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Development of risk assessment model for equipment within the petroleum industry

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Abstract: Maintenance department within petroleum industry seek to increase equipment safety by means of reducing the occurrence of the failure and its undesirable consequences. In this study, a risk assessment model is proposed, which includes the likelihood of the risk and the consequences of failure. A new mathematical equation is proposed to assess the likelihood of risk and identify the optimum inspection interval. In addition, modified mathematical equation to evaluate consequences of risk which allow more generalization and accuracy of weighing the possible losses (performance, financial, ecology and human) is developed. The results demonstrate an improvement at the assessment of the probability of risk and provide better understanding of the impact of the risk on the major identified areas within the petroleum industry.

Keywords: Maintenance Models and Engineering, Risk Assessment, Asset and maintenance management and Maintenance and Related Services

1. INTRODUCTION

Risk assessment within the petroleum industry is an important phase due to the intolerable consequences of failure. Therefore, Maintenance team plans their tasks for preventive maintenance (PM) for the petroleum equipment to identify the most optimum maintenance intervals from the perspective of reliability, availability and cost reduction as well as unpredictability or uncertainty of the occurrence of the failure. One of the maintenance's tasks is to ensure the system's reliability through preventing the possibility of the occurrence of failure and eliminate the consequences of the risk. Thus, ensuring that the equipment would serve as attended or planned till the next maintenance interval.

In order to enhance the reliability of a system, inspection interval would be planned to ensure that the equipment's reliability would meet the expectation of the planned preventive maintenance. Inspection frequency is determined according to risk exposure, which can be used to control any unacceptable risk (Chang et al 2005).

Dawotola et al (2012) defined risk as "the considered expected loss or damage associated with the occurrence of a possible undesired event". Reynolds (1996) stated that risk assessment may be quantitative or qualitative in nature. Khan et al (2001) defined the science of risk assessment (RA), which has emerged in recent years with ever-increasing importance as a process that includes both qualitative and quantitative determination of risks and their social evaluation. Maylor (2010) stated that the majority of risk management activities rely on qualitative data which is obtained based on people's perceptions of risk levels.

In this study, a risk assessment model is proposed to guide the maintenance team to carrying the risk assessment. The rest of the paper is divided to cover the architecture and the proposed model including the new and modified equations. The application and results of the proposed model are presented to validate the proposed models and finally the conclusion is drawn.

2. ARCHITECTURE OF THE PROPOSED MODEL

The proposed model is expected to enhance estimation of the risk and its consequences instead of the conventional method that considers the multiplication of the likelihood by consequences, which can be misleading. Incorporation of modified models and a newly developed equation is proposed in order to assess the risk. The proposed risk assessment model relies on the use of both qualitative and quantitative methods. Figure (1) demonstrates the contents of the proposed model of estimating the risk for equipment within the petroleum industry and the following sections provide detailed description of its components.

2.1 Likelihood Assessment

In this step, an estimation of the probability of failure occurrence is performed by qualitative and quantitative means to build generic conception that consider the majority of the facilities within the petroleum industry.

2.1.1 Qualitative Assessment

Probabilistic failure analysis is conducted using the fault tree analysis (FTA). The use of FTA along with components failure data and human reliability data enables the determination of the frequency of occurrence of an accident (Dawotola et al 2009). The top event is identified based on the detailed study of the process, control arrangement, and behaviour of components of the unit/plant. A logical

dependency between the causes leading to the top event (failure) is developed in this stage.
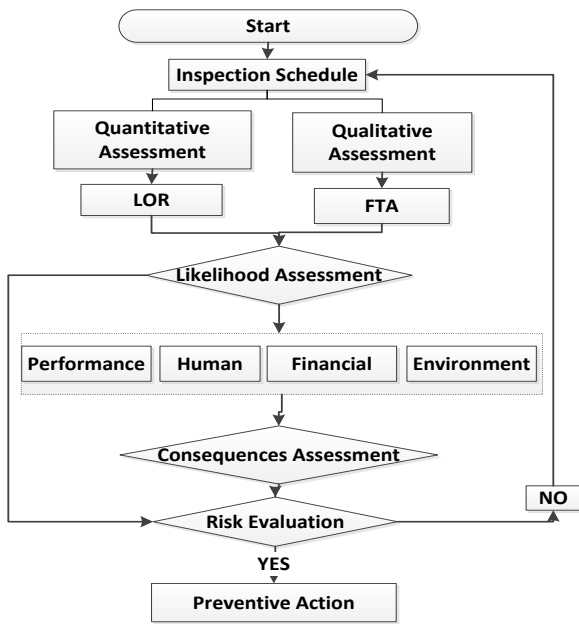

