CONSEQUENCE MODELLING, VULNERABILITY ASSESSMENT, AND FUZZY FAULT TREE ANALYSIS OF HAZARDOUS STORAGES IN AN INDUSTRIAL AREA

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by

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Ph.D. Thesis in the field of Fuzzy applications in Safety Engineering

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15th July 2010

Certificate

*This is to certify that the thesis entitled **Consequence modelling, vulnerability assessment and fuzzy fault tree analysis of hazardous storages in an industrial area** is an authentic original work done by Renjith V.R. under my supervision and guidance in the School of Engineering, Cochin University of Science and Technology. No part of this thesis has been presented for any other degree from any other institution.*

Prof. (Dr.) G. Madhu
(Supervising Guide)

Declaration

I hereby declare that the work presented in the thesis entitled **Consequence modelling, vulnerability assessment and fuzzy fault tree analysis of hazardous storages in an industrial area** is based on the original work done by me under the supervision and guidance of Prof. (Dr.) G. Madhu, Division of Safety and Fire Engineering, School of Engineering, Cochin University of Science and Technology. No part of this thesis has been presented for any other degree from any other Institution.

Renjith V.R.

Thrikkakara.
15th July 2010.

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A dedication to God, the Almighty, the real disaster manager and rehabilitator….

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ABSTRACT

The hazards associated with major accident hazard (MAH) industries are fire, explosion and toxic gas releases. Of these, toxic gas release is the worst as it has the potential to cause extensive fatalities. Qualitative and quantitative hazard analyses are essential for the identification and quantification of the hazards associated with chemical industries. This research work 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. A survey carried out in the major accident hazard (MAH) units in the industrial belt revealed that the major hazardous chemicals stored by the various industrial units are ammonia, chlorine, benzene, naphtha, cyclohexane, cyclohexanone and LPG. The damage potential of the above chemicals is assessed using consequence modelling. Modelling of pool fires for naphtha, cyclohexane, cyclohexanone, benzene and ammonia are carried out using TNO model. Vapor cloud explosion (VCE) modelling of LPG, cyclohexane and benzene are carried out using TNT equivalent model. Boiling liquid expanding vapor explosion (BLEVE) modelling of LPG is also carried out. Dispersion modelling of toxic chemicals like chlorine, ammonia and benzene is carried out using the ALOHA air quality model. Threat zones for different hazardous storages are estimated based on the consequence modelling. The distance covered by the threat zone was found to be maximum for chlorine release from a chlor-alkali industry located in the area. The results of consequence modelling are useful 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. Individual and societal risks are also estimated at different locations. Mapping of threat zones due to different incident outcome cases from different MAH industries is done with the help of Arc GIS.

Fault Tree Analysis (FTA) is an established technique for hazard evaluation. This technique has the advantage of being both qualitative and quantitative, if the probabilities and frequencies of the basic events are known. However it is often difficult to estimate precisely the failure probability of the components due to insufficient data or vague characteristics of the basic event. It has been reported that availability of the failure probability data pertaining to local conditions is surprisingly limited in India. This thesis outlines the generation of failure probability values of the basic events that lead to the release of chlorine from the storage and filling facility of a major chlor-alkali industry located in the area using expert elicitation and proven fuzzy logic. Sensitivity analysis has been done to evaluate the percentage contribution of each basic event that could lead to chlorine release. Two dimensional fuzzy fault tree analysis (TDFFTA) has been proposed for balancing the hesitation factor involved in expert elicitation.

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Chapter 1

INTRODUCTION

1.1 GENERAL

Along with the rapid progress of industrialisation, the risk of incidents (such as fire, explosion, and chemical release) is increasing as well. The release of chemical methyl isocyanate in Bhopal in 1984 resulted in a catastrophe leading to thousands of fatalities and tens of thousands of people were affected. [1]. The results of major industrial disasters can be devastating, as in the case Flixborough, England, which cost the lives of 28 people [2]. LPG explosion in Mexico city resulted in hundreds of deaths and several thousands of injuries [1]. A massive explosion in Pasadena, Texas in 1989 resulted in 23 fatalities and 314 injuries [1]. A number of such disastrous industrial events have occurred in the past and are still occurring in the world. Thousands of people are killed and injured during these disasters. Some times these disasters may also cause damage to the environment and economy of the nation. These disasters may have differed in the way in which they happened and the harmful chemicals that were involved, however they share a common feature that they were uncontrolled events involving fire, explosions or release of toxic substances [3]. The storage and use of flammable, explosive or toxic chemicals having the potential to cause such disasters are generally referred to as *major hazards*. This potential hazard is therefore a function of both the inherent nature of the chemical and the quantity that is present on site [3]. Accidents involving major hazards could include leakage of flammable material, mixing of the material with air, formation of flammable vapor cloud, and drifting of the cloud to the source of ignition, leading to a fire or explosion affecting the site and possibly populated areas.

In the case of the release of flammable materials, the greatest danger arises from the sudden massive escape of liquid or gases producing a large cloud of flammable and possibly explosive vapor. If the cloud is ignited, the effects of combustion would depend on many factors such as wind speed and the extent to which the cloud is diluted with air. Such hazards could lead to a large number of casualties and extensive damage on site and beyond its boundaries. Nevertheless, even for severe accidents the effects are generally limited to few hundred meters from the site of accident.

The sudden release of a very large quantity of toxic material has the potential to cause deaths and severe injuries at a much greater distance. In theory, such a release would, in certain weather conditions, produce lethal concentrations at several kilometers from the point of release, but the actual number of casualties would depend on the population density in the path of the cloud and effectiveness of the emergency arrangements, which might include evacuation.

Some installations or group of installations pose the threat of both fire and explosion. Moreover, blast and missiles from an explosion can affect the safety of adjoining industrial units dealing with flammable and toxic materials, thereby causing an escalation of the disaster, which is sometimes referred to as the *domino effect* [4]. This situation may exist in clusters of industrial units.

Disasters are major accidents, which cause wide spread disruption of human and commercial activities [5]. Normally common accidents are absorbed by the community, but disasters are major accidents and community may not be able to absorb them with their own resources. Most of the disasters, natural or man made have sudden onset and give very short notice or no time to prevent their occurrence. Disasters may cause loss of human life, injuries, and long term disablement of people working in the organization and local community around the industrial area. Normally, loss of lives, and total or partial disability have more impact on the community than damage to the property. However damage to property has a long-term social impact like loss of revenue, employment, and rebuilding cost and lead to severe economic constraints. Past experience indicates that the likelihood of disaster needs to be foreseen. Therefore, if disasters are foreseeable, the mitigating efforts can be planned in advance. Paramount importance should be given to protect human beings and environment in such planning.

The South Indian city of Cochin is often referred to as a *chemical hot spot* due to the presence of a large number of potentially hazardous industries. There are two industrial areas in Cochin city; Udyogamandal and Ambalamedu; which consist of a number of major accident hazard (MAH) industries. Udyogamandal area consists of about 60 industries out of which 6 are MAH and 54 are small-scale units. Two more MAH industries are located adjacent to the Udyogamandal area. Around 10,000 people are employed in various industries in the area. Population in the area and the surrounding panchayats is about 2, 00,000. In the event of a fire, explosion, or toxic gas release in this area, the chances of disasters similar to that of Bhopal and Mexico cannot be ruled out.

In this dissertation an attempt has been made to quantify the consequences involved in the hazardous chemical industries of Udyogamandal area due to fire, explosion and toxic gas release. The consequences including domino effects at various locations are presented. This research estimates the individual and societal risk posed by these major accident hazard installation. This research also made an attempt to assess the probability of chlorine release from a chlorine filling and storage facility using expert elicitation and proven fuzzy logic technique for Indian conditions. Two dimensional fuzzy fault tree analysis (TDFFTA) has been proposed for balancing the hesitation factor involved in the expert elicitation. The competent authorities, industrialists and risk experts may use these results to assess the vulnerability of the area surrounding an industrial site and to make better disaster management decisions and plans.

1.2 MOTIVATION BEHIND THE RESEARCH WORK

A large number of disasters have occurred in chemical process industries and hazardous storage installations in many parts of the world. Though lot of work has been done to develop qualitative and quantitative methods for hazard identification and risk assessment, little research has been carried out to develop country specific and industry specific equipment / component failure data which is very essential for the estimation of probability of occurrence of the disaster. The present study aims at developing such data by expert elicitation and fuzzy logic with special reference to storage installations. Such an attempt has not been made so far.

1.3 OBJECTIVES OF THE WORK

1. Consequence analysis of hazardous storages in the industrial area using fire modelling, explosion (BLEVE, VCE) modelling, and dispersion modelling.
2. Vulnerability assessment of the above consequences using effect models.
3. Estimation of individual and societal risk and mapping of threat zones.
4. Fault tree analysis of chlorine storage and filling facility from a chlor-alkali industry.
5. Generation of failure probability values under Indian conditions for basic events that lead to chlorine release from a chlorine storage and filling facility using expert elicitation and fuzzy logic.
6. Incorporation of hesitation factor in expert elicitation by introducing two dimensional fuzzy fault tree analysis (TDFFTA).

1.4 OUTLINE OF THESIS

Chapter 1 presents the introduction and objectives of this research work.

Chapter 2 deals with the various storage facilities in Udyogamandal area and its description.

Chapter 3 gives the details of consequence modelling of hazardous substances using fire, explosion and dispersion modelling. Results obtained from these modelling calculations are also presented in this chapter.

Chapter 4 deals with the vulnerability aspects of the hazardous storages and the incident outcome cases arising from these storages and its impact on the individual and society as a whole. It also gives the mapping of threat zones of different individual outcome cases.

Chapter 5 presents the results of fault tree analysis for chlorine storage and filling facility in a chlor-alkali industry. It also deals with the application of expert elicitation and fuzzy logic to generate failure probability values under Indian conditions for the various basic events that lead to a chlorine release. Two dimensional fuzzy fault tree analysis (TDFFTA) has been proposed for balancing the hesitation factor involved in expert elicitation.

Chapter 6 summaries the main findings of the research and its application.

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Chapter 2

STUDY AREA AND FACILITY DESCRIPTION

2.1 INTRODUCTION

The Udyogamandal industrial area of Cochin city consists of six major accident hazard (MAH) industries as per Manufacture storage and import of hazardous chemicals (MSIHC) Rules, 1989, India [1] and The Chemical accidents (Emergency planning, preparedness and response) Rules, 1996, India [2]. Udyogamandal industrial belt comes under Eloor panchayat, spreading over an area of 11.21 sq. km and has a population of 37,073 [3]. The location of Udyogamandal area in Ernakulam district is shown in Fig. 2.1 [4] & Fig. 2.2 [5] and the panchayats surrounding Eloor panchayat are shown Fig. 2.3. Various MAH industries [6] located in the Eloor grama panchayat are listed in the Table 2.1.

Table 2.1 MAH industries in Udyogamandal area.

Sl. No.	Name of Industry
1	Fertilizers and Chemicals Travancore (Petrochemical division)
2	Fertilizers and Chemicals Travancore (Udyogamandal division)
3	Hindustan Insecticides Ltd. (HIL)
4	Travancore Cochin Chemicals Ltd. (TCC)
5	Merchem
6	BSES Kerala Power Ltd.

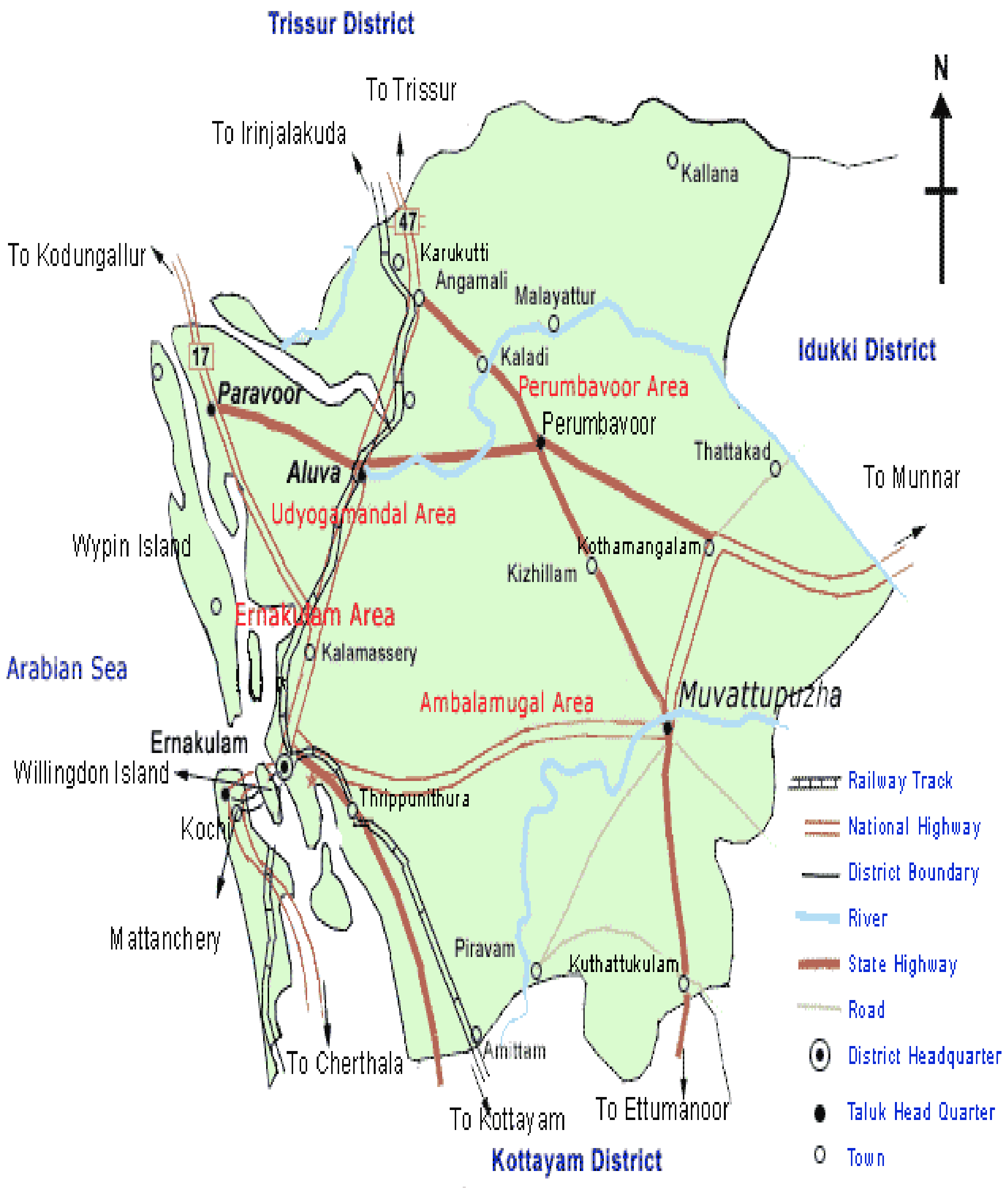

Fig. 2.1 Map of Ernakulam district

(Source: Crisis management plan for Ernakulam district)

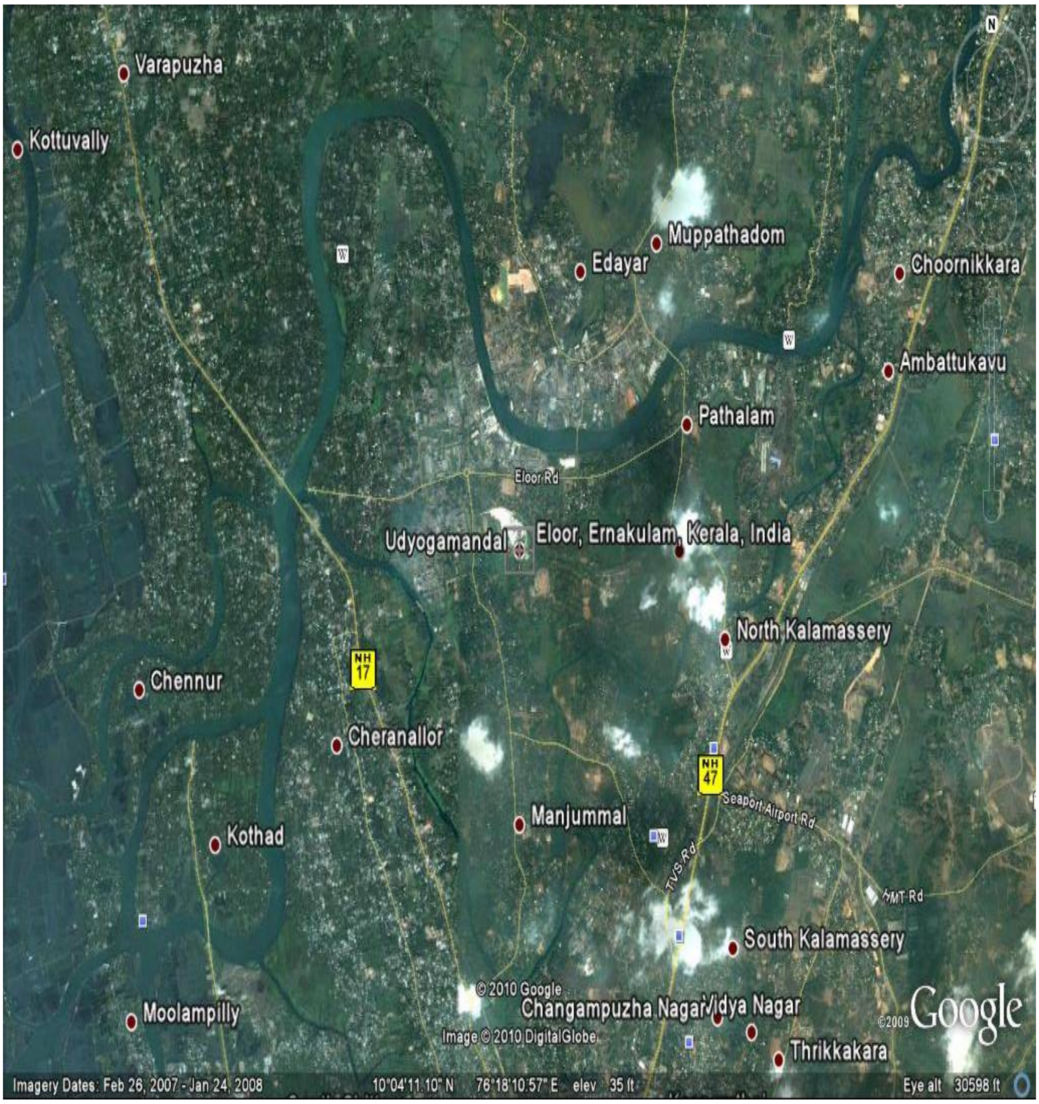

Fig. 2.2 Map of study area

Fig 2.3 Eloor and surrounding panchayats

(Source: Google map)

The demographic data pertaining to Eloor panchayat [3] is given in Table 2.2 and the various panchayats surrounding Eloor are listed in Table 2.3

Table 2.2 Demographic details of Eloor grama panchayat

Item	Description
Area	11.21sq. km.
Population	37,073
No. of Schools	15
No. of Hospitals	4
No. of Temples	4
No. of Churches	8
No. of Mosques	3
No. of Theatre	1
No. of Community hall	1
No. of convents	4

(Source: 10th five year plan report; Eloor panchayat)

Table 2.3 Various panchayats and municipality adjacent to Eloor

Location	Panchayats
East	Kalamassery Municipality, Choornikara panchayat
West	Varapuzha panchayat
North	Kadungallur and Alangad panchayats
South	Cheranaloor panchayat, Cochin corporation.

