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Consequence Analysis, Vulnerability Mapping and Fuzzy Fault Tree Analysis for a Better Disaster Management in and Around Chemical Industrial Areas

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Abstract
Chemical industries are prone to hazards like fire, explosion and toxic gas releases. Qualitative and quantitative hazard analyses are essential for the identification and quantification of the hazards associated with chemical industries. This study presents the results of a consequence analysis carried out to assess the damage potential of the hazardous material storages in an industrial area of central Kerala, India. These results are used for the estimation of individual risk and societal risk in the above industrial area. Vulnerability assessment is carried out using probit functions for toxic, thermal and pressure loads. Results of fuzzy Fault Tree Analysis (FTA) and Two dimensional fuzzy FTA (TDFFTA) are also discussed.

Keywords: *Consequence analysis, Vulnerability assessment, Individual Risk, Societal Risk, Fuzzy FTA*

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INTRODUCTION

The need for risk assessment and consequence modelling of process plant and hazardous storage facilities has become exceedingly critical due to the trend towards larger and more complex units that process toxic, flammable and otherwise hazardous chemicals under extreme temperature and pressure conditions. Moreover, the proximity of many such units to densely populated areas may magnify the potential damage. Consequence analysis is a tool which quantifies the consequences from the hazardous storages in the MAH industries. Fire associated with chemicals can take several different forms like flash fire, jet fire and pool fire [1]. Explosions are characterized by a shock wave which can be heard as a bang and which can cause damage to buildings, breaking windows and ejecting missiles over distances of several hundred meters [1]. The effects of toxic chemicals when considering major hazards, on the other hand, are quite different and are concerned with the acute exposure during and soon after a major accident rather than with long term chronic exposures.

Modelling of Pool Fires

Pool fire is a common type of fire, which can occur in the form of a tank fire or from a pool of fuel spread over a ground or water. A fire in a liquid storage tank and a trench fire are forms of pool fire. An empirical model commonly employed in the estimation of radiative flux from a pool fire is TNO model [2].

Modelling of Explosion

There are several types of explosion including deflagration, detonation, dust explosion, vapor cloud explosion and boiling liquid expanding vapour explosion (BLEVE).

Modelling of Vapor Cloud Explosion (VCE)

When a large amount of flammable vaporizing liquid or gas is rapidly released, a vapor cloud forms and disperses with the surrounding air. The release can occur from a storage tank, process vessels, transport vessel, or pipelines. If this cloud is ignited before the cloud is diluted below its lower flammability limit (LFL), a vapour cloud explosion (VCE) will occur. Centre for Chemical Process Safety (CCPS) of American Institute of Chemical

Engineers [3] provides an excellent summary of vapour cloud behaviour.

TNT Equivalent Model for VCE

The TNT equivalent model is based on the assumption of equivalence between the flammable material and TNT factored by an explosion efficiency term.

Modelling of Boiling Liquid Expanding Vapor Explosion (BLEVE)

BLEVE is an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure [3]. Boiling liquid expanding vapor explosion (BLEVE) is a type of physical explosion. The physical force that causes the BLEVE is on account of the large liquid to vapor expansion of the liquid in the container. LPG will expand to 250 times its volume when changing from liquid to vapor. It is this expansion process that provides the energy for propulsion of the container and the rapid mixing of vapor from the container with air, resulting in the fireball characteristic when flammable liquids are involved. In most BLEVE cases caused by exposure to fire, the container failure originates in the container metal significantly where it is not in contact with liquid. The liquid conducts the heat away from the metal and acts as a heat absorber. Therefore the metal around the vapor space can be heated to the point of failure. The major hazards of BLEVE are thermal radiation, velocity of fragments and over pressure from shock wave.

Dispersion Modeling

Dispersion [4] is a term used by modellers to include advection (moving) and diffusion (spreading). A dispersing vapor cloud will generally move in a downwind direction and spread (diffuse) in a crosswind and vertical direction (crosswind is the direction perpendicular to the wind). A cloud of gas that is denser or heavier than air (called a heavy gas) can also spread upwind to a small extent. Arial Locations of Hazardous Atmosphere [5] (ALOHA) air model developed by US- EPA is used for dispersion modeling.

Individual Risk

Individual risk is defined by AIChE/CCPS [1] as risk to a person in the vicinity of a hazard. This includes the nature of the injury to the individual, the likelihood of the injury occurring and the time period over which the injury might occur.

Estimation of Individual Risk

Total individual risk at any geographic location x,y in and around the industrial area is the sum of individual risk at that point, due to various incident outcome cases associated with the various industries in the industrial area. Individual Risk at a geographical location x, y is given by AIChE/CCPS as

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i} \text{-------------} (1)$$

where $IR_{x,y}$ is the total individual risk of fatality at geographic location x,y, $IR_{x,y,i}$ is the individual risk of fatality at geographical location x,y from the incident outcome case i, n is the total number of individual outcome cases from the industrial area.