Fig. 1. Description of Risk Estimation Model

2.1.2 Quantitative Assessment

Quantitative analysis is conducted to estimate the probability of the occurrence of the risk. In order to validate the proposed risk estimation model, a degree of acceptance of risk has to be set up against the estimated risk. The developed proposed mathematical model (Likelihood of Risk (LOR)) is based on the assumption that the risk depends exponentially on time P, where P is the physical age of the equipment and d is the design age of a part/machine(the expected life of equipment). The assumption is that risk depends exponentially on time (P) :- (Risk $\propto$ P).

$$Risk(P) = F(\Delta P) * G^{\wedge}(P/d) \qquad (1)$$

Where, G is a positive growth factor of the risk and the time required for risk to increase by one factor of G. F (ΔP) is the probability of the failure of the part/machine.

$$Risk \ (P + d) = \ F(\Delta P) \times G^{\wedge}((P + d)/d) \qquad (2)$$

d is the designed life of the part or equipment. The time required for risk to increase by one factor of G.

$$Risk \ (P + d) = \ F(\Delta P) \times G^{\wedge}(P/d) \ G^{\wedge}(d/d) \qquad (3)$$

Therefore, if d=0 and G>1 then LOR (P) has exponential growth. Thus, formula (3) can be written mathematically as: -
$$LOR = \ F(\Delta P) \ e^{\wedge}(P/d) \qquad (4)$$

The developed equation (4) is proposed to be applied for two main purposes. The first purpose is to estimate the likelihood of the risk instead of relying on solely failure distribution and the second purpose is to optimize the inspection intervals as extensively shown in section (3-1). Bertolini et al (2009) proposed classification of the occurrence degree of the failure to be compared to the outcomes of probability of the failure $F(\Delta t)$ as shown in table (1). He relies on the Cumulative Weibull distribution model to generate $F(\Delta t)$. However, in this work, the same classification is applied but will be

allocated to outcomes of developed equation LOR instead of using the $F(\Delta t)$.

Table.1. Assigning probability classifications

Class	Key Word	Absolute value of $F(\Delta t)$ /LOR
A	Very Unlikely	0.001
B	Unlikely	0.05
C	Neutral	0.3
D	Likely	0.5
E	Very Likely	1

2.2 Consequences assessment

The objective of this phase is to estimate the consequences of failure and its contribution to the system to prioritize equipment and their components on the basis of their undesirable contribution to the system. Khan and Haddara (2003) identified four impacted areas where consequences of the failure have to be evaluated which are: -system performance loss (A), financial Loss (B) human health loss (C) and environmental loss (C). Equation (5) presents the combined loss in order to find the overall consequences of the risk. Equation (5) is modified to enable maintenance team of prioritising the importance of the loss factors while investigating the four loss factors instead of following the proposed equation of Khan and Haddara (2003)which strict them into mathematically weighing the four losses equally.

$$Consequences = \{W_a \ A^2 + W_b \ B^2 + W_c \ C^2 + W_D \ D^2\}^{0.5} (5)$$

Where, W_a weight of performance loss, W_b weight of financial loss,W_c weight of human health loss and W_c weight of environment loss.

2.2.1 System Performance Loss

Factor (A) represents the system performance loss due to the equipment failure. Equation (6) is developed to represents the system performance loss.

$$A = \begin{cases} Function \ performance & Table \ (2) \\ 0 & Otherwise \end{cases} \qquad (6)$$

Equation (6) shows two possible scenarios: - If the equipment has a stand-by redundancy, then this factor is considered as zero. The second scenario: - if the equipment is a vital to the system then the proposed quantification scheme by Khan and Haddara (2003) is considered to take the measures of the loss as shown in table (2).