The population details of the panchayats [3] surrounding Eloor are listed in Table 2.4. The employee strength of the various industrial units in Eloor are given in Table 2.5

Table 2.4 Population details of the panchayats surrounding Eloor

Sl. No.	Panchayat	Population
1	Cheranalloor	29,177
2	Kadungallur	21,645
3	Varappuzha	14,451
4	Kadamakkudy	15,587
5	Kalamassery	38,327
6	Alangad	27,131
7	Choornikkara	18,461

Table 2.5 Employee strength of the various industrial units in Eloor.

Sl. No.	Industries in Eloor	Employee strength
1	Fertilizers and Chemicals Travancore (Petrochemical division) - FACT (PD)	1000
2	Fertilizers and Chemicals Travancore (Udyogamandal division) - FACT (UD)	1800
3	Travancore Cochin Chemicals Ltd. (TCC)	1500
4	Hindustan Insecticides Ltd. (HIL)	1000
5	BSES Kerala Power Ltd.	50
6	MERCHEM	200
7	Indian Rare Earths Ltd. (IRE)	500
8	Indian Aluminium Company Ltd. (INDAL)	100
9	Other Industries	200

2.2 MAH INDUSTRIES IN UDYOGAMANDAL AREA

Various MAH industries in Udyogamandal area are Fertilizers and chemicals Travancore Ltd. - Petrochemical division (FACT- PD), Fertilizers and chemicals Travancore Ltd. - Udyogamandal division (FACT- UD), Hindustan insecticides Ltd. (HIL), Travancore Cochin chemicals Ltd. (TCC), BSES Kerala power plant and Merchem.

2.2.1 About FACT - PD and FACT - UD

FACT, India's first large scale fertilizer unit was set up in 1943. In 1947, FACT Udyogamandal started production of ammonium sulphate with an installed capacity of 10,000 MT nitrogen. FACT became a Kerala state public sector enterprise on 15th August 1960. The Government of India became the major shareholder in November 1962. The 2nd stage of expansion of FACT was completed in 1962. The 3rd stage of expansion of FACT was completed in 1965 with the setting up of a new ammonium sulphate plant. A 900 Tonnes per day (TPD) ammonia plant was commissioned by FACT – UD in 1998. The company’s main business is manufacture and marketing of (a) fertilisers (b) caprolactam and engineering consultancy and fabrication of equipment [7].

The Petrochemical division has the capacity to produce 50,000 Tonnes per annum (TPA) of caprolactam. The employee strength in this unit is about 1000. This industry is located about 4.5 km away from NH 47. The hazardous chemicals stored and handled in this unit and the threshold quantities [8, 1] are given in Table 2.6.

Table 2.6 Hazardous chemicals stored in FACT (PD)

Sl. No.	Chemical	Threshold quantity (Tonnes)	Actual storage/process (Tonnes)
1	Ammonia	60	5,000
2	LPG	15	66
3	Benzene	1000	2,230
4	Cyclohexane	1000	1150
5	Oleum	15	300
6	Cyclohexanone	25	1400

The major products of FACT – UD are ammonium sulphate, ammonium phosphate, ammonia, hydrogen and carbon dioxide. The employee strength in this unit is about 1800. This industry is located about 4.0 km away from NH 47. The hazardous chemicals stored and handled in this unit and the threshold quantities [9, 1] are given in Table 2.7.

Table 2.7 Hazardous chemicals stored in FACT (UD)

Sl. No.	Chemical	Threshold quantity (Tonnes)	Actual storage/process (Tonnes)
1	Ammonia	60	2718
2	Oleum	15	3400
3	Naphtha	25	3400

2.2.2 About BSES Kerala Power

BSES Kerala power is jointly founded by the Reliance energy group as well as the Kerala State Industrial Development Corporation Limited. BSES Kerala Power Ltd. Company has established a 165 MW naphtha fuelled combined power station at Eloor Kochi, Kerala in the year 2001 [10]. The BSES Kerala Power Ltd. has entered into an agreement with the Indian Oil

Corporation for providing a regular supply of naphtha or LNG, the alternative fuel used in the power station. The employee strength in this unit is about 50. This industry is located about 3.0 km away from NH 47. The hazardous chemicals stored and handled in the unit and the threshold quantities [11, 1] are given in Table 2.8.

Table 2.8 Hazardous chemicals stored in BSES

Sl. No.	Chemical	Threshold quantity (Tonnes)	Actual storage/process (Tonnes)
1	Naphtha	25	11600

2.2.3 About Merchem

Merchem Limited mainly caters to rubber-based industries but it has a range of other products too. These find use in agriculture, water treatment, etc. The product range includes accelerators, antioxidants/antidegradants, processing aids, anti-ozonants/antiflex-cracking agents, water treatment chemicals, sulphur donors and agrochemical intermediaries [12]. The employee strength in this unit is about 200. This industry is located about 5.0 km away from NH 47 by road. The hazardous chemicals stored and handled in this unit and the threshold quantities [6, 1] are given in Table 2.9.

Table 2.9 Hazardous chemicals stored in Merchem

Sl. No.	Chemical	Threshold quantity (Tonnes)	Actual storage/process (Tonnes)
1	Carbon disulphide	20	30

2.2.4 About HIL

HIL is manufacturing various types of pesticides [13]. The employee strength in this unit is about 1000. This industry is located about 4.50 km away from NH 47. The hazardous chemicals stored and handled in this unit and the threshold quantities [6] are given in Table 2.10.

Table 2.10 Hazardous chemicals stored in HIL

Sl. No.	Chemical	Threshold Quantity (Tonnes)	Actual storage/process (Tonnes)
1	Chlorine	10	10
2	Oleum	15	40

2.2.5 About TCC

The Travancore Cochin chemicals Ltd. (TCC) is a State public sector undertaking owned by Government of Kerala [14]. TCC is a heavy chemical industry engaged in the manufacture and marketing of caustic soda, chlorine and allied chemicals [15]. The employee strength in TCC is about 1500. The hazardous chemicals [16, 1] stored and handled in this unit and the threshold quantities are given Table 2.11.

Table 2.11 Hazardous chemicals stored in TCC

Sl. No.	Chemical	Threshold quantity (Tonnes)	Actual storage/process (Tonnes)
1	Chlorine	10	220

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Chapter 3

CONSEQUENCE MODELLING OF HAZARDOUS STORAGES

3.1 INTRODUCTION

Consequence modelling refers to the calculation or estimation of numerical values (or graphical representation) that describes the credible physical outcomes of loss of containment scenarios involving flammable, explosive and toxic materials with respect to their impact on people, assets or safety functions [1]. 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

One of the most powerful and widely used concepts in risk assessment methodologies is quantified risk analysis (QRA) [2]. It involves the following steps

a. Development of credible accident scenarios.

b. Damage calculations through mathematical modelling. The impact of the scenarios is studied using available models such as VCE modelling, BLEVE modelling etc.

c. Risk estimation. Based on the damage potential estimated in the previous steps and the probability of occurrence of these credible accident scenarios, risk factors are estimated.

Quantified risk analysis (QRA) is the most effective way to represent the societal risks associated with MAH installations [3]. Increasing public awareness of technological risk has placed a greater responsibility on the process industries and district authorities to review and revise their current safety practices to make the process technologies both intrinsically and extrinsically safer. Consequence analysis is a tool which quantifies the consequences from the hazardous storages in the MAH industries.

Fire is a process of burning that produces heat, light and often smokes and flame [4]. Fire or combustion is defined by F.P Lees [5] as a chemical reaction in which a substance combines with oxygen and heat is released. Combustion is defined by NFPA [4] as an exothermic, self-sustaining reaction involving solid, liquid, and /or gas-phase fuel.

There are various classes of fire like Class A, Class B, Class C, and Class D [6, 7] based on the burning material involved. The fire associated with chemicals can take several different forms like flash fire, jet fire, and pool fire [8,9]. A flash fire is the non explosive combustion of a vapor cloud resulting from the release of a flammable material in to the open air [8]. The speed of burning is a function of the concentration of the flammable component in the cloud and also the wind speed [10, 11]. Within a few second of ignition the flame spreads both upwind and downwind of the ignition source. Initially the flame is contained within the cloud due to premixed burning of the regions within the flammable limits. Subsequently the flame extends in the form of a fire plume above the cloud. The downwind edge of the flame starts to move towards the spill point after consuming the flammable vapor downwind of the ignition source. Typical flame propagation speeds are of the order of 4 m/s [9, 10]. The flame velocity and dispersion increases with the wind speed. The duration of this fire is very short and the damage is caused by thermal radiation and oxygen depletion.

A jet fire occurs when a flammable liquid or gas is ignited after its release from a pressurized, punctured vessel or pipe [8]. The pressure of release generates a long flame, which is stable under most conditions. A flash flame may take the form of jet flame on reaching the spill point. The release rate and the capacity of the source determine the duration of the jet fire. Flame length increases directly with flow rate. Typically a pressurized release of 8 kg/s would have a length of 35 m [9]. The crosswinds also affect the flame length. An increase in the crosswind velocity increases the flame length. A pool fire occurs on ignition of an accumulation of liquid as a pool on the ground or on water or other liquid [9]. A steadily burning fire is rapidly achieved as the vapor to sustain the fire is provided by evaporation of liquid by heat from the flames. The maximum burning rate is a function of the net heat of combustion and heat required for its vaporization. Generally heat radiation dominates the burning rate for flame greater than 1 m diameter. Fire modelling of flammable substance like naphtha, benzene, cyclohexane, cyclohexanone and ammonia are carried out and results are discussed in this chapter.

Several definitions are available for the word “explosion”. AIChE/CCPS [12] defines an explosion as “a release of energy that causes a blast”. A blast is subsequently defined by CCPS as “a transient change in the gas density, pressure and velocity of the air surrounding an explosion point”. Crowl and Louvar [13] define an explosion as “a rapid expansion of gases resulting in a rapidly moving pressure or shock wave”. NFPA 69[14] defines an explosion as “the bursting or rupture of an enclosure or a container due to the development of internal pressure". Explosion generally occurs in situations where the fuel and oxidant have been allowed to mix intimately before ignition [4].

The injuries and damage are in the first place caused by the shock wave of the explosion itself [9]. People are blown over or knocked down and buried under collapsed buildings or injured by flying glass. Although the effects of overpressure can directly result in deaths, this would be likely to involve only those working in the direct vicinity of the explosion [9]. The history of industrial explosions shows that the indirect effects of collapsing buildings, flying glass and debris cause far more loss of life and severe injuries. The effects of the shock wave vary depending on the characteristics of the material, the quantity involved and the degree of confinement of the vapor cloud. The peak pressure in an explosion therefore varies between a slight over-pressure and a few hundred kilo Pascal (kPa). Direct injury to people occurs at pressures of 5-10 kPa with loss of life generally occurring at a greater over pressure, whereas dwellings are demolished and windows and doors broken at pressure of as low as 3-10 kPa. The pressure of the shock wave decreases rapidly with increase in the distance from the source of the explosion [8, 9]. As an example, the explosion of a tank containing 50 tonnes of propane results in pressure of 14 kPa at 250 meters and pressure of 5 kPa at 500 meters from the tank.

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 [15]. This chapter considers the storage and use of toxic chemicals, which would disperse with the wind and have the potential to kill or injure people living many hundreds of meters away from the plant, and being unable to escape or find shelter. Chemicals like chlorine, ammonia and methyl isocyanate are highly toxic materials and have history of major accidents. The dispersion modelling is an efficient tool to predict the affected area during a massive toxic gas release and this will be useful for the effective evacuation of people in the affected areas.

A survey carried out in the MAH units in Udyogamandal as per Manufacture storage and import of hazardous chemicals (MSIHC) Rules, 1989, India [16] and The chemical accidents (Emergency planning, preparedness and response) Rules, 1996, India [17] revealed that the major hazardous chemicals stored by the various industrial units are ammonia, chlorine, benzene, naphtha, cyclohexane, cyclohexanone and LPG. The damage potential of these chemicals is assessed using consequence modelling. Modelling of pool fires for naphtha, cyclohexane, cyclohexanone, benzene and ammonia are carried out using TNO model demonstrated in World Bank technical paper No.55 [18] and G. Madhu [19]. Vapor cloud explosion (VCE) modelling of LPG, cyclohexane and benzene are carried out using TNT equivalent model explained by AIChE/CCPS [8]. Boiling liquid expanding vapor explosion (BLEVE) modelling of LPG is also considered. BLEVE is defined by CCPS [8] as a sudden release of large mass of pressurized superheated liquid to the atmosphere. In our study the LPG storages are pressurized storages and benzene and cyclohexane storages are atmospheric storage. In the case of releases from liquefied gas storages, there is a possibility of both BLEVE and VCE. The liquefied gas that expands inside the storage vessel can lead to BLEVE whereas the vapor that comes over to atmosphere will result in an unconfined vapor cloud explosion. In the case of flammable liquids like benzene, and cyclohexane, the leakage or spillage from a storage tank may first form a pool outside and the vapors generated from the pool may cause a VCE in the presence of an ignition source. Another possibility is the escape of benzene or cyclohexane vapors from high temperature processes leading to an unconfined vapor cloud explosion. Dispersion modelling of toxic chemicals like chlorine, ammonia and benzene are analysed using ALOHA (Arial Locations of Hazardous atmosphere) [20] air quality model. For these analyses heat of combustion, heat of vaporization, specific heat at constant pressure and boiling point of the above hazardous chemicals are necessary. These values are obtained from Perry's Chemical engineers Handbook [21], Petroleum refining engineering [22] and CAMEO (Computer aided management in emergency operations) [23].

3.2 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 pool fire occurs when a flammable liquid spills into the ground and is ignited. A fire in a liquid storage tank and a trench fire are forms of pool fire. It has been observed that the characteristics of pool fire depend on the pool diameter [8]. Different authors have suggested a number of pool fire models. An empirical model commonly employed in the estimation of radiative flux from a pool fire is TNO model [18, 19]. This model uses classical empirical equations to determine burning rate, heat radiation and incident heat. For liquids with boiling point above ambient temperature, the rate of burning of the liquid surface per unit area is given by

$$\frac{dm}{dt} = \frac{0.001 H_c}{C_p \left(T_b - T_a\right) + H_{vap}} ------------- (3.1)$$

where H_c - heat of combustion (J/kg), C_p - Specific heat at constant pressure (J/kg K), T_b - boiling point in (K), T_a - ambient temperature (K), H_{vap} - heat of vaporization (J/kg).

