System Safety Assessment by Developing Hazard Rate Function Based on 5 years Incidents in an Oil Refinery Using Weibull Analysis and its Estimators

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ABSTRACT

A comprehensive study on system safety assessment of an Indian Oil Refinery incident for five years was done considering the effect of incidents on refinery infrastructure and human injury/causality. The impact of incidents has been assessed by two parameters first the time between two successive incidents and second its consequence. The hazard rate function and cumulative risk function for distinguished category of incident in oil refinery were developed. The study evaluated the status of safety level as well as the scope of improvement for the particular oil refinery safety.

Keywords: Hazard Rate Function, TBO, System Safety Assessment, Safety Analysis.

I. INTRODUCTION

Oil refineries are the major source of world’s fuel consumption. The oil refineries are enrich with the hazardous process and operations which includes higher pressure and temperature. The existing system of oil refining and process around the country have been subjected to deterioration due to aging, aggressive environmental factors, inadequate design and improper protect and maintenance. These facility often require extensive maintenance, repair, renewal practices and even replacement of certain components. The integrity of these facility is primary interest of oil refinery based company, governmental agencies, consumers and other stack holder due to potential adverse consequences related to public health, safety and heavy financial liabilities in case of systems failure.

The few large fire and explosion in petroleum and chemical industries which were attracted the attention of world society are as under.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Cause</th>
<th>Material</th>
<th>Quantity (tones)</th>
<th>Death (d), Injured (i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 July 1951</td>
<td>Port Newark, NJ, USA</td>
<td>Fire</td>
<td>Propane (70)</td>
<td>2600</td>
<td>14i</td>
</tr>
<tr>
<td>1955</td>
<td>Ludwigshafen, FRG</td>
<td>Railroad accident</td>
<td>LPG*</td>
<td>*</td>
<td>2i</td>
</tr>
<tr>
<td>1955</td>
<td>Cottage Grove, OR, USA</td>
<td>Storage vessel failure</td>
<td>LPG*</td>
<td>12d, 13i</td>
<td></td>
</tr>
<tr>
<td>8 January 1957</td>
<td>Montreal, Canada</td>
<td>Fire</td>
<td>Butane (5100)</td>
<td>1d</td>
<td></td>
</tr>
<tr>
<td>1958</td>
<td>Michigan, USA</td>
<td>Overfilling</td>
<td>Butane (55)</td>
<td>18d, 83i</td>
<td></td>
</tr>
<tr>
<td>4 January 1966</td>
<td>Feyzin, France</td>
<td>Fire</td>
<td>Propane (1000)</td>
<td>18d, 83i</td>
<td></td>
</tr>
</tbody>
</table>
Table 1.1 (Continued)

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Event</th>
<th>Chemical</th>
<th>Cases</th>
<th>Injuries</th>
<th>Health</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 January 1969</td>
<td>Laurel, MS, USA</td>
<td>Fire (derail)</td>
<td>Propane</td>
<td>65</td>
<td>2d, 976i</td>
<td></td>
</tr>
<tr>
<td>21 June 1970</td>
<td>Crescent City, IL, USA</td>
<td>Fire (Derailed)</td>
<td>Propane (5)</td>
<td>275</td>
<td>66i</td>
<td></td>
</tr>
<tr>
<td>30 March 1972</td>
<td>Rio de Janeiro, Brazil</td>
<td>Fire</td>
<td>Propane</td>
<td>100 0</td>
<td>37d</td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>Rio de Janeiro, Brazil</td>
<td>LPG Storage spheres (five on site) and cylinders</td>
<td>*</td>
<td>37d, 53i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 July 1973</td>
<td>Kingman, AZ, USA</td>
<td>Fire</td>
<td>Propane</td>
<td>100</td>
<td>13d, 95i</td>
<td></td>
</tr>
<tr>
<td>12 February 1974</td>
<td>Oneonta, NY, USA</td>
<td>Fire (Derailed)</td>
<td>Propane (4)</td>
<td>288</td>
<td>25i</td>
<td></td>
</tr>
<tr>
<td>30 May 1978</td>
<td>Texas City, TX, USA</td>
<td>Fire</td>
<td>Propanes(6)</td>
<td>150 0</td>
<td>7d, 10i</td>
<td></td>
</tr>
<tr>
<td>19 November 1984</td>
<td>Mexico City, Mexico</td>
<td>Fire</td>
<td>Propane (20)</td>
<td>300 0</td>
<td>650d, 6400i</td>
<td></td>
</tr>
<tr>
<td>August 1993</td>
<td>Panipat, India</td>
<td>Pressure build-up</td>
<td>Ammonia</td>
<td>*</td>
<td>6d, 25i</td>
<td></td>
</tr>
<tr>
<td>7 January 2001</td>
<td>Kanpur, India</td>
<td>Highway accident</td>
<td>LPG</td>
<td>*</td>
<td>12d, 6i</td>
<td></td>
</tr>
<tr>
<td>1 July 2001</td>
<td>Jamnagar, India</td>
<td>Damage</td>
<td>LPG</td>
<td>*</td>
<td>12d</td>
<td></td>
</tr>
<tr>
<td>19 January 2004</td>
<td>Skikida, Algeria</td>
<td>Explosions</td>
<td>LNG</td>
<td>*</td>
<td>13d, 75i</td>
<td></td>
</tr>
<tr>
<td>29 October 2009</td>
<td>Jaipur, India</td>
<td>Fire</td>
<td>Kerosine (SKO) Motor Spirit (MS)</td>
<td>100 0</td>
<td>11d, 7i</td>
<td></td>
</tr>
</tbody>
</table>