Table.2. Performance Function

Class	Description	Function
I	-Very important for system operation -Failure would shut down the system	8-10
II	-Important for good operation -Failure would adverse consequences	6-8
III	-Required for good operation -Failure may affect the performance and may lead to subsequent failure	4-6
IV	-Optional for good performance -Failure may have no immediate affect	2-4
V	-Optional for operation -Failure may not affect performance	0-2

2.2.2 Financial Loss (B)

Loss factor (B) accounts for the damages to the property or/and equipment and major costs are involved as a consequence of the failure. Equation (7) is proposed to calculate the financial loss (B) which considers the losses in terms of explosion as well as the losses in terms of corrective or preventive maintenance:-

$$B = ((B_p + C_{mc}) - P_{mc})/P_{mc} \qquad (7)$$

Where, B_p Denotes financial loss of the property and the facilities in terms of explosion or fire. C_{mc} and P_{mc} indicate the Corrective maintenance cost and Preventive maintenance cos respectively.

Khan and Haddara (2003) proposed equation (8) to calculate B_p as follows:-

$$B_p = (AR) \times (AD)/UFL \qquad (8)$$

Where:- AR is the area under the damage radius (m^2) and AD is the asset density in the vicinity of the event (up until 500 m radius) ($/m^2). UFL is The level of an unacceptable financial loss which can be decided the maintenance management and assumed by Khan and Haddara (2003) as $1000.Saad and Mohamed (2015) proposed mathematical equation to calculate the majority of the corrective maintenance cost within the specifically the petroleum industry and generally to any petrochemical environment.

$$C_{mc} = \left\{ \left(\sum_{i=1}^{n} C_{sp_n} \times P_{rp_n} \right) + (t_{ti} + t_{su}) \times \frac{\alpha}{\pi} + (V \times C_{pd}) + L_C + C_{wd} + C_{sd} + \left(\frac{(t_{ti}+t_{su})}{\pi} \times C_{pd} \right) + (C_{MT} - D_{FT}) \times C_h + (X_1 \times t_{tc} \times S_{mh}) + ((t_{ti} + t_{su}) \times S_{oh} \times X_2) \right\} \qquad (9)$$

where, C_{sp} Cost of spare parts ($), P_{rp} Probability of replacement, t_{ti} Production time loss excluding machine setup time (hrs), t_{su} Machine set up time (hrs), α Department's income due to one barrel ($), π Production cycle time (hrs), V Number of damaged production by barrel, C_{pd} Value of damaged production ($), L_C Legal fines in case of environmental damages ($), C_{wd} Cost of cleaning non-hazardous and hazardous materials ($), C_{sd} Cost of damaged parts due to the failure of another part ($), D_{FT} Due fine time (hrs), C_{MT} Time required complete corrective actions (hrs), C_h Cost of delay charges per unit ($), X_1 Number of maintenance personnel, t_{tc} Time spent by the maintenance personnel to repair failure(hrs), S_{mh} Maintenance hourly rate ($), S_{oh} Operator's hourly rate ($) and X_2 Number of operational personnel.

P_{mc} Indicates to the preventive maintenance cost that is required to preventive the failure and calculated by the developed equation (10) (Saad and Mohamed 2015).

$$P_{mc} = \left\{ \left(\sum_{i=1}^{n} C_{sp_n} \times Prp_n \right) + \left(X_1 \times S_{mh} \times t_{ip} \right) + C_{wp} + C_{oh} \right\} \qquad (10)$$

Where, C_{oh} Cost of outhouse maintenance ($) C_{wp} Waste disposable cleaning cost.

2.2.3 Human Health Loss (C)

The consequences of failure on human health loss or factor (C) are estimated using equation (11) (Khan and Haddara (2003).

$$C = (AR) \times (PDI)/UFR \qquad (11)$$

Where, AR Area under the damage radius (m^2) and UFR Unacceptable fatality rate "suggested value 10^{-3} (person) by Khan and Haddara (2003)". PDI Population density in the vicinity of the event (Persons/m^2). PDI is calculated by (12) which considers the Number of people within the radius of impacted area $PD1$ and $PDF1$ Population distribution factor that reflects the heterogeneity of the population distribution within the impacted area. Hirst and Carter (2000) assigned two values for this factor: - The factor is substituted as 1 if the population is uniformly distributed within 500m radius; 0.2 If the population is localized away from the point of accident.

$$PDI = PD1 \times PDF1 \qquad (12)$$

2.2.4 Environment Loss

The impact of failure on ecology (factor D) can be estimated by the use of the equation (13).