For liquids with a boiling point below ambient temp, the expression is

$$\frac{dm}{dt} = \frac{0.001 H_c}{H_{vap}} - - - - - (3.2)$$

The total heat flux from a pool of radius "r" (meters) is given by

$$Q = \frac{\left(\Pi r^2 + 2\Pi r H\right)\left[\frac{dm}{dt}\right]\eta H_c}{72\left[\frac{dm}{dt}\right]^{0.61} + 1} - - - - - (3.3)$$

where Q - total heat flux (W/m^2), H-flame height (m), η - efficiency factor . The efficiency factor of total combustion power is often quoted in the range of 0.15-0.35 [24, 25].

Flame height is given by G. Heskestad [26] as

$$H = 0.235 Q^{2/5} - 1.02 D - - - - - - (3.4)$$

Where D is the diameter of the storage tank (m)

Q is the total heat released by fire (kW/m^2)

The intensity of heat radiation at a distance R from the pool centre is given by

$$I = \frac{\tau Q}{4\Pi R^2} - - - - - (3.5)$$

where τ - transmissivity of air path, Q - total heat flux (W/m^2).

Burning rate and flame height are empirical but are well established methods for the determination of intensity of heat radiation [8].

The effects of intensity of heat radiation on human being and materials are given in Table 3.1.

Table 3.1 Various effects of intensity of heat radiation

Intensity of heat radiation (kW/m^2)	**Various effects.**
1.6	Insufficient to cause no discomfort for long exposure.
2.2	Threshold pain. No reddening or blister.
4.2	First degree burn
8.3	Second degree burn
10.8	Third degree burn
15.0	Piloted ignition of wood
25.0	Spontaneous ignition of wood
4.0	Glass cracks
12.0	Plastic melts
19.0	Cable insulation degrades
37.5	Damage to process equipment
100.0	Steel structure fail

(Source: AIChE/CCPS, Guideline for chemical process quantitative risk analysis)

3.3 MODELLING OF EXPLOSION

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

Table 3.2 Various effects of pressure wave

Pressure (kPa)	Damage
0.14	Annoying noise (137 dB)
0.28	Loud noise (143 dB)
0.69	Breakage of small windows under strain
1.03	Typical pressure for glass breakage
3.4-6.9	Large and small windows usually shattered; occasional damage to window frames.
4.8	Minor damage to house structure
6.9	Partial demolition of houses
9.0	Steel frame slightly distorted
13.8	Partial collapse of walls and roofs of house
17.2	50% destruction of brickwork of house
34.5	Damage to wooden poles
34.5-48.2	Complete distraction of houses
48.2	Loaded train wagon overturned
62.0	Loaded train boxes completely demolished
68.7	Total destruction of building, heavy machine tools etc.
2068	Limit of carter lip
2.07	Safe distance

(Source: AIChE/CCPS, Guideline for chemical process quantitative risk analysis)

3.3.1 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, 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 [9] provides an excellent summary of vapour cloud behaviour. They describe four features, which must be present for a VCE to occur. First the release material must be flammable. Second, a cloud of sufficient size must form prior to ignition. Third, a sufficient amount of the cloud must be within the flammable range. Fourth, sufficient confinement or turbulent mixing of a portion of the vapor cloud must be present [8].

Following models are used for VCE modelling

1. TNT equivalent model

2. TNO multi energy model

3. Modified Baker model

All of these models are quasi-theoretical and are based on the limited field data and accident investigation. TNT equivalency model is easy to use and has been applied for many QRA studies [8]. It is described in Baker [27], Decker [28], Lees [5] and Merex [29]. TNT model is well established for high explosives but when applied to flammable vapour clouds it requires the explosion yield η , determined from the past incidents. Following methods are used for estimating the explosion efficiency.

1. Braise and Simpson [30] uses 2% to 5% of the heat of combustion of the total quantity of fuel spilled.

2. Health and Safety Executive [31, 32] uses 3% of the heat of combustion of the quantity of fuel present in the cloud.

3. Industrial Risk Insures [33] uses 2% of the heat of combustion of the quantity of the fuel spilled.

4. Factory Mutual Research Corporation [34] uses 5%, 10% and 15% of the heat of combustion of the quantity of fuel present in the cloud, dependant on the reactivity of the material.

3.3.2 TNT Equivalent model for VCE

The TNT equivalent model [5, 8, 29] is based on the assumption of equivalence between the flammable material and TNT factored by an explosion efficiency term. The TNT equivalent W is given by

$$W = \frac{\eta M H_c}{E_{TNT}} ------(3.6)$$

where W - equivalent mass of TNT (kg), η - empirical explosion efficiency, M- mass of hydrocarbon (kg), H_c - heat of combustion of flammable substance (J/kg), E_{TNT} - heat of combustion of TNT (J/kg).

3.3.2.1 Pressure of blast wave

The explosion of a TNT charge is shown in Fig. 3.1 for a hemispherical TNT surface charge at sea level. The pressure wave effects are correlated as a function of scaled range. The scaled range is defined as distance X by the cube root of TNT mass.

$$Z = \frac{X}{W^{1/3}} - - - - - (3.7)$$

where Z - scaled distance in the graph, X- Radial distance from the surface of the fire ball (m), W - TNT equivalent (kg).

Using X and W, we can find out Z. From the graph we can find out over pressure corresponding to Z. Table 3.2 provides various effects of blast over pressure to human being and materials.

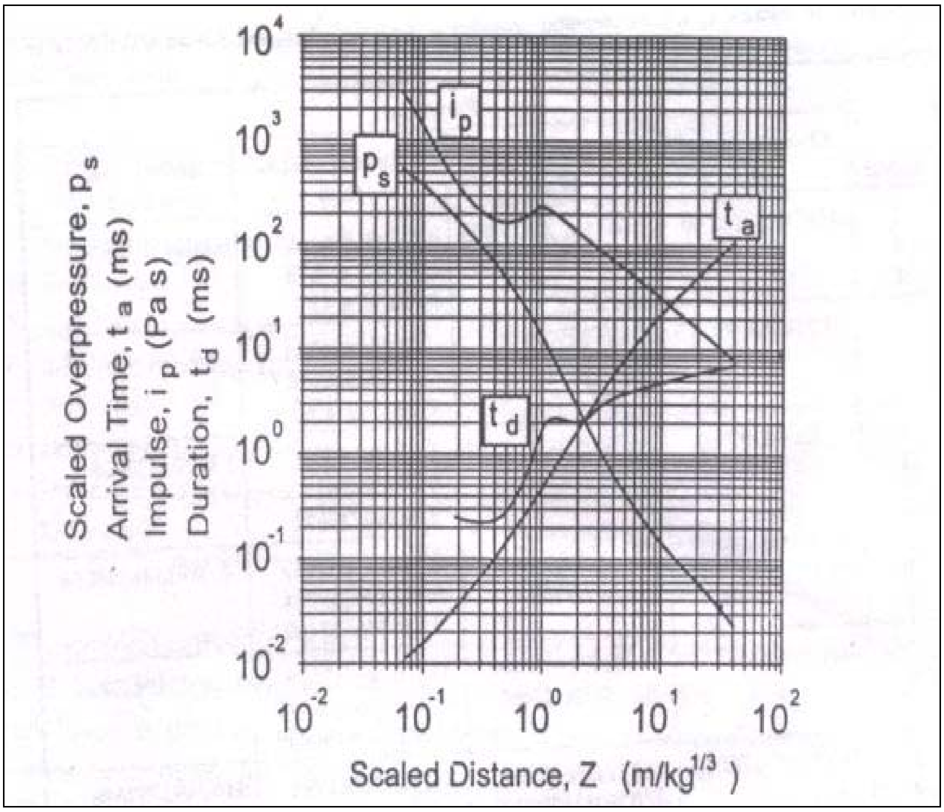

Fig. 3.1 Scaled distance vs. overpressure for VCE

(Source: AIChE/CCPS, Guideline for chemical process quantitative risk analysis)

3.3.3 Modelling of boiling liquid expanding vapor explosion (BLEVE)

Among the diverse major accidents which can occur in process industries, in energy installations and in the transportation of dangerous materials, Boiling liquid expanding vapor explosions or BLEVEs are important especially due to their severity and the fact that they involve simultaneously diverse effects which can cover large areas, overpressure , thermal radiation and missile effect [35]. Boiling liquid expanding vapor explosion (BLEVE) is a type of physical explosion that can affect almost any liquid contained in a closed vessel at a temperature significantly higher than its boiling point at atmospheric pressure [8,36]. 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. Boiling Liquid expanding vapour explosions were defined by Walls [37], who first proposed the acronym BLEVE as “a failure of a major container into two or more pieces occurring at a moment where the container is at a temperature above boiling point at normal atmospheric pressure.

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.

3.3.3.1 Radiation received by a target

The radiation received by a receptor (for the duration of BLEVE incident) is given by CCPS of AIChE [8] as.

$$E_r = \tau_a E F_{21} ------ (3.8)$$

where E_r - emissive radiative flux received by a receptor (W/m^2), τ_a - transmissivity (dimensionless), E -surface emitted radiative flux (W/m^2), F_{21} - view factor (dimensionless).

Roberts [38], Hymes [39] and CCPS [8] provide a means to estimate surface heat flux based on the radiative fraction of the total heat of combustion.

$$E = \frac{RMH_c}{\Pi D_{\max}{}^2 t_{bleve}} ------- (3.9)$$

where E - radiative emissive flux (W /m^2), R - radiation fraction of heat of combustion (dimensionless), M - initial mass of fuel in the fire ball (kg), H_c - heat of combustion per unit mass (J/kg), $D_{\max}$ - maximum diameter of fire balls (m), t_{bleve} - duration of fireballs

Hymes [39] suggest the following values for R, 0.3 for fireball from vessel bursting below the relief set pressure and 0.4 for fireballs from vessels bursting at or above the relief set pressure.

Pietersen and Huerta [40] and TNO [25] recommended a correlation formula that accounts the humidity for transmissivity.

$$\tau_a = 2.02\left(P_w X_s\right)^{-0.09} ------(3.10)$$

where τ_a - atmospheric transmissivity (0-1), P_w -water partial pressure (N/m^2), X_s - path length distance from the flame surface to the target (m).

An expression for water partial pressure as a function of the relative humidity and temperature of the air is given by Mudan and Corce [41].

$$P_w = 1013.25(RH)\exp\left(14.4114 - \frac{5328}{T_a}\right) ------(3.11)$$

where RH - relative humidity, T_a - ambient temperature (K).

As the effects of BLEVE mainly relates to human injury, a geometric view factor for a sphere to receptor is required. In general the fire ball centre has a height of H above the ground. The distance L is measured from a point at the ground directly beneath the centre of fire ball to the receptor at ground level. Equation for view factor given by Sengupta et.al. [42] are as follows

$$F_{12,H} = \frac{B - 1/s}{3.14\sqrt{B^2 - 1}} \tan^{-1} \sqrt{\frac{(B+1)(s-1)}{(B-1)(s+1)}} - \frac{A - 1/s}{3.14\sqrt{A^2 - 1}} \tan^{-1} \sqrt{\frac{(A+1)(s-1)}{(A-1)(s+1)}} \text{-----------------------------}(3.12a)$$

$$F_{12,V} = \frac{1}{3.14 - s} \tan^{-1}\left(\frac{h}{\sqrt{s^2 - 1}}\right) - \frac{h}{3.14.s} \tan^{-1}\left(\sqrt{\frac{s-1}{s+1}}\right) + \frac{Ah}{3.14.s\sqrt{A^2 - 1}} \tan^{-1} \sqrt{\frac{(A+1)(s-1)}{(A-1)(s+1)}} \text{----------}(3.12b)$$

$$F_{12} = \sqrt{F^2{}_{12,H} + F^2{}_{12,V}} \text{--------}(3.13)$$

Where $A = \frac{(h^2 + s^2 + 1)}{2s}$, $B = \frac{1 + s^2}{2s}$, $s = \frac{2L}{D}$,and $h = \frac{2H}{D}$ d

Pitblado [43] developed correlation for BLEVE fire ball diameter as a function of mass released and Tasneem Abbasi et.al. [44] compared the various correlations for BLEVE fire ball diameter calculation. The TNO formula proposed by Peterson and Huerta [40] give good overall fit to observed data. All models use power law correlations to relate BLEVE diameter and duration to the mass.

Empirical equations for maximum diameter of fire ball, duration of BLEVE and distance between the fireball centre and the ground given by AIChE/CCPS [12] are as follows

$$D_{\max} = 5.8M^{1/3} ------(3.14)$$

$$t_{bleve} = 2.6M^{1/6} ------(3.15)$$

$$H_{bleve} = 0.75D_{\max} -----(3.16)$$

where, M is the initial mass of the flammable material in kg.

3.3.3.2 Fragments and their effects

The prediction of fragments effects is important, as many death and domino damages effects are attributable to them. Specific work on BLEVE fragmentation was carried out by Association of American Railroads and by Holden and Reeves [45]. Fragments are usually not evenly distributed. The vessel’s axial direction receives more fragments than the side directions. The total number of fragments is approximately a fraction of vessel size. Holden and Reeves [45] suggest a correlation based on seven incidents (Eq. 3.17) is listed by Tasneem Abbasi et.al. [44].

$$N = -3.77 + 0.0096\,V\text{------------- (3.17)}$$

where N is the number of fragments, V is the vessel capacity in m^3. But this equation is valid only for the range of 700-2500 m^3. The correlation curves given by Holden and Reeves can be extrapolated for use in other ranges.

BLEVEs typically produce fewer fragments than high-pressure detonation. (Between 2 and 10 are typical) [8]. From the inner and outer diameter of the vessel, thickness of the vessel is estimated and the total mass of the vessel is also estimated using the density of the material. Appropriate assumptions can be made for the BLEVE scenarios [8, 46] for number of fragments. Total mass divided by the assumed number of fragments gives the average mass of one fragment. The average mass of the fragment is estimated by assuming that each shell fragment is crumbled up into spheres. BLEVEs usually do not develop high pressure that leads to greater fragmentation. Instead, metal softening from the heat exposure and thinning of the vessel will yield fewer fragments. Normally LPG storage tanks are designed for 250 psig working pressure. A normal burst pressure of four times the working pressure is expected for ASME coded vessels. Stawczyk [46] in a study of LPG cylinder of 5 kg and 11 kg capacities found that each BLEVEs gives three to five main projectiles and several smaller fragments.

BLEVEs usually occur because of flame impingement on the un-wetted portion (vapor space) of the tank. This area becomes sufficiently weakened and the tank fails at approximately 300 - 400 psig.

3.3.3.3 Velocity of fragments

Baker et.al. [27] and Brown [47] provide formulas for prediction of projectile effects. They consider fracture of cylindrical and spherical vessels into 2, 10 and 100 fragments. Typically for these types of events, only 2 or 3 fragments occur.

The first part of the calculation involves the estimation of an initial velocity. Once fragments are accelerated they will fly through the air until they impact another object or target on the ground. The second part of the calculation involves the estimation of the distance a projectile could travel.

For pressurized vessels, initial velocity of a fragment is given by Moorce [48]

$$u = 3.356\sqrt{\frac{PD^3}{W}} ------(3.18)$$

where u - initial velocity (m/sec), P - rupture pressure of the vessel (N/ m^2), D - fragment diameter (meters), W- weight of the fragment (Kg).

3.3.3.4 Distance travelled by the fragment.

From simple physics, it is well known that an object will fly the greatest distance at a trajectory angle of $45^{o.}$

The maximum distance is given by Baum [49]

$$r_{\max} = \frac{u^2}{g} ------(3.19)$$

3.3.3.5 Pressure of blast wave due to BLEVE

Procedure for determining the overpressure at a distance from a storage vessel is given by Baker et. al., [27] and Prugh [50].

$$W = 3.662\times10^{-6} V\left(\frac{P_1}{P_0}\right) R_g T_0 \ln\left(\frac{P_1}{P_2}\right) ----(3.20)$$

where W - energy (kg TNT), V -volume of the compressed gas (m^3), P_1-initial pressure of the compressed gas (N/ m^2), P_2- final pressure of the expanded gas (N/ m^2), P_0-standard pressure (N/ m^2), R_g - gas constant (J/Kg.mol K), T_0 - standard temperature (K).

$$P_b = P_s\left[1-\frac{3.5(\gamma-1)(P_s-1)}{\sqrt{\left(\gamma T/M\right)(1+5.9P_s)}}\right]^{-2\gamma/\gamma-1} -----(3.21)$$

where P_s - pressure at the surface of the vessel (bar abs.), P_b - burst pressure of the vessel (bar abs.), γ - heat capacity ratio of the expanding gas, M - molecular weight of the expanding gas (gm mole), T - absolute temperature of the expanding gas (K).

- The scaled distance Z, for the explosion is obtained from Fig. 3.1.
- A value for the distance R from the explosion center is calculated using the equation (3.7), where the equivalent energy of TNT, W has been calculated from the equation (3.6).
- The distance from the centre of the pressurized gas container to its surface is subtracted from the distance, R, to produce a virtual distance to be added to distance for shock wave evaluation.
- The overpressure at any distance is determined by adding the virtual distance to the actual distance, and then using this distance to determine Z, the scaled distance. Fig. 3.1 is used to determine the resulting overpressure.

3.4 DISPERSION MODELLING

Dispersion [51] 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.

