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Analysis of Major Cenrifugal Pumps Failures (With Application to Irrigation Pumps in Sudan)

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***Abstract*- Centrifugal pumps are one of the most widely used pumps in the world, with a wide range of applications, from the petroleum industry to the transportation of irrigation water. Despite the extensive use of pumps, few component failures cause severe degradation of pump performance and increase downtime, which adversely affect production. Therefore, in order to minimize downtime and improve pump reliability and availability, these pumps must be carefully controlled, diagnosed, maintained or replaced before a catastrophic pump failure occurs. This study investigated the major faults found in centrifugal pumps, especially in Sudan's irrigation pumps. In this study, we analyzed the problems faced by pump failures causing yield loss at the level of all privatization and parastatal pump schemes operating under government license, government pump stations in the four national government owner agricultural schemes (New Halfa, Rahad, Suki and Gezira & Managil), by using statistical methods. Results show that, at the technical level of the system, a probabilistic method based on the evolution of the pump state enables us to carry out preventive interventions; when the component reaches the degradation zone, it leads to an increase in periodic system intervention. For equipment, whose system schedule set in advance by the manufacturer cannot effectively meet the maintenance requirements; the mathematical model based on failure linearization can correct or even optimize the maintenance plan. Through our own investigation, we have concluded that it is necessary to change the structure of the maintenance cycle of the irrigation pumps under consideration. In this study, the feasibility of preventive maintenance based on reliability and conditional maintenance was verified. The results obtained are contributions to meet the reliability goals pursued by irrigation pumps.**

***Keywords*- Major Failures; Centrifugal Pumps; Probabilistic Method; Reliability.**

I. INTRODUCTION

Pumps are devices that move fluids or slurries, by mechanical action. Pumps operate by different mechanisms, and consume energy to perform mechanical work moving the fluid. Pumps operate via many energy sources including manual efforts, electrical, thermal, solar, and wind. Pumps are available in different design and sizes to accommodate all uses and to suit all conditions. Pumps are the core of most industrial processes, and the second most uses machine on the world.

Since they are so common, pumps are over looked as a possible wellspring of improved profitability or a reason for overabundance costs if not worked appropriately. Plant chiefs, maintenance specialists, and production supervisor ought to hold best practices and comprehend the operational do's and don'ts for utilizing pumps appropriately in manufacturing and industrial applications [1, 2].

In order to improve the availability of production equipment in general, it is very important to analyze the Reliability, Maintainability, and Availability indicators to know more about their conditions across their life cycle. This analyzes lead to determine the failures that greatly influence the condition of an item of equipment, and to implement a suitable maintenance policy in order to limit the interventions and increase the hours of operation.

Sudan’s irrigation pumps are more strategic at the level of agricultural schemes, so special attention and analysis are needed to reliably ensure food security for humans and animals, and export crops that can bring hard currency, such as cotton, sesame and other grains.

This study aims to analyze major mechanical failures and maintenance methods to improve centrifugal pumps availability, in Sudan, by reducing downtime. The main objective of this paper is to analyze the causes of irrigation pumps failures in the Sudanese government schemes, privatization schemes and parastatals schemes, and find solutions to reduce such failures.

The methodology adopted in this paper included office and field works. The data obtained from office and field was analyzed then accordingly the pumps failures were defined, their causes were determined and recommendations for elimination of these causes were given. The statistical Pearson correlation coefficient is used, and the statistical package for social studies (SPSS)

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software is used to measure the relationship between the studied variables. At the same time, a statistical test is performed; the SPSS is used to perform a Chi-square test to test the nature of the probability distribution of operating time between failures. In addition, Pareto diagrams, Weibull analysis, and Ishikawa diagrams are also used to analyze major pump failures.

II. PUMP MAINTENANCE AND FAILURE ANALYSIS

Maintenance as a process is simply all activities and resources required to maintain the specified performance and condition of the item within a given period. The technicalmeaning of maintenance involves functional inspections, services, repair or replacement of necessary devices, equipment, machinery, building infrastructure, and supporting utilities in industrial, commercial, government, and residential facilities. Over time, it has included a variety of wording describing various cost-effective practices for keeping equipment running; these activities occurred before or after failure.

1. Maintenance Types:
Generally, there are two main strategies for performing maintenance functions. The first is the preventive method; that is, maintenance is performed to prevent malfunctions or breakdowns. The second is the corrective method. Perform maintenance after failure or obvious failure. These two types of maintenance can be further divided, as shown in Figure (1) [3].

