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Safety Analysis based on Past Incidents Data using Weibull Distribution in an Oil Refinery

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***Abstract*— There are several statistical distributions which are fundamental in work on reliability. In this work, we are going to apply weibull distribution theory on collected incident data. The weibull distribution is used for conducting safety analysis as they use the incident details from historical data to predict the future incidents and the pattern followed by the past incidents. The weibull distribution is frequently used in reliability work to fit failure data because it is flexible enough to handle decreasing, constant and increasing failure rates. Probability is represented by the area under the curve of the density function which is calculated by an integral and thus the median of continuous distribution is the point on the real number line where exactly half of the area lies to the left. The mode of a continuous probability distribution is the point at which the probability density function attains its maximum value**

Keywords—Reliability, weibull distribution, safety analysis

I. INTRODUCTION

System safety is a specialty within system engineering that supports program risk management. It is the application of engineering and management principles, criteria and techniques to optimize safety. The goal of System Safety is to optimize safety by the identification of safety related risks, eliminating or controlling them by design and/or procedures, based on acceptable system safety precedence. System Safety Management is a Critical Functional Discipline to be applied during all phases of the life cycle of an acquisition. There is “five step” approach to safety risk management as (i) Planning, (ii) Hazard Identification, (iii) Analysis, (iv) Assessment and (v) Decision.

II. SAFETY RISK MANAGEMENT

A. Planning Principle

System safety must be planned. It is an integrated and comprehensive engineering effort that requires a trained staff experienced in the application of safety engineering principles. The effort is interrelated, sequential and continuing throughout all program phases. The plan must influence facilities, equipment, procedures and personnel. Planning should include transportation, logistics support, storage, packing, and handling. A System Safety Management Plan is needed in the Pre-investment Decision phases to address the management objectives, responsibilities, program requirements, and schedule.

B. Hazard Analysis

The term "hazard" is a condition, event, or circumstance that could lead to or contribute to an unplanned or undesired event and are subdivided into sub-categories related to environment such as system states, environmental conditions or "initiating" and "contributing" hazards. The analytical approach to safety requires four key elements if the resulting output is to impact the system in a timely and cost effective manner.

They are (i) Hazard identification- ‘Identification’,’ Evaluation’ and ‘Resolution’ (ii) Timely solutions-verification that safety requirements have been met or that risk is eliminated or controlled to an acceptable level.

The below definitions are used to define severity of consequence and event likelihood in Tables 1.1 and 1.2, respectively.

Table 1.1: Severity of Consequence

DESCRIPTION	CATEGORY	DEFINITION
Catastrophic	I	Death, and/or system loss, and/or severe environmental damage
Critical	II	Severe injury, severe occupational illness, major system and/or environmental damage
Marginal	III	Minor injury, minor occupational illness, and/or minor system damage and/or environmental damage
Negligible	IV	Less than minor injury, occupational illness, or less than minor system or environmental damage

Table 1.2: Event Likelihood (Probability)

DESCRIPTION	LEVEL	SPECIFIC EVENT
Frequent	A	Likely to occur frequently
Probable	B	Will occur several times in the life of system
Occassional	C	Likely to occur sometime in the life of the system
Remote	D	Unlikely but possible in the life of the system
Inprobable	E	So unlikely, it can be assumed that occurrence may not be experienced

C. Comparative Safety Assessment

Assessment of risk is made by combining the severity of consequence with the likelihood of occurrence in a matrix. Risk acceptance criteria are shown in Figure 1.1 and Figure 1.2

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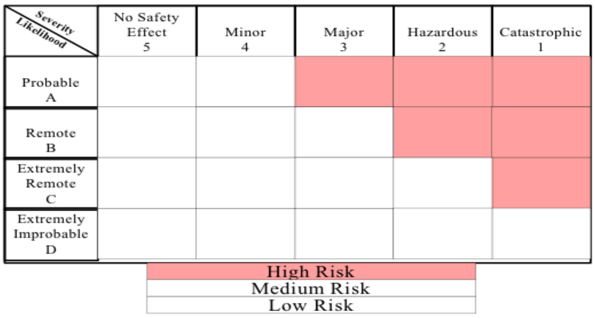

