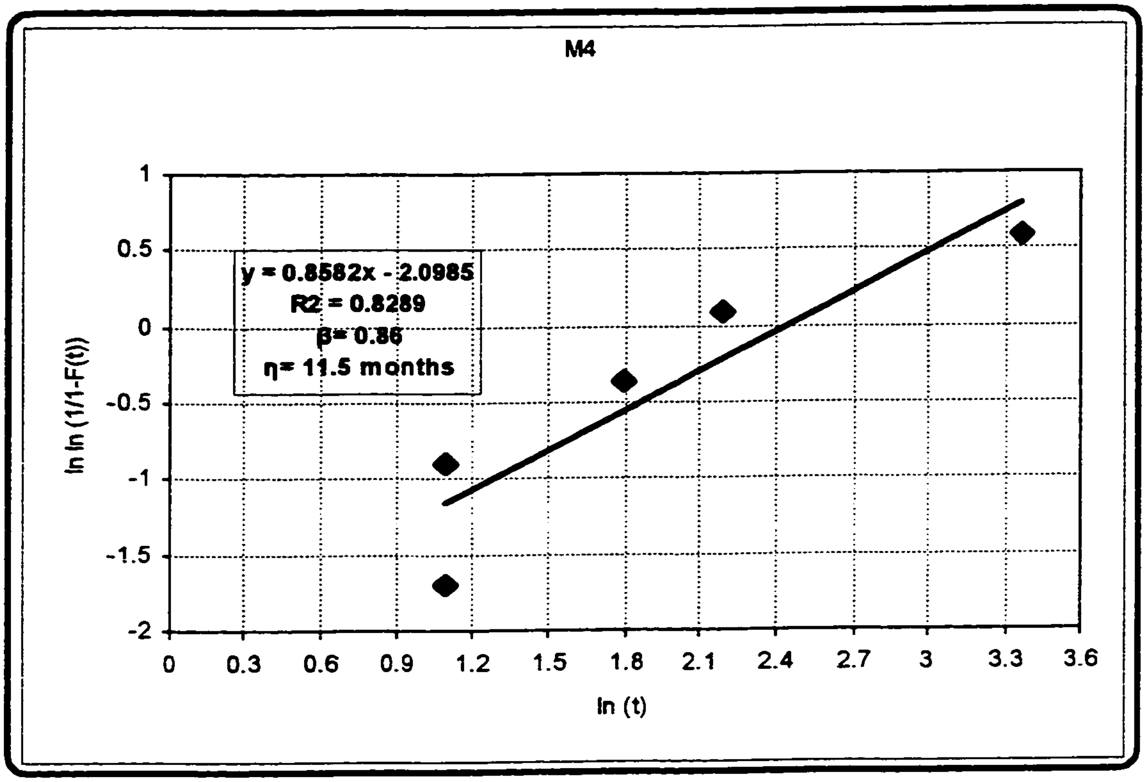


Figure 2.85. Weibull analysis of all modes of failure for M4.

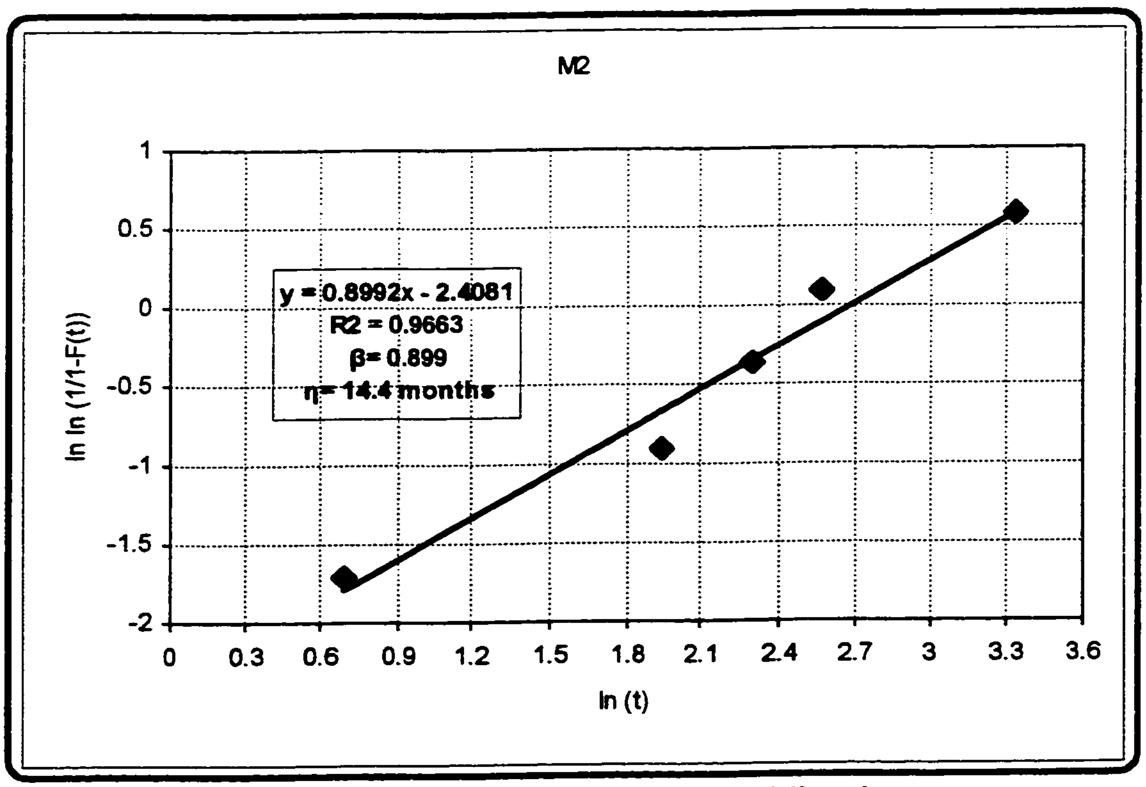


Figure 2.86. Weibull analysis of all modes of failure for M2.

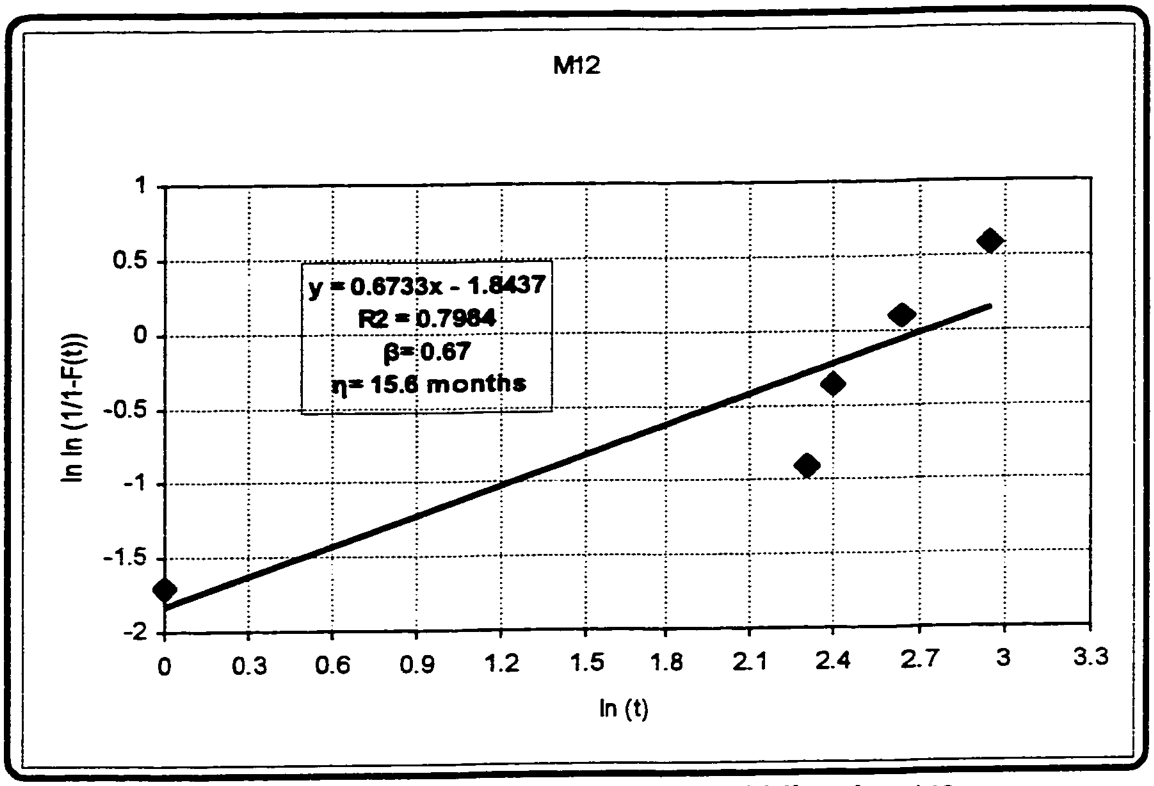


Figure 2.87. Weibull analysis of all modes of failure for M12.

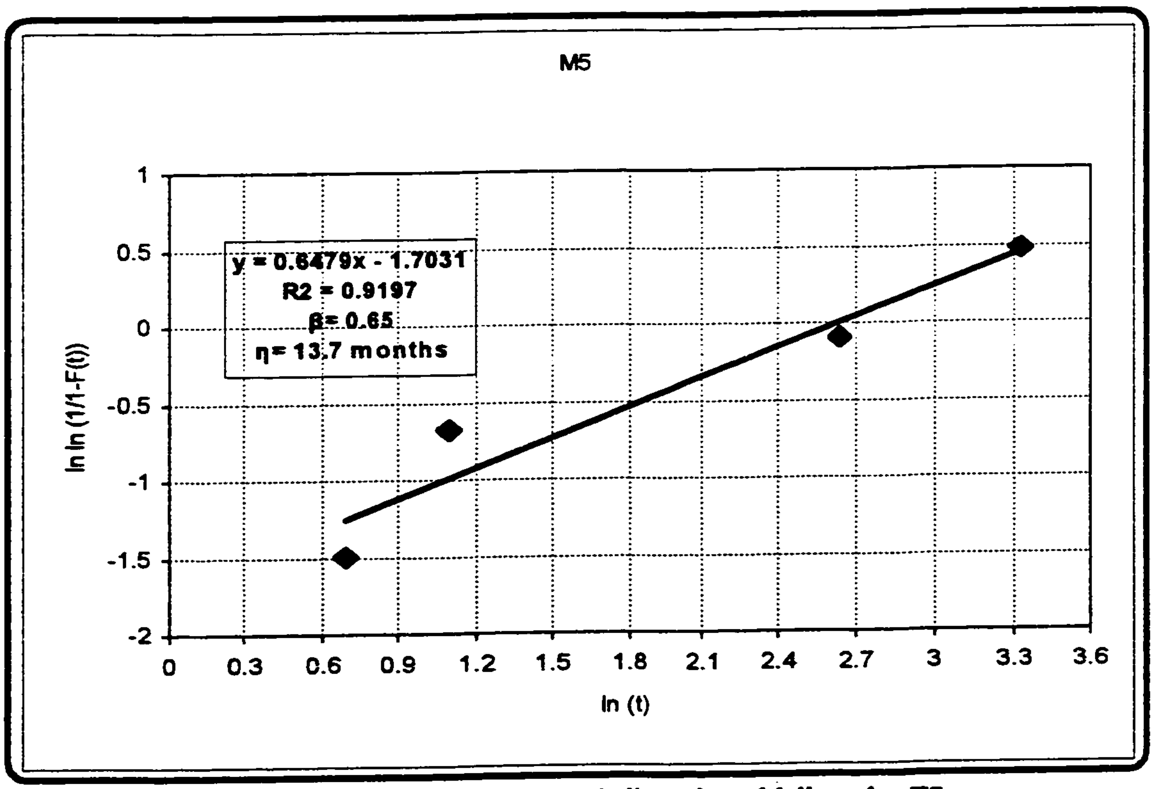


Figure 2.88. Weibull analysis of all modes of failure for T5.

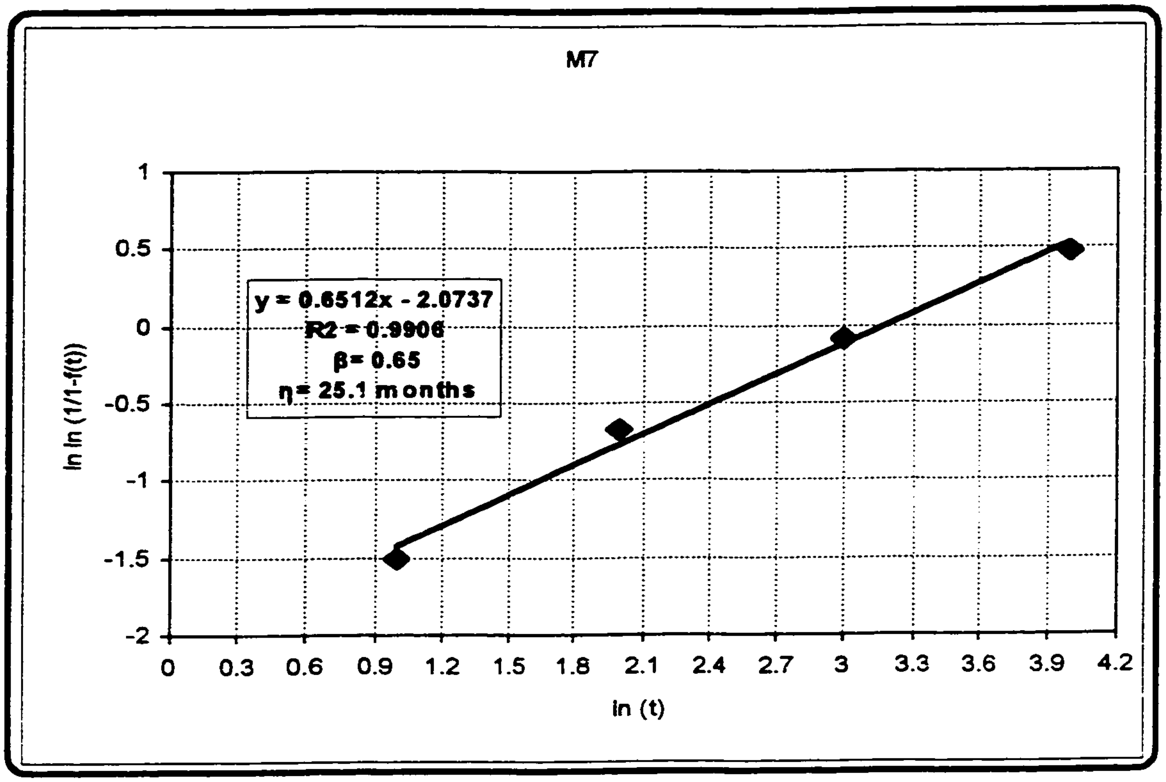


Figure 2.89. Weibull analysis of all modes of failure for M7.