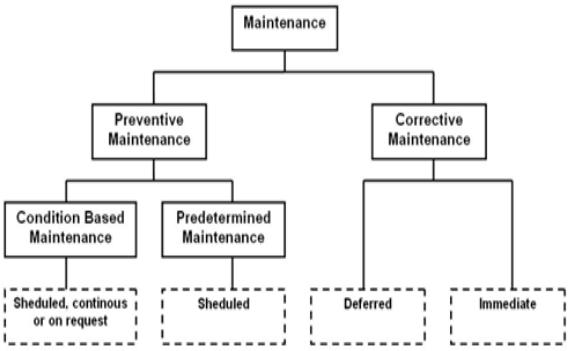

Fig 1. Different Maintenance Types.

2. Failure Analysis:
Despite the best efforts to avoid them, failures are still a common occurrence in every industry. Failure not only means that the technical attempts to design and operate complex systems are imperfect, but it also means that the organization cannot successfully manage the competing interests of time, quality and money [4]. Therefore, in order to continuously improve and learn all the abilities from these failures, it is our best interest, which allows us to avoid making the same mistakes.

2.1 Root Cause Analysis (RCA) is: a structured investigation designed to determine the real cause of the problem and the necessary measures to eliminate it [5]. From a technical point of view, it is usually a multidisciplinary problem and the necessary measures to eliminate it. From a technical point of view, it is usually a multidisciplinary problem, usually focusing on traditional engineering fields such as chemistry, physics, materials, statics, dynamics, and fluids. They are easily placed in engineering environments, and the real root cause may lie in human tissues [4]. There are several methods available to perform a structured analysis of the failure. The main goal of all these methods is to prevent failures, especially those with serious consequences. The method is divided into five tools.

2.2 Pareto Chart: Pareto analysis is an easy-to-use technique that helps to choose the most effective changes. It uses the Pareto principle, that is, by completing 20% of the work, you can generate an 80% advantage to complete the entire work. Pareto analysis is a formal technique used to discover the changes that will bring the greater benefit. This method is useful in situations where many possible actions are competing for attention [6]. The Pareto chart is a chart that combines a histogram or bar chart with a line chart. It groups the frequency or cost of different problems to show their relative importance. The bar graph displays the frequency in descending order, while the line graph displays the cumulative percentage or total moving from left to right.

2.3 The Five Whys: The "5 Whys" sometimes called GembaGembutsu (literally means location and information in Japanese, much of today's RCA methods taken from the Japanese automobile industry)[6]. Five Whys usually refers to the practice of asking five questions. Each question starts with why the failure occurred, to find the root cause of the problem. No special techniques or forms are required, but the results should be recorded in the worksheet. Five Whys is it best to use when solving simple RCA.

2.4 Cause and Effect Analysis: Cause and effect analysis is a graphical method used for failure analysis, called fishbone analysis. The name is derived from fish-shaped patterns and is used to plot the relationship between various factors that contribute to a specific event [7]. Fishbone analysis usually plots the four main categories of potential causes (ie, human, machine, material, and method), but can include any combination of categories.

2.5 Fault Tree Analysis (FTA): FTA is a top-down deductive failure analysis, which uses Boolean logic to combine a series of lower-level events to analyze the undesired state of the system. This analysis

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method is mainly used in safety engineering and reliability engineering to understand how the system fails, to determine the best way to reduce risks, and to determine (or perceive) the incidence of safety accidents or events at a specific system level failure. FTA is a graphical technique that provides a system description of the combination of situations that may occur in the system, and combines the system and human faults. The fault tree analysis can be displayed from left to right or top to bottom. Many professional software products can perform fault tree analysis, but both Microsoft Power Point and Visio can be used to complete these diagrams [6]. Figure (2) shows fault tree diagram.

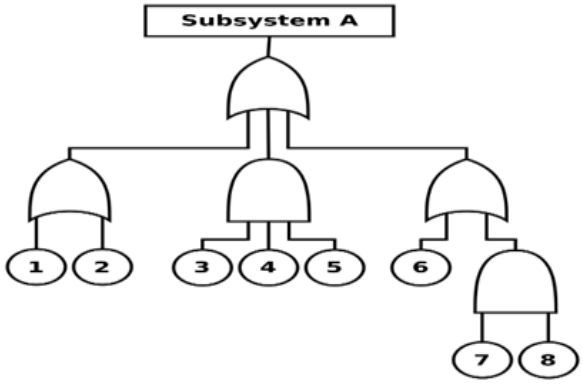

Fig 2. A Fault Tree Diagram.