Incident includes all undesired circumstances which could cause accidents; it is preferable to think incidents as part of single, much larger, group of undesired events which leads to accident.

Table 2: The main types of accident and incident data

<table>
<thead>
<tr>
<th>Quality</th>
<th>Environment</th>
<th>Injuries</th>
<th>Health</th>
<th>Asset damage and other losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer complaints</td>
<td>Spillage</td>
<td>Injuries to employees at work</td>
<td>Sickness absence</td>
<td>Damage to organizational assets</td>
</tr>
<tr>
<td>Product non-conformances</td>
<td>Emissions above consent levels</td>
<td>Injuries to others at work</td>
<td>Chronic illness</td>
<td>Damage to other people’s assets</td>
</tr>
<tr>
<td>Service non-conformances</td>
<td>Discharges above consent levels</td>
<td>Injuries during travel</td>
<td>Sensitization</td>
<td>Interruptions to production</td>
</tr>
<tr>
<td></td>
<td>Injuries arising from unsafe products</td>
<td>Damage arising from unsafe products</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B. Collection of Accident and Incident Data

One of the largest Oil Refineries in our country has been considered for this work and author had completed one month vocational training for the collection of accident and incident data for refinery. The major sources of accident and incident data within the oil refinery during vocational training includes Accidents Report, Accident / Incident Record, Accident notification and investigating report. In the oil refinery management system follow the chronology of an accident and the author identified the following states to accomplish the same.

1. The person, who sustains the injury, or someone else, reports that an accident/incident has happened, usually in a online system which is assessable to all EHS professional of refinery.
2. The EHS professional to whom the accident/incident is reported, makes a written record of the salient points, usually in a risk register form.
3. The accident is investigated and, if it is sufficiently serious, is reported to the relevant state authority which is Chief Factory Inspector Labor Department Govt. of M.P.

A. Incident Pattern and Type

There is no general agreement about how accidents and incidents should be defined. In view of this author would like to focus on various types of data which might be included in these two categories and the practical implications. Most commonly used distinction between accidents and incidents is that accidents have a specific outcome while incidents have no outcome such as injuries, damage, fire, leakage etc. in an organization. Accident includes any undesired circumstances which give rise to ill-health, damage to property, plant, products, production loss and increased liabilities.
4. The EHS professional who investigates the accident writes a report on his or her findings, to which are added any suggestions for remedial action.

5. The EHS professional who investigates the accident report back to those involved in the outcome of the investigation and the action to be taken.

The vocational training follows the three major steps in collecting accident and incident data of the oil refinery. First step involve the critical examination of all reported accident and incident available with the EHS department of oil refinery. The second step for checking of non-reporting incident and accident was beginning. Personal interview with people who are likely to have experience or knowledge of the accident or incident were commenced. People are more willing to talk about accident or incident they did not report if they are confident that there will be no adverse consequences as a result of their revelations. The author has carried out an appropriate sample of interviews which make a reasonable accurate assessment of the proportion of accidents or incident which is going unreported. Inspections of locations where incident/accident took place was done by author during these interviews and one set of incident record is keep ready for cross checking the statement given by individual person. A good data are available from year 2010 to 2015 for analysis of incident/accident within the oil refinery.

**Classification of Accident/Incident Data**

Incident type has been arranged date wise from last five years in risk register of the concern oil refinery. A short description about the incident/accident was found and based on which the type of incident/accident was categorize. The severity level broadly classified on to different aspect the first in terms of harm to personnel and second in terms of plant damage and loss production. The four major significant scales has been decided the severity level of individual incident which was took place. The detail description on these scales of consequences is given below.