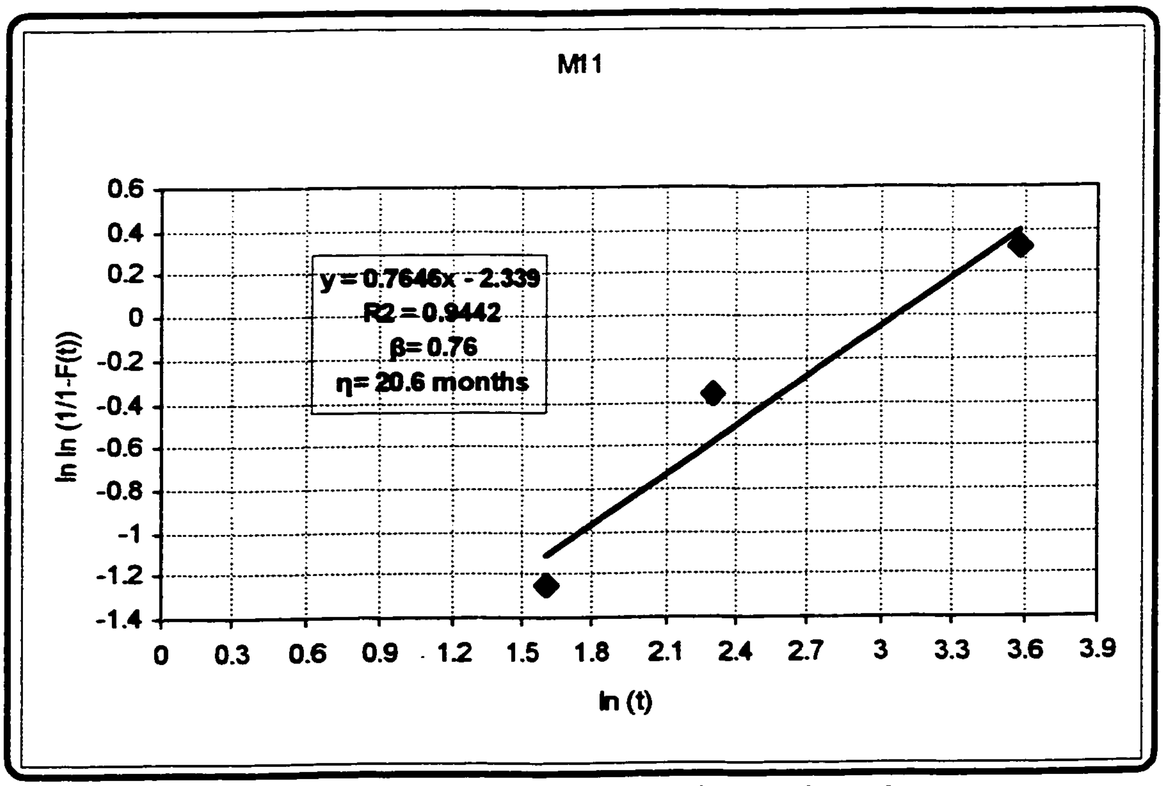


Figure 2.90. Weibull analysis of all modes of failure of M11.

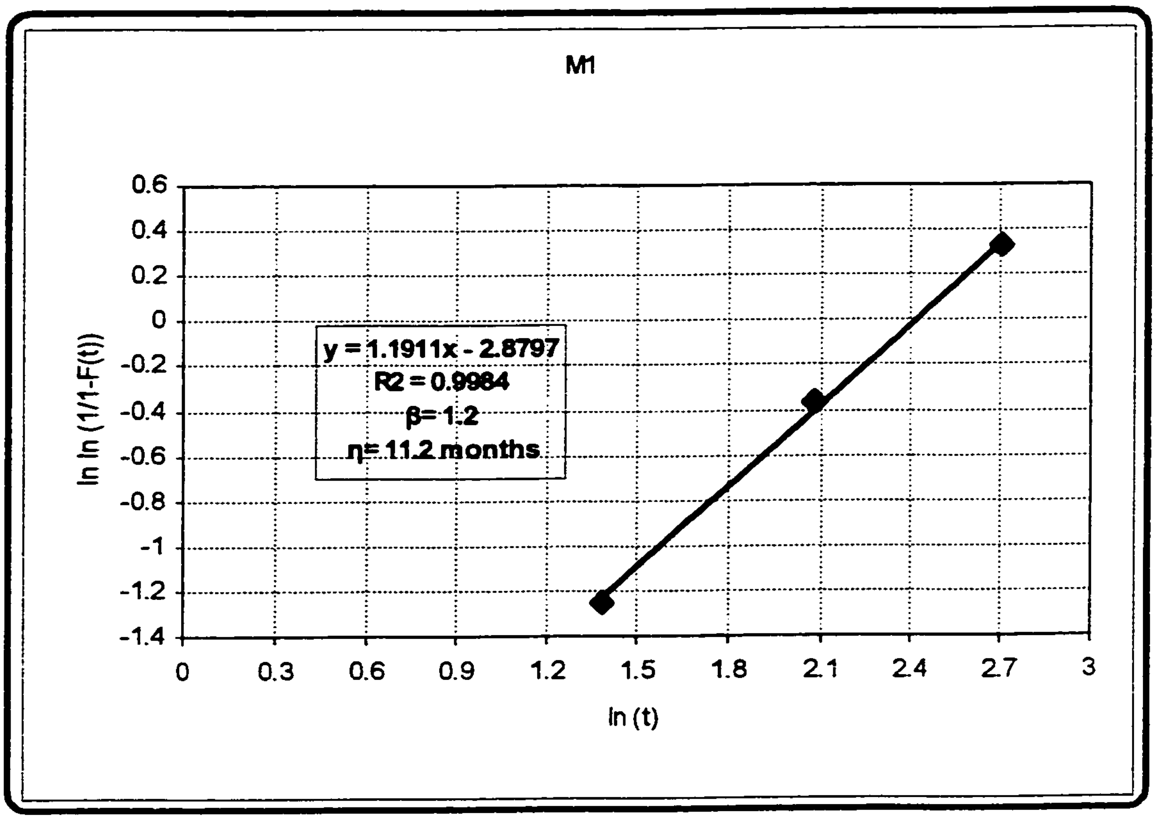


Figure 2.91. Weibull analysis of all modes of failure for M1.

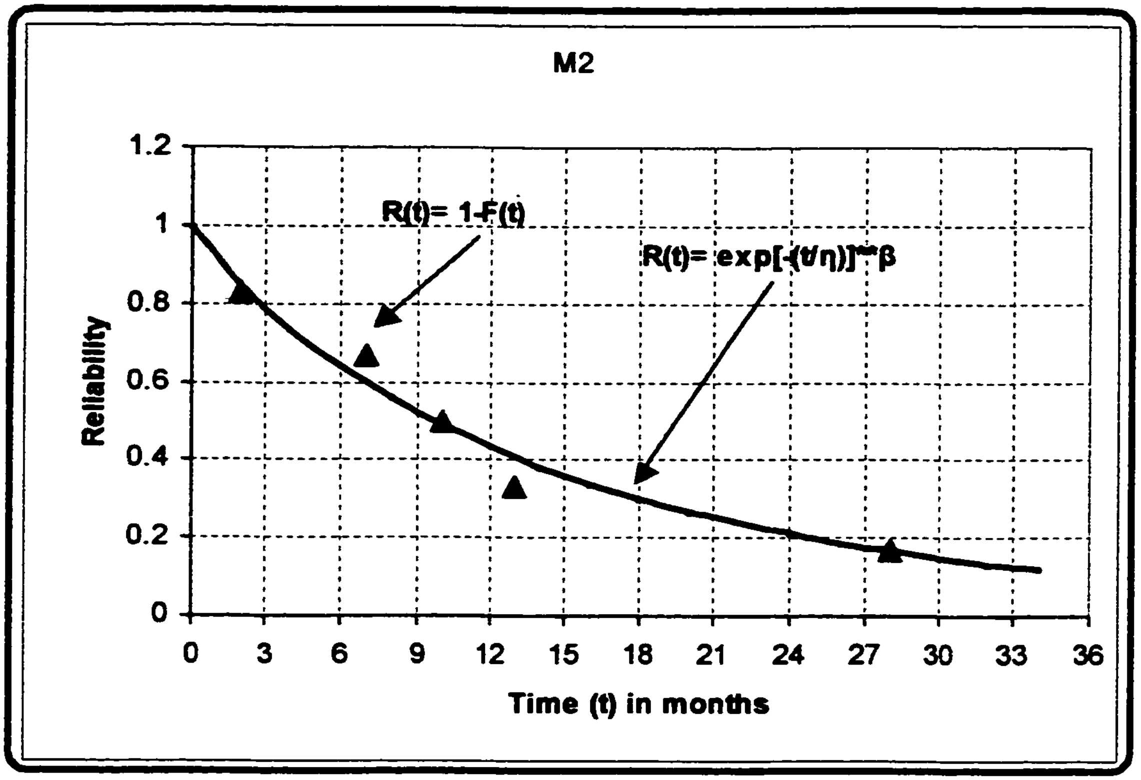


Figure 2.92. Reliability chart for motor M2.

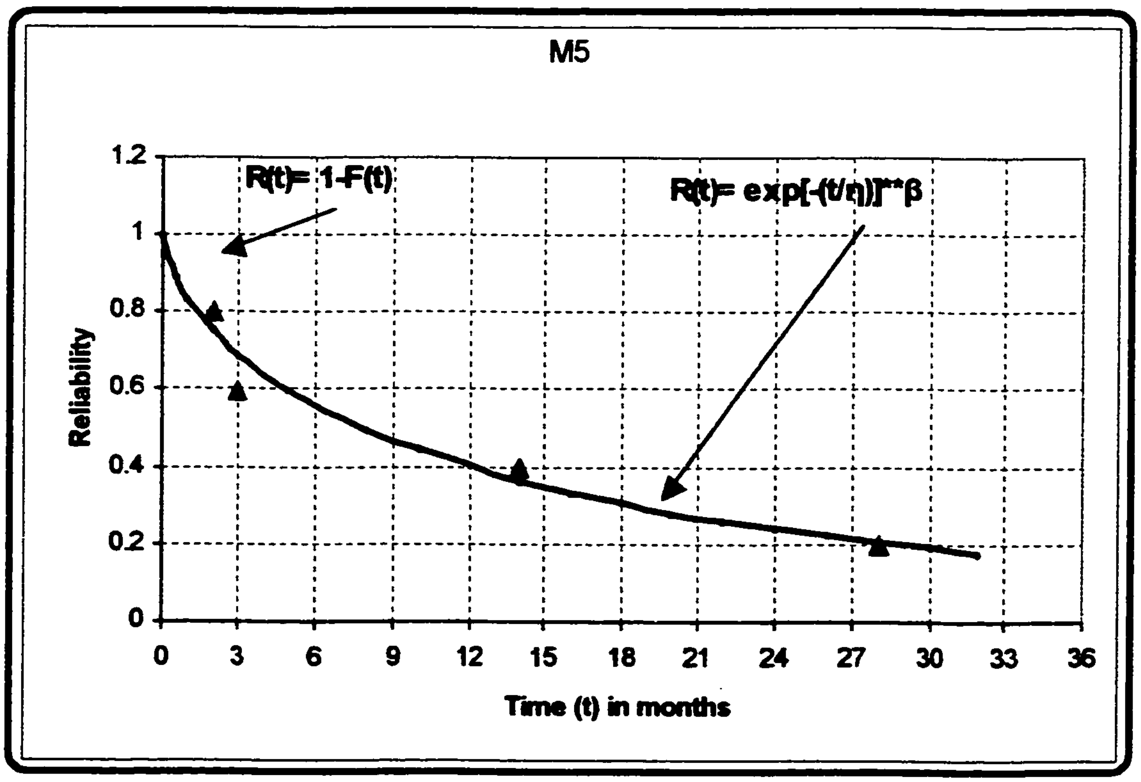


Figure 2.93. Reliability chart for motor M5.

2.4.3 Cost Analysis

2.4.3.1 Non-Repairable Parts

The Weibull chart of the motor bearing (Figure 2.94) shows that the shape parameter $\beta=1.1$ and characteristic life $\eta=8.9$ months. This means that the motor bearings last much lower than pump bearings and turbine bearings.

Figure 2.95 shows the behavior of spending the accumulative maintenance cost for the bearings of all the most critical bad actors motors. There was a significant increase in spending maintenance cost of bearings in the first three months of operation and from third month until twelfth months of operation the maintenance cost was decreased and from the period of twelfth months until the end of the study period there was not much maintenance cost and this may be due to modification to the motors or new bearings were installed.

2.4.3.2 Repairable Parts

The accumulative repairing cost for the repairable parts of all most critical bad actors motors was plotted in Figure 2.96 to show its behavior during the period of the study. In the first ten months, there was a high amount of repairing cost spent in this region. However, the repair cost was decreased in the second region, which is from the tenth month until the end of the study, and this is due to installation of new parts and motors. Both regions in Figure 2.96 were described in the dotted lines and a best straight line is fitted to describe the average behavior of the maintenance cost of repairable part for all most critical bad actors motors.

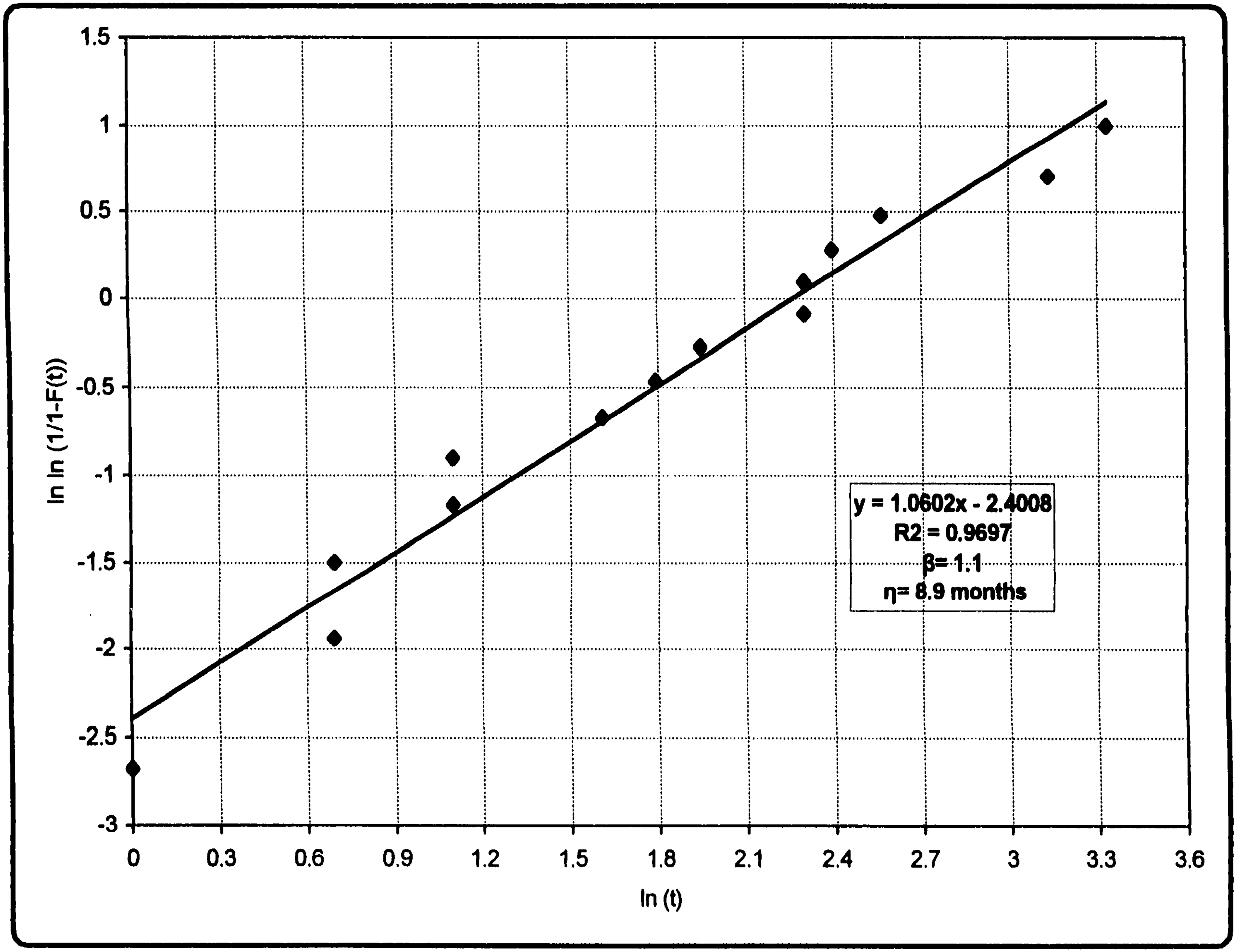


Figure 2.94. Weibull analysis for time to failure of bearing on all motors.