Fig. 1.1: Risk Acceptability Matrix

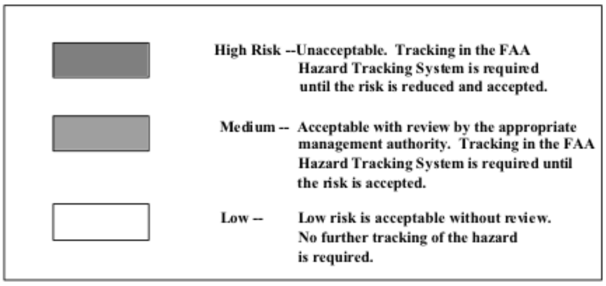

Fig. 1.2: Risk Acceptance Criteria

The Comparative Safety Assessment Matrix of Figure 1.3 illustrates an acceptance criteria methodology. Region R1 on the matrix is an area of high risk and may be considered unacceptable by the managing authority. Region R2 may be acceptable with management review of controls and/or mitigations, and R3 may be acceptable with management review. R4 is a low risk region that is usually acceptable without review.

FREQUENCY OF OCCURENCE	HAZARD CATEGORIES I CATASTROPHIC	II CRITICAL	III MARGINAL	IV NEGLIGIBLE
(A) Frequent	IA	IIA	IIIA	IVA
(B) Probable	R1 IB	IIB	IIIB	IVB
(C) Occasional	IC	IIC	IIIC	IVC R4
(D) Remote	R2 ID	IID	IIID	IVD
(E) Improbable	R3 IE	IIE	IIIEP	IVE

Hazard Risk Index (HRI)	Suggested Criteria
R1	Unacceptable
R2	Must control or mitigate (MA review)
R3	Acceptable with MA review
R4	Acceptable without review

Fig. 1.3: Example of a Comparative Safety Assessment Matrix

D. Risk Management Decision Making

For effective safety risk management, program managers should ensure that competent, responsible, and qualified engineers be assigned in program offices and contractor organizations to manage the system safety program. Ensure that system safety managers are placed within the organizational structure so that they have the authority and organizational flexibility to perform effectively. Ensure that all known hazards and their associated risks are defined, documented, and tracked as a program policy so that the decision-makers are made aware of the risks being assumed when the system becomes operational. Require that an assessment of safety risk be presented as a part of program reviews and at decision milestones. Make decisions on risk acceptability for the program and accept responsibility for that decision.

III. DATA COLLECTION AND INCIDENT ANALYSIS

Data collection refers to the collection of statistical data in areas such as lost-time accidents and other reportable injuries. Because such data are required by law, and because they are perceived to have a major impact on accident prevention via their motivational effects, considerable resources are expended every year to produce these data.

Types of Data Collection System-

"Incident reporting systems", designed to identify underlying and direct causes for larger numbers of incidents with relatively minor causes. The main function of an incident reporting system (IRS) is to identify recurring trends from large numbers of incidents with relatively minor outcomes, or from near misses. One of the important characteristics of an IRS is that the time and resources required to evaluate an incident and incorporate it into the database must be minimized.

"Near-miss reporting systems", Near misses represent an inexpensive way to learn lessons from operational experience, since they have the potential for providing as much information about the systemic causes of accidents as events with serious consequences. Van der Schaaf et al. (1991) provide a comprehensive discussion of near-miss reporting systems and data collection issues in general.

"Root cause analysis systems" , intended to provide in-depth evaluations of major incidents. The term root cause analysis system is used to denote systems that are concerned with the detailed investigations of accidents with major consequences such as loss of life, or severe financial or environmental implications.

Risk is measured on the basis of creating a scale based on product of frequency and consequences.

1. MINOR : Reversible health effects requiring first aid treatment
2. MEDIUM : Reversible health effects requiring medical treatment
3. SERIOUS : Serious reversible health effects causing lost time illness
4. MAJOR : Single fatality or irreversible health effects or disabling illness
5. CATASTROPHIC : Multiple fatalities or serious disabling illness to multiple people

When the product of frequency and consequence is high, the risk is obviously very high and is unacceptable.