Dispersion calculations provide an estimate of the area affected and the average vapour concentrations expected. The simplest calculations require an estimate of the rate of the gas (or the total quantity released), the atmospheric conditions (wind speed, time of day, cloud cover), surface roughness, temperature, pressure and the release diameter. More complicated models may require additional detail on the geometry, discharge mechanism, and other information on the release. Three kinds of vapor cloud behaviour such as neutrally buoyant gas, positively buoyant gas and dense buoyant gas are used in different models. Three different release-time modes such as instantaneous (puff), continuous release (plumes) and time varying continuous are also used in different models. The well known Gaussian models describe the behaviour of naturally buoyant gas released in the wind direction. Neutrally or positively buoyant plume and puff have been studied for many years using Gaussian models [8]. Dense gas plume and puffs have received more recent attention with a number of large-scale experiments and sophisticated models being developed in the past 30 years [52, 53]. The concentrations predicted by Gaussian models are time averages. Thus local concentrations might be greater than this average [8]. This result is important when estimating dispersion of highly toxic or flammable materials where local concentration fluctuations might have significant impact on the consequences. Hanna et.al, [54], Pasquill & Smith [55] and Crowl & Louar [13] provide good descriptions of plume and puff discharges.

ALOHA was designed with first responders in mind. It is intended to be used for predicting the extent of the area downwind of a short-duration chemical accident where people may be at risk of exposure to hazardous concentrations of a toxic gas. It is not intended for use with accidents involving radioactive chemicals. ALOHA is also not indented to be used for stack gas or modelling, chronic and low-level (fugitive) emissions. Since most first responders do not have dispersion modelling backgrounds, ALOHA has been designed for input data that are either easily obtained or estimated at the scene of an accident.

3.4.1 Introduction to ALOHA air modelling

ALOHA is an air dispersion model which can be used as a tool for predicting the movement and dispersion of gases. It predicts pollutant concentrations downwind from the source of a spill, taking into consideration the physical characteristics of the spilled material. ALOHA also accounts for some of the physical characteristics of the release site, weather conditions, and the circumstances of the release. Like many computer programs, it can solve problems rapidly and provide results in a graphic easy-to-use format. This can be helpful during an emergency response or planning for such a response.

ALOHA originated as a tool to aid in emergency response. It has evolved over the years into a tool used for a wide range of response, planning, and academic purposes. There are some features that would be useful in a dispersion model (for example, equations accounting for site topography) that have not been included in ALOHA because they would require extensive input and computational time.

Surface topography can modify the general pattern of wind speed and direction. One such case is the mountain breeze. During the day air near the mountain slope warms up faster than air at the same altitude but farther from the mountain [51]. This causes a local pressure gradient towards the mountain side and air is forced to flow up the mountain slope as mountain breeze. With sun set the pressure gradient is reversed and the less buoyant air flows downward into valleys.

One of the limitations of the ALOHA software is that, it doesn't account for the effects of topography. But Ichikawa and Sada [56] developed a model evaluating the topographical effect on atmospheric dispersion using numerical model. In this model, the topographical effect was evaluated in terms of the ratios of maximum concentration and the distance of the point of maximum concentration from the source on the topography to the respective values on a flat plane and the relative concentration distribution along the ground surface plume axis normalized for the maximum concentration on a flat plane

ALOHA is intended to be used for predicting the extent of area downwind of a chemical accident where people may be at risk of exposure to hazardous concentrations of toxic gas. It is not intended for use with accidents involving radioactive chemicals. Since most first responders do not have dispersion modelling background, ALOHA has been designed to require input data that are either easily obtained or estimated at the scene of an accident. The results of toxic gas dispersion modelling are used as input data for vulnerability modelling.

ALOHA use simplified DEGADIS [57] models and the following assumptions are made in the original DEGADIS model

a. ALOHA – DEGADIS assumes that all heavy gas releases originates at ground level.
b. The mathematical approximation procedure used for solving the model's equations are faster, but less accurate than those used in DEGADIS.
c. ALOHA-DEGADIS models sources for which release rate changes over time as a series of short, steady releases rather than as a number of individual point source.

ALOHA-DEGADIS was checked against DEGADIS to ensure that only minor difference existed in results obtained from both models. Considering the typical inaccuracies common in emergency response, these differences are probably not significant.

ALOHA models the dispersion of a cloud of pollutant gas in the atmosphere and displays a diagram that shows an overhead view of the area in which the gas concentrations may reach hazardous levels. This diagram is called the cloud's footprint. To obtain a footprint plot, a threshold concentration of an airborne pollutant, usually the concentration above which the gas may pose a hazard to people must be identified. This value is called the level of concern (LOC). The footprint represents the area within which the ground-level concentration of a pollutant gas is predicted to exceed the level of concern (LOC) at some time after a release begins.

The scenario considered for analysis is tank leak, which involves continuous release of chlorine, ammonia and benzene**.** The following are the input parameters of ALOHA.

3.4.1.1 Location information

The location selected for the study is Eloor. The location is to be added into the list of ALOHA.

3.4.1.2 Infiltration building parameters

We can specify either the type of building that is most common in the area downwind of a chemical release or the air exchange rate that is typical of building in that area. The choice could also represent the type of building that is of greatest concern. ALOHA will use building type along with other information such as wind speed and air temperature, to determine indoor infiltration rate and to estimate indoor concentration and dose at any locations that you specify. To estimate infiltration rate into a building, ALOHA assumes that all doors and windows are closed.

3.4.1.3 Chemical information

The chemicals selected for the study are chlorine, ammonia and benzene. Since these chemicals are included in the chemical library of ALOHA, they can be directly selected.

3.4.1.4 Atmospheric options

The information about current weather conditions into ALOHA is entered manually. ALOHA uses the information to account for the main processes that move and disperse a pollutant cloud within the atmosphere. These include atmospheric heating and mechanical stirring, low-level inversions, wind speed and direction, ground roughness, and air temperature. Wind directions and velocity are obtained from the wind roses published by the Meteorological department of India [58].

ALOHA accounts for the ground roughness, inversion and inversion height [59]. Ground roughness causes mechanical stirring. Atmospheric heating is a function of inversion. Inversion height will decide whether it is low level inversion or not. ALOHA considers all these parameters and from the available data, it estimates the value for the above parameters.

The degree of atmospheric turbulence influences how quickly a pollutant cloud moving downwind will mix with air around it and be diluted below level of concern (LOC). Friction between the ground and air passing over it is a cause of atmospheric turbulence. The rougher the ground surface, the greater the ground that develops roughness, and greater the turbulence [8].

3.4.1.5 Tank size and orientation

When we use ALOHA's tank source option to model the release of a liquid or gas from a storage vessel, we must indicate both the size of the tank and its general shape.

3.4.1.6 Credible scenarios for dispersion modelling

Dispersion modelling is done by assuming the following credible scenarios 1. Leak through a hole having one inch diameter 2. Leak through a hole having two inches diameter and 3) Catastrophic failure of the vessel.

A number of methodologies are available in the literature for the selection of hole size

a. World Bank [18] suggests that characteristic hole size for pipes varies from 20% to 100 % of the pipe diameter.

b. Some analysts use 2 inch and 4 inch holes regardless of the pipe size [8].

c. Some analysts use a range of hole sizes from small to large such as 0.2,1,4 and 6 inches [8].

In our study all the pipe connections to the storage vessel are of 1 and 2 inch diameter and we have assumed 100% diameter of pipe as the hole diameter.

Dispersion modelling for catastrophic failure is done by considering an opening large enough to release the entire mass in the storage vessel in a short period. This situation may happen when earth quake and such natural hazards affect the storage tank.

3.5 RESULTS AND DISCUSSION

Consequence modelling of hazardous chemicals storages like chlorine, benzene, cyclohexanone, naphtha, ammonia, LPG and cyclohexane, are carried out. Various input parameters provided for the modelling are also given. From the modelling of pool fires, following results are obtained. A comparison of heat radiation for the worst case fire scenario associated with different chemical storages from different MAH industries are presented. Hazardous distances (threat zones) for these storages are estimated and presented in this section. Pressure effects due to different incident scenarios like BLEVE and VCE are also estimated and presented. Threat zones are estimated for the pressure effects. Dispersion modelling is done for different toxic scenarios and the results are compared. These results are used for the vulnerability analysis in Chapter 4.

3.5.1 Consequence modelling of naphtha pool fire

Various input parameters for modelling the pool fire for naphtha storage tank having a radius of 12 m are given Table 3.3.

Table 3.3 Input parameters for fire modelling of naphtha tank from BSES

Parameters	Values
Heat of combustion	4.27×10^7 J/kg
Heat of vaporisation	3.02×10^5 J/kg
Specific heat at constant pressure	2931 J/kg K
Boiling point	115 ° C
Density of air	1.2 kg/m^3
Radius of tank	20 m
Ambient temperature	33° C

The intensity of heat radiation (kW/m^2) calculated using the TNO model for naphtha pool fire at various location are given in Table 3.4.

Table 3.4 Intensity of heat radiation from naphtha tank from BSES

Sl. No.	Distance	Target	Intensity (kW/m^2)	Remarks
1	10 m	Nearby tank	164.40	Tank failure
2	50 m	Plant and employees	6.57	First degree burns
3	100 m	TCC colony	1.64	No significant effect
4	100 m	Eloor High School	1.64	No significant effect
5	150 m	ESI Hospital	0.73	No significant effect

3.5.2 Consequence modelling of benzene pool fire

Various input parameters for modelling the pool fire for benzene storage tank having a radius of 6.25 m is given in Table 3.5.

Table 3.5 Input parameters for fire modelling of benzene tank from FACT (PD)

Parameters	Values
Heat of combustion	4.015 x 10^7 J/kg
Heat of vaporisation	4.36 x 10^5 J/kg
Specific heat at constant pressure	1696 J/kg K
Boiling point	80.1° C
Density of air	1.2 kg/m^3
Radius of tank	6.25 m
Ambient temperature	33° C

The intensity of heat radiation (kW/m^2) calculated using the TNO model for benzene pool fire at various location are given in Table 3.6

Table 3.6 Intensity of heat radiation from benzene tank from FACT (PD)

Sl. No.	Distance	Target	Intensity (kW/m^2)	Remarks
1	10 m	Nearby tanks	49.10	Chances of process equipment failure
2	50 m	Plant and employees	1.96	No significant effects
3	100 m	Plant and employees	0.49	No significant effects
4	150 m	Nearby plants, Schools and residential areas	0.22	No significant effects
5	200 m	Panchayat offices, residential area, other industries	0.12	No significant effects

3.5.3 Consequence modelling of cyclohexane pool fire

Various input parameters for modelling the pool fire for cyclohexane storage tank having a radius of 6m is given in Table 3.7.

Table 3.7 Input parameters for fire modelling of cyclohexane tank

Parameters	Values
Heat of combustion	4.344×10^7 J/kg
Heat of vaporisation	4.04×10^5 J/kg
Specific heat at constant pressure	1760 J/kg K
Boiling point	80° C
Density of air	1.2 kg/m^3
Radius of tank	6.0 m
Ambient temperature	33°C

The intensity of heat radiation (kW/m^2) calculated using the TNO model for cyclohexane pool fire at various location are given in Table 3.8.

Table 3.8 Intensity of heat radiation from cyclohexane tank

Sl. No.	Distance	Target	Intensity (kW/m^2)	Remarks
1	10 m	Near by tanks	56.500	Process equipment failure
2	50 m	Plant and employees	2.260	Threshold pain
3	100 m	Plant and employees	0.565	No significant effects
4	150 m	Nearby plants, schools and residential area	0.251	No significant effects
5	200 m	Residential area, Panchayat offices, and other industries	0.141	No significant effects

3.5.4 Consequence modelling of cyclohexanone pool fire

Various input parameters for modelling the pool fire for cyclohexanone storage tank having a radius of 6 m is given in Table 3.9.

Table 3.9 Input parameters for fire modelling of cyclohexanone tank

Parameters	Values
Heat of combustion	3.361×10^7 J/kg
Heat of vaporisation	4.80×10^5 J/kg
Specific heat at constant pressure	1890 J/kg K
Boiling point	155° C
Density of air	1.2 kg/m^3
Radius of tank	6.0 m
Ambient temperature	33°C

The intensity of heat radiation (kW/m^2) calculated using the TNO model for cyclohexanone pool fire at various location are given in Table 3.10.

Table 3.10 Intensity of heat radiation from cyclohexanone tank

Sl. No.	Distance	Target	Intensity (kW/m^2)	Remarks
1	10 m	Nearby tanks	23.85	Spontaneous ignition of wood
2	50 m	Plant and employees	0.954	No significant effects
3	100 m	Plant and employees	0.238	No significant effects
4	150 m	Nearby plants, Schools and residential areas	0.106	No significant effects
5	200 m	Panchayat offices, residential area, other industries	0.060	No significant effects

3.5.5 Consequence modelling of ammonia pool fire

Various input parameters for modelling the pool fire for ammonia storage tank having a radius of 11 m is given in Table 3.11.

Table 3.11 Input parameters for fire modelling of ammonia tank

Parameters	Values
Heat of combustion	1.87 x 10^7 J/kg
Heat of vaporisation	14.85 x 10^5 J/kg
Specific heat at constant pressure	4440 J/ kg K
Boiling point	-33.4°C
Density of air	1.2 kg/m^3
Radius of tank	11 m
Ambient temperature	33° C

The intensity of heat radiation (kW/m^2) calculated using the TNO model for ammonia pool fire at various location are given in Table 3.12.

Table 3.12 Intensity of heat radiation from ammonia tank

Sl. No.	Distance	Target	Intensity (kW/m^2)	Remarks
1	10 m	Nearby tanks	11.2800	Piloted ignition of wood
2	50 m	Plant and employees	0.4500	No significant effect
3	100 m	Plant and employees	0.1128	No significant effect
4	150 m	Nearby plants, Schools and residential areas	0.0515	No significant effect
5	200 m	Panchayat offices, residential area, other industries	0.0280	No significant effect

3.5.6 Consequence modelling of naphtha pool fire

Various input parameters for modelling the pool fire for naphtha storage tank having a radius of 6 m is given in Table 3.13.

Table 3.13 Input parameters for fire modelling of naphtha tank

Parameters	Values
Heat of Combustion	4.27×10^7 J/kg
Heat of vaporisation	3.02×10^5 J/kg
Specific heat at constant pressure	2931 J/kg K
Boiling point	115° C
Density of air	1.2 kg/m^3
Radius of tank	6 m
Ambient temperature	33° C

The intensity of heat radiation (kW/m^2) calculated using the TNO model for naphtha pool fire at various location are given in Table 3.14.

Table 3.14 Intensity of heat radiation from naphtha tank

Sl. No.	Distance	Target	Intensity	Remarks
1	10 m	No important things	41.00	Failure of process equipments
2	50 m	Plant and employees	1.60	No significant effects
3	100 m	Plant and employees	0.40	No significant effects
4	150 m	Plant and employees	0.18	No significant effects
5	200 m	Public places	0.10	No significant effects

A comparison of intensity of heat radiation for various chemicals is given in Table 3.15 and Fig. 3.2. From the analysis the hazardous distance up to which the intensity of heat radiation of pool fire may affect people also listed in Table 3.16.

Table 3.15 Comparison of intensity of heat radiation for various flammable substances

Distance to the target	**Naphtha R=12 m (kW/m^2)**	**Cyclohexane R=6 m (kW/m^2)**	**Cyclohexanone R=6 m (kW/m^2)**	**Benzene R=6.2 m (kW/m^2)**	**Naphtha R = 6 m (kW/m^2)**	**Ammonia R=11 m (kW/m^2)**
10 m	164.40	56.50	23.85	49.10	41.00	11.28
50 m	6.60	2.26	0.95	1.96	1.60	0.45
100 m	1.60	0.57	0.24	0.49	0.40	0.11
150 m	0.70	0.25	0.11	0.22	0.18	0.05
200 m	0.40	0.14	0.06	0.12	0.10	0.03

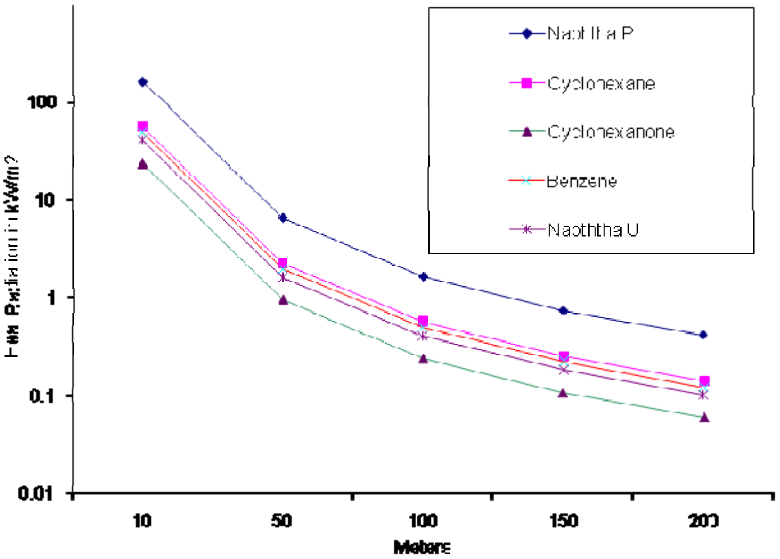

Fig. 3.2 Comparison of pool fire modelling results for naphtha P, cyclohexane, cyclohexanone, benzene and naphtha U.