$$D = (AR) \times (IM)/UDA \qquad (13)$$

Where, UDA Unacceptable damaging (m^2). This value of this parameter may change from one case to another due to the estimated damaged area. IM Indicates to the Impact factor and if the damage radius is greater than the distance between an accident and the location of the ecosystem. This parameter can be quantified using figure (2) (Khan and Haddara 2003).
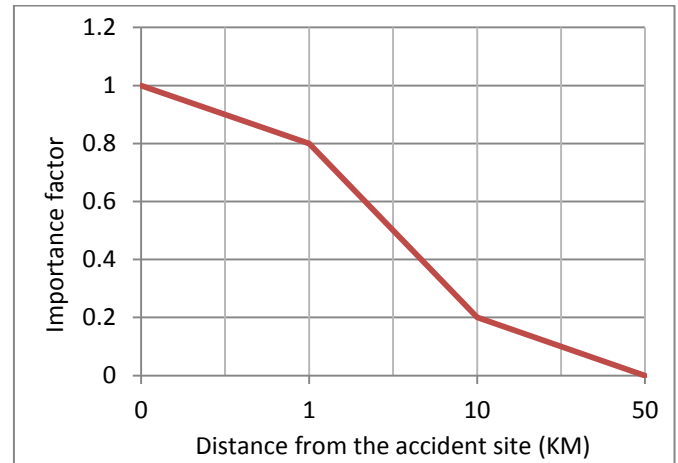

Fig. 2. Quantification of Importance Factor (IM)

3. APPLICATIONS AND RESULTS

In this section, application of the proposed risk estimation is applied on two parts (Mixer 100 and Valve 101) of high pressure separator (Khan and Haddara 2004). The assumption made for this application is the result of the qualitative assessment for the likelihood of the risk is equal and therefore is not discussed in this application. Averages mean time between failure (MTBF) for Mixer 101 is 6667 hrs (9.26 months) and MTBF for Valve 101 is 6410 hrs (8.90 months). The outcome of the applied proposed LOR and its recommendations for the inspection intervals will be

compared to the average MTBF of the parts in order to estimate the validity of the proposed model in this aspect.

3.1 Application (1): Mixer 100

Table (3) demonstrates time (T) in months and the implementation of the developed mathematical equation to quantify the likelihood of risk (LOR) by considering the growth factor (G) which is calculated by dividing physical life by the design life. Mixer 100 physical life is considered to be (9 months). For space limitation, not all data interned.

Table. 3. LOR and Growth Factor (G) for Mixer 100

T	G	LOR	T	G	LOR
3.7	0.41	0.18	6.4	0.71	0.64
3.8	0.42	0.19	6.5	0.72	0.66
3.9	0.43	0.20	6.6	0.73	0.69
4	0.44	0.21	6.7	0.74	0.71
4.1	0.46	0.23	6.8	0.76	0.74
4.2	0.47	0.24	6.9	0.77	**0.76**
4.3	0.48	0.25	7	0.78	0.79
4.4	0.49	0.27	7.1	0.79	0.81
4.5	0.50	0.28	7.2	0.80	0.84
4.6	0.51	0.29	7.3	0.81	0.87
4.7	0.52	0.31	7.4	0.82	0.90
4.8	0.53	0.32	7.5	0.83	0.93
4.9	0.54	0.34	7.6	0.84	0.96
5	0.56	0.36	7.7	0.86	0.99
5.1	0.57	0.37	7.8	0.87	**1.02**
5.2	0.58	0.39	7.9	0.88	1.05
5.3	0.59	0.41	8	0.89	1.08
5.4	0.60	0.43	8.1	0.90	1.11
5.5	0.61	0.45	8.2	0.91	1.14
5.6	0.62	0.47	8.3	0.92	1.18
5.7	0.63	0.49	8.4	0.93	1.21
5.8	0.64	0.51	8.5	0.94	1.24
5.9	0.66	0.53	8.6	0.96	1.28
6	0.67	0.55	8.7	0.97	1.31
6.1	0.68	0.57	8.8	0.98	1.35
6.2	0.69	0.59	8.9	0.99	1.39
6.3	0.70	0.61	9	1.00	1.42