2.6 Failure Mode and Effects Analysis (FMEA): Failure Mode and Effects Analysis (FMEA) is a design evaluation process used to identify potential failure modes and determine the impact of each mode on system performance. This process formally records standard practices, generates historical records, and serves as the basis for future improvements. The (FMEA) process is a series of logical steps, starting with the analysis of lower-level subsystems or components. The analysis starts from the point of view of failure and identifies potential failure modes and failure mechanisms. Then, trace the impact of each failure mode back to the system level. According to the probability of occurrence, severity and gratitude, a severity level is assigned to each failure mode and impact. For failures with a higher score on the critical level, design changes are recommended to reduce the failure rate [7].

III. WEIBULL DISTRIBUTION

Weibull distribution is one of the widely used distributions in technology practice. Swedish scientist Walodi Weibull (1887-1979) used it in reliability theory and introduced this distribution for the first time. Today, the Weibull distribution is also used in the field of mechanics such as determining the wind speed distribution in the design layout of wind power plants. The advantage of this law is that it is very flexible and can be adapted to different experimental results [8].

1. The Bathtub curve and product failure behavior:
Reliability experts usually use a graphical representation called a bathtub curve to describe the life of a group of products. The bathtub curve includes three periods: the infant mortality period at which the failure rate decreases, followed by the normal life period (also known as the useful life), the failure rate is relatively low and relatively constant, and concluding with a wear-out period that exhibits an increasing failure rate. The Bathtub curve and product failure behavior shown in Figure (3) [9, 10].

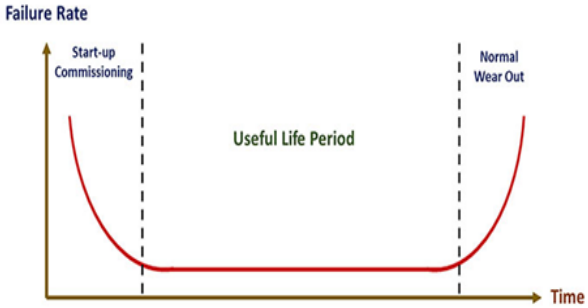

Fig 3. Bathtub curve of component reliability.

2. Determining the failure frequencies:
By classifying all defective parts in ascending order according to their life characteristics, Equation (1), can be used to determine the corresponding failure probability F(i) in a very simple form for the case N < 20, assign a rank "Ni" (approximate value of the middle rank) to each failure[11]:

$$\boldsymbol{F(i) = \frac{Ni + 0.3}{N + 0.4} \approx F(t)} \ldots\ldots\ldots\ldots (1)$$

Where;
i: Ordinal for sorted defective parts,
N: Reference quantity, e.g. production quantity,

3. F (t) defines the failure failing or failure probability, and can be obtained by Equation (2) [12].

$$\boldsymbol{F(t) = 1 - e^{-\left[\frac{t-\gamma}{\eta}\right]^{\beta}}} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

From which;

$1 - F(t) = e^{-\left[\frac{t}{\eta}\right]^{\beta}}$, $\frac{1}{1-F(t)} = e^{\left(\frac{t}{\eta}\right)^{\beta}}$, $lnln\left(\frac{1}{1-F(t)}\right) = \beta \ln t - \beta \ln \eta$ that is similar to: $Y = \beta X + A$

The expression Y = βX + A is the familiar formula for a straight line. By choosing ln (t) as X, the scale on the abscissa, and lnln $lnln\left(\frac{1}{1-F(t)}\right)$ as y, the scale on the ordinate, the cumulative Weibull distribution can represented as a straight line.

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4. The characteristics of Weibull distribution parameter:
The most general Weibull distribution or function has three parameters:

4.1 Shape parameter (β) – it defines the shape of the distribution [8].
4.2 Scale parameter (η) – it defines the spread of the distribution.It can be obtained by equations (3) and (4) [13].

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

$$\lambda(t) = \frac{\beta}{\eta}\left[\frac{t-\gamma}{\eta}\right]^{\beta-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where;
λ (t): Failure rate,
R (t): Reliability value

4.3 The location parameter (γ): Usually, the location parameter is not used, and the value of this parameter can be set to zero. In this case, the Weibull distribution parameter will be reduced to only two parameters.