We have set up a scale of harm to personnel as:

- **Minor** - Reportable but non-disabling injuries causing over 3 days absence.
- **Critical** – Disabling injury or severe injury requiring extensive recovery and 1 in 10 chance of fatality.
- **Severe** – Critical injuries and possibly 1 fatality.
- **Catastrophic** – One or more fatalities.

Also when a scale of loss in terms of plant damage and lost production is concern an incident/accident severity described as:

- **Minor** - Short-term loss of production.
- **Critical** - Damage to machines repairable in short time.
- **Severe** - Damage to plant, major repair costs and serious loss of production.
- **Catastrophic** - Substantial damage to plant and potential loss of overall plant.

**C. Proposed Safety Assessment using Weibull Analysis**

**The Weibull Distribution**

The weibull distribution is one of the most widely used lifetime distribution in reliability engineering. It is a versatile distribution that can take on the characteristics of other types of distributions, based on the value of the shape parameter and scale parameter. To apply Weibull distribution to the available data from Oil Refinery we have to categories the data in four major category and the estimates of the parameters of the Weibull distribution can be found graphically via probability plotting paper, using least squares (rank regression) analysis.

**Estimation of the Weibull Parameters**

The steps for determining the parameters of the Weibull representing the data, using probability plotting, are First rank the time between occurrence in ascending order as shown in table for All four major category. The method of probability plotting takes of the cdf of the distribution and attempts to linearize it by employing a specially constructed paper. The following sections illustrate the steps in this method using 2 parameter Weibull distribution.

1. Linearize the unreliability function.
2. Construct the probability plotting paper
3. Determine the X and Y positions of the plot points.

**Constructing the Paper**

The next task is to construct the Weibull probability plotting paper with the appropriate y and x axes. The x-axis transformation is simply logarithmic of time between occurrence (TBO) and y-axis is a bit more...
Complex requiring a double log reciprocal transformation as
\[ y = \ln(\ln\left(\frac{1}{1\text{-median rank of } y}\right)) \]
\[ x = \ln(TBO) \]

**Figure 1**: Weibull paper for Minor Incident 2010 to 2015

Least Square Analysis for Minor Incidents & Weibull Estimator
\[
\hat{b} = \frac{\sum_{i=1}^{133}(Inti)y_i - \left(\sum_{i=1}^{133} Inti\right)\left(\sum_{i=1}^{133} y_i\right) / 133}{\sum_{i=1}^{133}(Inti)^2 - \left(\sum_{i=1}^{133} Inti\right)^2 / 133}
\]
\[
= \frac{833.598 - (227.5682)(-380.8489) / 133}{1141.255 - (227.5682)^2 / 133}
\]
\[
= \frac{833.598 + 130.92}{1141.255 - 78.2285} = \frac{1063}{133} = 0.6618
\]
\[
\hat{a} = \frac{\sum_{i=1}^{133} y_i - \hat{b} \sum_{i=1}^{133} Inti}{662} = \frac{-380.8489 - (0.6616 \times 227.5682)}{662}
\]
\[
= -0.5753 - 0.2274 = -0.8027
\]
\[
\hat{\beta} = \hat{b} = 0.6618
\]
\[
\hat{\eta} = e^{-\frac{\hat{a}}{\hat{\beta}}} = e^{-\frac{-0.5753}{0.6618}} = e^{2.130} = 3.363
\]

**Figure 2**: Weibull paper for Critical Incident 2010 to 2015

Least Square Analysis for Critical Incidents & Weibull Estimator
\[
\hat{b} = \frac{\sum_{i=1}^{133}(Inti)y_i - \left(\sum_{i=1}^{133} Inti\right)\left(\sum_{i=1}^{133} y_i\right) / 133}{\sum_{i=1}^{133}(Inti)^2 - \left(\sum_{i=1}^{133} Inti\right)^2 / 133}
\]
\[
= \frac{232.8262 - (299.914)\left(-75.7878\right) / 133}{109.0762 + 123.75}
\]
\[
= \frac{232.8262 - 354.6098}{109.0762 + 123.75} = 0.7763
\]
\[
\hat{a} = \frac{\sum_{i=1}^{133} y_i - \hat{b} \sum_{i=1}^{133} Inti}{133} = \frac{-75.7878 - 0.7763 \times 217.1707}{133}
\]
\[
= -0.5698 - 1.2675 = -1.8337
\]
\[
\hat{\beta} = \hat{b} = 0.7763
\]
\[
\hat{\eta} = e^{-\frac{\hat{a}}{\hat{\beta}}} = e^{-\frac{-1.8337}{0.7763}} = e^{2.366} = 10.6638
\]