Table 3.16 Hazardous distance for heat radiation from pool fires for different flammable substances.

Sl. No.	Unit	Chemical	Storage capacity (Tonnes)	Tank type and dimensions	Flame height (m)	Hazardous distance (m)
1	BSES	Naphtha	11600	Vertical cylinder with a radius 12 m	38.0	87.0
2	FACT (PD)	Benzene	1115	Vertical Cylinder with a radius 6.25 m	24.0	47.0
3	FACT (PD)	Cyclohexane	1150	Vertical cylinder with radius 6 m	25.0	51.0
4	FACT (PD)	Cyclohexanone	1400	Vertical cylinder with radius 6 m	17.0	33.0
5	FACT (PD)	Ammonia	5000	Vertical cylinder with radius 11 m	12.0	23.0
6	FACT (UD)	Naphtha	800	Vertical cylinder with radius 6 m	24.0	43.0

Modelling of hazardous chemicals like LPG, benzene and cyclohexane are carried out. For LPG, both VCE modelling and BLEVE modelling are done. For benzene and cyclohexane only VCE modelling is done. Various input parameters provided for the modelling is also provided. From the modelling of VCE, following results are obtained.

3.5.7 VCE modelling of LPG

Various input parameters for VCE modelling of LPG bullet storage facility having a radius of 6 m are given in table 3.17.

Table 3.17 Input parameters for VCE modelling of LPG

Parameters	**Values**
Capacity of the LPG Vessel	22 m^3
Volume of LPG (85% full)	18.7 m^3
Density of LPG	480 kg/m^3
Mass of LPG in the tank	8975 kg
Equivalent weight of TNT	4581 .75 kg.
Heat of combustion for LPG	45940 kJ/kg.
Maximum fireball diameter (D_{max})	120m.
Distance between the ground and Fireball centre (H)	90 m
Duration of fire ball (t_{bleve})	10.36 s.
Water partial pressure	4034.26 N/ $m^{2.}$

The pressures of blast waves estimated at various locations using the TNT equivalent model (VCE) for LPG are given in Table 3.18.

Table 3.18 Pressure effect from VCE of LPG

Location of target (horizontal distance)	**Pressure (kPa)**
20 m	8.000
50 m	1.000
100 m	0.300
150 m	0.097
200 m	0.004

3.5.8 VCE modelling of benzene

Various input parameters for modelling the VCE for storage facility having a radius of 6.25 meters are given in Table 3.19.

Table 3.19 Input parameters for VCE modelling of benzene

Parameters	Values
Capacity of the vessel	1349.9 m^3.
Mass of benzene in the tank	3739.2 kg.
Equivalent weight of TNT	1770000 kg.
Heat of combustion for benzene	4.27 x 10^7 kJ/kg.

The overpressure of blast wave resulting from the VCE modelling of benzene is shown in Table 3.20.

Table 3.20 Pressure effects from VCE of benzene

Location of target (horizontal distance)	Pressure (kPa)
20 m	400.00
50 m	150.00
100 m	55.00
150 m	20.00
200 m	15.00
500 m	1.00
1000 m	0.25

3.5.9 VCE modelling of cyclohexane

The various parameters for VCE modelling of cyclohexane are given in Table 3.21.

Table 3.21 Input parameters for VCE modelling of cyclohexane

Parameters	Values
Capacity of the vessel	1538.12 m^3.
Mass of cyclohexane in the tank	4460.5 kg.
Equivalent weight of TNT	12900000 kg.
Heat of combustion of cyclohexane	4.344 x 10^7kJ/kg.

The overpressure of blast wave resulting from the VCE modelling of cyclohexane is shown in Table 3.22

Table 3.22 Pressure effects from VCE of cyclohexane

Location of target (horizontal distance)	Pressure (kPa)
20 m	415.00
50 m	180.00
100 m	40.00
150 m	28.00
200 m	9.50
500 m	1.00
1000 m	0.25

3.5.10 BLEVE modelling of LPG

The input parameters for the BLEVE modelling of LPG is the same as that of VCE modelling given in Table 3.17 and the results obtained from the BLEVE modelling of LPG are given in Table 3.23 along with other parameters. Pressure of blast waves at various locations due to BLEVE are given in Table 3.24.

Table 3.23 Heat radiation from BELVE of LPG

Horizontal distance	Path length (m)	Transmi -ssivity	View Factor	Radiation flux (kW/m^2)	Radiation received by a target (kW/m^2)
20 m	91.00	0.65	0.4123	308.06	82.55
50 m	98.00	0.64	0.2960	308.06	57.17
100 m	120.00	0.63	0.1475	308.06	28.62
150 m	152.00	0.61	0.1005	308.06	18.88
200 m	190.00	0.60	0.0680	308.06	12.53
500 m	462.00	0.56	0.0137	308.06	2.36
1000 m	951.00	0.52	0.0040	308.06	0.64
2000 m	1945.00	0.49	0.0009	308.06	0.13

Table 3.24 Pressure of blast wave from BLEVE of LPG

Location of target (horizontal distance)	Pressure (kPa)
20 m	5.00
50 m	0.85
100 m	0.20
150 m	0.09
200 m	0.03

The number of fragments, fragments velocity, initial velocity of fragment and the maximum distance travelled during a BLEVE scenario is given Table 3.25. Comparisons of pressure of blast waves due to VCE for various chemicals are given in the Table 3.26. Comparisons are given in the graphical form (Fig. 3.3) and the maximum threat zones for pressure waves are given in the Table 3.27.

Table 3.25 Fragments effects from BLEVE of LPG

Item	Values
No. of fragments	8
Fragment's mass	1072 kg
Initial velocity of the fragments	6.08 m/s.
Maximum distance travelled by the fragment	3.77 m

Table 3.26 Comparison of results from VCE modelling of LPG, benzene and cyclohexane

Location of target (horizontal distance)	LPG Pressure (kPa)	Benzene Pressure (kPa)	Cyclohexane Pressure (kPa)
20 m	8.000	400.00	415.00
50 m	1.000	150.00	180.00
100 m	0.300	55.00	40.00
150 m	0.097	20.00	28.00
200 m	0.004	15.00	9.50
500 m	-	1.00	1.00
1000 m	-	0.25	0.25

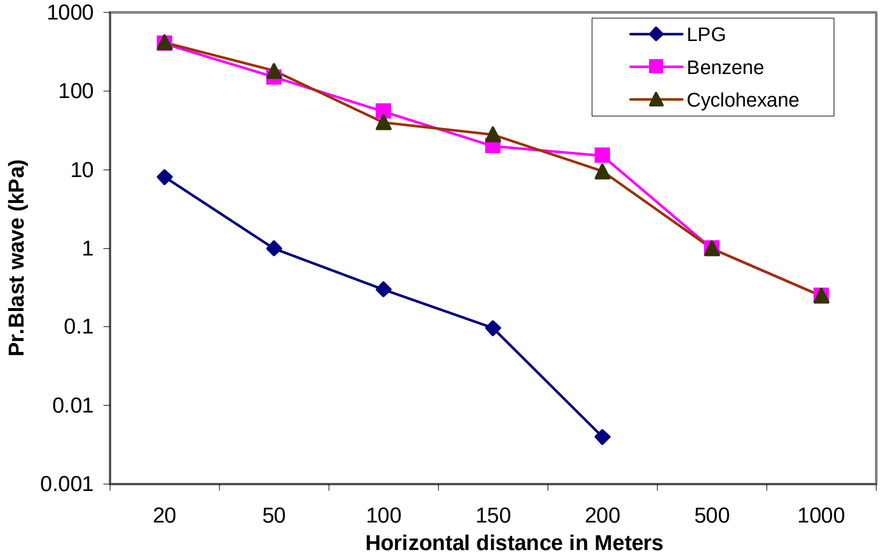

Fig. 3.3 Comparison of results of VCE

Table 3.27 Maximum threat zones for explosion

Sl. No.	Unit	Chemical	Storage capacity (Tonnes)	Tank type and dimensions	Maximum threat zone (m)
1	FACT (PD)	Benzene	1115	Vertical cylinder with a radius 6.25 m	290
2	FACT (PD)	Cyclohexane	1150	Vertical cylinder with radius 6 m	560
3	FACT (PD)	LPG	11	Bullet tank	40

3.5.11 Dispersion modelling of chlorine release

Various input parameters for dispersion modelling of chlorine are listed in Table 3.28.

Table 3.28 Input parameters for dispersion modelling of chlorine

Item	Description
Location Name	Eloor
Approximate location	Latitude 9 deg. 54 min. North Longitude 76 deg. 12 min. East
Approximate elevation	3 feet
Country	India
Building type	Single storied buildings
Building surroundings	Sheltered Surrounding (trees, bushes etc.)
Wind speed	4.1 m/s
Wind direction	Towards NW
Measurement height (Wind)	10 m
Ground roughness	Urban or forest
Cloud cover	Full cloud
Stability class	D
Inversion	Nil
Humidity	88%
Tank type and orientation	Horizontal cylinder
Tank dimension	2.8 m dia. and 7.31m length
State of chemical	Liquid
Temperature inside the tank	-5°C
Mass in the tank	50 Tonnes
Diameter of opening	1 in. (2.54 cm) and 2 in. (5.08 cm) hole
Leak through	Hole
Height of tank opening	0.28 m above the bottom of the tank
Level of concern	IDLH

The results obtained from the modelling of chlorine release through 1 in. (2.54 cm) and 2 in. (5.08 cm) holes at various months at morning 8.30 AM and evening 5.30 PM are given in the Tables 3.29, 3.30, 3.31 and 3.32.

Table 3.29 Hazardous distance at 08.30 AM (leak scenario of 1 in. (2.54 cm) hole from chlorine storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (km)
January	2.8	E	22	80	2.88
February	2.2	E	24	80	3.20
March	2.2	E	25	80	3.20
April	2.2	E	26	80	3.20
May	1.9	E	26	80	3.52
June	1.9	E	22	88	3.48
July	4.1	NW	21	88	2.35
August	3.8	NW	22	80	2.40
September	1.7	E	23	84	3.68
October	1.4	E	24	84	3.84
November	1.9	E	22	80	3.52
December	2.8	NE	22	80	2.88

Table 3.30 Hazardous distance at 05.30 PM (leak scenario of 1 in. (2.54 cm) hole from chlorine storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (km)
January	4.2	W	26	80	2.24
February	4.4	W	29	80	2.24
March	4.4	W	30	80	2.24
April	4.9	NW	31	80	2.24
May	4.4	NWN	31	80	2.24
June	3.6	NWN	25	88	3.84
July	3.8	NW	25	88	3.84
August	3.8	NW	26	80	2.40
September	3.8	NW	27	84	2.40
October	3.6	W	28	84	2.56
November	3.6	W	26	80	2.56
December	4.2	W	26	80	2.40

Table 3.31 Hazardous distance at 08.30 AM (leak scenario of 2 in. (5.08 cm) hole from chlorine storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (km)
January	2.8	E	22	80	7.1
February	2.2	E	24	80	8.0
March	2.2	E	25	80	8.0
April	2.2	E	26	80	8.0
May	1.9	E	26	80	8.5
June	1.9	E	22	88	8.4
July	4.1	NW	21	88	5.9
August	3.8	NW	22	80	6.1
September	1.7	E	23	84	8.9
October	1.4	E	24	84	9.2
November	1.9	E	22	80	8.2
December	2.8	NE	22	80	7.1

Table 3.32 Hazardous distance at 05.30 PM (leak scenario of 2 in. (5.08cm) hole from chlorine storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (km)
January	4.2	W	26	80	6.3
February	4.4	W	29	80	6.1
March	4.4	W	30	80	6.1
April	4.9	NW	31	80	5.8
May	4.4	NWN	31	80	6.1
June	3.6	NWN	25	88	6.8
July	3.8	NW	25	88	6.6
August	3.8	NW	26	80	6.6
September	3.8	NW	27	84	6.6
October	3.6	W	28	84	6.8
November	3.6	W	26	80	6.8
December	4.2	W	26	80	6.3

3.5.12 Dispersion modelling of ammonia release

Input parameters for dispersion modelling of ammonia are given in the Table 3.33.

Table 3.33 Input parameters for dispersion modelling of ammonia

Item	Description
Location Name	Eloor
Approximate location	Latitude 9 deg. 54 min. North Longitude 76 deg. 12 min. East
Approximate elevation	3 feet
Country	India
Building type	Single storied buildings
Building surroundings	Sheltered Surrounding (trees, bushes etc.)
Wind speed	4.1 m/s
Wind direction	Towards NW
Measurement height (Wind)	10 m
Ground roughness	Urban or forest
Cloud cover	Full cloud
Stability class	D
Inversion	Nil
Humidity	88%
Tank type and orientation	Vertical cylinder
Tank dimension	22 m dia. and 20.77 m length
State of chemical	Liquid
Temperature inside the tank	-33.2°C
Mass in the tank	5000 Tonnes
Diameter of opening	1 in. (2.54 cm) , 2 in (5.08 cm) and 5 in. 12.7 cm)in.
Leak through	Hole
Height of tank opening	2.2 m above the bottom of the tank
Level of concern	IDLH

Hazardous distance at various leak scenarios such as leaks from 1 inch, 2 inches and 5 inches are obtained from the dispersion modelling and are presented in the following Tables 3.34, 3.35, 3.36, 3.37, 3.38.and 3.39.

Table 3.34 Hazardous distance at 08.30 AM (leak scenario of 1 in. (2.54cm) hole from ammonia storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (km)
January	2.8	E	22	80	1.41
February	2.2	E	24	80	1.53
March	2.2	E	25	80	1.54
April	2.2	E	26	80	1.54
May	1.9	E	26	80	1.61
June	1.9	E	22	88	1.61
July	4.1	NW	21	88	1.07
August	3.8	NW	22	80	1.08
September	1.7	E	23	84	1.32
October	1.4	E	24	84	1.44
November	1.9	E	22	80	1.27
December	2.8	NE	22	80	1.14

Table 3.35 Hazardous distance at 05.30 PM (leak scenario of 1 in. (2.54 cm) hole from ammonia storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (km)
January	4.2	W	26	80	1.07
February	4.4	W	29	80	1.07
March	4.4	W	30	80	1.07
April	4.9	NW	31	80	1.06
May	4.4	NWN	31	80	1.07
June	3.6	NWN	25	88	1.09
July	3.8	NW	25	88	1.08
August	3.8	NW	26	80	1.08
September	3.8	NW	27	84	1.09
October	3.6	W	28	84	1.10
November	3.6	W	26	80	1.09
December	4.2	W	26	80	1.07

Table 3.36 Hazardous distance at 08.30 AM (leak scenario of 2 in. (5.08cm) hole from ammonia storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (km)
January	2.8	E	22	80	1.77
February	2.2	E	24	80	1.77
March	2.2	E	25	80	1.77
April	2.2	E	26	80	1.77
May	1.9	E	26	80	1.93
June	1.9	E	22	88	1.93
July	4.1	NW	21	88	1.61
August	3.8	NW	22	80	1.61
September	1.7	E	23	84	1.93
October	1.4	E	24	84	2.09
November	1.9	E	22	80	1.93
December	2.8	NE	22	80	1.77

Table 3.37 Hazardous distance at 05.30 PM (leak scenario of 2 in. hole from ammonia storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (km)
January	4.2	W	26	80	1.61
February	4.4	W	29	80	1.61
March	4.4	W	30	80	1.61
April	4.9	NW	31	80	1.61
May	4.4	NWN	31	80	1.61
June	3.6	NWN	25	88	1.61
July	3.8	NW	25	88	1.61
August	3.8	NW	26	80	1.61
September	3.8	NW	27	84	1.61
October	3.6	W	28	84	1.77
November	3.6	W	26	80	1.77
December	4.2	W	26	80	1.61

Table 3.38 Hazardous distance at 08.30 AM (leak scenario of 5 in. hole from ammonia storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (km)
January	2.8	E	22	80	4.19
February	2.2	E	24	80	4.51
March	2.2	E	25	80	4.51
April	2.2	E	26	80	4.51
May	1.9	E	26	80	4.83
June	1.9	E	22	88	4.67
July	4.1	NW	21	88	3.70
August	3.8	NW	22	80	3.70
September	1.7	E	23	84	4.99
October	1.4	E	24	84	5.15
November	1.9	E	22	80	4.67
December	2.8	NE	22	80	4.19

Table 3.39 Hazardous distance at 05.30 PM (leak scenario of 5 in. (12.7 cm) hole from ammonia storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (km)
January	4.2	W	26	80	3.54
February	4.4	W	29	80	3.54
March	4.4	W	30	80	3.54
April	4.9	NW	31	80	3.38
May	4.4	NWN	31	80	3.54
June	3.6	NWN	25	88	3.86
July	3.8	NW	25	88	3.86
August	3.8	NW	26	80	3.86
September	3.8	NW	27	84	3.86
October	3.6	W	28	84	4.03
November	3.6	W	26	80	4.03
December	4.2	W	26	80	3.54

3.5.13 Dispersion modelling of benzene release

Input parameters for dispersion modelling of benzene are given in Table 3.40.