5. Performing a Weibull analysis:
Weibull plotting is a graphical method used to informally check the assumptions of the Weibull distribution model and estimate of the two Weibull parameters. In the Weibull analysis, η is defined as the time when 63.2% of the analyzed systems or components fail (the intersection of maintainability and Weibull curve, when M (t) = 63.2%) [11, 14].

IV. AVAILABILITY

Availability (A) can be described as the ability of the item to be in a certain state, in this state, it can perform a given function under given conditions at a given point in time or within a given time interval, assuming the required external resources need to provide. Instantaneous availability refers to the probability that an item can perform the required function under the given conditions within a given time, that is, provide the required external resources, or the probability that a system will be available for use at any random time (t) after the start of operation [15, 16].

Clearly, availability represents the possibility that a system can perform its required functions when called without failure or maintenance. Therefore, availability is not only a function of reliability, but also a function of maintainability. Inherent availability (Ai), express by equation (5) [17]:

$$(Ai) = \frac{MTBF}{MTBF + MTTR} \quad \ldots\ldots\ldots\ldots\ldots (5)$$

Where;
MTBF is the mean time between failures; MTTR is the mean time to repair.

V. FAILURE ANALYSIS IN SUDAN IRRIGATION PUMPS

Failures, maintenance methods and management vary from site to site. The Blue Nile, White Nile and Main Nile have the same pump types, so although the maintenance and management methods are different, their failures and effects are similar. The Guneid pumping station, located east of the Blue Nile Bank, north of the city of Roffaa, irrigates Guneid's sugar scheme. The pump type is 605/ WPA 2/0023, installed in 1962. The technical specifications shown in Table (1).

Table 1. Technical specifications of Guneid units.

Quantity	Discharge m^3/s	Head m	Motor power(kw)	Pump power (kw)
4	3.5	24	1000	900

Table (2) shows the recorded failures of pump components from 2010 to 2020.

Table 2. Number of failures per pump from 2010 to 2020.

Cause	No. of failures	DT
Bearing	65	4680
Shaft sleeve	63	4536
Wear ring	30	1500
Impeller	3	1200
Gland packing	25	200
None return valve	4	3

Table (3) shows continuous wear failures of bearings and sleeves from 2019 to 2020.

Table 3. Failure history of bearings and shaft sleeves.

n	Date	TBF	TTR
1	25-7-2019	600	11
2	10-8-2019	360	25
3	7-9-2019	640	30
4	21-10-2019	1032	45
5	30-11-2019	930	80
6	15-3-2020	900	100
7	20-4-2020	720	48
8	30-5-2020	700	120
9	3-7-2020	680	200
10	5-8-2020	620	110

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1. Analysis of the root cause of the failure:

The practical application of the ABC (Pareto) predictive analysis method to the type 605 / WPA 2/0023 pumps in the failure history record. Use the original data in the Table (3) to find the major cause of the failure. For the application of the ABC method, it is first necessary to classify the failures in descending order of the hours of the failures, as shown in Table (4), and then proceed to the establishment of a Pareto chart, as shown in Figure (4).

Table 4. Classification of failures in descending order.

Cause	No. of failures	Down time	Cumulative failure	% Cumulative Failure	Cumulative down time	% Cumulative down time
Bearing	65	4680	65	34.2105	4680	38.6171
Shaft sleeve	63	4536	128	67.3684	9216	76.0459
Wear ring	30	1500	158	83.1579	10716	88.4231
Impeller	3	1200	161	84.7368	11916	98.3249
Gland packing	25	200	186	97.8947	12116	99.9753
None return valve	4	3	190	100	12119	100

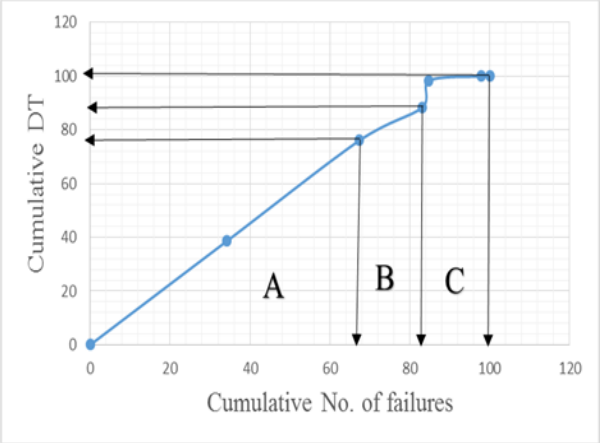

Fig 4. ABC analysis (Pareto).