Figure (3) shows the behaviour of the probability of failure and LOR against the part's life ratio. It demonstrates that the LOR crosses the life ratio of the part at about 6.9 months (4968hrs) and reaches 100% at 7.8 months (5616hrs).
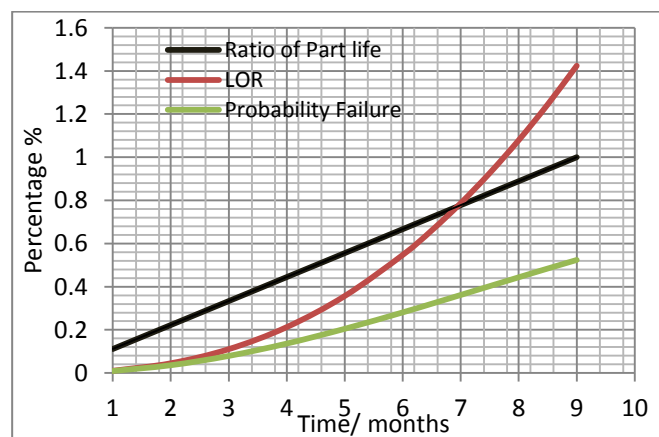

Fig. 3. The Behaviour of LOR and **FΔt** (Mixer 100)

The mean time between failures for Mixer 100 is 9.3 months. Likelihood of risk crosses the growth factor at (4968hrs) and reached 100% at (5616hrs). The advised interval inspection time is accordingly suggested to take place between 6.9 months and 7.8 months to ensure the part's health state can reach the next scheduled maintenance time (figure 4). In comparison with the reliance on the probability of the failure, LOR proposed mathematical equations shows better translation of understanding and estimating the inspection interval time. In terms of overlapping inspection jobs, the priority of the inspection is decided on the highest value of the consequences damages.
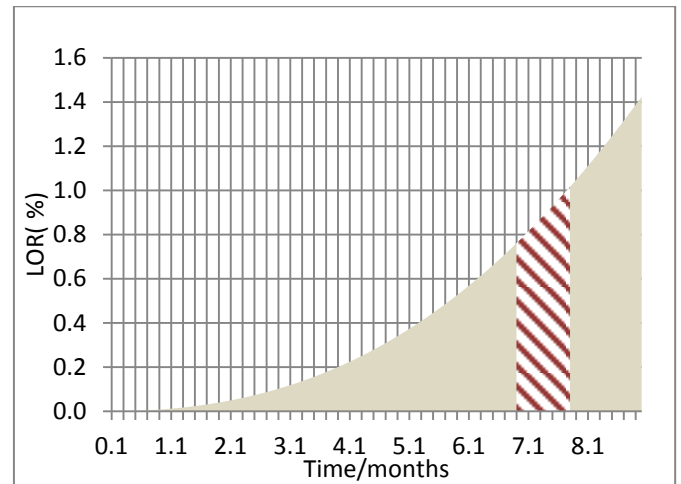

Fig.4. Optimum Inspection Interval for Mixer 100

3.2 Consequences of the Failure for the Mixer 100

Once the assessment of the likelihood of the risk is conducted the maintenance team should move to the estimation of the consequences of the failure.

Performance loss: - In this case, the assumption is that the failure of the mixer 100 would lead to the stoppage of the separator unit and therefore the performance loss would be classified as the highest (10). The financial loss estimated by applying Equation (7). Due to the fact that the failure of the equipment has got no financial impact in terms of fire and explosion leading to B_p to be considered having zero value. Table (4) presents the assumed related costs for maintenance.

Table.4. Related maintenance Costs (Mixer 100)

Cost	Value	Unit
Csp	500	$
Prp_n	100	%
Cwd	100	$
Soh	10	$/hrs
Smh	10	$/hrs
X_1	5	
X_2	5	
t_{tc}	5	hrs
t_{ti}	7	hrs
t_{su}	1	hrs
α	50	$
π	300/24= 0.08	$/hrs

Few assumptions are presumed in order to apply equation (7)

- The equipment has no alternative (stand-by equipment).

- Costs are calculated in US dollar.

- The equipment process 300 barrels a day.