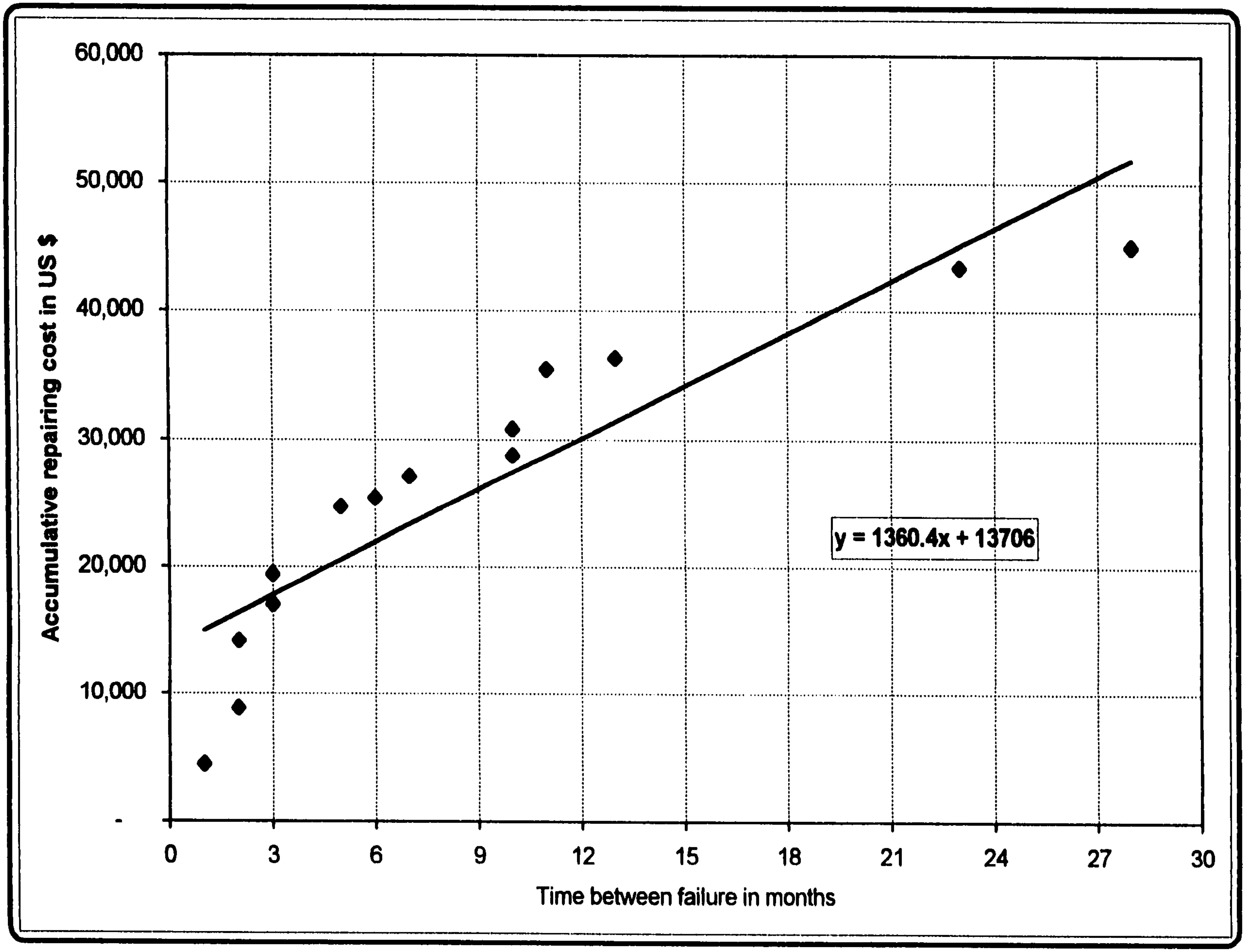


Figure 2.95. Accumulative cost of bearings for bad actor motors.

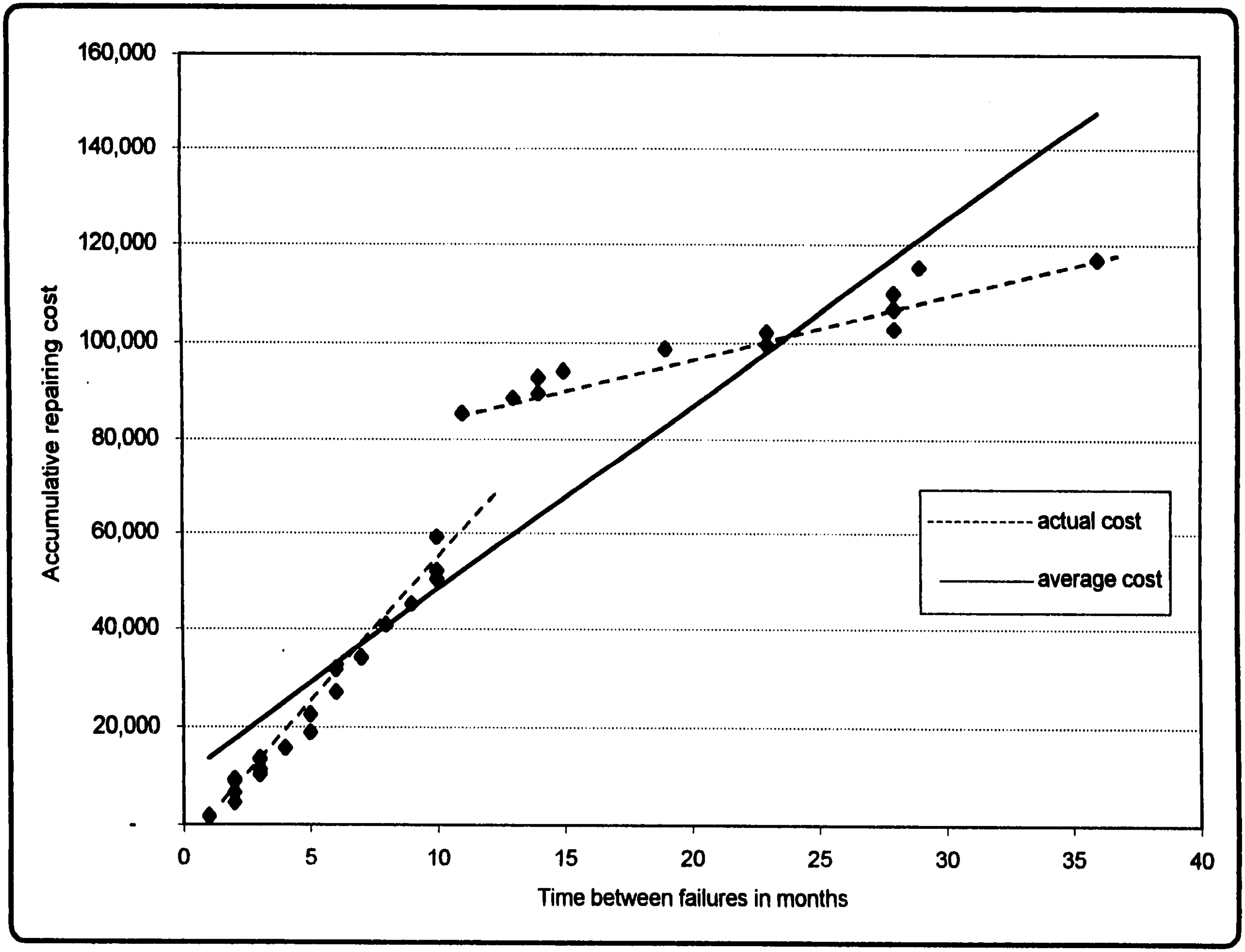


Figure 2.96. Accumulative repairing cost for bad actor motors.

Chapter 3

Maintenance Strategies

3.1 Maintenance Types

Maintenance can be defined as the combination of activities by which equipment or a system is kept in or restored to a state in which it can perform its designated function. To have a high level of reliability and availability, equipment must operate within specifications that are attainable by timely maintenance actions.

Machinery maintenance types can be classified into three main categories. They are: corrective maintenance, predictive maintenance and preventive maintenance.

3.1.1 Corrective Maintenance

It is applying the necessary repairs for equipment when they are failed because of variety of technical problems in order to return the equipment to service as soon as possible. This includes all unscheduled maintenance actions performed as a result of system failure, to restore the system to a specified condition. The corrective maintenance cycle includes failure identification and verification, localization and fault isolation, reassembly, checkout and condition verification. Corrective maintenance may be measured in terms of MTBF and MTTR.

3.1.1.1 Maintainability

It can be observed clearly that there is a direct relation between the corrective maintenance and the maintainability. As it was described in Chapter 1, we can establish maintainability by using the same logic and mathematics that we used for the reliability. The main parameters that we utilize more in the maintainability analysis is MTTR. It can be calculated by knowing the time to repair for each equipment.

3.1.1.2 Availability

The availability is very useful for studying corrective maintenance strategies. It combines reliability and maintainability characteristics. For repairable systems, the availability is very important factor and it is an important indicator of operational readiness of an equipment. The asymptotic availability of a rotating equipment will be given by the following well-known equation [11]:

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

where:

MTBF is the mean time between failure
MTTR is the mean time to repair

The mean time to repair is the time required to repair the equipment and put it back into service.

The maintainability, reliability and availability parameters from each of the most critical bad actor rotating equipment (pumps, turbines, motors) are summarized in Table 3.1.

The maintainability, reliability and availability of the bad actors rotating equipment were calculated and summarized in one table to compare them. It is observed that the motors availability are higher than pumps and turbines availability. This is because of the high MTBF of motors. It was also observed that the availability of some pumps are very low (from 40% to 50%) and this is because of high MTTR. The main factors that can be used to improve the availability is the MTTR, which means we have to reduce the time required for repairing and this will happen by providing the spare parts in advance to avoid waiting time for materials, as well as minimizing the actual repair activities time in the repair facilities.

Table 3.1. Maintainability, Reliability and Availability Parameters for each of the Most Critical Bad Actor Rotating Equipment.

Equipment#	*Code #*	*Maintainability*			*Reliability*			*Availability*
		m	θ	*MTTR* (months)	β	η	*MTBF* (months)	*A*(∞) (%)
				PUMPS				
P41	35-G103B	0.63	9.83	13.72	0.84	10.17	11.10	75.00
P39	35-G102B	1.04	5.29	5.20	1.00	9.00	9.00	63.30
P40	35-G103A	0.94	6.45	6.63	1.70	5.00	4.50	40.40
P38	35-G102A	0.76	6.55	7.66	1.00	7.70	7.80	50.60
P3	30-2-G58	1.72	8.51	7.58	1.20	7.10	6.70	47.10
P42	38-G103	2.08	1.04	0.92	1.30	6.00	5.50	85.80
P7	30-1-G203	0.93	6.89	7.11	1.50	9.60	8.60	54.90
P22	34-G53	0.70	6.81	8.56	1.10	7.00	6.70	44.00
P29	34-G764A	1.07	4.46	4.35	1.00	11.40	11.60	72.70
P37	30-G980A	0.88	1.55	1.65	0.60	9.30	12.90	88.60
P32	34-G980B	0.89	6.94	7.32	2.00	8.50	7.50	50.80
P15	32-G127A	0.55	4.20	7.10	2.10	6.60	5.80	45.20
P19	34-G664	1.32	3.56	3.28	1.30	8.70	8.10	71.20
P18	34-866A	1.36	4.09	3.75	1.00	6.60	6.60	63.80
P24	34-G56	1.12	4.09	3.91	1.20	10.30	9.70	71.20
P26	34-G664A	1.08	4.27	4.14	0.90	11.20	11.50	73.60
				TURBINES				
T1	35-3-GT104A	0.78	1.68	1.93	0.92	3.33	3.47	64.20
T3	35-3-GT103B	0.70	4.02	5.09	0.73	7.61	9.30	64.60
T4	32-KT106	0.88	1.78	1.88	1.04	4.09	4.02	68.10
T5	32-KT107	0.84	2.77	3.03	0.85	6.41	6.98	69.80
T6	32-GT111C	1.12	3.16	3.03	0.96	7.29	7.42	71.00
T7	32-GT111D	1.36	2.37	2.17	1.05	4.90	4.80	68.80
T8	30-1-GT91B	0.94	2.97	3.04	0.64	12.55	17.50	85.20
T9	30-1-GT90B	1.28	3.17	2.94	0.94	4.46	4.58	60.90
T10	32-KT108	0.52	2.15	4.01	0.57	5.73	9.34	70.00
T13	30-1-GT91A	1.06	2.74	2.67	1.23	6.23	5.82	68.50

cont ... Table 3.1

Equipment #	*Code #*	*Maintainability*			*Reliability*			*Availability*
		m	θ	*MTTR* (months)	β	η	*MTBF* (months)	$A(\infty)$ (%)
				MOTORS				
M4	34-1-GM983D	1.23	7.81	7.29	0.86	11.50	12.50	63.10
M2	38-GM12	1.18	2.16	2.03	0.90	14.60	15.30	88.30
M12	30-2-GM241D	0.90	4.97	5.21	0.67	15.50	20.30	79.60
M5	34-1-GM56	0.70	5.35	6.76	0.65	13.80	19.00	73.70
M7	30-2-GM42	1.56	5.26	4.73	0.65	24.20	32.90	87.50
M11	38-GM103	1.56	3.64	3.27	0.76	21.30	25.00	88.40
M1	22-FM102	1.73	5.36	4.61	1.20	11.00	10.40	69.30

3.1.2 Predictive Maintenance

This type of maintenance is based on the periodic inspection activities (or continuous inspection activities, i.e., condition monitoring) followed by replacement or overhaul, if incipient defects are detected. Predictive maintenance addresses the randomly and suddenly occurring failure modes, as far as possible, by searching for them and by effecting timely repairs. Predictive maintenance strategy should dictate a continuous search for defects.