1.1 Results of ABC Curve:

1.1.1Zone A: As a result, the cumulative number of failures corresponding to 67.37% accounted for 76.04% of the downtime. This is the area of the front and rear bearings and the shaft protection sleeve, it has a lot of downtime, so this area is very important. Therefore, in order to reduce downtime, preventive maintenance becomes necessary or even mandatory. Maintenance must be carried out in short time intervals; it includes monitoring of detectable parameters such as vibration, temperature, flow, and pressure. In addition, condition monitoring also allows us to plan and prepare parts that may fail.

1.1.2Zone B: This area is not as important as area A, the number of failures is 15.79%, accounting for 12.37% of the downtime. This area of replacement of the wear ring, so preventive maintenance is recommended.

1.1.3Zone C: In this area, 16.84% of failures accounted for only 11.59% of downtime. In this case, corrective maintenance is sufficient, because a large amount of repair time is not required to indicate a failure.

2. Weibull distribution for the reliability of bearings and sleeves (zone A):

According to the Table (3) and using Equation (1), (because in our case N = 10 , which mean N < 20), the calculations and results shown in the Table (5), which contain TBF classified in ascending order, the rank for each TBF, and the F (i).

Table 5. Reliability calculation results.

n	TBF	TTR	N	Σni	F(i)	F(i)%
1	360	25	1	1	0.067	6.731
2	600	11	1	2	0.163	16.346
3	620	110	1	3	0.259	25.962
4	640	30	1	4	0.356	35.577
5	680	200	1	5	0.452	45.1923
6	700	120	1	6	0.548	54.8077
7	720	48	1	7	0.644	64.4231
8	900	100	1	8	0.740	74.0385
9	930	80	1	9	0.836	83.6539
10	1032	45	1	10	0.932	93.2692

2.1 Determine the parameters β and ŋ:

According to Equation (2), $\frac{1}{1-F(t)} = e^{\left(\frac{t}{\eta}\right)^{\beta}}$, $lnln\left(\frac{1}{1-F(t)}\right) = \beta \ln TBF - \beta \ln \eta$, is similar to Y=BX+A.

Select from Table (5) ln (TBF) as X axis, and $lnln\left(\frac{1}{1-F(t)}\right)$ as y axis, as shown in Table (6), the

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cumulative Weibull distribution can be expressed as a straight line, as shown in Figure (2).

Table 6. Construction of abscissa (t) and ordinate (Y).

Construction of abscissa (t)		Construction of ordinate (Y)	
TBF	Ln (TBF)	F (i)	$(\ln(\ln(\frac{1}{1-F(t)}))$
360	5.886104	0.067308	-2.66384
600	6.39693	0.163462	-1.72326
620	6.429719	0.259615	-1.20202
640	6.461468	0.355769	-0.82167
680	6.522093	0.451923	-0.5086
700	6.55108	0.548077	-0.23037
720	6.579251	0.644231	0.032925
900	6.802395	0.740385	0.299033
930	6.835185	0.836538	0.593977
1032	6.939254	0.932692	0.992689

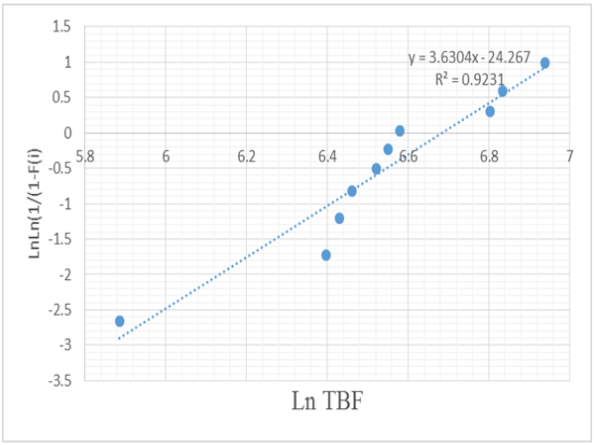

Fig 5. Cumulative Weibull distribution.

