WEIBULL ANALYSIS OF TIME BETWEEN FAILURES OF PUMPS USED IN AN OIL REFINERY

Anwar Khalil Sheikh[1], Muhammad Younas[1], Dahham Matar Al-Anazi[2]

1: King Fahd University of Petroleum and Minerals, Dhahran 31261
2: Saudi Aramco, Dhahran 31311

myounasa@kfupm.edu.sa, anazidm@aramco.com.sa

ABSTRACT

This paper is based on the time to failure or time between failure data and associated maintenance cost for a set of pumps used in an oil refinery collected over a period of five years. Out of a large number of pumps in operation, a set of pumps are identified which have experienced 3 failures in five years. The Pareto analysis performed on this set of pumps further narrowed down the group of most critical (worst performing) pumps. This group of most critical pumps is the primary target for the further investigation and Weibull reliability analysis. The analysis started by determining the failure modes of each pump .The highest number of failures are attributed to the failure of pump seals followed by downtime due to overhaul, malfunction of impeller, failures of bearings, impellers, shaft, couplings, etc. Seals and bearings are essentially non-repairable items and are currently being replaced upon failure. It is found that majority of pump failures is because of seals, overhaul, impellers and bearings.

The Weibull analysis helps to determine the reliability function, $R(t) = \exp[-(t/\eta)^{\beta}]$ and its parameters (β, η). The shape parameter β is a function of σ/μ i.e., $\beta = \phi(\sigma/\mu)$, where σ and μ are the mean and standard deviation of life respectively. The other parameter η is the characteristic life. By utilizing Excel spreadsheet, each pump was analyzed and its related reliability parameters β, η MTBF, standard deviation, mode T_m, and median time $T_{0.5}$ were determined. The shape parameter β helps to select appropriate maintenance and part replacement strategies.

The cost analysis is conducted for both repairable parts and non-repairable parts. The accumulative repairing costs for all modes of failure for the groups of 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. This type of cost analysis can help in deciding if we have to continue to repair the equipment or have to purchase a new one to replace it because repair cost is becoming much higher than the cost of new pump.

Keywords: *Repairable system, reliability, Weibull analysis, reliability model, parameters, Pareto analysis, non-repairable parts, cost analysis,*

الملخص

تعتمد هذه الورقة على معطيات تتعلق بوقت مابين الأعطال والتكاليف لمجموعة مضخات مستعملة في مصفاة نفط وقد جمعت هذه المعطيات خلال خمسة أعوام. وقد تم اختيار المضخات التي لها أداء متدني لتكون موضوع هذه الدراسة.

تبدأ الدراسة بتحديد أنواع الأعطال لكل مضخة واتضح أن أكثر الأعطال سببها حلقة منع التسرب يليها أعطال التوضيب ثم أعطال العنفة أعطال المحمل وعمود الإدارة ... إلخ. حلقة منع التسرب والمحمل هي من القطع التي لايمكن أصلاحها ويتم استبدالها عند العطل. تحليل وايبل يساعد في تحديد دالة الاعتمادية ومعالمها ومعلم الشكل بالتحديد يساعد في تحديد نوع الصيانة المناسب واستراتيجية تغيير قطع الغيار. وقد تم تحليل التكلفة للقطع القابلة للإصلاح والقطع الغير قابلة للإصلاح. تم رسم التكلفة التراكمية لكل أنواع الأعطال مع الزمن وهذا النوع من التحليل يساعد في اتخاذ القرارات بخصوص مواصلة الإصلاح أو استبدال قطع الغيار عند الصيانة.

1. INTRODUCTION

Failure history of a set of pumps used at a large Refinery plants obtained from their Computerized Maintenance Management System [Samaha, 1997] has been utilized to perform Weibull analysis. These pumps are essentially repairable systems. Every action after observing a failure is of corrective nature (corrective maintenance situation). Some parts in these systems need replacement rather than repair. The Weibull reliability analysis [Kolarik, 1995], [Peterlik, 1995], [Lewis, 1987], [Abernathy, 1996], [Kapur, and Lamberson, 1977] 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 the pump replacements and a proper selection of pump maintenance strategy. Analysis focuses on the most critical bad actors equipment with highest rate of failure and repairing cost.

2. PARETO ANALYSIS

In the Maintenance Management System, the time of failure, 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 were classified as the bad actor pumps because each one of them has experienced 3 failures in the five years period

The Pareto analysis [Samaha, 1997] was used to judge the relative severity of bad actors in the refinery plant and to identify the *most critical bad* actors pumps out of these 44 bad actors pumps .The decision was based on a suitable criteria of certain percentage of repairing cost (50 %) and certain percentage of number of failures (50%) contributed by this narrowed down group of pumps. Thus , out of 44 pumps 17 pumps are chosen to be the most critical bad

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actors and listed in Table 1, they will be referred to as "***the most critical bad actors pumps***." This group of most critical pumps is the primary target for investigation and reliability analysis. The Weibull reliability analysis will be performed on these pumps by using their time between failure data.