Societal Risk

Societal risk is a measure of risk to a group of people. It is most often expressed in terms of the frequency distribution of multiple casualty events (F-N curve.) The calculation of societal risk requires the same frequency and consequence information as individual risk. Additionally, societal risk estimates requires a definition of the population at risk around the facility. This definition can include the population type, the likelihood of people being present, or mitigation factors.

Estimation of Societal Risk

Number of people affected by all incident outcome cases can be estimated using the following equation

$$N_i = \sum_{x,y} P_{x,y} p_{f,i} \text{--------} (2)$$

where N_i is the number of fatalities resulting from incident outcome case I, $P_{x,y}$ is the number people at locations x,y and $p_{f,i}$ is the probability that that incident outcome case i will result in a fatality at location x,y.

Incident Identification

Potential incident for analysis are identified by applying appropriate identification techniques, including historical information, checklist or any one of the hazard identification techniques presented in the "Guidelines for Hazard evaluation Procedures" of AIChE/ CCPS [6]. In this work preliminary hazard analysis (PHA) and HAZOP study [7] are conducted for hazard identification.

Incident Outcomes

The identified incident may have one or more outcomes, depending on the sequence of the events which follows the original incident. For example a leak of LPG from a storage tank can be jet fire (if the hole is only a puncture), flash fire (when the vapor cloud catches fire) vapor cloud explosion (when the cloud exploded) or BLEVE (when there is no sufficient cooling to the storage tank)

Consequence Analysis

Estimation of the impact of each incident requires two steps. First a model estimates a physical concentration of material or energy at each location surrounding the facility- for example, radiant heat from the fire, overpressure from the explosion, and concentration of toxic material in the atmosphere. A second set of models estimates the impact that this physical concentration of material or energy has on people, the environment or property-for example toxic material dose response relationships. Consequence analysis of hazardous storages in the selected industrial area are carried out and results are published in our previous study [8]

Impact Analysis

Effect models are used for the impact analysis. These models used to determine how people are injured by exposure to heat and toxic load. Effect models make use of a probit function. In probit function a link exists between the load and percentage of people exposed who suffer particular type of injury (AIChE/CCPS). The probit models are generally expressed as.

$$P_r = k_1 + k_2(\ln V) ------(3)$$

where P_r is the probit, the measure for the percentage of people exposed who incur a particular injury, k_1 constant depending on the type of injury and type of load, k_2 is another constant depending on the type of load. V is the load. AIChE/CCPS provides the conversion table from probit to percentage. It also provides values for constant k_1, k_2 for different chemicals. Probit equations are available for a variety of exposures, including exposure to toxic materials, heat, pressure and radiation, impact and sound.

Frequency Analysis

Many techniques are available for estimating the frequency of the incidents including fault tree analysis, event tree analysis, and the use of historical incident data. In the present work, frequencies of incident outcome cases are obtained from the historical incident data and from our previous work using fuzzy logic and expert elicitation [9].

Fault Tree Analysis

Fault tree analysis (FTA) is a widely used tool for system safety analysis. It is a deductive (backward reasoning) logic technique that focuses on one particular hazardous event (e.g. toxic gas release, explosion, fire etc.) and provides a method for determining the causes of hazardous event. FTA is a powerful diagnostic technique used widely for demonstrating the root causes of undesired events in a system using logical functional relationship among components, manufacturing process and sub systems [10–12]. FTA is also used in other fields such as flexible manufacturing systems [11], LNG terminal emergency shutdown systems [13] and nuclear power plants [14, 15]. In conventional FTA, the probability of failure of basic event must be known in advance. It is very difficult to estimate the failure probability of basic events due to insufficient data. Fuzzy methods along with expert elicitation can be used to generate failure probability values in such cases. Failure probability values of basic events that lead to chlorine release were estimated using expert elicitation and fuzzy logic. Linguistic expressions about the failure probability of the basic events are obtained from the experts and are treated as fuzzy number. Two dimensional fuzzy fault tree analysis [10] are used to incorporate hesitation factor during expert elicitation.

RESULTS AND DISCUSSIONS

The hazardous distances up to which the intensity of heat radiation of pool fire may affect people are listed in Table 1. The results of consequence modelling reveal that the maximum intensity of heat radiation is experienced for naphtha pool fire having a radius of 12 meters. This is mainly due to the large radius of the storage tank and comparatively high heat of combustion and heat of vaporization values of naphtha.