From Figure (2), Y = 3.6304 and X – 24.267, which mean β = 3.6304
A = 24.267 = β ln (η)

$$\therefore \eta = ln^{-1}\frac{24.267}{3.6304} = 799.82\ hrs$$

2.2 Determination of MTBF:
From the table Distribution of WEIBULL: values of the coefficients A and B according to the shape parameter, when β = 3.63, we find that A = 0.901 and B = 0.277, but MTBF = A.η+γ= 0.901 x 799.82+ 0

$$\therefore MTBF = 720.635\ hrs$$

2.3 Determine the reliability function:
According to Equation (3), when t = MTBF = 720.635,

$$R(t = MTBF) = e^{-\left(\frac{720.635-0}{799.82}\right)^{3.63}} = 0.504,$$

The reliability function calculation of each TBF shown in the Table (7), the relationship between TBF and R(t) shown in Figure (3).

Table 7. Calculation of the reliability function of each TBF.

TBF	R(t)	F(t)	f(t)	λ(t)
360	0.637564	0.362436	0.000526	0.000556
600	0.472287	0.527713	0.001498	0.002131
620	0.460624	0.539376	0.001562	0.002323
640	0.449248	0.550752	0.001618	0.002525
680	0.427333	0.572667	0.001701	0.002962
700	0.41678	0.58322	0.001726	0.003196
720	0.406488	0.593512	**0.001739**	0.003442
900	0.324571	0.675429	0.001334	0.00619
930	0.312622	0.687378	0.001198	0.006748
1032	0.275191	0.724809	0.000712	0.008872

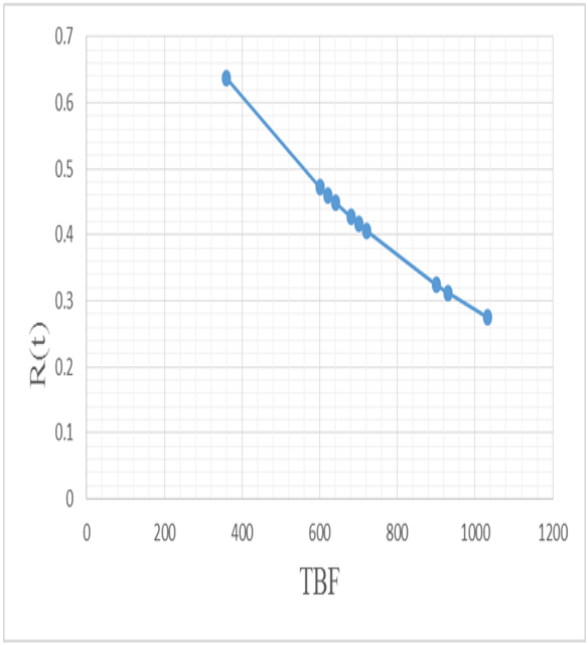

Fig 6. Reliability curve.

The graph shows the change in reliability over time (TBF). As (TBF) increases, the reliability of the pump decreases, which explains the degradation phenomenon.

2.4 Determine the distribution function F (t):
From Equation (2),
when;

$$(MTBF) = 720.635,$$

$$then,\ F(t = MTBF) = 1 - e^{-\left(\frac{720.635-0}{799.82}\right)^{3.63}} = 49.6\%$$

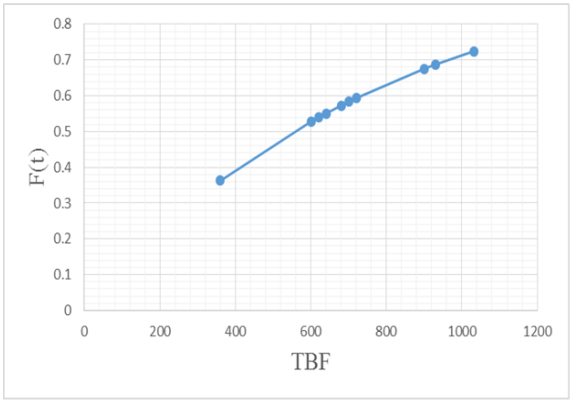

Fig 7. Distribution function curve.

Table (7) shows the calculation of F (t) for each (TBF), and Figure (4) shows the relationship between (TBF) and F (t).

2.4.1 Curve analysis: The failure function increases as the time between failures (TBF) increases.

2.5 Determine the probability density f (t):
Combined with Equations (3) and (4) this gives:

$f(t) = \frac{\beta}{\eta}\left[\frac{t-\gamma}{\eta}\right]^{\beta-1} e^{-\left[\frac{t-\gamma}{\eta}\right]^{\beta}}$, So $f(t) = \lambda(t).R(t)$,

The calculation results are shown in Table (7). The relationship between TBF and f (t) is shown in Figure (5).