IV. DESCRIPTION ON MATERIAL, PROCESS AND OPERATION

A. Industry introduction

Petroleum refineries make useful products out of unprocessed petroleum also known as crude oil. After being pumped from the ground, crude oil must be sent to a petroleum refinery where it will be converted into a variety of fuels mostly gasoline, waxes, greases, lubricants and chemical feedstocks which are the raw materials that are sent to the petrochemical plants to produce plastics or synthetic fibers). Petroleum refining begins with the distillation, or fractionation, of crude oils into separate hydrocarbon groups. The resultant products are directly related to the characteristics of the crude oil being processed.

Most of these products of distillation are further converted into more useable products by changing their physical and molecular structures through cracking, reforming and other conversion processes. These products are subsequently subjected to various treatment and separation processes, such as extraction, hydrotreating and sweetening, in order to produce finished products. Whereas the simplest refineries are usually limited to atmospheric and vacuum distillation, integrated refineries incorporate fractionation, conversion, treatment and blending with lubricant, heavy fuels and asphalt manufacturing; they may also include petrochemical processing.

B. Refinery processes and operation

The basic job of a refinery is to separate crude oil into hydrocarbon groups, or "fractions," and transform each fraction into a useful product. Thus, much of the refining process, after the initial separation of crude oil into hydrocarbon fractions, consists of manipulating the molecular structure of oil to convert heavier fractions into lighter ones. Crude oil is delivered from production wells (sites where oil is pumped from the ground) to refineries by pipeline, tanker ship, rail or truck.

There are four basic steps in the refining process: separation, conversion, treating and blending. Separation divides crude oil into hydrocarbon fractions. Conversion changes less valuable fractions into more valuable ones. Treatment removes any impurities from the fractions. Blending mixes additives and processed fractions to form finished products.

V. METHODOLOGY

A. Reliability engineering

BS 4778: Part 1:1987 defines reliability as “the ability of an item to perform a required function under stated conditions for a stated period of time”. It is entirely right that the process industries should seek to apply the techniques and obtain the benefits of reliability engineering. The process industries are particularly concerned with mechanical equipment reliability.

Reliability engineering involves an iterative process of reliability assessment and improvement and the relationship between these two aspects is important. Work on the reliability of a system necessarily involves assessment of the reliability. In some cases the assessment shows that the system is sufficiently reliable. In other cases the reliability is found to be inadequate, but the assessment work reveals ways in which the reliability can be improved.

The incident data collected from the oil industries referring the incident/ accident reporting system help the investigation to the root cause of the incident/ accident. Further this collected data gives the statistics of the accidents caused and helps performing safety system assessment for the industry. Work on the reliability of a system necessarily involves assessment of the reliability. In some cases the assessment shows that the system is sufficiently reliable. In other cases the reliability is found to be inadequate, but the assessment work reveals ways in which the reliability can be improved. The statistical data has been collected in areas such as lost-time accidents and other reportable injuries. Such data is required because they are perceived to have a major impact on accident prevention via their motivational effects, considerable resources are expended every year to produce these data.

B. Reliability relationship

There are several statistical distributions which are fundamental in work on reliability. In this work, we are going to apply weibull distribution theory on collected incident data. The weibull distribution is used for conducting safety analysis as they use the incident details from historical data to predict the future incidents and the pattern followed by the past incidents. This distribution use real time data to get the estimation of the lengths of the inter-arrival times between incidents. The weibull distribution is frequently used in reliability work to fit failure data because it is flexible enough to handle decreasing, constant and increasing failure rates. Probability is represented by the area under the curve of the density function which is calculated by an integral and thus the median of continuous distribution is the point on the real number line where exactly half of the area lies to the left. The mode of a continuous probability distribution is the point at which the probability density function attains its maximum value.

C. Weibull distribution

The primary advantage of Weibull analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with extremely small samples. Solutions are possible at the earliest indications of a problem without having to "crash a few more." Small samples also allow cost effective component testing. Another advantage of Weibull analysis is that it provides a simple and useful graphical plot of the failure data. The Weibull distribution has the great advantage in reliability work that by adjusting the distribution parameters it can be made to fit many life distributions. It is independent of other variables and uses real time incidents data making them more reliable for this study.