Table 1 Most Critical Pumps Among The Bad Actor Pumps.

Pump #	***Pump Description***	***Process Type***	***No. of Failures in 5 years***	***Cost in US $***
P41	High Lift Pump	Seawater pump	7	488,269
P39	High Lift Pump	Seawater pump	7	459,617
P40	High Lift Pump	Seawater pump	8	319,968
P38	High Lift Pump	Seawater pump	7	240,946
P3	Salt Water Pump	Seawater pump	9	233,429
P42	Fire Water Pump	Seawater pump	10	150,550
P7	Feed Water Pump	Seawater pump	6	148,793
P22	Brine Recycle Pump	Seawater pump	5	113,789
P29	Distillate Pump	Distillate pump	6	111,722
P8	Feed Water Pump	Distillate pump	4	146,529
P32	Sump Pump	Distillate pump	7	105,965
P15	Super-Heater Pump	Distillate pump	8	100,849
P19	Distillate Pump	Distillate pump	6	92,735
P33	Sump Pump	Distillate water pump	6	48,765
P24	Booster Pump	Distillate water pump	7	73,060
P26	Distillate Pump	Seawater pump	7	56,327
P18	Booster Pump	Distillate water pump	7	84,481

3. DETERMINING FAILURE MODES

The analysis started by determining the failure modes and the time to failure of each pump. Before we proceed further a brief description of mostly used pumps , their main parts and associated failure classifications are given below.

The types of pumps that are most commonly used in a Refinery plant are centrifugal pumps. 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 paper are impellers, shafts, seals and bearings.

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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 is a very important part in the pump. Seals 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. The failures causing the stoppage of the pumps are primarily experienced by these parts and will be termed as failure modes. 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.

** *Overhaul is necessitated due to any unidentified mode of failure, and its impact is the nonavailability of the pump, therefore as a whole it is being grouped as a failure mode.*

Figure 1and Figure 2 show the Pie diagrams of two of these 17 most critical bad actor pumps for different modes of failures. To develop a comprehensive picture; all modes of failure for all of these 17 most critical bad actor pumps were determined and sorted by the number of failures associated with their failure modes; the results are presented in Figure 3 .The highest

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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. 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%).

4. TWO PARAMETER WEIBULL MODEL AND ITS CHARACTERISTIC

The two parameter Weibull Cumulative Distribution Function (CDF), F(t) defines the fraction failing or probability of failing before time t (or unreliability at time t) and has an explicit equation [Lewis, 1987], [Abernathy, 1996], [Kapur, and Lamberson, 1977]:

$$F(t) = 1 - e^{-(t/\eta)^{\beta}} \tag{1}$$

and the reliability function or probability of survival at time t is given by

$$R(t) = e^{-(t/\eta)^{\beta}} \tag{2}$$

The shape parameter (β) is a non-dimensional parameter and reflect the type of failure mode, such as infant mortality (β<1), random (β=1), or wear-out (β>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 whenβ=1, MTTF = η. The general relationship between η and MTTF is given by the following equation: [Lewis, 1987]

$$MTTF = E(T) = \mu = \eta \Gamma\left[1 + \frac{1}{\beta}\right] \tag{3}$$

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

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

$$\lambda(t) = -\left(\frac{1}{R(t)}\frac{dR(t)}{dt}\right) = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} \tag{4}$$

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

$$\sigma^2 = \eta^2\left[\Gamma\left(1+\frac{2}{\beta}\right)-\Gamma^2\left(1+\frac{1}{\beta}\right)\right] \tag{5}$$

2. Mode

$$T_m = \eta\left[\frac{\beta-1}{\beta}\right]^{\frac{1}{\beta}} \tag{6}$$

3. Co-efficient of Variation

$$K = \frac{\sigma}{\mu} = \frac{\sqrt{\Gamma\left(1+\frac{2}{\beta}\right)-\Gamma^2\left(1+\frac{1}{\beta}\right)}}{\Gamma\left(1+\frac{1}{\beta}\right)} \tag{7}$$

4. Quantile t_p is given by

$$t_p = \eta\left(\ln\frac{1}{1-p}\right)^{1/\beta} \tag{8}$$

where $F(t_p)=p$.