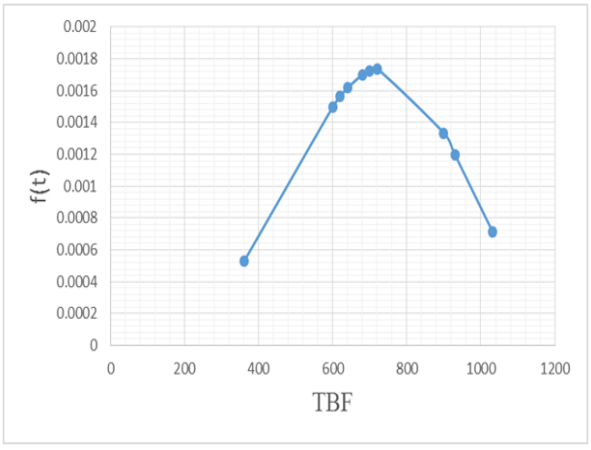

Fig 8. Probability density curve.

2.5.1 Curve analysis: According to this curve, we find that the function f(t) increases with time TBF up to time (TBF = 720 hrs), and after this value, the function f(t) decreases with time.

2.6 Failure Rate Curve:

From Table (5) and using Equation (4), $\lambda(t) = \frac{\beta}{\eta}\left[\frac{t-\gamma}{\eta}\right]^{\beta-1}$, the result of the failure rate corresponds to TBF shown in Table (7). While Figure (6) represents the failure rate (λ) as a function of time (TBF).

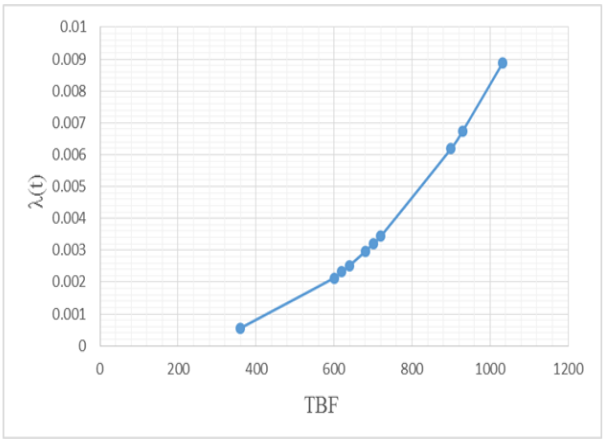

Fig 9. Failure rate curve.

2.6.1 Curve analysis: The calculation results show that (β >1), and λ increases with time (TBF). Referring to the bathtub curve, we find that the pump is in normal wear out stage.

2.7 Calculation of MTTR:
From Equation (3.9),

$$MTTR = \frac{\Sigma TTR}{N} = \frac{769}{10} = 76.9\ hrs$$

2.8 Calculation of availability (Ai):
From Equation (5),

$$(Ai) = \frac{MTBF}{MTBF + MTTR} = \frac{720.635}{720.635+76.9} = 90.36\%$$

The study proved in the previous results: β = 3.63 >1, and the failure rate λ (t) increases with time, and then we infer that the centrifugal pump studied is in the wear phase. It is also proved that when the time is equal to MTBF, the availability rate of the pump is equal to 90.36%, which is very beneficial to operation. This can be explained by downtime, which is almost short due to the complexity of the failure and the use of any material to repair the pump regardless of the impact on other pump components.

VI. CONCLUSION

In this paper the author discusses about the failures that happen in irrigation pumps, accompanying Sudanese pump station established since the seventies of previous century like Meina and Guneid pumping units. He mainly concluded that, it is necessary to change the structure of the maintenance cycle of the irrigation pumps under consideration. It is clear that by using the Bathtub curve to forecast the type of failure of the pump type 605/WPA 2/0023, it is essential to decide the best maintenance strategy and estimate the probability of random failure.

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The findings show that Guneid pump type 605/WPA 2/0023 reaches the wear stage. In this investigation, the feasibility of preventive maintenance based on reliability and conditional maintenance was verified for components, such as; bearings, gland packing and gearbox. The results obtained are contributions to meet the reliability goals pursued by irrigation pumps.

The author recommends that, the maintenance department should have a database containing computerized files of all pumps and their characteristics in the schemes. This allows quick access to pump documentation during failures.

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