Applying equation (9) of all expected and assumed costs in terms of corrective maintenance; we obtain the cost that may occur:-

$$C_{mc} = \{(500 \times \%100) + ((5+1) \times \left(\frac{50}{0.08}\right) + 100 +$$

$$\left(\frac{5+1}{0.08}\right) + (5 \times 5 \times 10) + (5 + 1 \times 5 \times 10)$$

$$C_{mc} = 500 + 3750 + 100 + 75 + 250 + 300$$

$$C_{mc} = \$4975$$

Applying equation (10) we can calculate the preventive maintenance cost with the assumption that the production time loss is less (8hrs) in the case of corrective action. C_{wd} and C_{oh} ohare assumed to be zero:

$$P_{mc} = (500 \times \%100) + (5 \times 10 \times 8) = \$900$$

Therefore, substituting the values of C_{mc} and P_{mc} into equation

$$B = \frac{4975-900}{900} = 4.53$$

The failure of the part has no environmental or human loss impact and therefore, substitute the determined values for the performance loss and the financial loss into equation (5)with the assumption that the weight given by the maintenance to prioritize the loss factors is equally (0.25).

$$Consequence = \{(0.25 \times 10^2) + (0.25 \times 4.53^2)\}^{0.5}$$
$$Consequence = 5.49$$

The outcome of the consequences will be taken into account while evaluating the overall risk of the equipment. For demonstration purposes, the substituted values of given weights were considered to be equal in the provided case. However, it may vary from one loss to another, which would lead to different consequences' results

3.3 Application (2): Valve 102

The failure frequency for the Valve 102 is 6410/hours and this value is converted into months (8.902 months).The designed life for Valve 102 is assumed as 9 months.

Figure (4) demonstrates the comparison between the cumulative distribution function ($F\Delta t$) and 1 (LOR). The capture of the figure is taken until the assumed physical life time ends.

The consideration of the physical life of parts/equipment through the application of LOR assists in the prioritization of planning the inspection intervals maintenance intervention. The growth factor (G) crosses the LOR at almost 6.6 month (4752hrs) which is suggested the time of inspection until the time where LOR =100% at 7.59 months (5465hrs).In comparison with the MTBF of valve 102 (6410hrs) 8.90

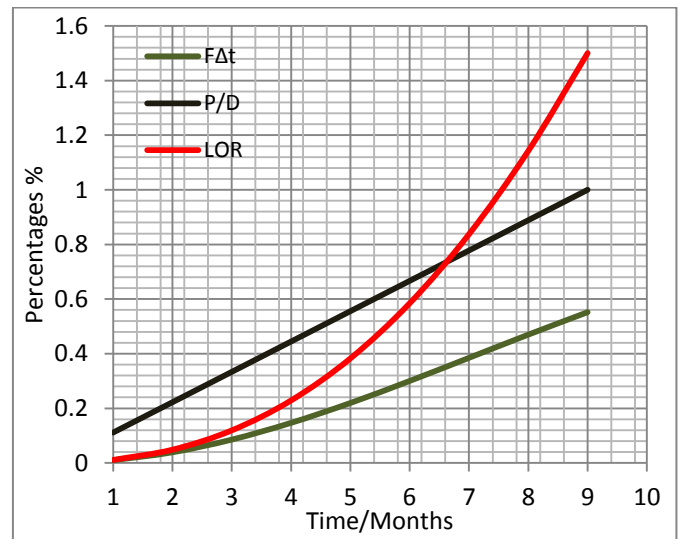months, the suggested time seems to leave enough time before the recorded average of MTBF.

Fig.4. The Behaviour of LOR and FΔt Valve 102

Figure (5) demonstrates the suggested inspection interval for valve 102. The designed life of part/equipment is a main parameter for the outcomes of LOR. In case of the two parts having the same value of probability of failure, the part with shorter designed life will be resulting in higher value of LOR, which leads to prioritizing it for inspection.
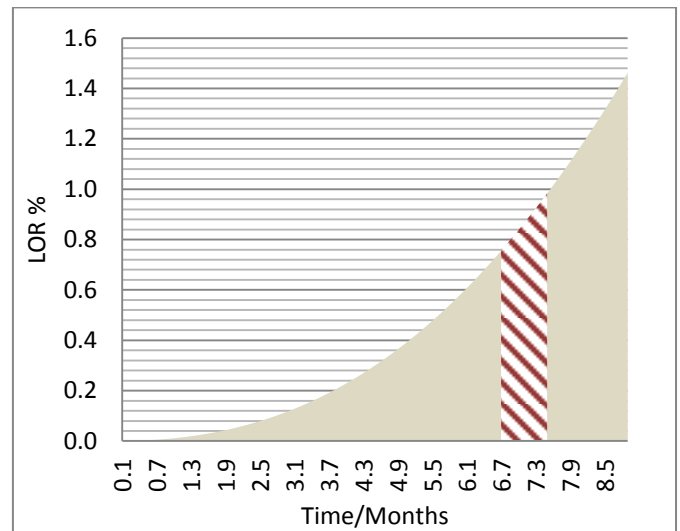