5. Median $T_{0.5}$

$$T_{0.5} = \eta(\ln 2)^{1/\beta}\,. \tag{9}$$

The Weibull analysis helps to determine the reliability function, $R(t)=\exp[-(t/\eta)^{\beta})$and its parameters $\tilde{\beta}$, η, MTBF, etc.). From Eq. 7 $\beta_{.}= \phi(\sigma/\mu)$, where μ and σ^2 are the mean and variance of life, respectively. The other parameter $\tilde{\eta}$, is the characteristic life. By plotting the time between failure for these pumps, it was observed that there is no underlying trend in the data so the Weibull reliability analysis can be used. By utilizing Excel spreadsheet, regression analysis of transformed time to failure data [Lewis, 1987] of each pump was analyzed and its related reliability parameters were determined. In this analysis each pump is considered to be a repairable system including all types of failures/ malfunctions. Figure 4 and Figure 5 show the linearized Weibull plots for the time between failure data of two of the most critical bad actor pumps. Table 2 shows the reliability parameters for all of the 17 most critical bad actor pumps.

Table 2. Reliability Parameters For The Most Critical Bad Actor Pumps.

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

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The reliability parameters of the most critical bad actors are very important to study its reliability and maintenance. These parameters β, MTBF, standard deviation, mode T_m, and median time $T_{0.5}$. The shape parameter 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 failures (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).

6. 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 is replacing them with new ones when they fail. In this analysis, as shown in Table 2, the most critical bad actor pumps are segregated based on their process (for example, seawater pumps, distillate pumps). As shown in Figures 6 and 7, 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 pumps seals are combined together and plotted in one figure (Figure 6). 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 types of non-repairable parts of the pump are bearings. As shown in Figure 7, 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 (=1.76 for seals and =1.74 for bearings).

7. COST ANALYSIS OF REPAIRABLE SYSTEM (PUMPS)

The cumulative repairing cost for all modes of failure for each pump versus the five years of operation was 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 8 and 9. The cost analysis is conducted for both repairable parts (all modes of failures combined together) 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 a typical pump is estimated and plotted. However, for non-repairable parts, the repairing cost versus the time between failures is plotted for both seals and bearings.

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8. COST ANALYSIS OF NON-REPAIRABLE PARTS

The repairing (replacing) costs for seals of all of the most critical bad actor pumps are plotted versus the operation time as shown in Figure 10. 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. Similarly the repairing (replacing) cost for bearings of all of the most critical bad actors pumps versus operation time are plotted in Figure 11.

9. DISCUSSION

1. The time to failure or malfunction data of the most critical bad actor pumps were gathered from computer maintenance system and from on-line monitoring of process variable data retrieved from distributed control system of the refinery. The period of the investigation is five years from 1995 to 2000. All of these pumps were analyzed in depth as repairable systems. Some of their non-repairable parts, such as seals and bearings, were analyzed separately.
2. Pumps are found to have a large number of bad actors. 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 are depending on two main factors, which are the number of failures and their associated repairing costs. The criteria used in Pareto analysis of the pumps is to identify those pumps that contribute to 50% of total number of failures and /or 50% of the total repairing cost. Accordingly, 17 pumps, 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 malfunctions leading to overhaul (23%). The overhaul means that the equipment is sent to the Machine Shop with unknown reasons to inspect it and replace the defective parts. The failure due to impeller (11.7%), bearings (9%) and shaft (6.3%) are other significant modes of failures.
5. The various reliability parameters and indices of these most critical pumps are β and η. The Weibull reliability analysis is found to be very beneficial to characterize the equipment time between failures of the pumps, and to select appropriate maintenance strategy for a given pump. These parameters are β, η , MTBF, standard deviation, mode

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T_m, and median time $T_{0.5}$. The shape parameter β is important to characterize the failure rate of the equipment and type of maintenance that should be applied. Ten (10) pumps are found to have increasing failure rate (β≥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. By using the fitted Weibull model as a predictive tool, the operation management can take the appropriate decision in advance to avoid any operational upset.