Table 3.40 Input parameters for dispersion modelling of benzene

Item	Description
Location Name	Eloor
Approximate location	Latitude 9 deg. 54 min. North Longitude 76 deg. 12 min. East
Approximate elevation	3 feet
Country	India
Building type	Single storied buildings
Building surroundings	Sheltered Surrounding (trees, bushes etc.)
Wind speed	4.1 m/s
Wind direction	Towards NW
Measurement height (Wind)	10 m
Ground roughness	Urban or forest
Cloud cover	Full cloud
Stability class	D
Inversion	Nil
Humidity	88%
Tank type and orientation	Vertical cylinder
Tank dimension	12. 5 m dia. and 11 m length
State of chemical	Liquid
Temperature inside the tank	30°C
Mass in the tank	1115 Tonnes
Diameter of opening	1 in. (2.54 cm) , 2 in (5.08 cm) and 5 in. (12.7 cm)
Leak through	Hole
Height of tank opening	1.1 m above the bottom of the tank
Level of concern	IDLH

Hazardous distance at various leak scenarios such as leaks from 1 in., 2 in., and 5 in. holes are obtained from the dispersion modelling and are presented in the Tables 3.41, 3.42, 3.43, 3.44, 3.45 and 3.36.

Table 3.41 Hazardous distance at 08.30 AM (leak scenario of 1 in. (2.54 cm) hole from benzene storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (m)
January	2.8	E	22	80	58
February	2.2	E	24	80	71
March	2.2	E	25	80	71
April	2.2	E	26	80	70
May	1.9	E	26	80	73
June	1.9	E	22	88	73
July	4.1	NW	21	88	46
August	3.8	NW	22	80	48
September	1.7	E	23	84	75
October	1.4	E	24	84	78
November	1.9	E	22	80	73
December	2.8	NE	22	80	58

Table 3.42 Hazardous distance at 05.30 PM (leak scenario of 1 in. (2.54 cm) hole from benzene storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidit y	Hazardous distance (m)
January	4.2	W	26	80	48
February	4.4	W	29	80	48
March	4.4	W	30	80	49
April	4.9	NW	31	80	46
May	4.4	NWN	31	80	49
June	3.6	NWN	25	88	51
July	3.8	NW	25	88	51
August	3.8	NW	26	80	51
September	3.8	NW	27	84	51
October	3.6	W	28	84	53
November	3.6	W	26	80	53
December	4.2	W	26	80	48

Table 3.43 Hazardous distance at 08.30 AM (leak scenario of 2 in. (5.08 cm) hole from benzene storage tank

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (m)
January	2.8	E	22	80	135
February	2.2	E	24	80	144
March	2.2	E	25	80	144
April	2.2	E	26	80	144
May	1.9	E	26	80	149
June	1.9	E	22	88	148
July	4.1	NW	21	88	95
August	3.8	NW	22	80	101
September	1.7	E	23	84	152
October	1.4	E	24	84	158
November	1.9	E	22	80	147
December	2.8	NE	22	80	135

Table 3.44 Hazardous distance at 05.30 PM (leak scenario of 2 in. (5.08 cm) hole from benzene storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidity	Hazardous distance (m)
January	4.2	W	26	80	99
February	4.4	W	29	80	99
March	4.4	W	30	80	101
April	4.9	NW	31	80	95
May	4.4	NWN	31	80	101
June	3.6	NWN	25	88	123
July	3.8	NW	25	88	104
August	3.8	NW	26	80	104
September	3.8	NW	27	84	106
October	3.6	W	28	84	123
November	3.6	W	26	80	123
December	4.2	W	26	80	99

Table 3.45 Hazardous distance at 08.30 AM (leak scenario of 5 in. (12.7 cm) hole from benzene storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp. (°C)	Humidit y	Hazardous distance (m)
January	2.8	E	22	80	355
February	2.2	E	24	80	401
March	2.2	E	25	80	405
April	2.2	E	26	80	400
May	1.9	E	26	80	428
June	1.9	E	22	88	314
July	4.1	NW	21	88	321
August	3.8	NW	22	80	323
September	1.7	E	23	84	427
October	1.4	E	24	84	459
November	1.9	E	22	80	409
December	2.8	NE	22	80	352

Table 3.46 Hazardous distance at 05.30 PM (leak scenario of 5 in. (12.7cm) hole from benzene storage tank)

Month	Wind velocity (m/s)	Wind direction	Temp (°C)	Humidity	Hazardous distance (m)
January	4.2	W	26	80	315
February	4.4	W	29	80	316
March	4.4	W	30	80	318
April	4.9	NW	31	80	306
May	4.4	NWN	31	80	320
June	3.6	NWN	25	88	321
July	3.8	NW	25	88	328
August	3.8	NW	26	80	326
September	3.8	NW	27	84	327
October	3.6	W	28	84	337
November	3.6	W	26	80	313
December	4.2	W	26	80	314

Hazardous distances for chlorine, ammonia and benzene are compared in the Tables 3.47 and 3.48.

Table 3.47 Hazardous distance in kilometers at 08.30 AM for ammonia, chlorine and benzene

Months	**Dispersion for ammonia**		**Dispersion for chlorine**		**Dispersion for benzene**	
	Leak from 1 in. (2.54 cm) hole	Leak from 2 in. (5.08 cm) hole	Leak from 1 in. (2.54cm) hole	Leak from 2 in. (5.08 cm) hole	Leak from 1 in. (2.54cm) hole	Leak from 2 in. (5.08cm) hole
January	1.41	1.77	2.88	9.0	0.058	0.135
February	1.53	1.77	3.20	9.2	0.071	0.144
March	1.54	1.77	3.20	9.2	0.071	0.144
April	1.54	1.77	3.20	9.2	0.070	0.144
May	1.61	1.93	3.52	8.6	0.073	0.149
June	1.61	1.93	4.48	8.6	0.073	0.148
July	1.07	1.61	3.52	8.6	0.046	0.095
August	1.08	1.61	2.40	9.0	0.048	0.101
September	1.32	1.93	3.68	8.5	0.075	0.152
October	1.44	2.09	3.84	8.1	0.078	0.158
November	1.27	1.93	3.52	8.6	0.073	0.147
December	1.14	1.77	2.88	9.0	0.058	0.135

Table 3.48 Hazardous distance in kilometers at 05.30 PM for ammonia, chlorine and benzene

Months	Dispersion for ammonia		Dispersion for chlorine		Dispersion for benzene	
	Leak from 1 in. (2.54 cm) hole	Leak from 2 in. (5.08 cm) hole	Leak from 1 in. (2.54cm) hole	Leak from 2 in. (5.08cm) hole	Leak from 1 in. (2.54cm) hole	Leak from 2 in. (5.08cm) hole
January	1.07	1.77	2.4	9.0	0.048	0.099
February	1.07	1.77	2.24	9.0	0.048	0.099
March	1.07	1.77	2.24	9.0	0.049	0.101
April	1.06	1.77	2.24	9.0	0.046	0.095
May	1.07	1.93	2.24	9.0	0.049	0.101
June	1.09	1.93	3.84	9.0	0.051	0.123
July	1.08	1.61	2.84	9.0	0.051	0.104
August	1.08	1.61	2.40	9.0	0.051	0.104
September	1.09	1.93	2.40	9.0	0.051	0.106
October	1.10	2.09	2.56	9.2	0.053	0.123
November	1.09	1.93	2.56	9.0	0.053	0.123
December	1.07	1.77	2.40	9.0	0.048	0.099

Table 3.49 Maximum threat zone and direction of toxic gas release for different chemicals

Chemical	Hazardous distance and direction for release from 1 in. (2.54 cm) hole		Hazardous Distance and direction for release from 2 in. (5.08 cm)hole	
	8.30 AM	5.30 PM	8.30 AM	5.30 PM
Chlorine	4.480 km E	3.840 km NW	9.200 km E	9.200 km W
Ammonia	1.610 km E	1.100 km W	2.090 km E	2.090 km W
Benzene	0.078 km E	0.053 km W	0.158 km E	0.123 km W

The intensity of the heat radiation resulting from pool fires at various locations is estimated. A comparison of intensity of heat radiation at various locations is given in Table 3.15 and Fig. 3.2 for various chemicals. The intensity of heat radiation is the maximum at 10 meters from the source of pool fire for all the chemicals. A naphtha pool fire having a radius of 12 meters is found to have maximum intensity of heat radiation. 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. For ammonia, even though the radius of the tank is large, the intensity of heat radiation is less. This is mainly because of the low heat of combustion and heat of vaporization values of ammonia. The hazardous distances up to which the heat radiation of pool fire may affect people are listed in Table 3.16. The various effects of pressure waves are given in Table 3.2. A comparison of pressure of blast waves due to VCE for various chemicals is given in the Table 3.26. From this table it is observed that the pressure of a blast wave is very less for LPG and high for cyclohexane. This may be attributed to the to less storage quantity of LPG and its lower heat of combustion values. However, the corresponding values for benzene and cyclohexane are found to be high. It is also observed that the pressure of blast wave due to VCE is higher than that of the BLEVE (Table 3.24). This is because some amount of energy of the explosion is utilized for the fragmentation of the vessel and its missile effects. Comparison is given in the graphical form (Fig. 3.3). The maximum threat zones for pressure waves resulting from the VCE of various chemicals are given in Table 3.27. The results of ALOHA air modelling for chlorine, ammonia and benzene are given in the Tables 3.47 & 3.48 for various leaks scenarios. It is observed that the threat zones are the maximum for chlorine, for both morning and evening and it is around 9.2 kilometers for a leak scenario for a 2-inch hole. The maximum threat zones for various chemicals and its direction are given in Table 3.49. These results will give us a clear picture of the hazard potential of these storages. Estimation of the hazard potential is the first step in any disaster management plan. The results obtained from the above analysis will also provide guidelines for land use planning in the areas surrounding the MAH industries.

3.6 CONCLUSIONS

Consequence analysis is gaining importance in the industrial disaster mitigation and management decisions. 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 modelling shows that the hazardous distances for certain chemicals extended up to 90 meters which might prevent effective fire fighting 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 taken in to account while deciding the distance between the tanks. The consequence calculations have been made for explosion scenarios also. 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. This threat zone can be shortened by reducing the inventory of cyclohexane. It is observed that as the wind velocity increases, threat zone distance decreases. As the wind speed increases, the material is carried down by the wind faster, but the material is also diluted faster by a large quantity of air [8]. So when wind velocity increases, even though we expect a large threat zone, we will get only a smaller threat zone with specific level of concern because of the dilution of the cloud with air. But as the temperature increases threat zone distance increases. But the low temperature variation doesn't have much influence on the threat zone. Dispersion modelling results and the wind direction for a particular period, can greatly improve emergency preparedness and can be powerful decision making tools for locating rehabilitation centres and the local emergency control rooms.

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Chapter 4

VULNERABILITY ASSESSMENT

4.1 INTRODUCTION

Risk [1] is defined as a measure of human injury, environmental damage, or economic loss in terms of the incident likelihood and the magnitude of the injury, damage, or loss. Risk analysis involves the development of an overall estimation of risk by gathering and integrating information about scenarios, frequencies and consequences. Risk indices are single numbers or tabulation of numbers which are correlated to the magnitude of risk. Some risk indices are relative values with no specific units, which only have meaning within the context of the risk index calculations. Other risk indices are calculated from the various individual or societal risk data sets and represent a condensation of the information contained in the corresponding data set. Individual risk is defined as the probability of death per year of exposure to an individual at a certain distance from the hazardous source. It is usually expressed in the form of iso-risk contours. 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.). Quantified risk analysis is the most effective way to represent the societal risks associated with MAH installations [2]

Researches on vulnerability can be traced back to the 1970s in natural hazard studies. There are many papers on vulnerability assessment form different perspectives. There are some attempts to quantify environmental vulnerability referring to specific systems including risks posed by chemical industries to the surrounding environment. Vulnerability has been defined in various ways such as the threat of exposure, the capacity to suffer harm and the degree to which different social groups are at risk by Cutter [3]. Souza and Freitas [4, 5] explored vulnerability to major chemical accidents in industrialized countries only from the perspective of socio-political structures. In some sense, population density is often used to reflect relative human vulnerability in urban area [6]. Li et. al., [7] mapped the human vulnerability to chemical accidents in the vicinity of chemical industry parks. Young et.al., [8] estimated individual risk associated with a high pressure natural gas pipeline. AIChE/CCPS [9] gives a clear cut guideline to estimate the individual risk and societal risk associated with different incident outcome cases from major accident industries. In this chapter vulnerability is assessed using probit functions and individual and societal risks are estimated. Mapping of the impact zones of incident outcome cases are also done and individual and societal risk are estimated at different locations of the impact zones.

4.2 STUDY AREA

The South Indian city of Cochin is often referred to as a *chemical hot spot* due to the presence of large number of potentially hazardous industries. There are two major industrial areas in Cochin City, which consist a number of (MAH) industries. Udyogamandal is one among them, where more than five MAH units are located. Moreover about four MAH industries are located very near to the Udyogamandal industrial belt. Around 10,000 people are employed in various industries in the Udyogamandal industrial area and the population in Udyogamandal and the surrounding panchayats is more than 2,00,000. The population density in this area is around 3000 per sq. kilometer. Udyogamandal belongs to Eloor grama panchayat as shown in Fig. 2.2 [10] and the approximate land area of Eloor grama panchayat is around 11.21 sq. km. Demographic details of Eloor grama panchayat is given in Table 2.2. The area selected for the present study is approximately 300 sq. km (20 km x 15 km) and is shown in Fig 4.1. This dimension includes all consequence of flammable, explosive and toxic gas release events.

Fig. 4.1 Area selected for study

4.3 ESTIMATION OF INDIVIDUAL RISK

Individual risk is defined by AIChE/CCPS [9] 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. Individual risk can be estimated for the most exposed individual, for groups of individuals at particular places or for an average individual in an effect zone. For a given incident or set of incidents, these individual risk measures have different values.

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 [9] as

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i} \text{-------------} (4.1)$$

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. $IR_{x,y,i}$, can be estimated using the equation.

$$IR_{x,y,i} = f_i p_{f,i} \text{-------------} (4.2)$$

where f_i is the frequency of incident outcome case *i,* from the frequency analysis and $p_{f,i}$ is the probability that incident outcome case *i* will result in a fatality at location *x, y,* from the consequence and effect models. Frequency f_i of incident outcome case is estimated as discussed by AIChE /CCPS

$$f_i = F_I \, p_{O,i} \, p_{OC,i} \text{------} (4.3)$$

where F_I is the frequency of incident *I* which has incident outcome case *i* as one of its incident outcome case (yr^{-1}), $p_{O,i}$ is the probability that incident outcome, having *i* as one of its incident outcome cases, occurs, given that incident *I* has occurred and $p_{OC,i}$ probability that incident outcome case *i* occurs given the occurs of the precursor incident *I* and the incident outcome corresponding the outcome case *i*.

4.4 ESTIMATION OF 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.) However, societal risk can also be expressed in terms similar to individual risk. For example, the likelihood of 100 fatalities at a specific location *x, y* is a type of societal risk measure. The calculation of societal risk requires the same frequency and consequence information as individual risk. Additionally, societal risk estimates require 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.

Individual and societal risks are the different presentation of the same underlying combinations of incident frequency and consequences. Both of these measures may be of importance in assessing the benefits of risk reduction measures or in judging the acceptability of a facility in absolute terms.

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

$$N_i = \sum_{x,y} P_{x,y} p_{f,i} --------(4.4)$$

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 incident outcome case *i* will result in a fatality at location *x*, *y*.

4.5 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 [11]. In this work preliminary hazard analysis (PHA) and HAZOP study [12] are conducted for hazard identification. Sample work sheets for PHA and HAZOP are attached as Annexure A and Annexure B respectively.

4.6 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 a 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).

4.7 IMPACT ANALYSIS

The calculation of the individual and societal risk involves calculation of probability of death of a person at a given exposure [13]. The probability of death is calculated using probit. 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 [9]. The probit models are generally expressed as

$$P_r = k_1 + k_2(\ln V) ------(4.5)$$

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 [9] and TNO [13] 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. The probit equations used in this work are shown in Equations (4.5) - (4.9).

$$P_r = a + b(c^n t) ------(4.6)$$

where P_r is the probit, a is a constant depending on the toxic load, b is the constant depending the toxic substance, c is the concentration of the substance in ppm, t is the exposure time in minutes, n is the constant depend on the toxic substance. Eisenberg et. al., [14] provides a probit model to describe the effects on structures. Eisenberg also provides a probit for fatalities due to direct effect of overpressure as follows.

$$P_r = -77 + 6.91(\ln P^o) -------(4.7)$$

Where P^o is the peak over pressure (Pa).