**Figure 3**: Weibull paper for Severe Incident 2010 to 2015

Least Square Analysis for Severe Incidents & Weibull Estimator
\[
\hat{b} = \frac{\sum_{i=1}^{39}(Inti)y_i - \left(\sum_{i=1}^{39} Inti\right)\left(\sum_{i=1}^{39} y_i\right) / 39}{\sum_{i=1}^{39}(Inti)^2 - \left(\sum_{i=1}^{39} Inti\right)^2 / 39}
\]
\[
\hat{a} = \frac{\sum_{i=1}^{39} y_i}{39} - \hat{b} = \frac{\sum_{i=1}^{39} lnti}{39}
\]
\[
= -21.7429 \times \frac{39}{39} - 0.8045 \times \left( \frac{-115.2579}{39} \right)
\]
\[
= 0.5575 - 2.3775
\]
\[
\hat{a} = 2.9350
\]
\[
\hat{\beta} = \hat{b} = 0.8045
\]
\[
\hat{\eta} = e^{-\frac{\hat{a}}{\hat{b}}}
\]
\[
= e^{-\frac{2.9350}{0.8045}}
\]
\[
= e^{3.6482}
\]
\[
\hat{\eta} = 38.4065
\]

**Figure 4:** Weibull paper for Catastrophic Incident 2010 to 2015

Least Square Analysis for Catastrophic Incidents & Weibull Estimator

\[
\hat{b} = \frac{\sum_{i=1}^{39} lnti y_i - \left( \sum_{i=1}^{39} lnti \right) \left( \sum_{i=1}^{39} y_i \right)}{\sum_{i=1}^{39} lnti^2 - \left( \sum_{i=1}^{39} lnti \right)^2} / 7
\]
\[
= 5.6829 \times \left( \frac{-3.5564}{7} \right)
\]
\[
= \frac{166.817 - (31.6077)^2 / 7}{5.6829 + 16.0585}
\]
\[
= 166.817 - 14.2709
\]
\[
\hat{b} = 103.756 / 24.0961 = 0.4305
\]

\[
\hat{\alpha} = \frac{\sum_{i=1}^{39} lnti}{7} - \hat{b} = \frac{\sum_{i=1}^{39} lnti}{7}
\]
\[
= -3.5564 - 0.4305 \times \left( \frac{31.6077}{7} \right)
\]
\[
= -0.575 - 0.1463
\]
\[
\hat{\beta} = \hat{b} = 0.937
\]
\[
\hat{\eta} = e^{-\frac{\hat{a}}{\hat{b}}}
\]
\[
= e^{-\left( -\frac{0.7213}{0.937} \right)}
\]

**Figure 5:** Weibull paper for All Incident 2010 to 2015

Least Square Analysis for All Incidents & Weibull Estimator

\[
\hat{b} = \frac{\sum_{i=1}^{839} lnti y_i - \left( \sum_{i=1}^{839} lnti \right) \left( \sum_{i=1}^{839} y_i \right)}{\sum_{i=1}^{839} lnti^2 - \left( \sum_{i=1}^{839} lnti \right)^2} / 839
\]
\[
= \frac{1069.634 - (131.06)(-482.97) / 839}{1242.06 - (131.06)^2 / 839}
\]
\[
= 1069.63 + 75.44 = 1145.07
\]
\[
\hat{b} = 0.937
\]
\[
\hat{\alpha} = \frac{\sum_{i=1}^{839} lnti}{839} - \hat{b} \frac{\sum_{i=1}^{839} lnti}{839}
\]
\[
= \frac{-482.97}{839} \times (0.937 \times 131.06)
\]
\[
= -0.575 - 0.1463
\]
\[
\hat{\beta} = \hat{b} = 0.937
\]
\[
\hat{\eta} = e^{-\frac{\hat{a}}{\hat{b}}}
\]
\[
= e^{-\left( -\frac{0.7213}{0.937} \right)}
\]
D. Probability Distribution Function and Hazard Rate Function Development

Weibull Probability Distribution function (PDF) is given by

\[ F(x) = \left( \frac{\beta}{\eta} \right) \left( \frac{x}{\eta} \right)^{\beta-1} \exp\left( -\frac{x}{\eta} \right)^\beta \]

and Hazard function is given by

\[ h(x) = \left( \frac{\beta}{\eta} \right) \left( \frac{x}{\eta} \right)^{\beta-1} \]