6. In reliability literature there is a wealth of knowledge on preventive maintenance policies for repairable systems and part replacement strategies [Kolarik, 1995], [Lewis, 1987], [Sheikh, et al, 2000], [Sheikh, 1990], [Sheikh, 1991], [Blischke, and Murthy, 2000]. A major application of the reliability analysis results is to decide about the appropriate maintenance strategy. The detail maintenance and availability related analysis of these pumps is presented in another follow up paper [Sheikh, et al, 2002]. The Weibull shape parameter β of the most critical bad actors is very important to recommend the appropriate maintenance strategy. It is generally recommended [Blischke and Murthy, 2000] that; for β<1 (decreasing failure rate) predictive maintenance, β =1 (constant failure rate) corrective maintenance, and for β >1 (increasing failure rate) preventive maintenance could be adopted. Similarly for aging non repairable parts such as seals for which failure rate is reflected by β >1, an optimal replacement strategy could be either preventive planned replacements or scheduled replacements at fixed intervals rather than the current practice of replacing them upon failure. However with advances in condition monitoring tools and sensors it is often preferable whenever such monitoring is feasible and economically viable to adopt for the predictive maintenance.
7. 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. 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 9. Also, the average accumulative repairing costs versus the operation time of a typical bad actors pump is estimated and plotted in Figure 10.However, for non-repairable parts, the repairing costs versus the time between failure is plotted for both seals Figure 11.The accumulative cost of the non-repairable parts includes the cost of repairing auxiliaries that are related to the pump seal.

10. CONCLUSIONS AND RECOMMENDATIONS

The Weibull reliability analysis is found to be very beneficial to characterize the equipment time to failure data and to design appropriate maintenance strategies using Weibull model as a predictive model [Black, and Geitam, 1983], [Kelly, 1997], [Ben-Daya and Dufuaa, 2000], [Jeong and El-Sayed, 2000]. Based on this analysis, operation management will be able to take the right decision in advance to avoid any operational upset and plants downtime.

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1. The Weibull model can be applied to rotating equipment such as pumps 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.
2. 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.
3. 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. Using Weibull reliability analysis of non-repairable parts and the methodology explained in References [Sheikh, et al, 2000], [Sheikh, 1990], [Sheikh, 1991], the future needs of seals and bearings can be determined for a specified planning horizon.

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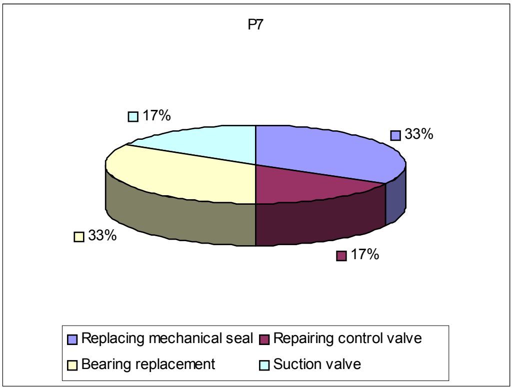

Figure 1. Modes of failure of most critical bad actor pump P7.

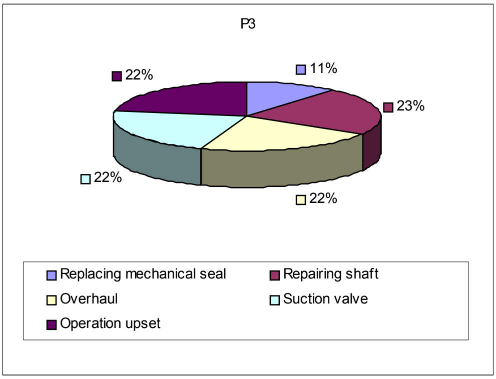

Figure 2. Modes of failure of most critical bad actor pump P3.

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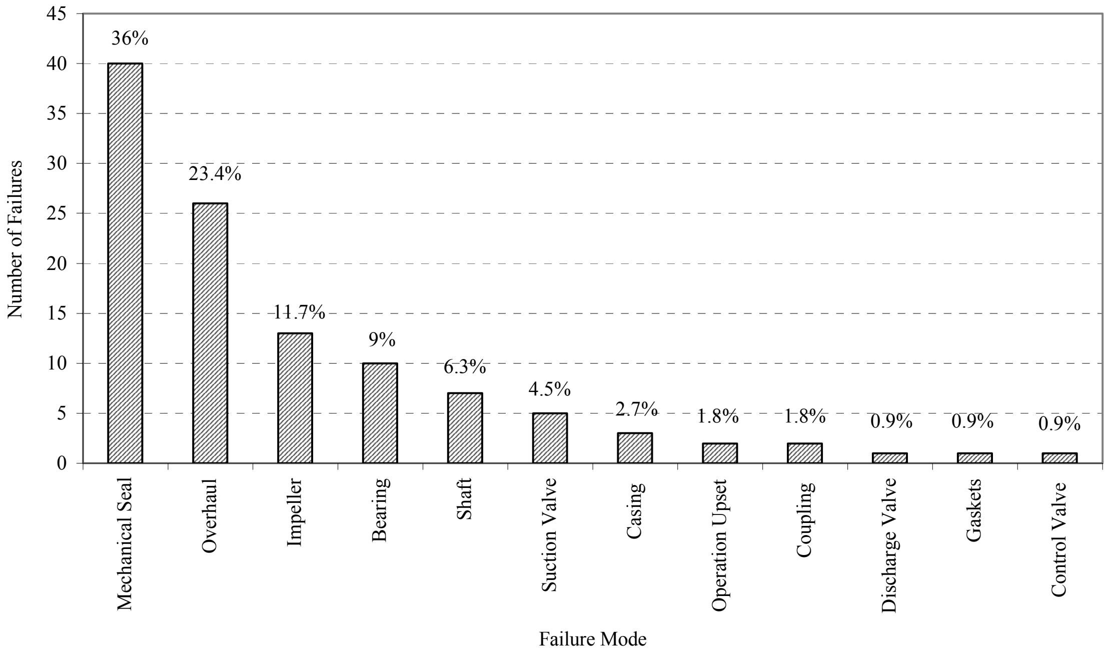