It is assumed that everyone inside the area covered by a fire ball, a jet fire, a burning pool (pool fire) or gas cloud will be burnt to death or will asphyxiate. The probit functions shown in Equations (4.8) and (4.9) are used to calculate the percentage of lethality and first degree burns respectively that will occur at a particular thermal load and period of exposure of an unprotected body.

$$P_r = -36.38 + 2.56\ln(tq^{4/3}) ------(4.8)$$

$$P_r = -39.83 + 3.0186\ln(tq^{4/3}) -----(4.9)$$

4.8 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. Table 4.1 shows the frequencies of various incident outcome cases. In the present work, frequencies of incident outcome cases are obtained from the historical incident data presented in OGP [15], HSE [16], TNO [13], CCPS [9] and from fuzzy fault tree analysis (FFTA) [17].

Table 4.1 Frequency of incident outcome cases

Incident outcome cases	Frequency per year (*fi*)
Chlorine dispersion in a particular wind direction	$7.96\text{x}10^{-2}$
Ammonia dispersion in a particular direction	$2.50 \text{ x } 10^{-8}$
BLEVE fire ball (LPG)	$4.70 \text{ x } 10^{-7}$
VCE pressure effects(cyclohexanone)	$1.20 \text{ x } 10^{-5}$
VCE pressure effects(LPG)	$1.20 \text{ x } 10^{-5}$
Pool fire (Naphtha)	$1.20 \text{ x } 10^{-4}$
VCE pressure effects (cyclohexane)	$1.2 \text{ x } 10^{-5}$

4.9 RESULTS AND DISCUSSION

The hazardous distances up to which the intensity of heat radiation of pool fire may affect people are listed in Table 3.16. Maximum threat zones for pressure waves (VCE) are given in Table 3.23. From the dispersion modelling of chlorine and ammonia, (Tables 3.47 & 3.48) 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 (5.08 cm) hole on chlorine storage of 50 tonnes, with IDLH as level of concern. This indicates that, in case of a disaster in these industries the population falling within the exposure zone of the vapour plume can survive only for thirty minutes. Moreover depending on the wind pattern the plume directions may change in a 0-360 degree range. Table 4.2 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. Table 4.3 shows the various individual outcome cases, its threat zone and the percentage fatality estimated from the effect models. Fig. 4.2 shows the threat zone of chlorine gas for IDLH and 100 ppm concentrations, superimposed on the map of the study area. Fig. 4.3 shows the threat zone for ammonia dispersion. Fig. 4.4 shows the threat zones (explosion and fire) for various hazardous chemicals like cyclohexane, cyclohexanone, LPG and naphtha. Fig. 4.5 shows the map of vulnerable areas corresponding to different individual outcome cases in the Udyogamandal industrial area. All the threat zones in the industrial area are super imposed in Fig. 4.6 Fig. 4.7 gives the location, where individual risk is estimated and the estimated individual risk at different locations is listed in Table 4.4. The individual risk is found to be a maximum at locations A, B, G, H, M, and N (approximately $1x10^{-2}$ 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 tank. A broadly acceptable level of individual risk as per the ALARP (As low as reasonably practicable) concept of HSE, UK [18] is 10^{-6}/year. Based on these criteria, the individual risk experienced at locations C, D, E, F, I, J, K, L, O, and P are within the acceptable levels. Table 4.5 gives the individual outcome cases, area of threat zone, population density in each threat zone, probability of wind, 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). In the case of ammonia (with level of concern 300 ppm), the probable number of fatalities is estimated as 170. It is found that the population density in the threat zones for various incident outcome cases plays a major role in the societal risk. It is also recommended that a real time dispersion modelling system be installed in MAH industries and should be networked with district administration, so that in case of a major disaster, responsible authorities concerned can visualize the vulnerable areas and take appropriate decision. This approach will reduce the number of fatalities in case of a disaster.

Table 4.2 Maximum threat zone for ammonia and chlorine

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

Table 4.3 Percentage fatality from different incident outcome cases and level of concern

Chemical	Incident outcome case	Level of concern	Treat zone distance	% fatality (*pfi)*
Chlorine	Catastrophic failure	100 ppm	3.6 km	15
Ammonia	Catastrophic failure	300 ppm	4.2 km	12
Naphtha	Pool fire	2.32 kW/ m^2	150 m	8
LPG	BLEVE	2.32 kW/ m^2	500 m	46
Cyclohexane	VCE	150 kPa	50 m	64
Cyclohexanone	VCE	180 kPa	50 m	96
LPG	VCE	150 kPa	10 m	75

Table 4.4 Individual risk at different locations

Location	Total individual risk of fatality/ per year
A	1.194×10^{-2}
B	1.194×10^{-2}
C	3.000×10^{-9}
D	3.000×10^{-9}
E	2.160×10^{-7}
F	2.160×10^{-7}
G	1.194×10^{-2}
H	1.194×10^{-2}
I	2.190×10^{-7}
J	2.190×10^{-7}
K	9.816×10^{-6}
L	9.816×10^{-6}
M	1.194×10^{-2}
N	1.194×10^{-2}
O	3.150×10^{-7}
P	3.150×10^{-7}

Table 4.5 Societal risk due to different incident outcome cases

Incident Outcome	Area of threat. zone (m^2)	Population density/ sq. km	% Fatality	Probability of wind	Availability of people	No. of Fatalities
Chlorine release in a particular direction (catastrophic failure)	2.8800	3000	15	0.4	0.7	362
Chlorine release in opposite direction (catastrophic failure)	2.8800	3000	15	0.4	0.7	362
Ammonia release in a particular direction (LOC – 300 ppm)	3.3600	3000	12	0.4	0.7	170
Ammonia release in opposite direction (LOC-300 ppm)	3.3600	3000	12	0.4	0.7	170
LPG (BLEVE – heat radiation)	0.7850	1000	46	1	0.5	230
Cyclohexane (VCE –Pr. Effects)	0.0080	1000	64	1	0.5	5
Cyclohexanone (VCE –Pr. Effects)	0.0003	1000	96	1	0.5	6
Naphtha (pool fire)	0.0710	3000	8	1	0.7	12

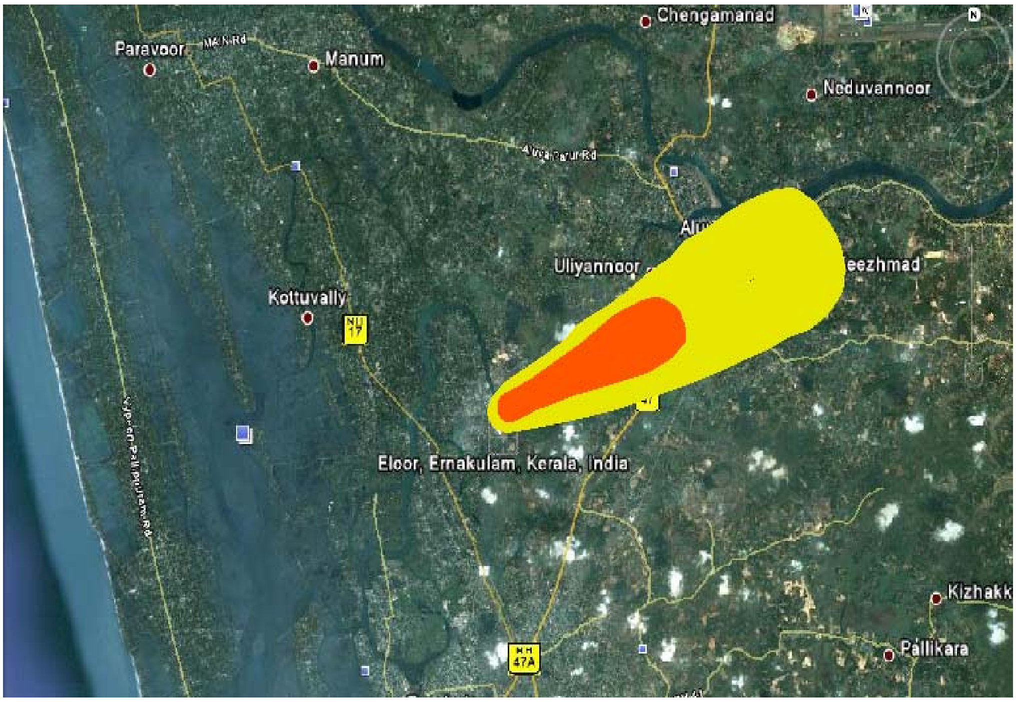

Fig. 4.2 Threat zone for chlorine release in North-East direction

Fig. 4.3 Threat zone for ammonia release in North-East direction

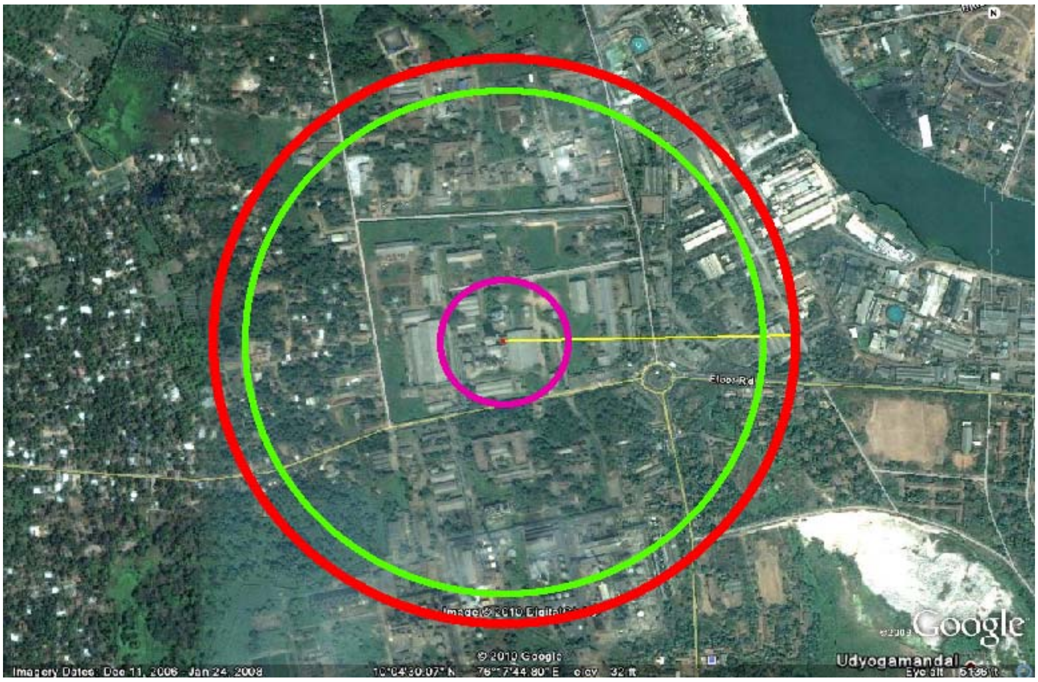

Fig. 4.4 Threat zone for cyclohexane, cyclohexanone and LPG

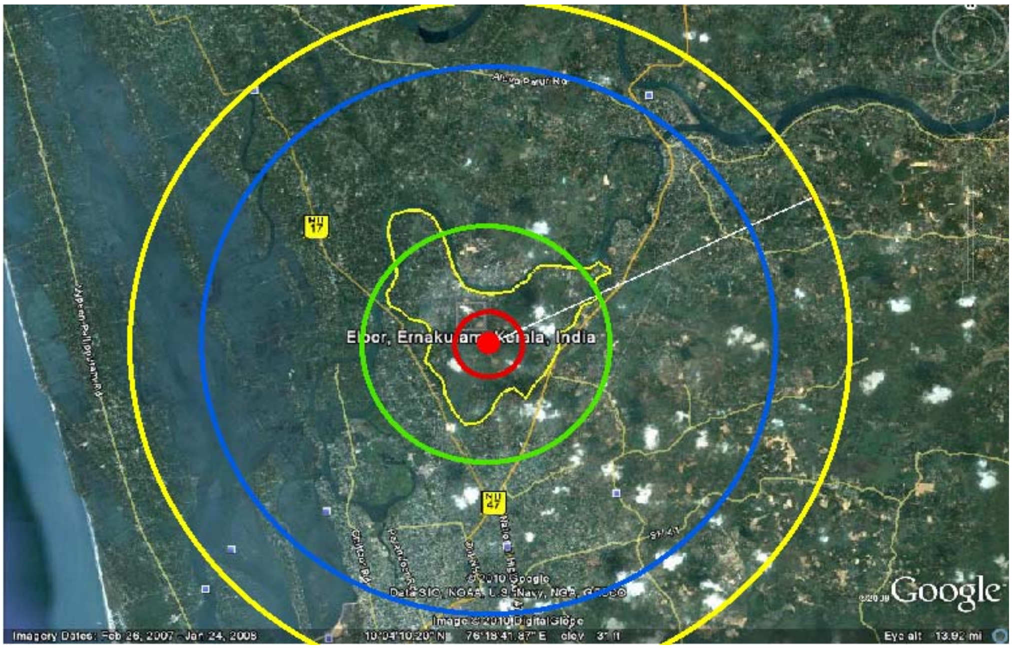

Fig. 4.5 Map of vulnerable areas of different individual out come cases

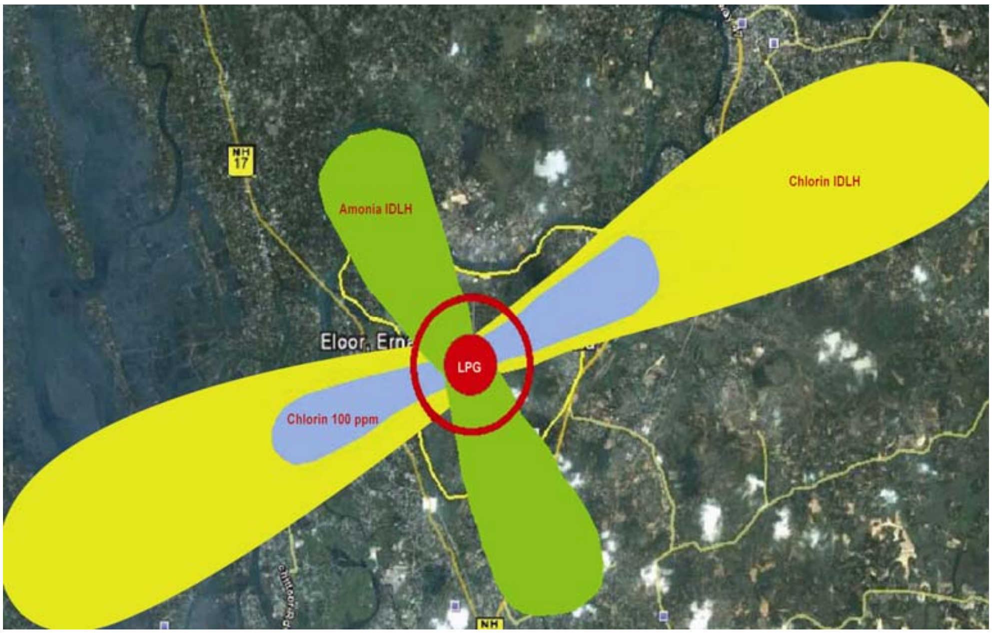

Fig. 4.6 Threat zones superimposed on the map of study area.

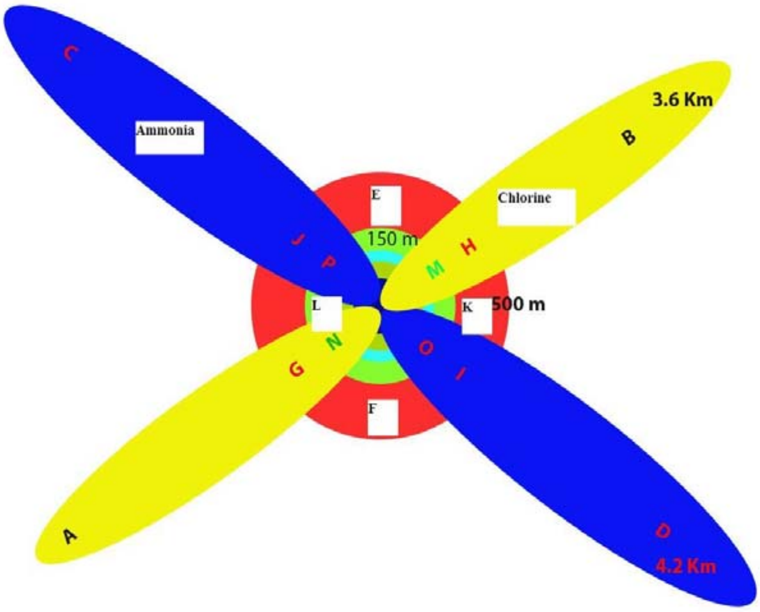

Fig. 4.7 Different locations in the map where individual and societal risk are estimated

4.10 CONCLUSIONS

An attempt has been made in this chapter to estimate the individual and societal risk at various locations. The individual risk is found to be higher than the acceptable level of risk (10^{-6} fatalities/year) is mainly due to the very high concentration of chlorine gas that may result from the catastrophic failure of chlorine storage. 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). In the case of ammonia (with level of concern 300 ppm), the probable number of fatalities is estimated as 170. 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 points to the need for maintaining buffer zones (with no human inhabitation) around hazardous industrial areas. The above method will be useful for land use planning in the areas surrounding industrial belt.