Table 1: *Hazardous Distance for Heat Radiation from Pool Fires.*

Sl. No.	Chemical	Storage capacity in tones	Flame height in meters	Hazardous distance in Meters
1.	Naphtha	11600	38.0	87.0
2.	Benzene	1115	24.0	47.0
3.	Cyclohexane	1150	25.0	51.0
4.	Cyclohexanone	1400	17.0	33.0
5.	Ammonia	5000	12.0	23.0
6.	Naphtha	800	24.0	43.0

From the dispersion modeling of chlorine and ammonia, it is observed that the threat zone is maximum for chlorine, for the atmospheric conditions during morning and evening. It is around 9.2 kilometers for a leak scenario of 2-inch hole on chlorine storage of 50 tonnes, with IDLH as level of concern. Table 2 gives the threat zone corresponding to chlorine at a level of concern of 100ppm (catastrophic failure of chlorine storage tank) and ammonia at a level of concern of 300 ppm. Figure 1 shows the map of vulnerable areas corresponding to different individual outcome cases in the industrial area.

Table 2: *Maximum Threat Zone for Ammonia and Chlorine.*

Name of chemical	Level of concern	Threat zone distance
Ammonia	300 ppm	4.2 kilometers
Chlorine	100 ppm	3.6 kilometers

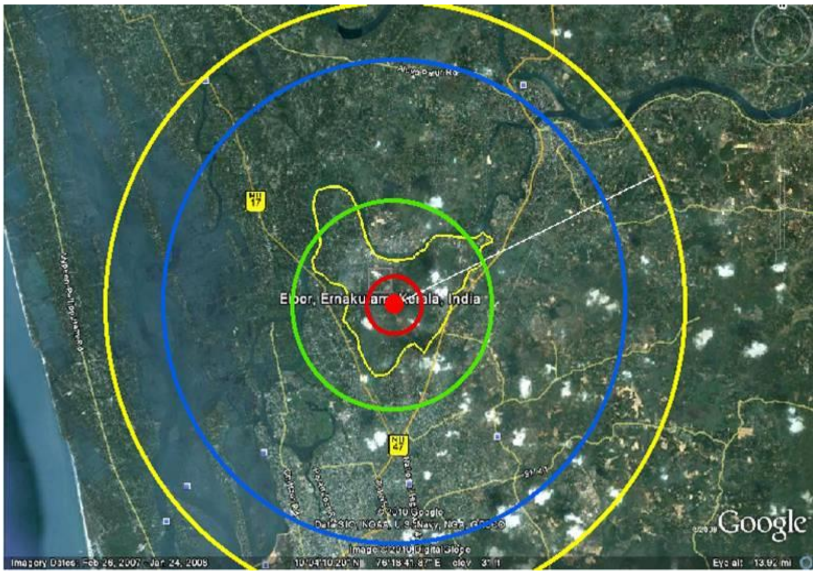

Fig. 1: *Map of Vulnerable Areas of Different Individual Outcome Case.*

Figure 2 gives the location, where individual risk is estimated and the individual risk at different location is listed in Table 3. The individual risk is found to be a maximum at locations A, B, G, H, L, M, and N (approximately 5x10-3 per year). The reasons for high individual risk at locations A, B, G, H, M and N should be the presence of very high concentration of chlorine gas resulting from the catastrophic failure of storage. A broadly acceptable level of individual risk as per the ALARP (As low as reasonably practicable) concept of HSE, UK [12] is 10 -6 /year. Based on these criteria, the individual risk experienced at locations C, D, E, F, I, J, K, O, and P are within the acceptable levels. Table 4 gives the individual outcome cases, threat zone area, population density in each threat zone, probability of wind direction, probability of availability of people in the threat zone and the number of fatality per year (societal risk) associated with each individual outcome cases. A maximum societal risk of 362 fatalities is obtained for chlorine release (catastrophic failure) in a particular direction. This is followed by 230 fatalities for LPG (BLEVE- heat radiation). It is found that the population density in the threat zones for various incident outcome cases plays a major role in the societal risk. This point to the need for maintaining buffer zones (with no human inhabitation) around hazardous industrial areas. Failure probability values of basic events obtained from the international data are compared with those generated using fuzzy logic and TDFFTA are presented in Table 5.

Table 3: *Individual Risk at Different Locations.*

Location	Total individual risk of fatality/ per year	Location	Total individual risk of fatality/ per year
A	$4.781x10^{-3}$	I	$1.007x10^{-6}$
B	$4.781x10^{-3}$	J	$1.007x10^{-6}$
C	$9.600x10^{-9}$	K	$5.800x10^{-6}$
D	$9.600x10^{-9}$	L	$5.800x10^{-3}$
E	$1.000x10^{-6}$	M	$4.787x10^{-3}$
F	$1.000x10^{-6}$	N	$4.787x10^{-3}$
G	$4.782x10^{-3}$	O	$5.807x10^{-6}$
H	$4.782x10^{-3}$	P	$5.807x10^{-6}$