Figure 3 Failure modes for the most critical bad actors pumps.

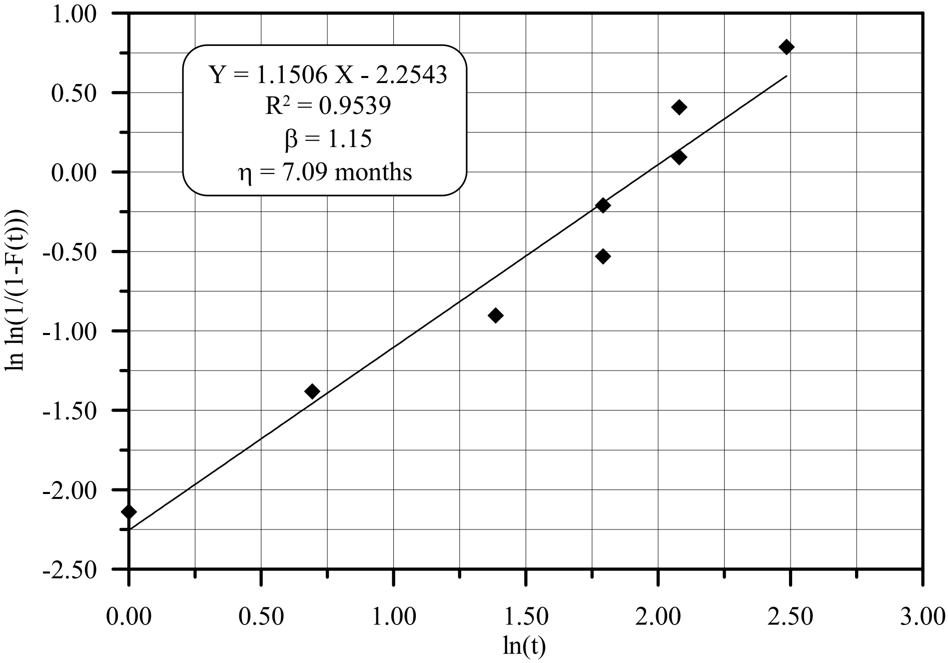

Figure 4. Weibull plot for most critical bad actor pump P3.

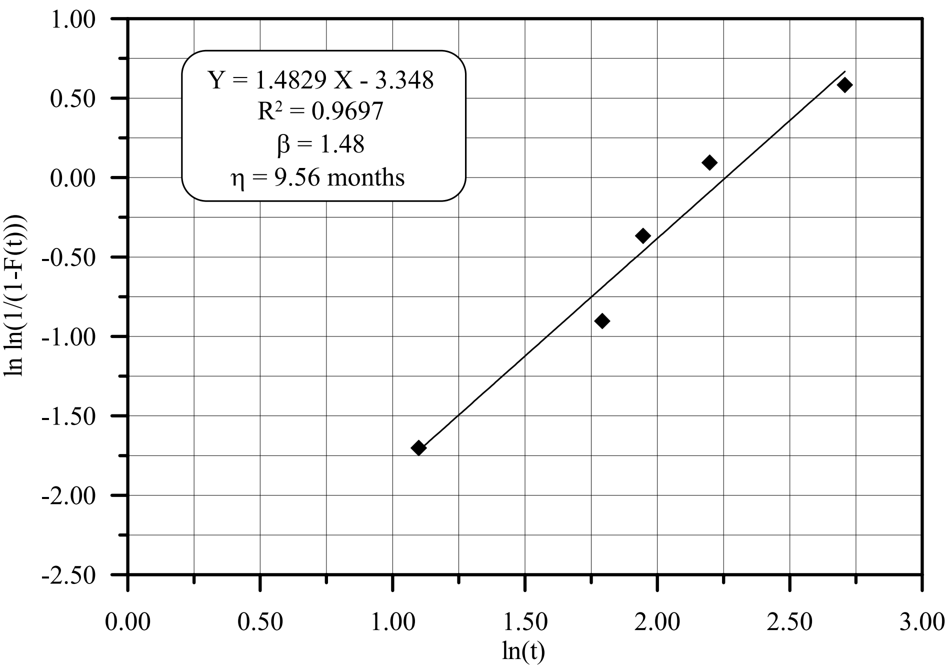

Figure 5. Weibull plot for most critical bad actor pump P7.