Fig. 5. Optimum Inspection Interval for Valve 102

3.4 Consequences of the Failure for Valve 102

The consequences of the risk on the system performance loss are considered to be at the highest given the function of the valve and therefore are substituted as 10. Equation (8) is applied to calculate the financial loss under the assumption that the failure of the valve would cause explosion. The area under the damage (AR) is estimated 40 m^2 and the estimated assets density is 10000\$/m^2.

$$B_p = ((40 \times 10000)/1000) = \$400$$

The corrective maintenance cost (Cmc)and preventive maintenance cost Pmc that occurs due to the failure of valve

102 are assumed to be equal to the Cmc and Pmc that was calculated for mixer 100 which was Cmc=\$4975 and Pmc=\$900. Thus, the financial loss is computed as followed (equation 7-8)

$$B = ((400 + 4975) - 900)/900$$

$$B = 4.97$$

The human health loss factor is calculated by applying equation (11) and (12). The values of AR and UFR are (40 m2) and (10^{-3} person) respectively. The population distribution factor PDF1 is substituted as (1) on the assumption that the population is localised within less than 500m and the number of people within that area is 10 persons. Thus:-

$$PDI = 10 \times 1 = 10 \, persons/m^2$$

Resulting into the human health loss (C)

$$C = (40 \times 10)/10^{-3} = 400000$$

Equation (13) is applied to calculate the environmental loss (D), with AR 40 m^2 and from figure (2) IM is obtained (0.99). Unacceptable damaging level (UDA) is assumed to be $2m^2$ as the closest next equipment is placed close by. Thus:-

$$D = (40 \times 0.99)/2 = 19.8$$

For The consequences damages are estimated by adding up the entire applied factors, using equation (7-6)

$$Consequence = \{(0.25 \times 10^2) + (0.25 \times 4.97^2) + (0.25 \times 400000^2) + (0.25 \times 19.8^2)\}^{0.5} = 200,000$$

If we assume that the consequences of the failure for both parts (Mixer 100 and Valve 102) were as resulted from, the above calculation (5.49 and 200,000) respectively then Valve 102 would be prioritized for maintenance action over Mixer 100. The weight of the loss factors would play a principal role in prioritizing the importance of the loss factors which would lead to different scenarios. For instance, for the Mixer 100 if the performance loss factor was weighted lower than the financial loss because of having stand by system, it would mean that the performance of the system would decrease but would not completely stopping the production.

4. CONCLUSION

The estimation of risk has been discussed and used to assess equipment health within the petroleum industry. The proposed model clearly can be used to assist in the estimation of risk likelihood, optimisation of the inspection scheduling and evaluation of the consequences of risk into four areas. In addition, the proposed mathematical model facilitated the calculation of Likelihood of Risk (LOR) and also has shown better reflection of the reality of the equipment risk's probability than the usage of cumulative failure distribution. LOR and its consideration of the parameters of designed life and physical life (growth factor) help the inspector to prioritize optimally the inspection intervals.

The proposed consequences equation would allow more generalisation and accuracy of weighing the losses through the flexibility of the weight of the loss factors. A modified equation was developed for the performance loss consequences that include the condition of having stand by spare system to accurately simulate the performance loss of the production line. The equation of the financial loss was developed to involve the balance between costs of corrective and preventive actions. The analysis of the major related costs assists in alerting the maintenance team to have an estimation of the involved costs and the possibility of avoiding risk. The contribution of this work to the assessment and estimation of the probability of risk and its consequences within the oil and gas industry can improve the responsiveness to the possibility of risk as well as providing better understanding of the impact of the risk on the major areas within this industry. Overall, this will particularly enhance the efficiency of maintenance by evaluating risk which is imperative to the nature of the petroleum industry.

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