It was mentioned before that maintenance actions or policies can be classified into three main categories, corrective maintenance, predictive maintenance and preventive maintenance.

Predictive maintenance results in two benefits. The first benefit is the result of taking a machine off-line at a predetermined time which allows production loss to be minimized by scheduling production around the downtime. Since defective components can be predetermined, repair parts can be ordered and manpower scheduled for the maintenance accordingly. The second benefit is that only defective parts need to be repaired or replaced and the components in good working order are left as is, thus, minimizing repair costs and downtime.

There are three main tasks to be fulfilled for predictive maintenance. The first task is to find the condition parameter which can describe the condition of the machine. A condition parameter could be any characteristic, such as vibration, sound, temperature, corrosion, crack growth, wear and lubricant condition. The second task is to monitor the condition parameter and to assess the current machine condition from the measured data. The final task is to determine the limit value, S_L, of the condition parameter and its two components, the alarm value, S_a, and the breakdown value, S_b. If a running machine reaches the alarm value, it is an indication that it is experiencing intensive wearing. If a machine reaches the breakdown value, the shutdown of a machine for maintenance becomes necessary.

As shown in Figure 3.1 through Figure 3.4, each rotating equipment in the Refinery Plant are under close monitoring. The vibration behavior (Figure 3.1) is one of the online monitoring that is carried on each equipment. If the vibration reading reach the alarm value, we start investigating the problem before it became catastrophic failure and this is one of the benefit of online monitoring or predictive maintenance. The other important reading that should be closely monitored is the lubrication oil temperature of the rotating equipment (Figure 3.2). It is obvious that when oil temperature reading start increasing, this means that there is a problem in the bearing of the oil cooler which need to be resolved. Operation parameters, such as pressure and flow should also be monitored (see Figures 3.3 and 3.4) to predict any operational upset and try to solve them to avoid catastrophic failures to the equipment.

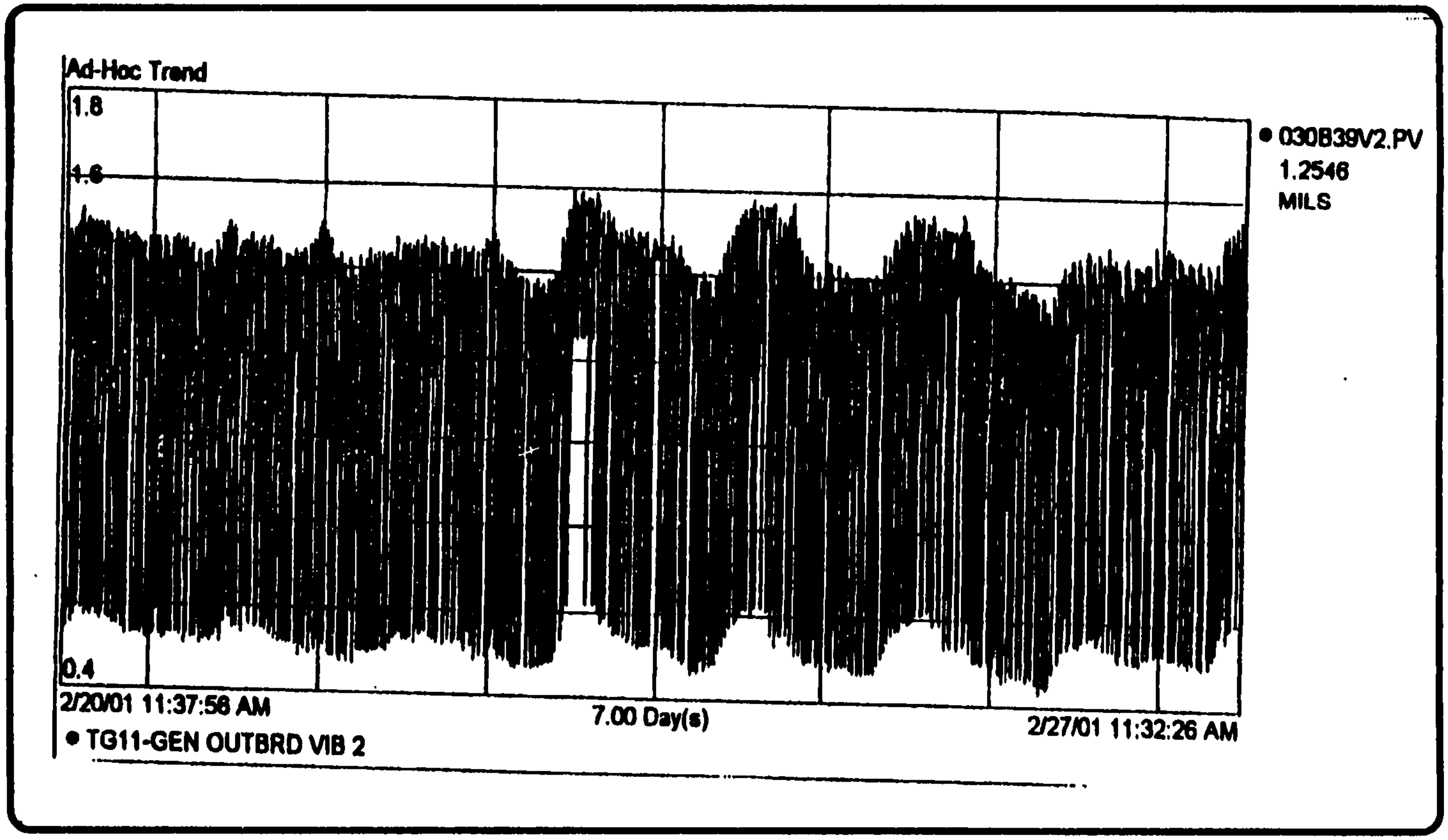


Figure 3.1. Vibration behavior of rotating equipments.

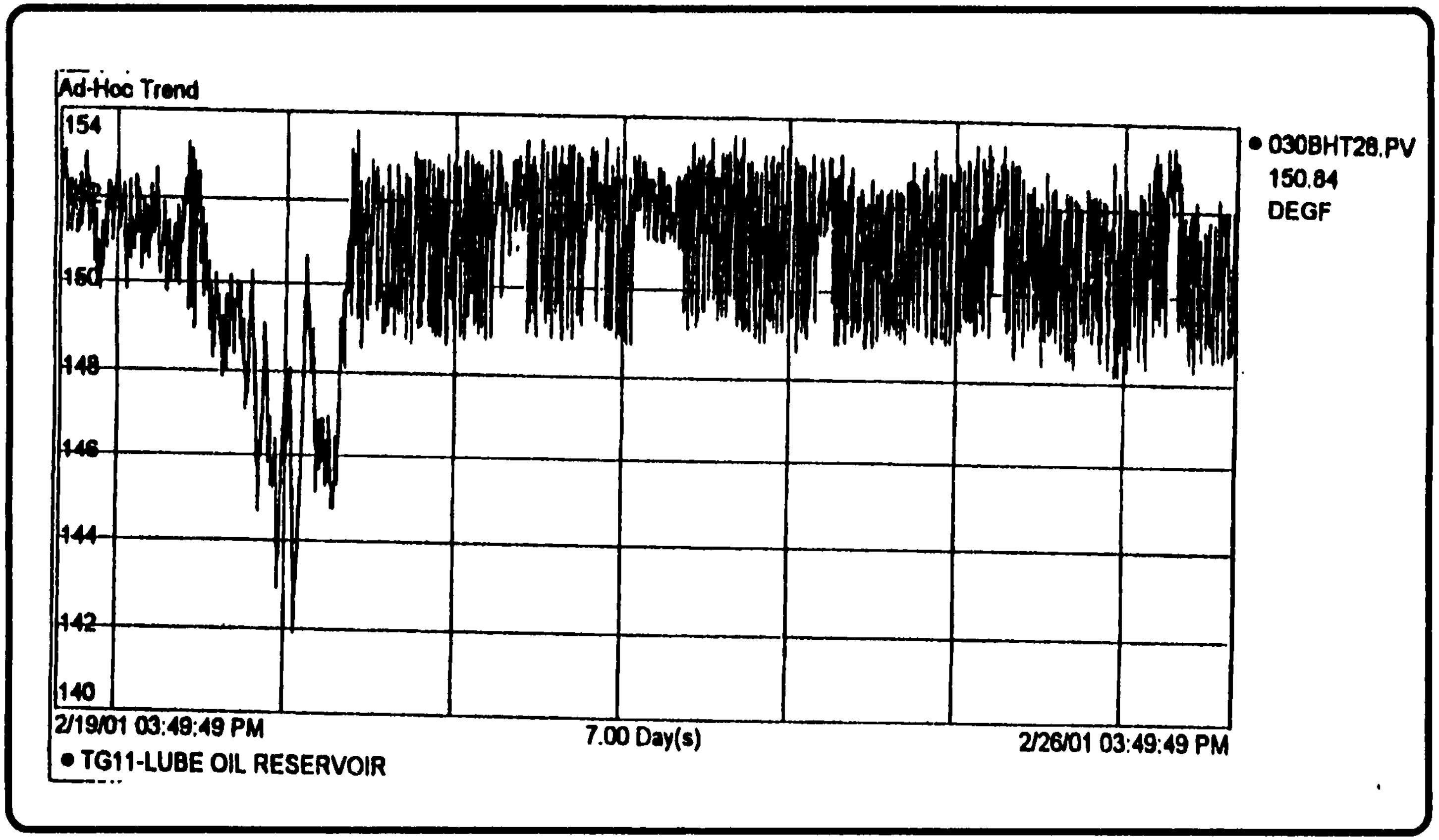


Figure 3.2. Lubrication oil temperature of the rotating equipments.

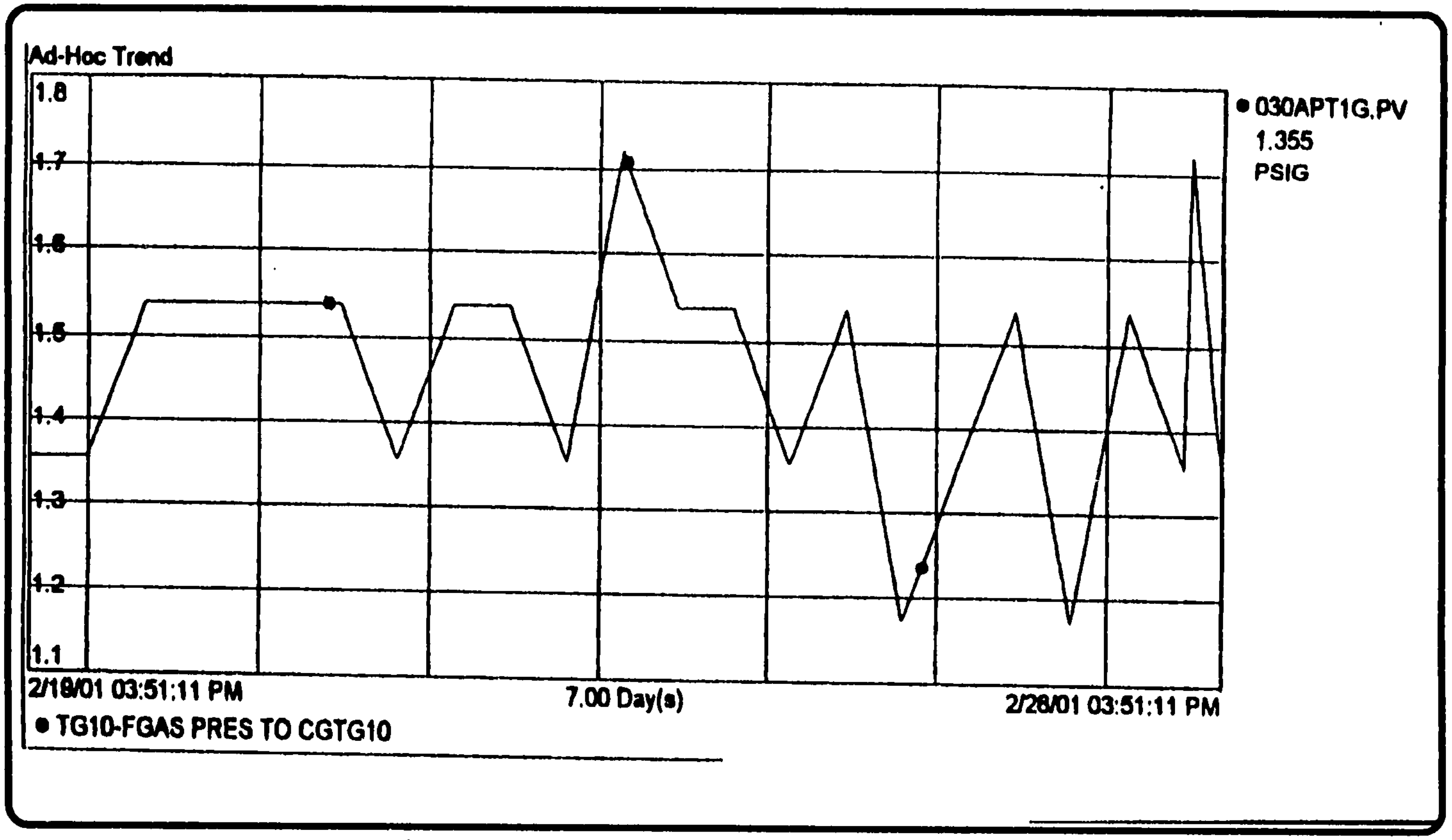


Figure 3.3. Monitoring of pressure of rotating equipment.