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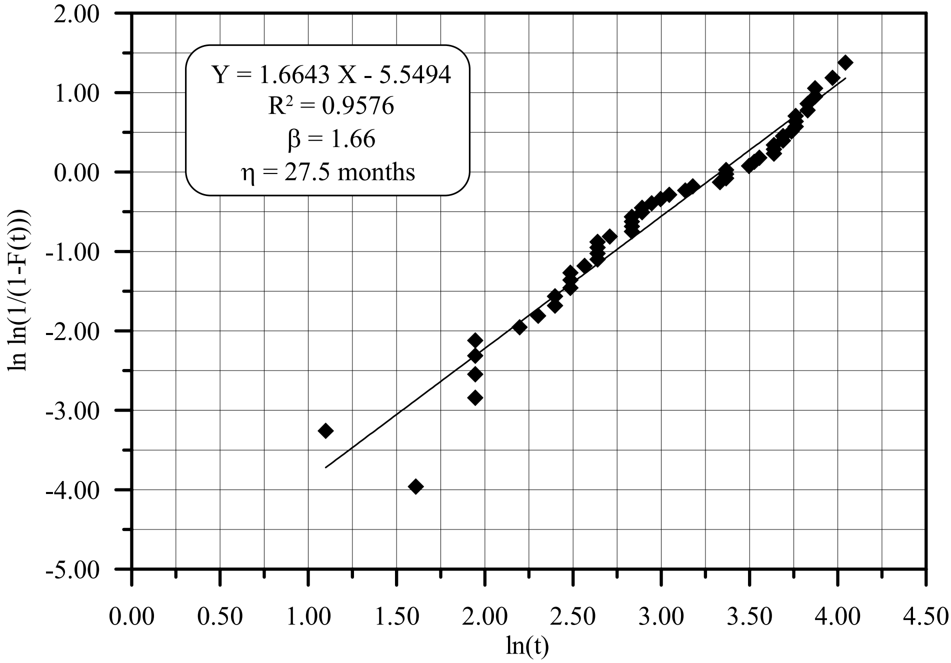

Figure 6. Weibull analysis of seals for all types of most critical bad actors pumps.

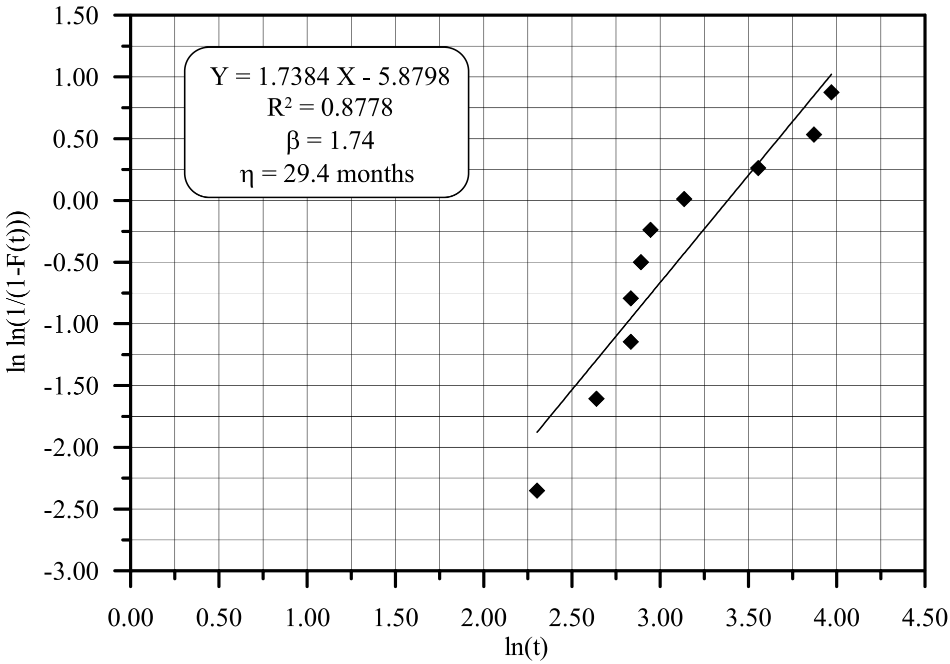

Figure 7. Weibull analysis of bearings for all typesof most critical bad actors pumps.