Weibull analysis includes:

- Plotting the data and interpreting the plot
- Failure forecasting and prediction
- Evaluating corrective action plans
- Test substantiation for new designs with minimum cost Maintenance planning and cost effective replacement strategies
- Spare parts forecasting
- Warranty analysis and support cost predictions
- Controlling production processes
- Calibration of complex design systems, i.e., CAD\CAM, finite analysis, etc.
- Recommendations to management in response to service problems

Data problems and deficiencies include:

- Censored or suspended data

- Mixtures of failure modes
- Nonzero time origin
- Unknown ages for successful units
- Extremely small samples (as small as one failure)
- No failure data
- Early data missing

The Weibull reliability function is,

$$R(t) = \exp\left[-\left(\frac{t}{ŋ}\right)^{\beta}\right]$$

Where β is the shape parameter and ŋ is the scale parameter or characteristic life. The two-parameter Weibull distribution is by far the most widely used distribution for life data analysis.

D. Benard's approximation method

Benard's approximation method for calculating the median rank is sufficiently accurate for plotting Weibull probability distribution and estimating the parameters. Benard's approximation is accurate to 1% for N=5 and 0.1% for N=50.
Benard's Median Rank = (i - 0.3) / (N + 0.4)
The least square parameter estimation method provides following equations for calculation on shape and scale parameter.

Shape parameter,

$$\beta = \frac{\sum_{i=1}^{N}(lnTi)Yi - \left(\sum_{i=1}^{N} lnTi\right)\left(\sum_{i=1}^{N} Yi\right)/N}{\sum_{i=1}^{N}(lnTi)^2 - \left(\sum_{i=1}^{N} lnTi\right)^2/N}$$

$$\hat{a} = \frac{\sum_{i=1}^{N} Yi}{N} - ƀ\,\frac{\sum_{i=1}^{N}(lnTi)}{N}$$

Scale parameter,
$$ŋ = e\text{^}(-\hat{a}/\beta)$$

Weibull probability density function, PDF, is:

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

And Weibull hazard function, the instantaneous failure rate is:

$$h(t) = \left(\frac{\beta}{ŋ}\right)\left(\frac{t}{ŋ}\right)^{\beta-1}$$

E. Weibull Probability Plotting

The steps for determining the parameters of the Weibull representing the data, using probability plotting are:

1. Ranking the time between occurrence in ascending order for all the respective categories of incidents and calculate the median value.
2. Conduct the least square analysis method to obtain the values of shape parameter and scale parameter.
3. Construct the weibull probability plotting paper where X axis represents transformation of simple logarithmic of time between occurrences(TBO) and Y axis represents a complex double log reciprocal transformation.
4. Obtain the values of X and Y axes using the formulae X = ln (TBO) and Y= ln(ln(1/(1-Median rank)))

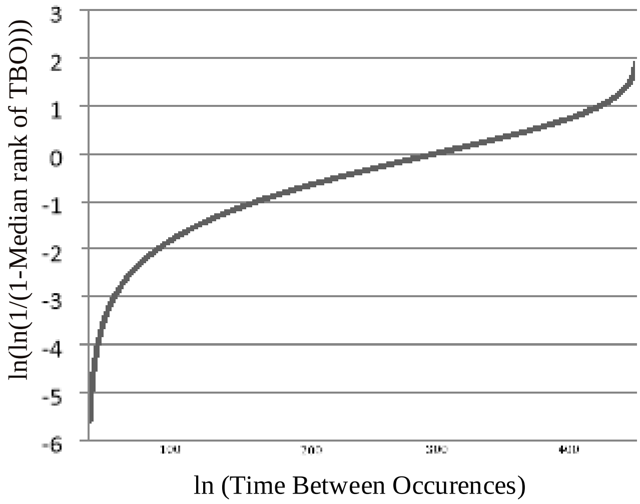

Fig. 5.1: Weibull Probability Plotting Paper for Minor Incidents

Least square analysis for Minor incidents,

$$ƀ = \frac{\sum_{i=1}^{449}(lnTi)Yi - \left(\sum_{i=1}^{449} lnTi\right)\left(\sum_{i=1}^{449} Yi\right)/449}{\sum_{i=1}^{449}(lnTi)^2 - \left(\sum_{i=1}^{449} lnTi\right)^2/449}$$