Put the value for all incidents as \( \beta = 0.937, \eta = 2.159 \)

\[ = 2.159 \left( \frac{\beta}{\eta} = 0.433 \right), \beta - 1 \]

\[ = -0.063 \]

We have

\[ f(x)_{\text{All incident}} = 0.45 x^{-0.063} \exp(-0.46 x)^{0.937} \]

\[ h(x)_{\text{All incident}} = 0.45 x^{-0.063} \]

Put the value for Minor Incidents as \( \beta = 0.6618, \eta \)

\[ = 3.363, \left( \frac{\beta}{\eta} = 0.196 \right), \beta - 1 \]

\[ = -0.03382 \]

\[ f(x)_{\text{Minor incident}} = 0.295 x^{-0.3382} \exp(-0.29 x)^{0.6618} \]

\[ h(x)_{\text{Minor incident}} = 0.29 x^{-0.3382} \]

Put the value for Critical Incidents as \( \beta = 0.7763, \eta \)

\[ = 10.66, \left( \frac{\beta}{\eta} = 0.072 \right), \beta - 1 \]

\[ = -0.223 \]

\[ f(x)_{\text{Critical incident}} = 0.00074 x^{-0.223} \exp(-0.09 x)^{0.7763} \]

\[ h(x)_{\text{Critical incident}} = 0.00074 x^{-0.223} \]

Put the value for Severe Incidents as \( \beta = 0.8045, \eta \)

\[ = 38.40, \left( \frac{\beta}{\eta} = 0.020 \right), \beta - 1 \]

\[ = -0.1955 \]

\[ f(x)_{\text{Severe incident}} = 0.4 x^{-0.195} \exp(-0.26 x)^{0.8045} \]

\[ h(x)_{\text{Severe incident}} = 0.4 x^{-0.195} \]

Put the value for Catastrophic Incidents as \( \beta \)

\[ = 0.4305, \eta = 124.77, (\beta/\eta) = 3.4 \times 10^{-3}, \beta - 1 = -0.569 \]

\[ f(x)_{\text{Catastrophic incident}} = 0.053 x^{-0.569} \exp(-0.008 x)^{0.4305} \]

\[ h(x)_{\text{Catastrophic incident}} = 0.053 x^{-0.569} \]

III. RESULTS AND DISCUSSION

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Type of Incident</th>
<th>Value of ( \beta ) (shape parameter)</th>
<th>Value of ( \eta ) (scale parameter)</th>
<th>Probability Distribution function ( f(x) )</th>
<th>Hazard Rate Function ( h(x) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>All</td>
<td>0.937</td>
<td>2.159</td>
<td>( 0.45 x^{-0.063} \exp(-0.46 x)^{0.937} )</td>
<td>( 0.45 x^{-0.063} )</td>
</tr>
<tr>
<td>2.</td>
<td>Minor</td>
<td>0.6618</td>
<td>3.363</td>
<td>( 0.295 x^{-0.3382} \exp(-0.29 x)^{0.6618} )</td>
<td>( 0.29 x^{-0.3382} )</td>
</tr>
<tr>
<td>3.</td>
<td>Critical</td>
<td>0.7763</td>
<td>10.66</td>
<td>( 0.00074 x^{-0.223} \exp(-0.09 x)^{0.7763} )</td>
<td>( 0.00074 x^{-0.223} )</td>
</tr>
<tr>
<td>4.</td>
<td>Severe</td>
<td>0.8045</td>
<td>38.40</td>
<td>( 0.4 x^{-0.195} \exp(-0.26 x)^{0.8045} )</td>
<td>( 0.4 x^{-0.195} )</td>
</tr>
<tr>
<td>5.</td>
<td>Catastrophic</td>
<td>0.4305</td>
<td>124.77</td>
<td>( 0.053 x^{-0.569} \exp(-0.008 x)^{0.4305} )</td>
<td>( 0.053 x^{-0.569} )</td>
</tr>
</tbody>
</table>

IV. CONCLUSION

The hazard function defined as the limit of the failure rate as the interval approaches zero. Thus the hazard function is the instantaneous failure rate of any incident type. The quantity \( h(x)dx \) represents the probability that a incident of particular category having time \( x \) will be took place within the small interval of time \( x \) to \( x+dx \). Hazard function indicates the change in failure rate over the life of a population of point in time.

V. REFERENCES