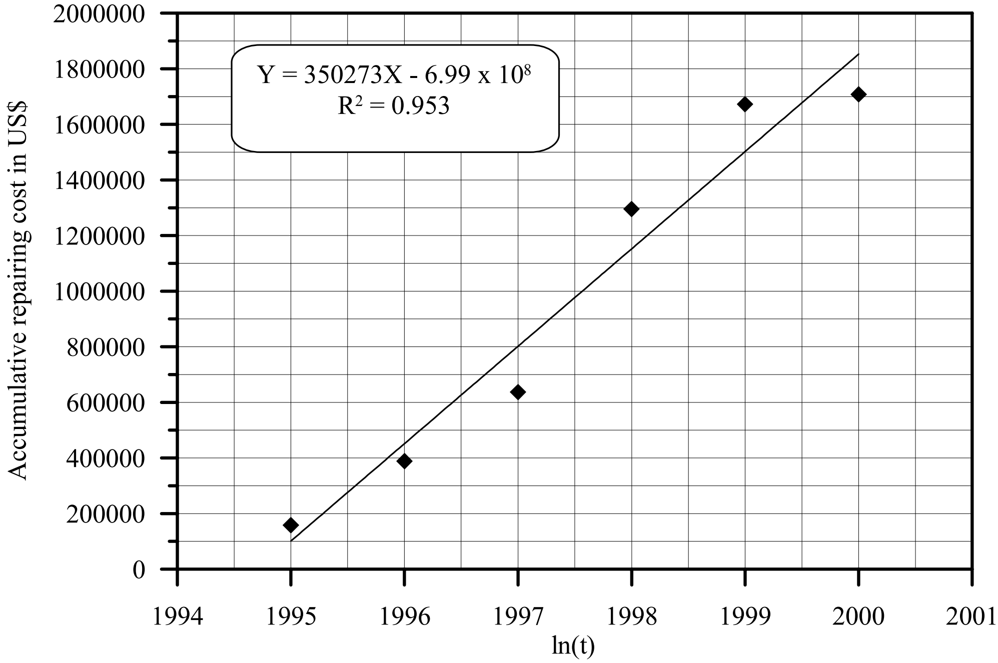

Figure 8. Accumulative repair costs versus time of operation for the most critical bad actors pumps (all failure modes).

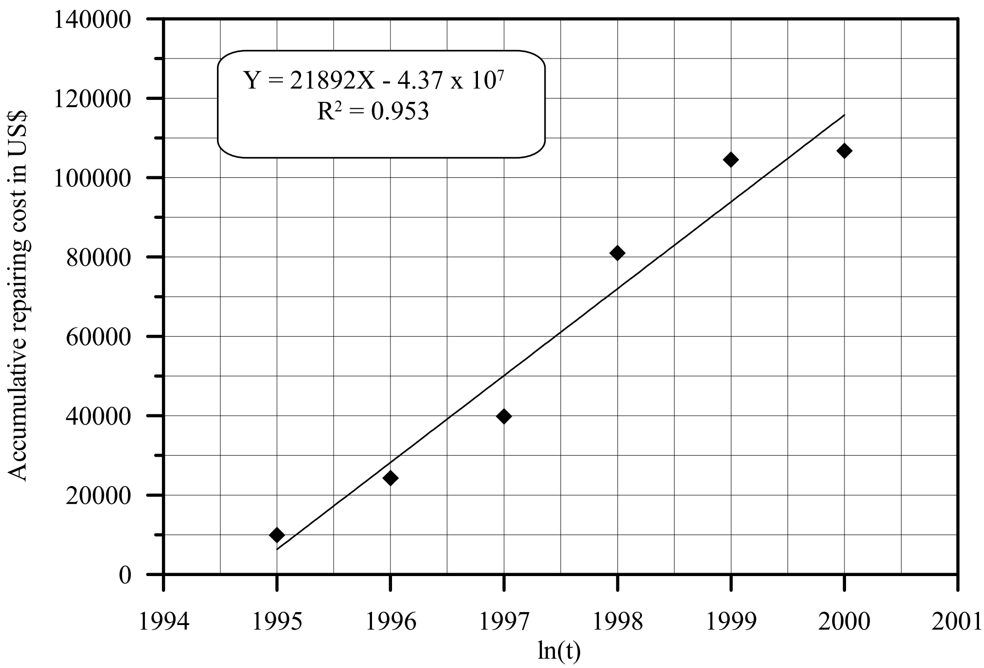

Figure 9. Average accumulative repair costs versus time of operation for the most critical bad actors pumps (all failure modes).