$$ƀ = \frac{83.917039 - (508.42798)(-257.9717947)/449}{810.87183 - (508.42798)^2/449}$$

$$ƀ = \frac{83.917039 + 292.116}{810.87183 - 575.721} = \frac{376.033039}{235.15083}$$

$$ƀ = 1.5991$$

$$\hat{a} = \frac{\sum_{i=1}^{449} Yi}{449} - ƀ\,\frac{\sum_{i=1}^{449}(lnTi)}{449}$$

$$\hat{a} = \frac{-257.9717947}{449} - \frac{(1.5991 * 508.42798)}{449}$$

$$\hat{a} = -0.574547 - 1.810767$$

$$\hat{a} = -2.3853$$

β = ƀ = 1.5991 (shape parameter)

ŋ = $e^\wedge(-\hat{a}/ƀ)$

ŋ = $e^\wedge(-(-2.3853)/1.5991) = e^\wedge 1.4916$

ŋ = 4.4442 (scale parameter)

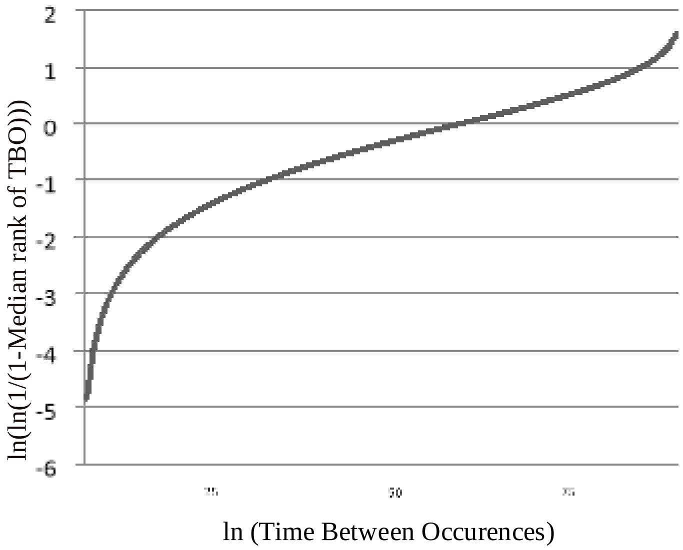

Fig. 5.2: Weibull Probability Plotting Paper for Medium Incidents

Least square analysis for Medium incidents,

$$ƀ = \frac{\sum_{i=1}^{88}(lnTi)Yi - (\sum_{i=1}^{88} lnTi)(\sum_{i=1}^{88} Yi)/88}{\sum_{i=1}^{88}(lnTi)^2 - (\sum_{i=1}^{88} lnTi)^2/88}$$

$$ƀ = \frac{2.1329 - (203.3629)(-49.8856)/88}{583.4733 - (203.3629)^2/88}$$

$$ƀ = \frac{2.1329 + 115.2827}{583.4733 - 469.9598} = \frac{117.4156}{113.5134}$$

ƀ = 1.0343

$$\hat{a} = \frac{\sum_{i=1}^{88} Yi}{88} - ƀ\frac{\sum_{i=1}^{88}(lnTi)}{88}$$

$$\hat{a} = \frac{-49.8856}{88} - \frac{(1.0343 * 203.3629)}{88}$$

â = -0.5669 - 2.3902

â = -2.9571

β = ƀ = 1.0343 (shape parameter)

ŋ = $e^\wedge(-\hat{a}/ƀ)$

ŋ = $e^\wedge(-(-2.9571)/1.0343) = e^\wedge 2.859$

ŋ = 17.444 (scale parameter)