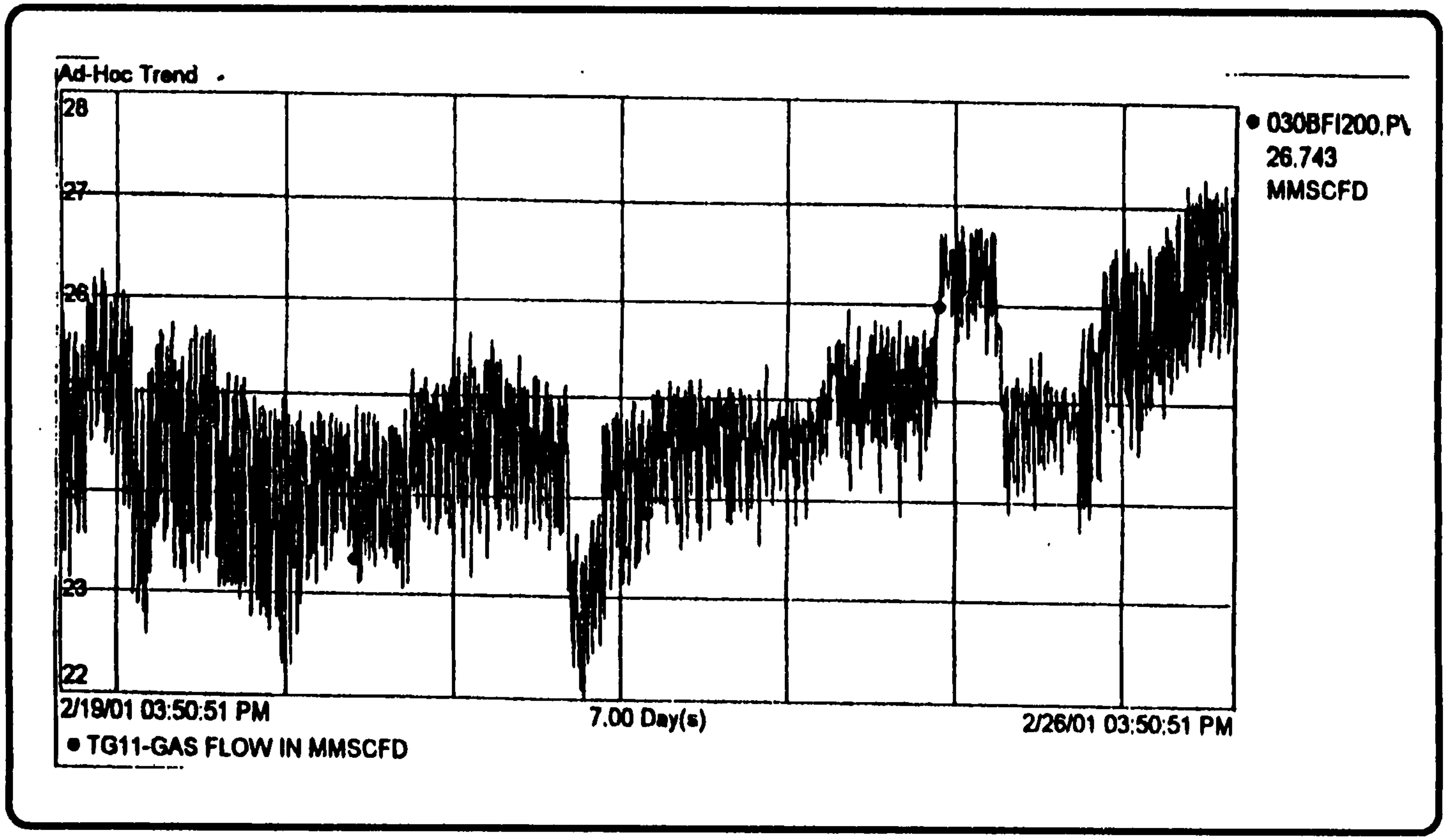


Figure 3.4. Monitoring of flows of rotating equipment.

3.1.3 Preventive Maintenance

It is the periodic or scheduled activities which have, as its objective, the direct prevention of failure or to minimize the damaging effect of various modes of failures. In preventive maintenance, parts are replaced, lubricants changed or adjustments made before failure occurs. The objective of preventive maintenance is to increase the reliability of the system over the long-term by staving off the aging effects of wear, fatigue and related phenomena.

Preventive maintenance (PM) depends upon a series of preplanned tasks performed to counteract the known causes of potential failures of the intended functions of an asset.

Preventive maintenance is the preferred approach to assess management in the following:

- It can prevent premature failure and reduce its frequency.
- It can reduce the severity of failure and mitigate its consequences.
- It can provide warning of an impending or incipient failure to allow planned repair.
- It can reduce the overall cost of asset management.

Maintenance is not a purpose in itself and quite often when applying preventive maintenance strategy in an excessive way caused more downtime and cost increase. To determine the appropriate type of maintenance that should be used for a system, let us consider the reliability $R(t)$ using in Weibull distribution for this system without maintenance.

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{3.1}$$

Then the reliability for the maintenance system $R_m(t)$ [11] is

$$R_m(t) = e^{-N\left(\frac{t}{\eta}\right)^{\beta}} e^{-\left(\frac{t-NT_{pm}}{\eta}\right)^{\beta}} \tag{3.2}$$

$$NT_{pm} \le t < (N+1)T_{pm}$$

$$N = 0,\ 1,\ 2,\ \ldots.$$

where T_{pm} is the time between preventive maintenance of the system.

To examine the effect of maintenance, we calculate the ratio $R_m(t)/R(t)$. The relationship is simplified if we calculate this ratio at the time of maintenance $t = NT_{pm}$.

$$\frac{R_m(NT_{pm})}{R(NT_{pm})} = e^{-N\left(\frac{t}{\eta}\right)^{\beta} + \left(\frac{NT_{pm}}{\eta}\right)^{\beta}} \tag{3.3}$$

Thus, there will be a gain in reliability from maintenance only if the argument of the exponential is positive, that is, if $(NT_{pm}/\eta)^{\beta} > N(T_{pm}/\eta)^{\beta}$. This reduces to the condition

$$[N^{\beta-1}] - 1 > 0 \tag{3.4}$$

This state simply that β must be greater than one for maintenance to have a positive effect on reliability, it corresponds to a failure rate that is increasing with time through aging. Conversely, for $\beta < 1$, preventive maintenance decreases reliability. This corresponds to a failure rate that is decreasing with time through early failure. Specially, if new defective parts are introduced into a system that has already been worn in increased rates of failure may be expected. These effects on reliability are shown in ***Figure 3.5***, where Equation 3.2 is plotted for both increasing ($\beta > 1$) and decreasing ($\beta < 1$) failure rates, along with random failures ($\beta = 1$).

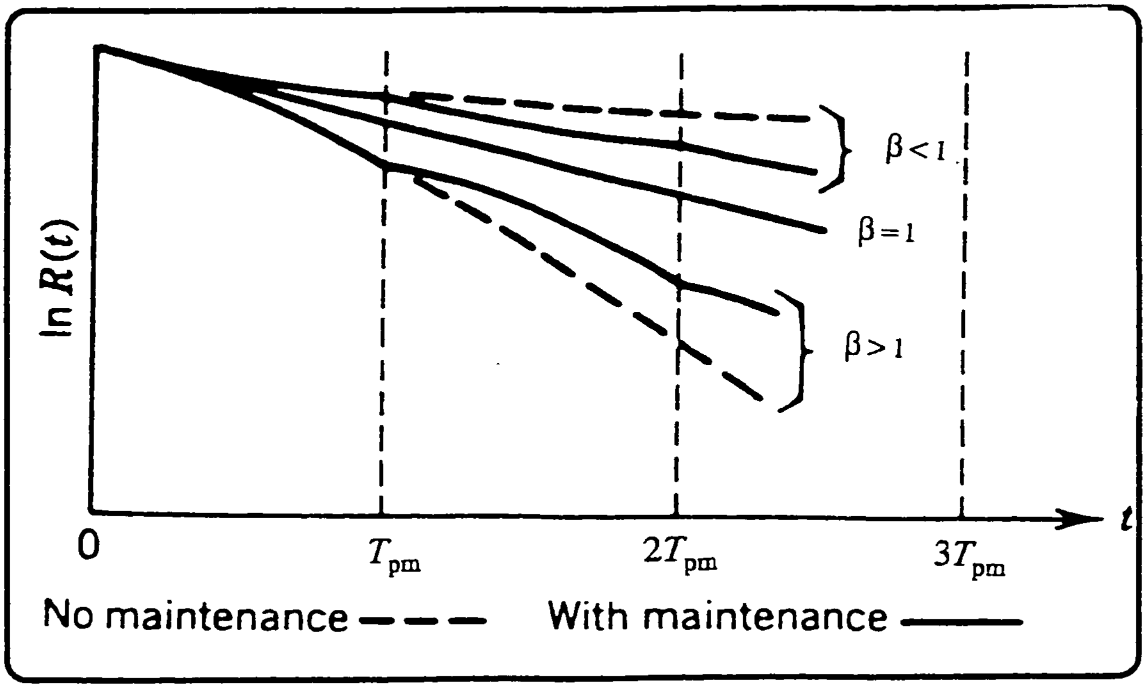


Figure 3.5. The effect of preventive maintenance on reliability.

Table 3.2 shows the types of maintenance for pumps, turbines and motors, respectively.

Table 3.2. Recommended Types of Maintenance for all Most Critical Bad Actors Rotating Equipments.

	Equipment #	*Code #*	*MTBF*	*β*	*Maintenance Type*
PUMPS	P41	35-G103B	11.10	0.84	Predictive
	P39	35-G-102B	8.95	1.02	Corrective
	P40	35-G103A	4.48	1.71	Preventive
	P38	35-G102A	7.83	0.97	Corrective
	P3	30-2-G58	6.75	1.15	Corrective
	P42	38-G103	5.54	1.26	Corrective
	P7	30-1-G203	8.64	1.48	Preventive
	P22	34-G53	6.71	1.11	Corrective
	P29	34-G764A	11.56	0.97	Corrective
	P33	30-G980A	12.86	0.64	Predictive
	P32	34-G980B	7.51	1.97	Preventive
	P15	32-G127A	5.85	2.09	Preventive
	P19	34-G664	8.08	1.26	Corrective
	P18	34-G866A	6.60	0.99	Corrective
	P24	34-G56	9.69	1.19	Corrective
	P26	34-G664A	11.52	0.93	Predictive
	P8	30-1-G202	19.10	0.86	Predictive
TURBINES	T1	35-3-GT104A	3.46	0.91	Predictive
	T3	35-3-GT103B	9.29	0.72	Predictive
	T4	32-KT106	4.01	1.04	Corrective
	T5	32-KT107	6.98	0.84	Predictive
	T6	32-GT111C	7.41	0.96	Corrective
	T7	32-GT111D	4.79	1.05	Corrective
	T8	30-1-GT91B	17.50	0.63	Predictive
	T9	30-1-GT90B	4.57	0.94	Corrective
	T10	32-KT108	9.34	0.56	Predictive
	T13	30-1-GT91A	5.82	1.23	Corrective
MOTORS	M4	34-1-GM983D	12.47	0.85	Predictive
	M2	38-GM12	15.33	0.89	Predictive
	M12	30-2-GM241D	20.34	0.67	Predictive
	M5	34-1-GM56	18.98	0.64	Predictive
	M7	30-2-GM42	32.94	0.65	Predictive
	M11	38-GM103	24.97	0.76	Predictive
	M1	22-FM102	10.40	1.19	Corrective

The maintenance strategies that are discussed in this project have four main parts. They are the types of maintenance (corrective, predictive, preventive), maintainability, availability and spare parts forecasting. By utilizing the Weibull model and from the calculated shape parameters, the appropriate type of maintenance to each rotating equipment was recommended as shown in Table 3.2. If $\beta < 1$, we recommend to apply predictive maintenance and if $\beta = 1$, we recommend to apply corrective maintenance, and if $\beta > 1$ then preventive maintenance is recommended. It is observed that the motors have shape parameters less than one and the only type of maintenance that should be applied to motors is predictive maintenance, which means that each motor should be under close online monitoring and this may include lubrication oil temperatures, vibration and oil flow to bearing. However, for steam turbines, we do not recommend to apply preventive maintenance because β is less than or equal to one for all bad actors steam turbines. On the other hand, we recommend the three types of maintenance for pumps depending on their shape parameter values.

3.2 Spare Parts Calculations for Failure Replacements

Replacements of individual units are made just after their failure. This type of replacements are primarily made for parts which will not cause any further damage to the system due to their failure in operation.

One realization of the renewal or counting process of failure replacements is shown in Figure 3.6.

The renewal function $H(t) = E[N(t)] = \bar{N}(t)$ defines the expected number of failures in time t and is given by the following integral equation:[15]

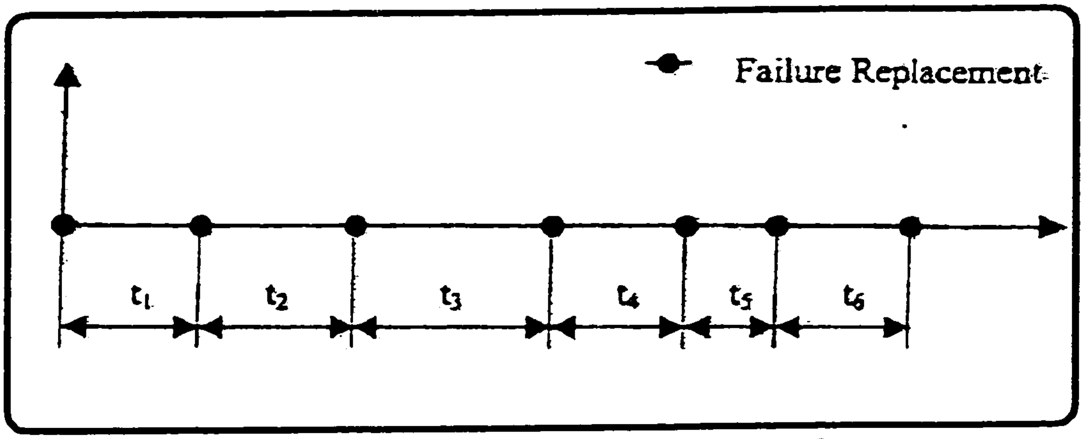


Figure 3.6. Renewal or counting process of failure replacements.

$$H(t) = E[N(t)] = f(t) + \int_0^t H(t-x)df(x) \tag{3.5}$$

The renewal rate function is

$$h(t) = \frac{dH(t)}{dt} \tag{3.6}$$

The variance of number of renewals $V[N(t)]$ is

$$V[N(t)] = \sigma^2[N(t)] = 2\int_0^t H(t-x)dH(x) + H(t) - H^2(t) \tag{3.7}$$

For the Weibull model where $f(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^\beta\right]$, the renewal functions for different values of β or $k = \frac{1}{\beta}$ can be calculated.

Let us consider replacements of a part having an average time between failure as $\bar{T}$ and standard deviation of time between failures as (T), $k = \frac{\sigma(T)}{\bar{T}}$. If the operation time t of the machine on which this part is installed is quite long and several replacements need to be made during this period, then the average number of failures $E[N(t)] = H(t)$ will stabilize to the following asymptotic value of the renewal function [15].

$$\bar{N}(t) = H(t) = E[N(t)] = \frac{t}{\bar{T}} + \frac{1}{2}(k^2 - 1) = \frac{t}{\bar{T}} + \frac{1}{2}\left(\frac{1}{\beta^2} - 1\right) \tag{3.8}$$

and the renewal rate function is given by

$$h(t) = \frac{dE[N(t)]}{dt} = \frac{1}{\bar{T}} \tag{3.9}$$

The variance of number of failures in time t is

$$V[N(t)] = k^2\left(\frac{t}{\bar{T}}\right) = \frac{1}{\beta^2}\left(\frac{t}{\bar{T}}\right) \tag{3.10}$$

The standard deviation of number of failures is

$$\sigma[N(t)] = \frac{\sigma(T)}{\bar{T}}\sqrt{\frac{t}{\bar{T}}} = \frac{1}{\beta}\sqrt{\frac{t}{\bar{T}}} \tag{3.11}$$

If time t representing a planning horizon is large, then from central limit theorem $N(t)$ is normally distributed with mean $\bar{N}(t)$ and standard deviation $\sigma[N(t)]$, the number of spares $N(t)$ needed during this period with a probability of shortage $= 1-p$, is given by [15]

$$N(t) = \frac{t}{\bar{T}} + \frac{1}{2}\left(\frac{1}{\beta^2} - 1\right) + \frac{1}{\beta}\sqrt{\frac{t}{\bar{T}}}\,\Phi^{-1}(p) \tag{3.12}$$

where $\Phi^{-1}(p)$ is the inverse of normal function.