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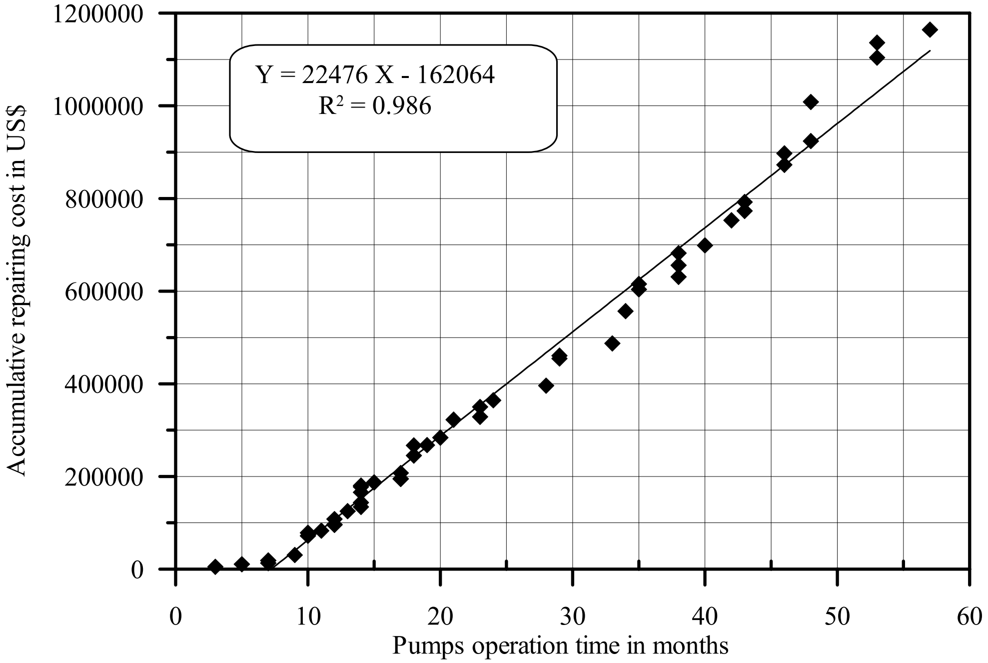

Figure 10. Accumulative repairing cost for seals of all pumps versus operation time.

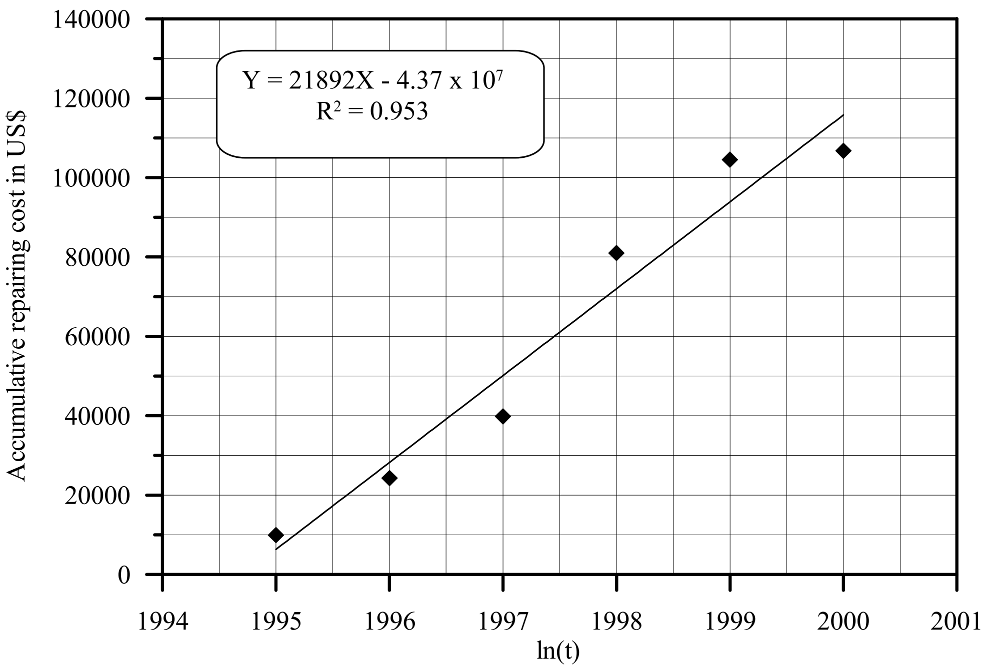

Figure 11. Average accumulative repair costs versus time of operation for the most critical bad actors pumps (all failure modes).

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