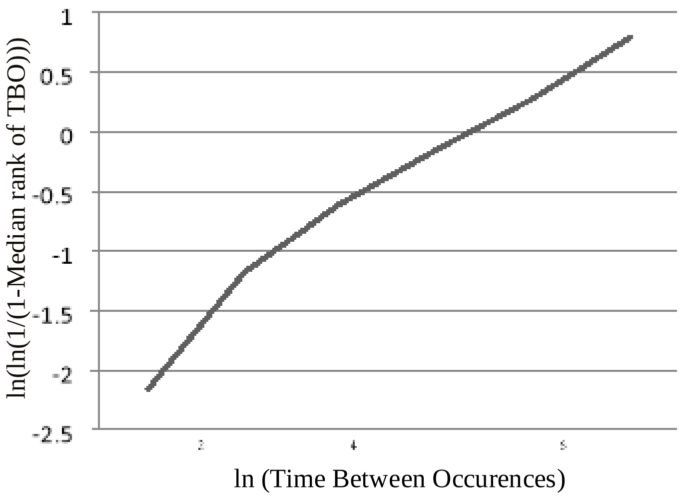

Fig. 5.3: Weibull Probability Plotting Paper for Major Incidents

Least square analysis for Major incidents,

$$ƀ = \frac{\sum_{i=1}^{6}(lnTi)Yi - (\sum_{i=1}^{6} lnTi)(\sum_{i=1}^{6} Yi)/6}{\sum_{i=1}^{6}(lnTi)^2 - (\sum_{i=1}^{6} lnTi)^2/6}$$

$$ƀ = \frac{-0.01117 - (24.4091)(-3.00344)/6}{126.9127 - (24.4091)^2/6}$$

$$ƀ = \frac{-0.01117 + 12.2185}{126.9127 - 99.3006} = \frac{12.20733}{27.612}$$

ƀ = 0.4421

$$\hat{a} = \frac{\sum_{i=1}^{6} Yi}{6} - ƀ\frac{\sum_{i=1}^{6}(lnTi)}{6}$$

$$\hat{a} = \frac{-3.00344}{6} - \frac{(0.4421 * 24.4091)}{6}$$

â = -0.50057 - 1.7985

â = -2.29907

β = ƀ = 0.4421 (shape parameter)

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ŋ = $e\wedge(-\hat{a}/$ƀ$)$

ŋ = $e\wedge(-(-2.29907)/0.4421) = e\wedge 5.2003$

ŋ = 181.33(scale parameter)

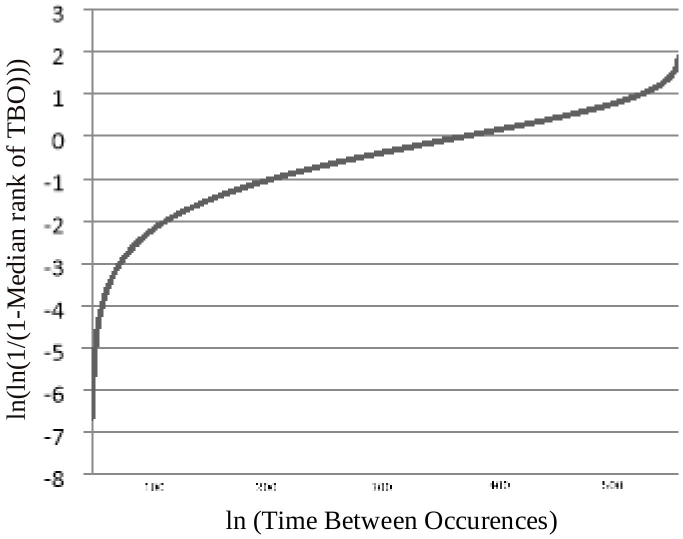

Fig. 5.4: Weibull Probability Plotting Paper for All Incidents

Least square analysis for All incidents,

ƀ = $\dfrac{\sum_{i=1}^{544}(lnTi)Yi - (\sum_{i=1}^{544} lnTi)\,(\sum_{i=1}^{544} Yi)/544}{\sum_{i=1}^{544}(lnTi)^2 - (\sum_{i=1}^{544} lnTi)^2\,/544}$