To apply the theory of the replacement parts and renewal function, let us consider the non-repairable parts of the previous bad actors rotating equipment (pumps, turbines and motors). By investigating the non-repairable and repairable parts of bad actors pumps, we found that the seals and bearings are the most frequent failed parts. The pumps were segregated by their processes (distillate pumps, seawater pumps, etc.). Similarly, for motors, the bearings are found to be the most frequent failed parts. However, for the turbines the seals are the frequent failed parts. The calculation of spare parts in the renewal function is based on five-years period of time (60 months). The results are summarized in Table 3.3. From this table, it was found that we should have 11 bearings available in spare parts inventory for motors. It is logic when you see the low value of MTTF (8.9 months). The other seals and bearings for pumps and turbines were calculated to be 4 and the MTTF are 25 months.

Table 3.3. Replacement Parts Inventory Based on the Renewal Functions.

Type of Equipment	β	η (months)	*MTTF* (months)	t (months)	*Needed Parts* $N(t)$
Distillate Pumps (Seals)	1.51	28.12	25.35	60	3.75 ≈ 4
Seawater Pumps (Seals)	1.62	28.30	25.42	60	3.60 ≈ 4
All Pumps (Bearings)	1.73	29.44	26.22	60	3.38 ≈ 4
Motors (Bearings)	1.06	9.58	9.36	60	10.28 ≈ 11
Turbines (Seals)	1.09	27.42	26.48	60	4.44 ≈ 5

Chapter 4

Discussion

1. Three types of rotating equipment, which are pumps, steam turbines and electric motors, were found to have a good failure history. The time to failure or malfunction data of these rotating equipment were gathered from Saudi Aramco computer maintenance system and from on-line monitoring of process variable data retrieved from distributed control system. The period of the investigation is five years from 1995 to 2000. Each of these equipment were analyzed in depth as a repairable system. Some of their non-repairable parts, such as seals and bearings, were analyzed separately.

2. Pumps are found to have higher number of bad actors than steam turbines and motors. However, in terms of percentage, steam turbines have 26% of total number of steam turbines in operation as bad actors, whereas pumps have 15% and motors have 4%. Our definition of the bad actors equipment is "*the equipment that have more than three failures or malfunctions in five years.*"

3. The pareto analysis was utilized effectively to identify the most critical bad actors rotating equipment. The Pareto analysis criteria is depending on two main factors, which are the number of failures and their associated repairing costs. The determining of Pareto criteria is different from a person to another depending on how much efforts and money he wants to spend. As shown in Figures 2.1 and 2.2, the criteria of Pareto analysis of the pump is 50% of number of failures and 50% of repairing cost. However, for steam turbines, as shown in figure 2.45 and 2.46,

the Pareto criteria is to select the equipment those have less than 75 accumulative percent of number of failures and repairing cost. For motors, as shown in Figures 2.76 and 2.77, the criteria is 60% for number of failures and repairing costs. Accordingly, 17 pumps, 10 steam turbines and 7 motors were determined to be the most critical bad actors equipment by utilizing Pareto analysis.

4. The failure modes of pumps are figured out and plotted in Pie charts to visualize the relative contribution of each failure mode. It is found that the mechanical seals of pumps have the highest failure mode which is 36% of the total number of failure (111). The other highest type of failure is the malfunction due to overhaul (23%). The overhaul means that the equipment is sent to the Machine Shop with unknown reasons to inspect it and replace the defected parts. The failure due to impeller (11.7%), bearings (9%) and shaft (6.3%) are other significant modes of failures.

Turbine failure modes are also figured out in Pie charts to see and compare the frequent modes of failures for each steam turbine. It is found that the repairable parts of steam turbine have the highest failure rates. These are governors (28%), lubrication oil coolers (25.7%) and throttle valves (24.3%). The non-repairable parts are found to have 7.5% failures for the seals and 4.1% failures for the bearings.

Motors are found to have variety of failure modes. It is not like pumps and turbines where there is a common failure mode. In motors only non-repairable parts (bearings) is the highest failure percentage out of the total number of failures (44%). The other highest failure modes are grounded (12.5%), overhaul (12.5%) and rewinding (9.4%).

5. The Weibull parameters of the most critical bad actors are very important to study their reliability and availability. These parameters are β, η, MTBF, standard deviation, mode T_m, and median time $T_{0.5}$. The shape parameter β is important to determine the type of failure of the equipment and type of maintenance that should be applied. Ten (10) pumps are found to have $\beta \geq 1$. The mean time between failure (MTBF) is also calculated for each pump. From the MTBF, we can predict the failure time of the pump to plan ahead of time the right action to minimize the downtime of the plant.

The reliability parameters for steam turbines are calculated and found to have $\beta \leq 1$ in almost all bad actors steam turbines and characteristic life are found also to be small compared to pumps. The range of η is between 3 months to 7 months except one steam turbine (T8) which is 12 months. However, for motors, it is found that the characteristic life is higher than pumps and turbines (from 11 months to 21 months), but the shape parameters, β, is less than one. The MTBF for motors are high. Some of them are 33 months, 25 months and 20 months. The lowest MTBF is 12.5 months which are considered high compared to pumps and steam turbines.

6. The reliability charts for selected equipment is demonstrated to trace its reliability through the operation time. We have selected four equipment that have different β (i.e., $\beta > 1$, $\beta < 1$, $\beta = 1$). The reliability curve that was drawn from the reliability equation of the Weibull distribution is compared with the reliability points that is calculated from the probability of failure (1-$F(t)$). Most of the rotating equipment reliability curves are fitted well with the reliability data that was calculated from the Weibull models. From these curves, the reliability of each equipment can be predicted at any given time.

7. Reliability of the non-repairable parts and repairable parts of each equipment was discussed. It was found that the common non-repairable parts of the most critical bad actors pumps are seals and bearings. For the pumps, we segregated the pumps according to their process (seawater pumps and distillate pumps). It is found that the behavior of the failure of seals for both seawater pumps and distillate pumps are same. So, the time to failure of the seal for the pumps are combined together and plotted in one figure, as shown in Figure 2.44. The other type of non-repairable parts of the pump is bearings. It is found that the bearing lasts little bit more than seals in service. Their characteristic life is 29.4 months, however, the characteristic life of the pump seals is 27.5 months.

The frequently failed repairable parts of the steam turbines are due to failures in governors, coolers and throttle valves. Each of these failure modes is discussed in depth from cost point of view. However, seal is found to be the only non-repairable part for the steam turbines. For motors all failure modes studied are due to the failure of repairable parts. However, the non-repairable parts of the motors are found to be bearings. The characteristic life of motor bearing is very low compared to pumps and steam turbines (8.9 months).

8. The cost analysis is conducted for both repairable parts and non-repairable parts for the most critical bad actors rotating equipment. A best straight line is fitted to trace the behavior of spending the maintenance repairing cost against the operation time for repairable and non-repairable systems. Some times, like in the motor bearings (Figure 2.95), the shape of the repairing cost data looks like exponential line, but this will not be correct because of the nature of the spending the repairing cost which is increasing with time. Thus, the straight line is the best to describe the behavior of the repairing cost. The accumulative repairing costs for all modes of failure for the 17 most critical bad actors pumps versus the time of operation for five years of operation are plotted in Figure 2.42. Also, the average accumulative repairing costs versus the operation time of each bad actors pump is estimated and plotted in Figure 2.47. However, for non-repairable parts, the repairing costs versus the time between failure is plotted for both seals and bearings. However,

for the seals of all pumps (non-repairable parts), it is found that the maintenance cost is increasing significantly after 10 months of operation as shown in Figure 2.44. The accumulative cost of the non-repairable parts includes the cost of repairing auxiliaries that is related to the pump seal.

The cost analysis of the repairable parts of the most critical bad actors steam turbines include the mechanical governors, lubrication oil coolers and throttle valves. For steam turbines mechanical governor as shown in Figure 2.72, the maintenance cost spending is repeated each 20 months and is getting increased. The spending cost for lubrication oil coolers is shown in Figure 2.73. The dotted lines shows the actual maintenance cost and the solid lines shows the best fitted straight line of the average spending maintenance cost. This figure shows a significant increase of repairing cost from 40 months to 55 months compared to the first region, which is from 10 months to 40 months, and this is due to severe corrosion in the suction and discharge nozzles of these coolers.

Most of the throttle valves repairing cost, as shown in Figure 2.74, was spent in the first 20 months of operation. The accumulative repairing cost for all modes of failures (repairable parts) in motors, as shown in Figure 2.96, has two regions. In the first region (from 0 to 10 months), there was a high spending cost, but it was reduced in the second region (from 10 months to the end) due to installation of new parts.

However, the maintenance cost for the bearings of all the most critical bad actors motors was drawn in Figure 2.95. It shows that most of bearings maintenance cost was spent in the final 12 months of operation period.

9. The maintenance strategies that are discussed in this project have four main parts. They are the types of maintenance (corrective, predictive, preventive), maintainability, availability and spare parts forecasting. By utilizing Weibull analysis and calculated shape parameters, the appropriate type of maintenance of each rotating equipment was recommended. If $\beta < 1$, we recommend to apply predictive maintenance and if $\beta \simeq 1$, we recommend to apply corrective maintenance, and if $\beta > 1$ then preventive maintenance is recommended. It is observed in Table 3.2 that the motors have shape parameters less than one and the only type of maintenance that should be applied to motors is predictive maintenance, which means that each motor should be under close online monitoring to include lubrication oil temperatures, vibrations and oil flow to bearings. However, for steam turbines, we do not recommend to apply preventive maintenance because β is less than or equal to for most of the bad actors steam turbines. On the other hand, we recommend to apply the three types of maintenance for pumps depending on their shape parameters.

10. The maintainability, reliability and availability of the most critical bad actors rotating equipment were calculated and summarized in Table 3.1. It is

observed that the motors availability are higher than pumps and turbines availability. This is because of the high MTBF of motors. It was also observed that the availability of some pumps are very low (from 40% to 50%) and this is because of high MTTR.

11. The renewal function of spare parts are utilized to calculate the required number of spare parts in this project for non-repairable parts of the bad actors rotating equipment. This will help in reducing the repairing time (MTTR) and will increase the equipment availability. The non-repairable parts of rotating equipment that were discussed in this projects are seals and bearings. We found that for pumps, we should have at least 4 bearings and 4 seals that we expect to use them for the most critical bad actors pumps. However, for the most critical motors, we should have at least 11 bearings which is logic when you know that the shape parameters of motor bearings is 9 months. For the most critical bad actors steam turbines we should also have at least 5 seals in spare parts inventory.

Chapter 5

Concluding Remarks and Recommendations

1. The Weibull reliability analysis is found to be very beneficial to characterize the equipment time to failure and time to repair and to design appropriate maintenance strategies using Weibull model as a predictive model. Based on this analysis, operation management will be able to take the right decision in advance to avoid any operational upset and plants downtime.
2. The Weibull model can be applied to rotating equipment to represent the three types of failures, which are early failure or wear-in, random failure, and wear-out failure, by determining the shape parameter β for repairable and non-repairable parts of each rotating equipment.
3. Pareto analysis is found to be very helpful tool in reliability analysis which is used to assist the management quickly identify the most critical bad actors rotating equipment, such analysis is based on a selected criteria depending on ranking the number of failures and their associated repairing cost for each equipment. Selecting the criteria of Pareto analysis is different from one person to another and it depends on how much money and efforts are needed to spend.
4. Pump failures due to seals are the highest failure modes, which is 36% of the total number of failures. Accordingly, it is recommended for providing more efforts to investigate the root cause of seals failure and replacing the existing types of seals to better types. Also, same recommendations are applicable for motor bearings, since 44% of the motor failures are due to bearing problems.

5. Weibull analysis parameters are very important tools to study the reliability, maintainability and availability of rotating equipment. All the reliability parameters are depending on two main parameters that can be calculated from Weibull model, they are characteristic life η and shape parameter β. Also, by utilizing the reliability parameters, the reliability chart of each rotating equipment can be drawn to trace its reliability at any time of operation.

6. By conducting the cost analysis for steam turbines, it is recommended to retrofit the mechanical governor to electric type to minimize the frequent failures of the steam turbines due to mechanical governors. Also, no lubrication oil coolers, for steam turbines are recommended. The existing coolers have severe corrosion in the suction and discharge nozzles which can not be repaired.

7. The availability of each rotating equipment was calculated. One of the objectives is to increase the equipment availability. The main contributing factor to the availability is the MTTR, as MTTR decrease the availability increases. Most of rotating equipment MTTR are high because they are on-hold in repair shop awaiting spare parts. Accordingly, it is recommended to keep good spare parts inventory to reduce the MTTR and as a result the availability of equipment will increases.

8. To reduce repairing cost, the suitable type of maintenance (preventive, predictive and corrective) should be applied to the rotating equipment and this depends mainly on the failure rate or shape parameter of each equipment. It is found that what is

done in the refinery plants as a preventive maintenance is small (changing the lubricant), so we recommend including other activities of preventive maintenance like scheduled replacement for parts expected to fail.

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APPENDIX A

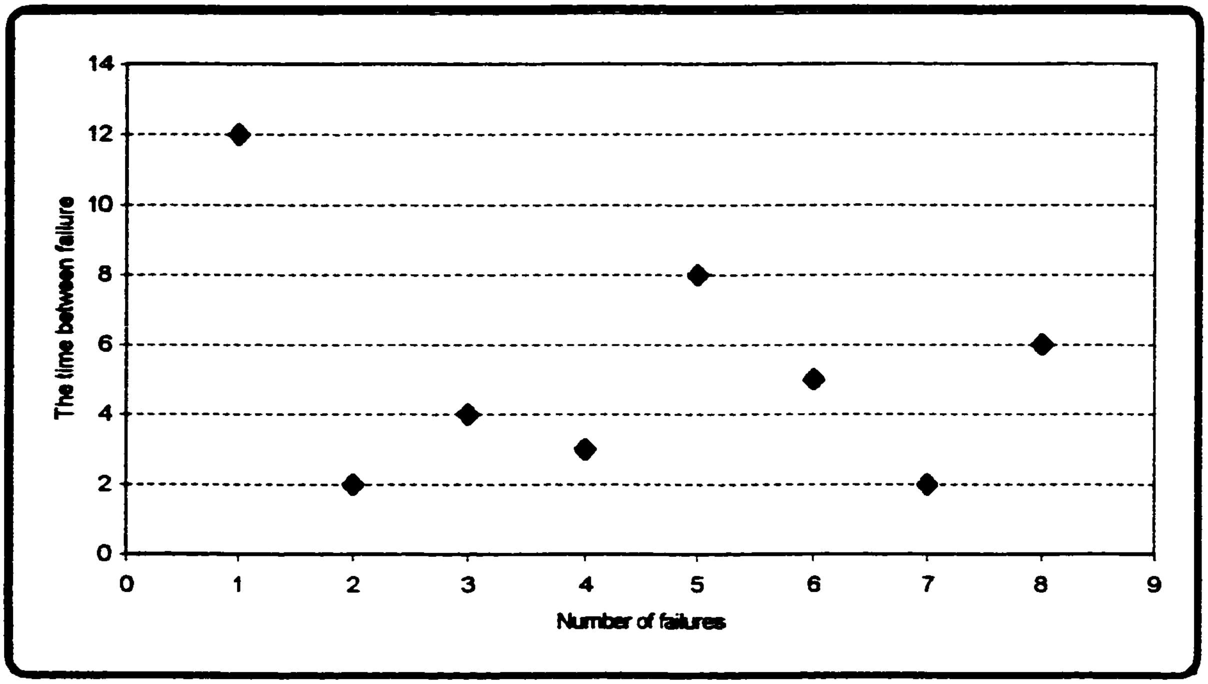


Figure A.1. Scatter chart for P40 to show no trend.