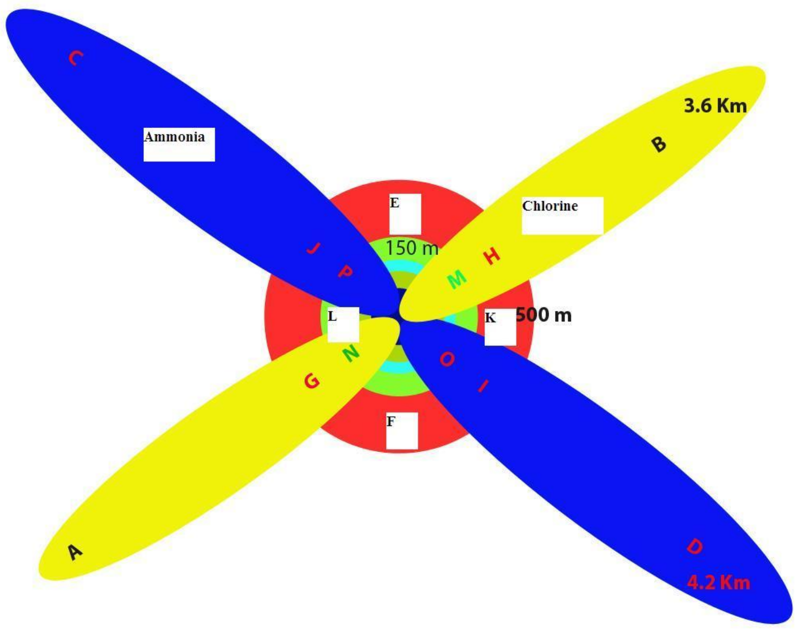

Fig. 2: *Different Location in the Map Where Individual and Societal Risk Estimated.*

Table 4: *Societal Risk due to Different Incident Outcome Cases.*

Incident Outcome	Threat. Zone Area(m^2)	Population Density/ sq. Km	% Fatality	Probability of Wind	Probability of Availability	No. of Fatalities
Ch1C	3.6x0.8	3000	15	0.4	0.7	362
Ch2C	3.6x0.8	3000	15	0.4	0.7	362
Ammonia 1	4.2x0.8	3000	12	0.4	0.7	170
Ammonia 2	4.2x0.8	3000	12	0.4	0.7	170
LPG	0.5 m	1000	46	1	0.5	230
Cyclo-hexane	0.05 m	1000	64	1	0.5	5
Cyclo-hexanone	0.01 m	1000	96	1	0.5	6
Naphtha	0.15 m	3000	8	1	0.7	12

Table 5: *Failure Probability Values of Basic Events Lead to Chlorine Release.*

Basic event Number	Available data	Using FFTA	*Modified values using TDFFTA*
X1	$8.76x10^{-6}$	$8.57x10^{-4}$	$6.75x10^{-4}$
X2	$8.76x10^{-6}$	$3.90x10^{-3}$	$3.30x10^{-3}$
X3	$8.76x10^{-6}$	$9.23x10^{-4}$	$7.32x10^{-4}$
X4	$4.38x10^{-3}$	$8.00x10^{-3}$	$7.00x10^{-3}$
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X24	$4.40x10^{-3}$	$2.50x10^{-3}$	$2.10x10^{-3}$
X25	Not available	$5.33x10^{-4}$	$4.03x10^{-4}$
X26	Not available	$8.99x10^{-4}$	$7.10x10^{-4}$
X27	*Not available*	$6.71x10^{-4}$	$5.19x10^{-4}$

CONCLUSIONS

The present study shows that industries having bulk storages of hazardous chemicals could pose a high potential for damage to those inside and outside the industry. Fire modeling shows that the hazardous distances for certain chemicals extended up to 90 meters which might prevent effective firefighting in case of a pool fire. The domino effects on adjacent tanks are also found to be significant in many cases. Consequence analysis results should be incorporated while deciding the distance between the tanks which is not a practice in India. The consequence calculations have been made for explosion scenarios. A maximum threat zone of 560 meters is observed in the case of cyclohexane. This may be due to the highly explosive nature of cyclohexane. In dispersion modeling, the wind direction and air temperature are found to be the deciding factors for the larger threat zones. Dispersion modelling results and the wind direction for a particular period, can greatly improve emergency preparedness and can be powerful decision making tools for the location of rehabilitation centers and the local emergency control rooms. This work integrates the various islands of safety engineering such as consequence modelling, vulnerability assessment and hazard mapping, to predict the damage potential of hazardous storages, and their impact on the society. This integrated approach can be a potential tool for policy makers, decision makers, MAH industries, risk experts and district authorities to assess the vulnerability of the areas surrounding the industrial belt. The above method will be useful for land use planning areas surrounding industrial belt. FTA with fuzzy logic and expert elicitation may be useful to generate failure probability values of the basic events that lead to fire, explosion and toxic gas releases.

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