ƀ = $\dfrac{110.56 - (\,549.006\,)\,(\,-312.7728\,)/\,544}{773.866 - (549.006)^2/\,544}$

ƀ = $\dfrac{110.56 + 315.651}{773.866 - 554.58} = \dfrac{426.211}{219.808}$

ƀ = 1.939

$\hat{a} = \dfrac{\sum_{i=1}^{544} Yi}{544} -$ ƀ $\dfrac{\sum_{i=1}^{544}(lnTi)}{544}$

$\hat{a} = \dfrac{-312.7728}{544} - \dfrac{(1.939 * 549.006)}{544}$

$\hat{a} = -0.57495 - 1.95686$

$\hat{a} = -2.53181$

β = ƀ = 1.939 (shape parameter)

ŋ = $e\wedge(-\hat{a}/$ƀ$)$

ŋ = $e\wedge(-(-2.53181)/1.5991) = e\wedge 1.5833$

ŋ = 4.871 (scale parameter)

VI. CONCLUSION

From the above calculations and research it can be concluded that.

- The data of incident occurrences based in an oil refinery including minor, medium, major, serious and catastrophic help in the system safety assessment in any organization
- The system safety assessment has been conducted on the collected incidents data in an oil refinery where also a rank regression analysis and least square parameter estimation have been performed on developing procedure for estimating the time between occurrences
- Weibull distribution theory help to further document the statistics of duration between the occurrence and reoccurrence of any particular type of incident
- This research work provides algorithm evaluation using weibull distribution for development of probability density function and hazard rate function based on incident occurrences

Now put the values of β and ŋ for all the incidents calculated above accordingly to get the Weibull probability density function and Weibull hazard function.

Weibull probability density function, PDF, is:

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

And Weibull hazard function, the instantaneous failure rate is:

$$h(t) = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1}$$

For all incidents,

β = 1.939, ŋ = 4.871, $\frac{\beta}{\eta} = 0.398$ and β-1 = 0.939

$f(t)_{All\ Incidents} = 0.09\ t^{0.939} \exp(-0.046t)^{1.939}$

$h(t)_{All\ Incidents} = 0.09\ t^{0.939}$

For Minor incidents,

β = 1.5991, ŋ = 4.4442, $\frac{\beta}{\eta} = 0.36$ and β-1 = 0.599

$f(t)_{Minor\ Incidents}$ = 0.147 $t^{0.599}$ $\exp(-0.09t)^{1.599}$

$h(t)_{Minor\ Incidents}$ = 0.147 $t^{0.599}$

For Medium incidents,

β = 1.0343, ŋ = 17.444, $\frac{\beta}{ŋ}$ = 0.059 and β-1 = 0.0343

$f(t)_{Medium\ Incidents}$ = 0.05 $t^{0.0343}$ $\exp(-0.05t)^{1.0343}$

$h(t)_{Medium\ Incidents}$ = 0.05 $t^{0.0343}$

For Major incidents,

β = 0.4421, ŋ = 181.33, $\frac{\beta}{ŋ}$ = 0.0024 and β-1 = -0.558

$f(t)_{Major\ Incidents}$ = -0.001 $t^{-0.558}$ $\exp(-0.096t)^{0.4421}$

$h(t)_{Major\ Incidents}$ = -0.001 $t^{-0.558}$

Table 6.1: Weibull analysis as Probability density function and hazard rate function

Type of Incident	Shape parameter (β)	Scale parameter (ŋ)	$f(t)$ Probability density function	$h(t)$ Hazard rate function
Minor	1.5991	4.4442	0.147 $t^{0.599}$ exp $(-0.09t)^{1.599}$	0.147 $t^{0.599}$
Medium	1.0343	17.444	0.05 $t^{0.0343}$ exp $(-0.05t)^{1.0343}$	0.05 $t^{0.0343}$
Major	0.4421	181.33	-0.001 $t^{-0.558}$ exp $(-0.096t)^{0.4421}$	-0.001 $t^{-0.558}$
All	1.939	4.871	0.09 $t^{0.939}$ exp $(-0.046t)^{1.939}$	0.09 $t^{0.939}$

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