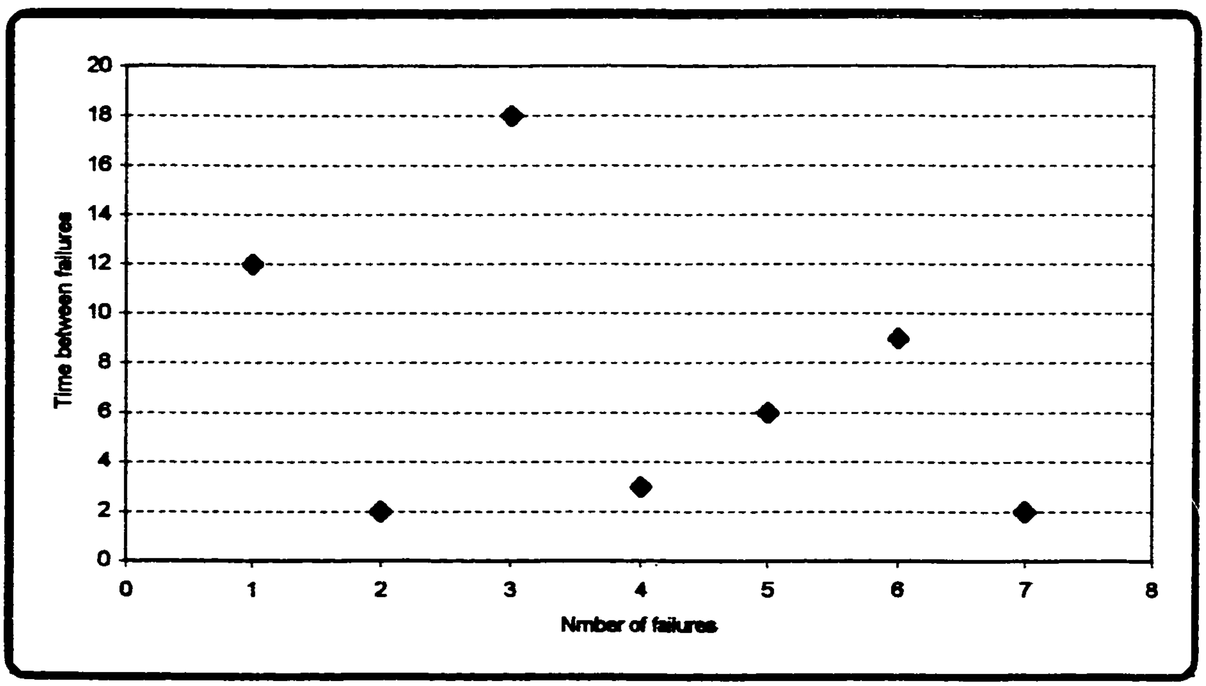


Figure A.2. Scatter chart for P38 to show no trend.

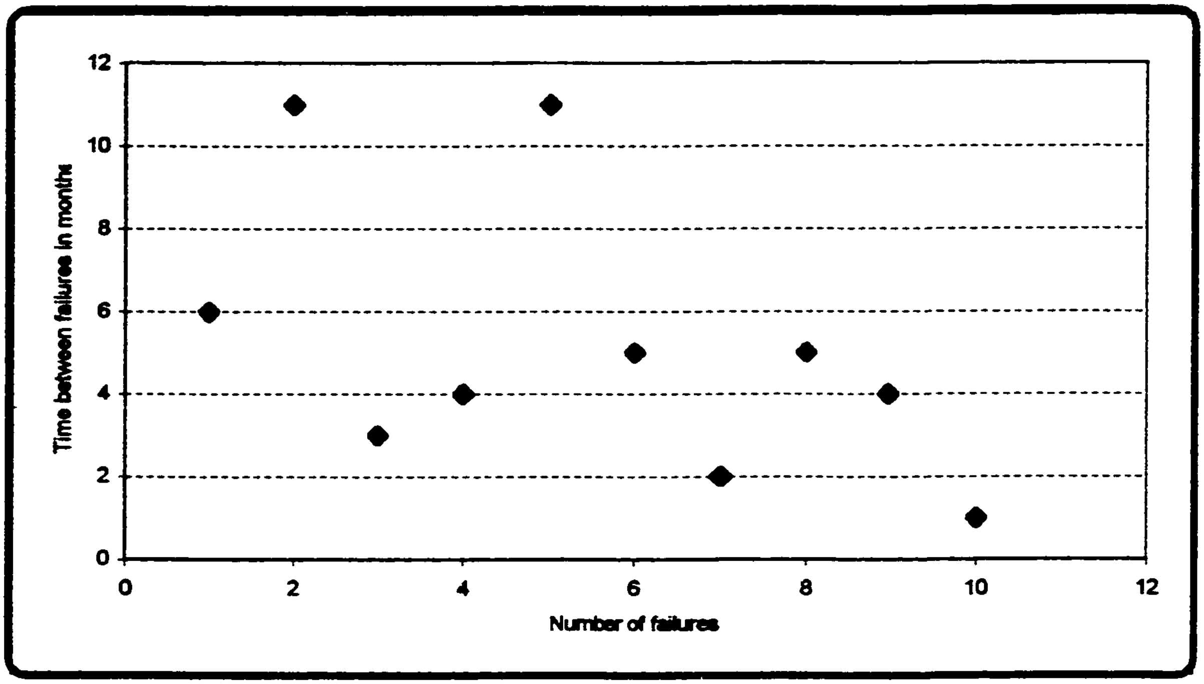
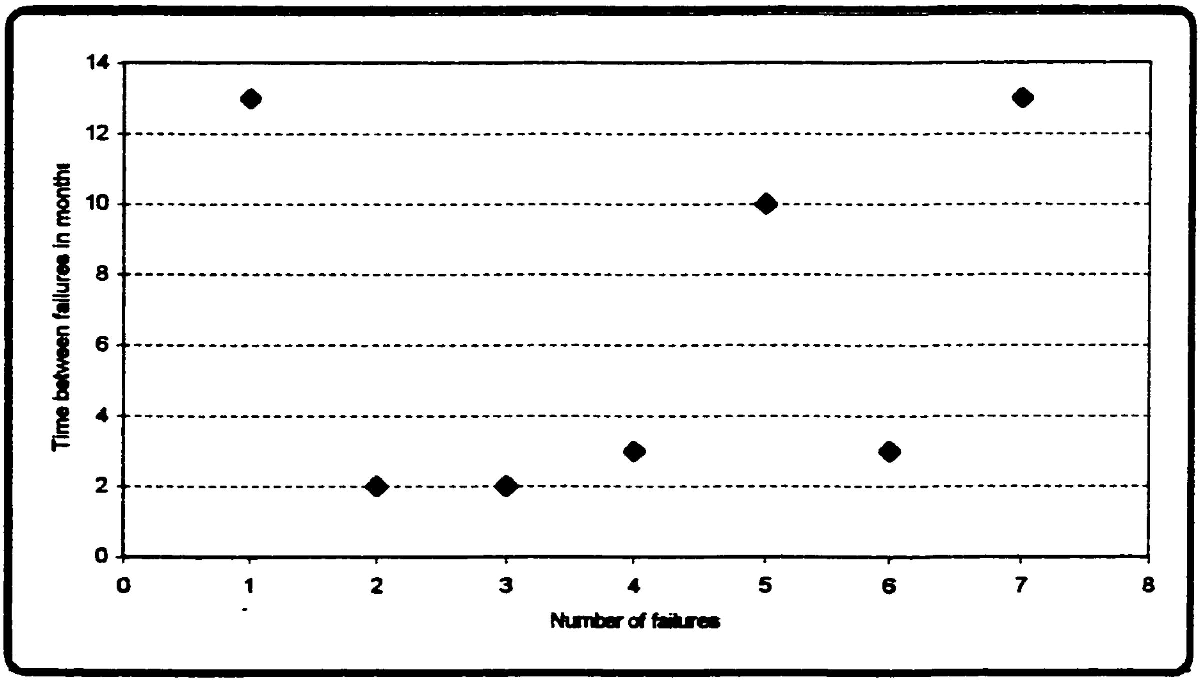


Figure A.3. Scatter chart for P42 to show no trend.



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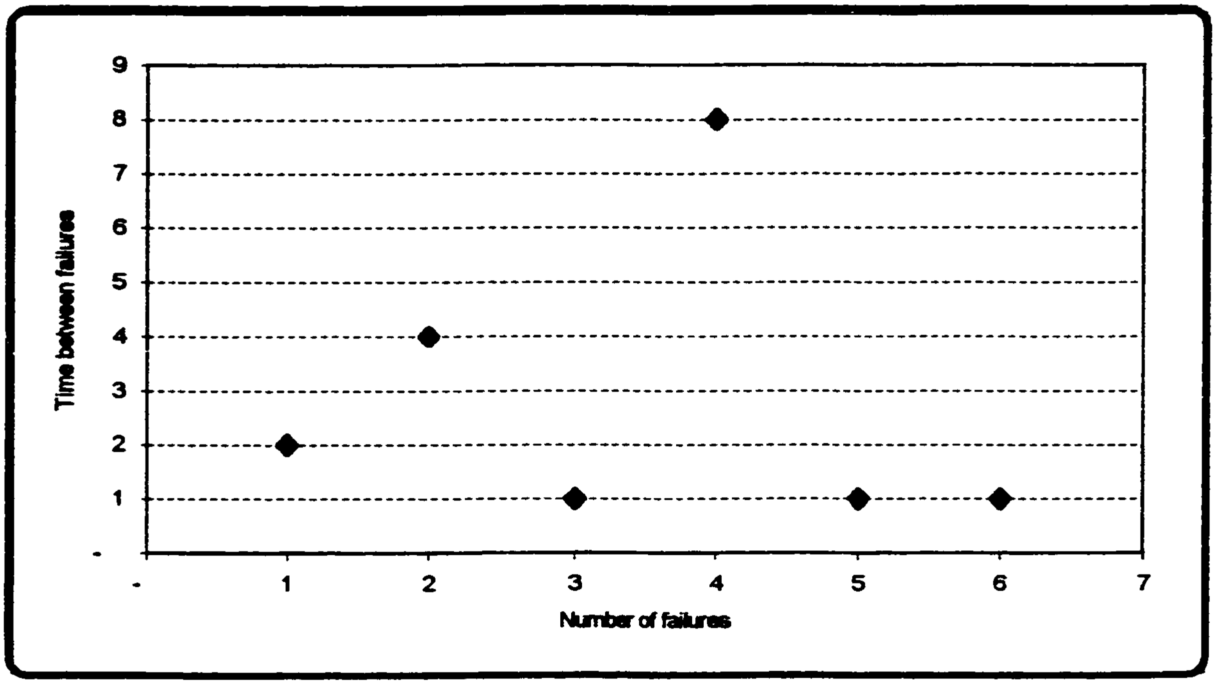
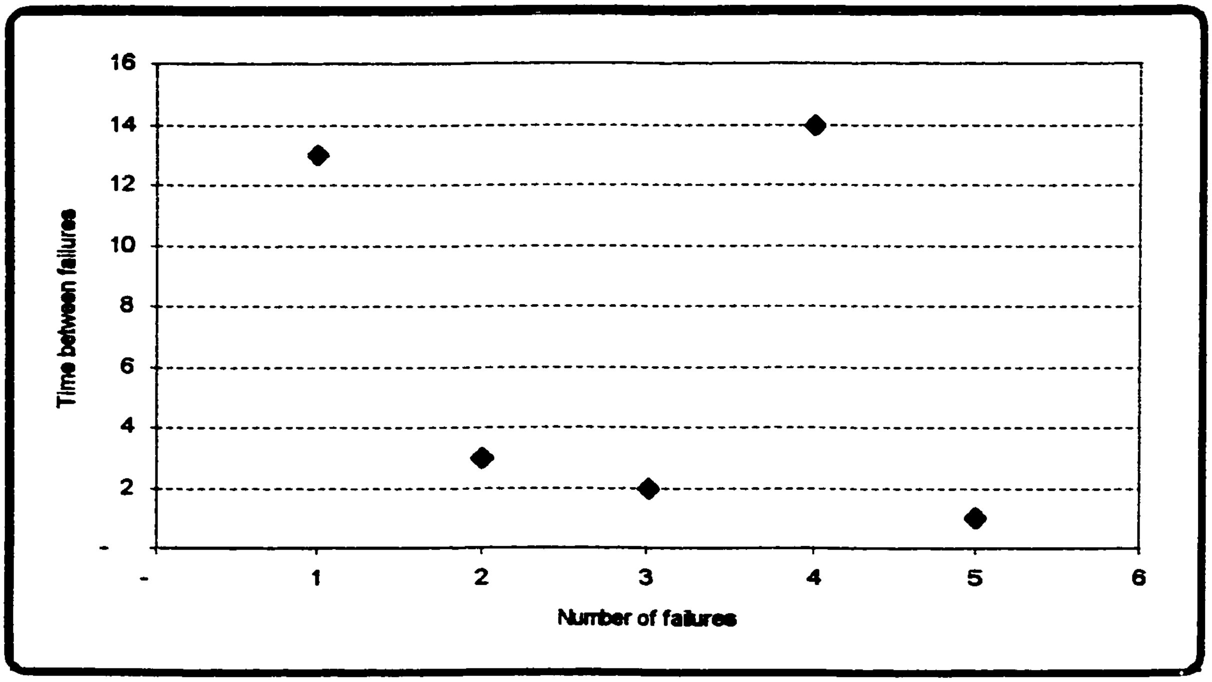


Figure A.5. Scatter chart for T1 to show no trend.



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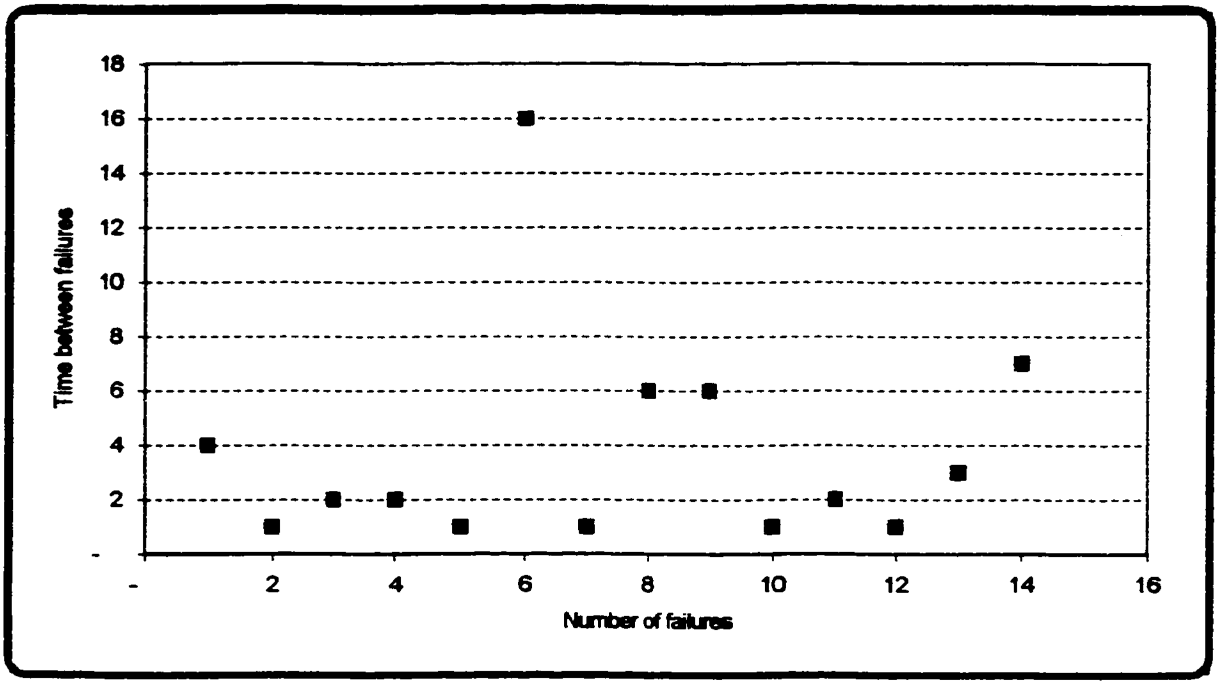

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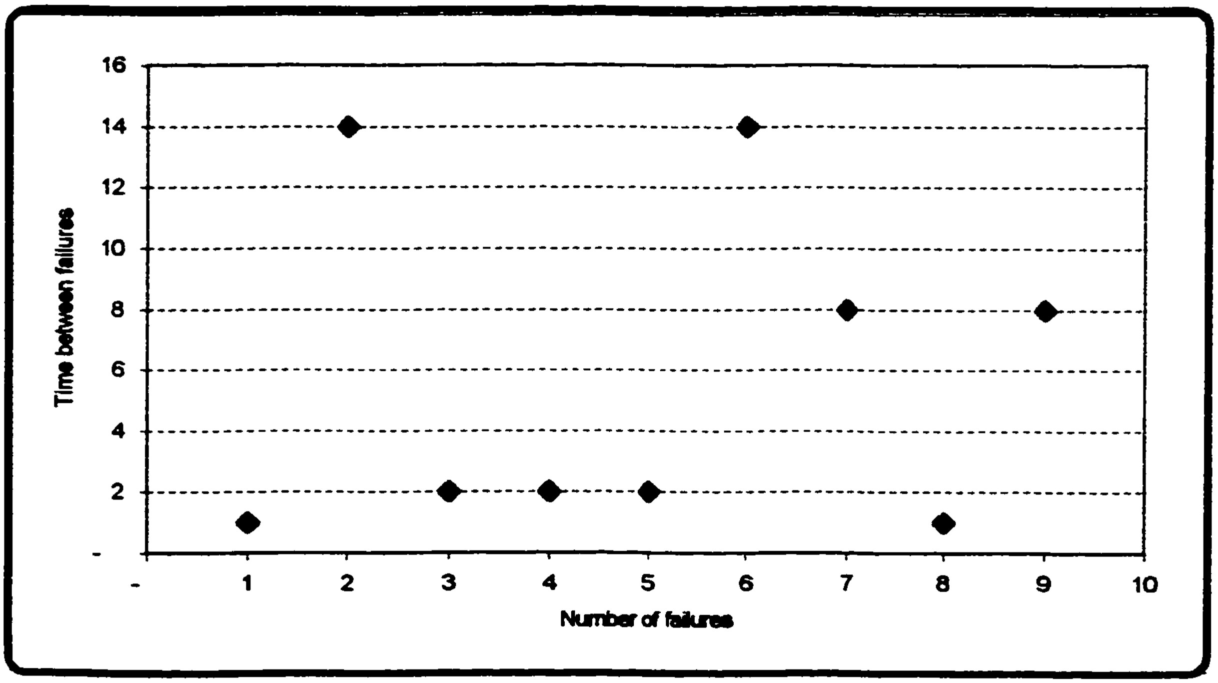

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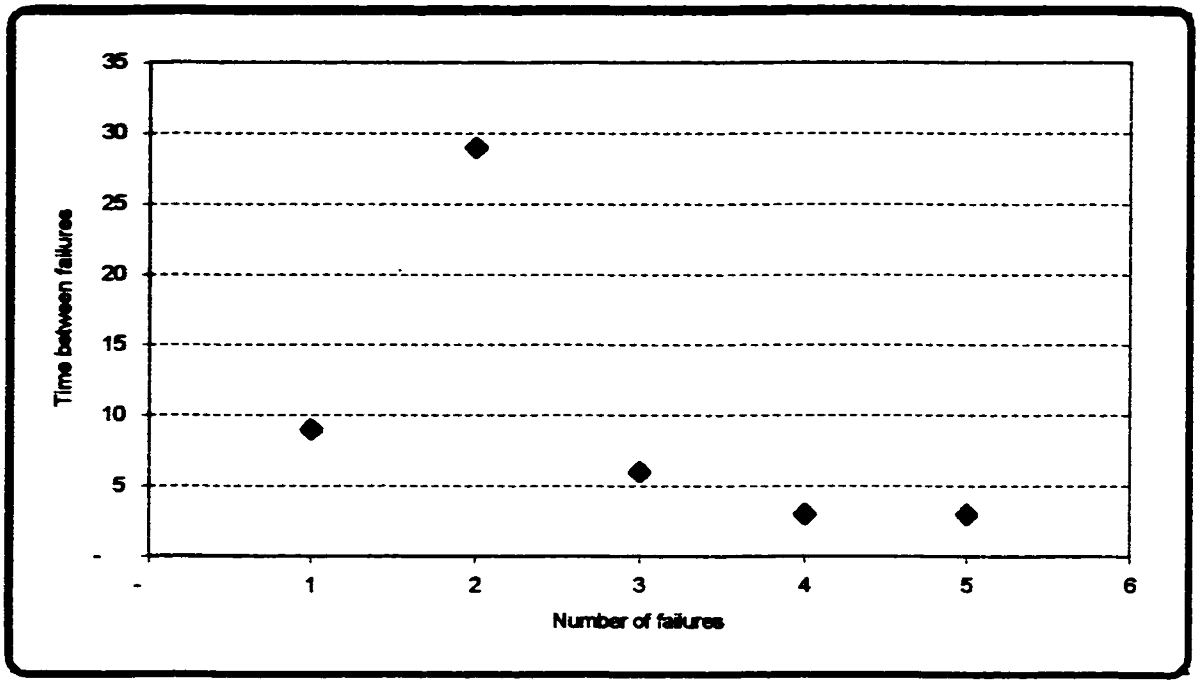
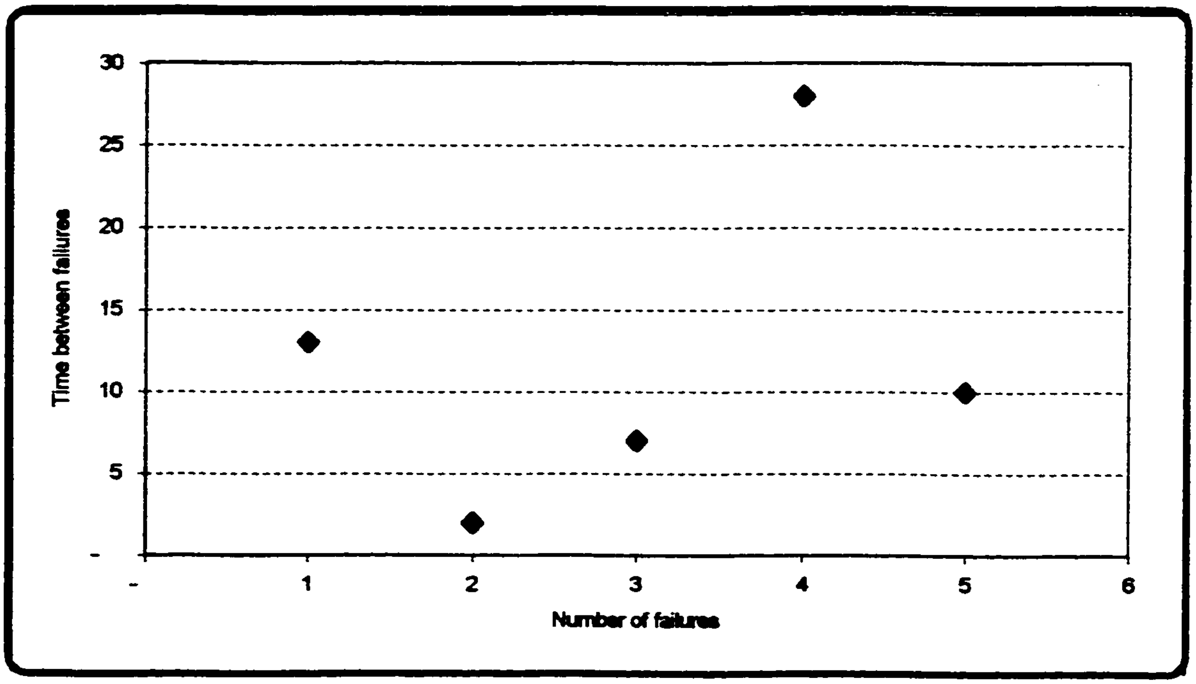


Figure A.9. Scatter chart for M4 to show no trend.



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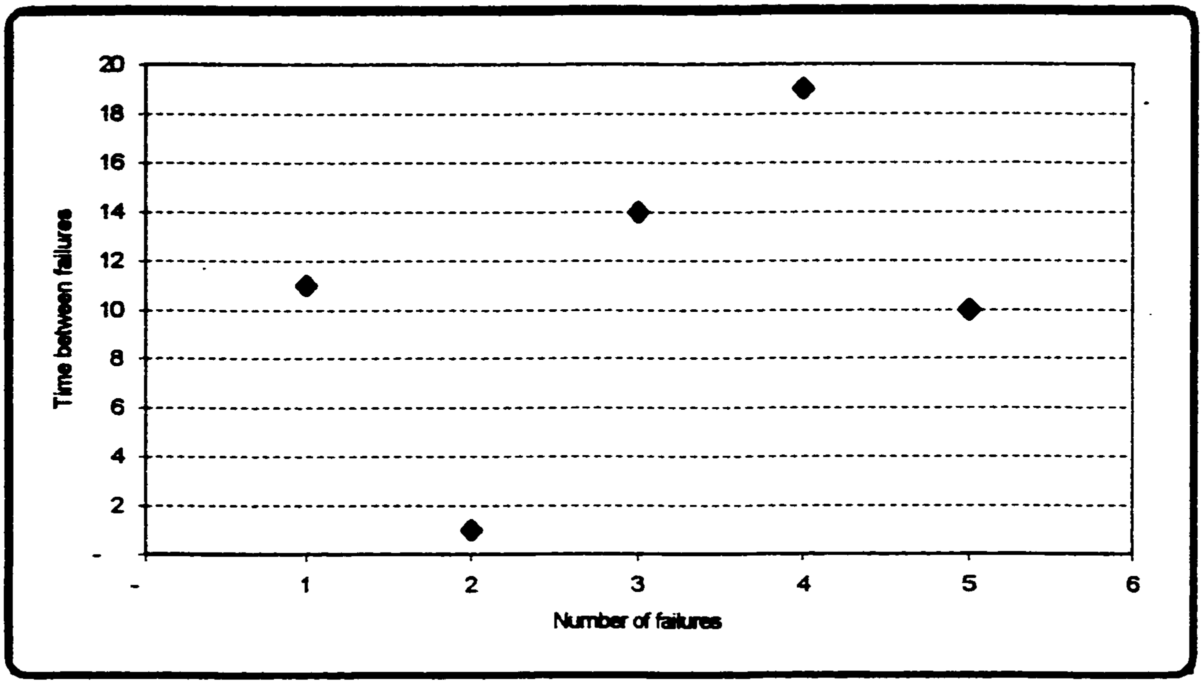

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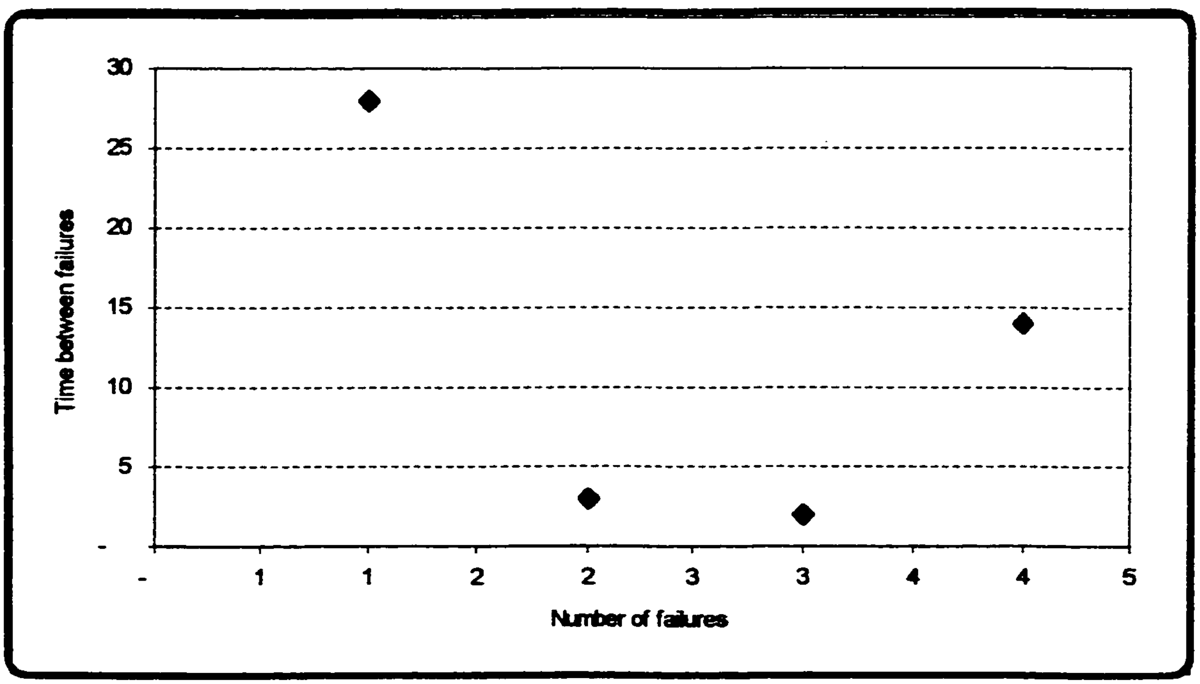

Figure A.12. Scatter chart for M5 to show no trend.