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Chapter 5

TWO DIMENSIONAL FUZZY FAULT TREE ANALYSIS

5.1 INTRODUCTION

Chemical industries are complex systems with innumerable chemicals being used in various phases in the operations. The raw materials, processes, intermediate products, final products, and waste products in the operations can lead to a host of accident situations. Three significant hazards are fire, explosion, and toxic gas release. Of these, toxic gas release is the most damaging as it has the potential to annihilate a large number of people on exposure. Bhopal (India) gas disaster proved that a toxic gas release can be a catastrophe of massive proportion in an area with large populations causing many fatalities and long term health impact on the exposed population. Chlorine, a highly toxic chemical, a major by-product of chlor-alkali industry is liquefied and stored at (-) 5^{o}C and has an expansion ratio of 460 which is a matter of great public concern. So this exercise has been taken up against this background to develop failure probability values for FTA using fuzzy logic and expert elicitation.

Fault tree analysis (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 [1,2,3]. FTA is also used widely in many fields, such as semi conductor industry [3], man-machine system [4], flexible manufacturing systems [2], nuclear power plants [5] transmission pipelines [6], chemical industries [1, 7] and LNG terminal emergency shut down systems [8]. Shu et al., [9] applied fuzzy set theory for fault tree analysis on printed circuit boards industry. Refaul et al., [10] developed computer aided fuzzy fault tree analysis. Doytcin and Gerd [11] combined task analysis with fault tree analysis for accident and incident analysis.

In conventional FTA, the process should be fully understood and the probability of failure of basic events must be known. However it is often difficult to estimate precisely the failure probability of the components due to insufficient data or vague characteristic of the basic event. It has been pointed out that in India, availability of the failure probability data pertaining to local condition is surprisingly limited [12]. In the absence of such data, failure and event probability data published by OGP [13], Health Safety Executive [14], TNO [15] and Lees [16] are used in fault tree analysis. These values published internationally may not be suitable for Indian conditions, because of the tropical climatic conditions, inconsistent service conditions and unsystematic operating and maintenance practices.

Fuzzy methods could be the only way to generate failure probability values when little quantitative information is available regarding fluctuations of the parameters [17,18,19] and the probabilities of basic events are treated as fuzzy numbers. Lin and Wang, [4] combined fuzzy set theories with expert elicitation to evaluate failure probability of basic events of a robot drilling system, based on triangular and trapezoidal fuzzy numbers. In a transmission expansion planning, Chanda and Bhattacharjee, [20] considered uncertain nature of failure rate of the components, and introduced fuzzy failure probability of the components. Antonio and Nelson [21] developed a new computational system for reliability analysis using fault tree and fuzzy logic. Khan and Abbasi [1] developed computer automated tool software for evaluating the reliability of chemical process industries. Roy et al., [7] used fuzzy logic in fault tree analysis of titanium tetra chloride plant using rough estimation or modified version of the available data for Indian conditions.

5.2 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. The basic process in the technique of FTA is to identify a particular effect or outcome from the system and trace backward into the system by the logical sequence to prime cause(s) of this effect. In the present study, an attempt is made to evaluate the probability of chlorine release from a storage tank of 50 tones capacity and filling facility (Fig. 5.1) using fault tree analysis (Fig. 5.2). Failure probability values of basic events of chlorine release from the storage tank and chlorine filling facility 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 is introduced to incorporate hesitation factor during expert elicitation.

5.2.1 Fault tree construction

The first step in the fault tree construction is defining the top event accurately. The top event is the undesired event that is the subject of fault tree analysis. After the identification of the top event, the immediate essential causes that result in the top event should be identified. The immediate causes should be connected to the top event with appropriate logic gates to show their relationship. Each of the immediate causes is then treated in the same manner as the top event and its immediate essential causes are identified and shown on fault tree with appropriate logic gates. This top-down approach continues starting from the top event and coming down through *intermediate* event until all *intermediate* events / faults have been developed into their basic events.

5.2.2 Fault tree evaluation

There are a number of methods for fault tree evaluation such as 1. Minimal cut sets 2.Gate by gate method 3. Monte Carlo simulation [22]. In the first method probabilities of the event may be calculated from the probabilities of the minimal cut sets C_i and is given by

$$P(T) = P(\sum_{i=1}^{n})Ci - - - - - - - (5.1)$$

The second method consists of working up the tree gate-by- gate from the bottom, calculating the frequency or probability of the output event of each gate from those of the input events. The application of Monte Carlo simulation to fault tree evaluation involves a series of trials. In a given trial each primary event either occurs or does not occur, the occurrence being determined by the sampling.

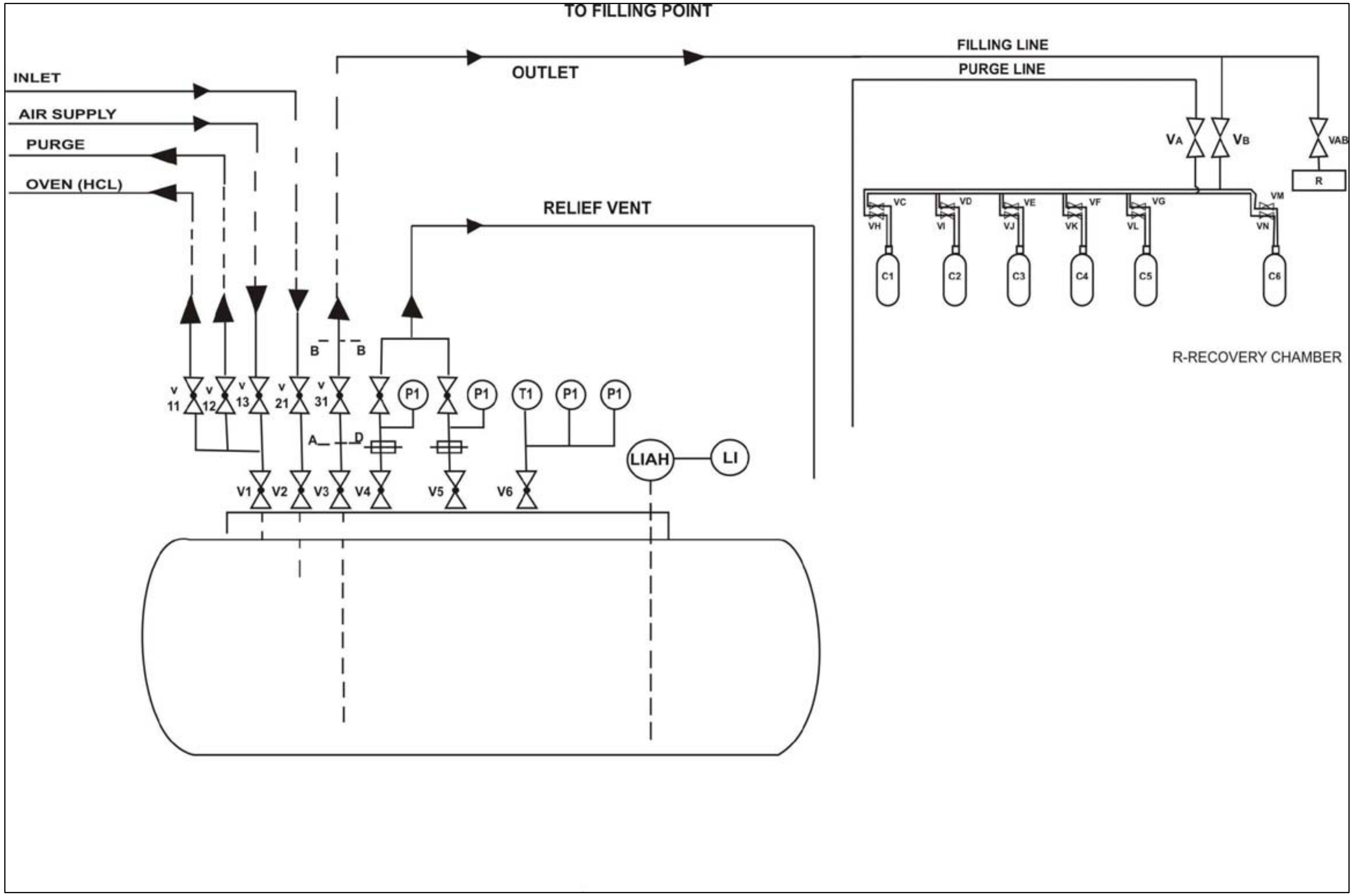

Fig. 5.1 Schematic diagram of chlorine storage and filling facility

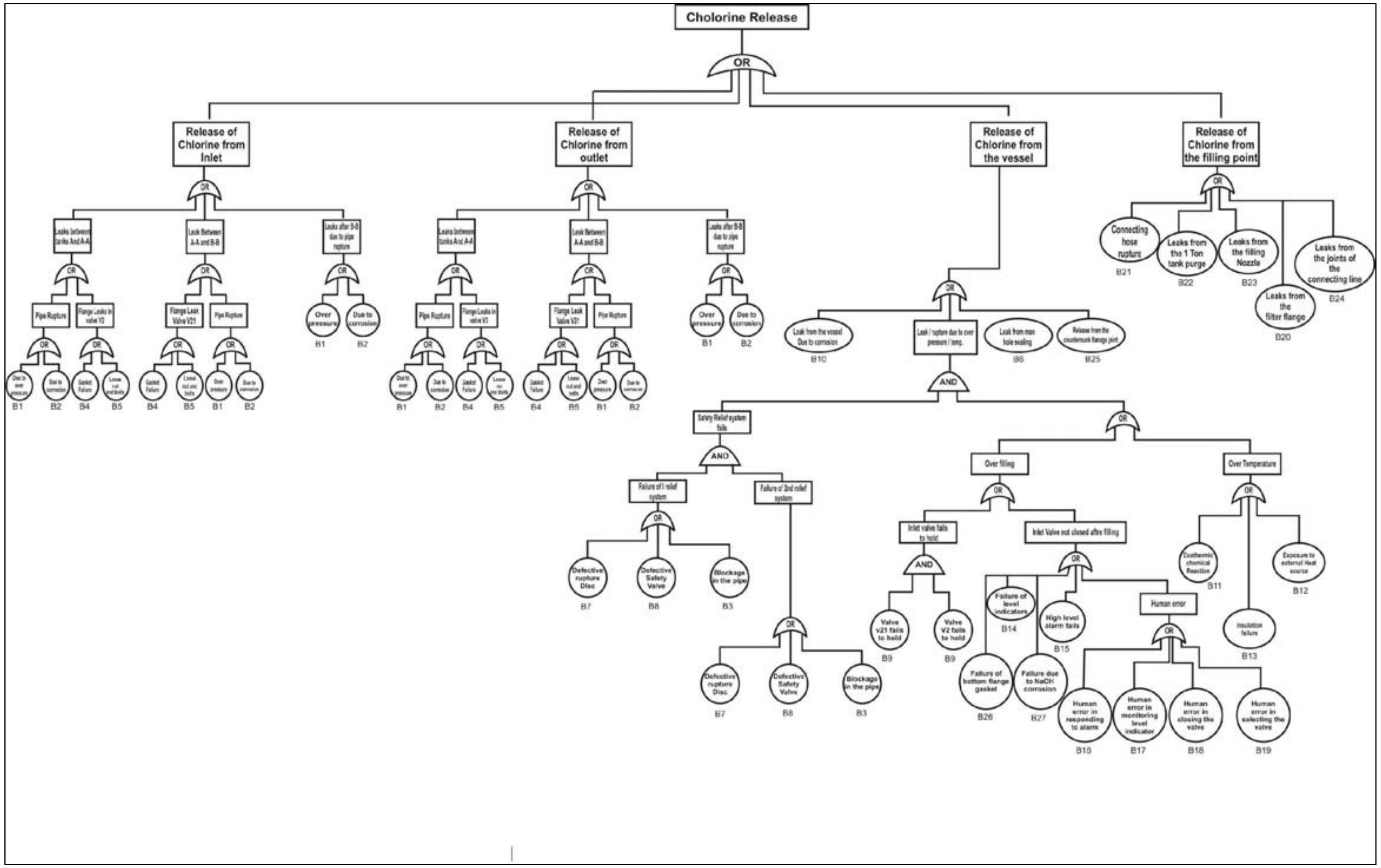

Fig. 5.2 Fault tree for chlorine release

In order to evaluate the failure frequency of the top event, it is necessary to assign numerical values to all inputs and the logic gates. The values are mathematically estimated through the tree from bottom to top and there arriving at predicted frequency for top events. The sensitivity of prediction to the data, which is uncertain, should always be checked to determine whether variation in such data would have serious effects on the results or not.

5.2.3 Failure rates of basic events

Failure rate of the basic events must be known in advance, in order to evaluate failure probability of the top event. This work uses expert elicitation and fuzzy logic to generate the probabilities of the basic events. Expert elicitation or expert judgment is one of the methods of evaluating probability of events. This method provides some useful information for assessing risks and making decisions. It includes interview [16], Delphi method, ranking and scaling, method of paired comparison [23], and Saaty's [24] method. Table 5.1 gives a list of basic events that lead to chlorine release.

Table 5.1 List of basic events that lead to chlorine release.

Sl. No.	Basic event Number	Description of Basic event
1	B1	Pipe rupture due to overpressure
2	B2	Pipe rupture due to corrosion
3	B3	Pipe rupture due to blockage in the pipeline
4	B4	Flange leak due to gasket failure
5	B5	Flange leak due to loose nut and bolts
6	B6	Leak through man hole sealing
7	B7	Defective Rupture disc
8	B8	Defective safety Valve
9	B9	Leak due to valve fail to hold
10	B10	Leak from storage tank due to corrosion
11	B11	Leak from storage tank due to exothermic chemical reaction
12	B12	Leak from storage tank due to Exposure to external heat
13	B13	Leak from storage tank due to insulation failure and hence temp rise
14	B14	Failure of level indicators in the storage tank
15	B15	Failure of high level alarm
16	B16	Human error in responding to alarms
17	B17	Human error in monitoring level indicator
18	B18	Human error in closing the important valves during emergency
19	B19	Human error in selecting the valve during emergency
20	B20	Leaks at the filter flange
21	B21	Connecting hose rupture
22	B22	Leaks from the 1 tonne tank-purge
23	B23	Leaks from the filling Nozzle
24	B24	Leaks from the joints of the connecting line
25	B25	Leaks from the countersunk flange joint (vessel)
26	B26	Failure of bottom flange (gasket failure)- level indicator
27	B27	NaOH corrosion- level indicator bottom

Direct interaction/interview with the experts is adopted in the present study. Experts from different fields will make judgments about probability of events based on working experience and exposure to various situations. Because the experts cannot exactly evaluate the probability of events, and sometimes some of the events are vague, they tend to apply natural linguistic expressions, such as ‘very low’, ‘low’, ‘medium’, ‘high’ and ‘very high’, to describe the probability of events. Conventional mathematical methods cannot handle natural linguistic expressions efficiently because of their fuzziness [25]. Fuzzy set theory is used to overcome this shortcoming. There are many forms of fuzzy numbers such as triangular and trapezoidal to represent the linguistic expression [25].

Table 5.2 Scores assigned for different experts based on their merit.

Constitution	Classification	Score
Title	Professor, GM/DGM, Chief Engineer, Director	4
	Asst. Prof., Manager, Factory Inspector, Controller of explosives	3
	Supervisors, Foreman, Graduate apprentice	2
	Operator	1
Experience in years	Greater than 30	4
	20-30	3
	10-20	2
	5-10	1
Educational Qualification	Ph.D./M.Tech.	5
	M.Sc./B.Tech.	4
	Diploma/B.Sc.	3
	ITI	2
	Secondary school	1
Age in years	50-70	4
	40-50	3
	30-40	2
	20-30	1

Table 5.3 Determination of weighting factors for 100 experts

Sl. No.	Title	Educational level	Service time	Age	Weighting score	Weighting Factor
1	3	4	3	4	14	0.010
2	2	4	2	3	11	0.008
3	2	5	2	2	11	0.008
4	1	4	2	2	9	0.007
5	5	5	4	4	18	0.013
6	5	4	3	3	15	0.011
7	5	5	4	4	18	0.014
8	5	5	4	4	18	0.013
9	5	5	4	4	18	0.013
10	4	4	3	4	15	0.011
11	4	4	2	3	13	0.009
12	5	4	4	4	17	0.012
13	4	4	3	3	14	0.010
14	4	5	2	3	14	0.010
15	1	4	1	1	7	0.005
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85	4	3	4	4	15	0.011
86	5	4	3	4	16	0.012
87	5	4	3	4	16	0.012
88	5	4	3	4	16	0.016
89	5	4	3	4	16	0.012
90	3	4	1	2	10	0.007
91	5	4	3	4	16	0.012
92	5	4	3	3	15	0.011
93	3	2	3	3	11	0.008
94	3	4	2	3	12	0.009
95	4	4	3	3	14	0.010
96	4	4	1	2	11	0.008
97	4	4	1	2	11	0.008
98	3	2	3	4	12	0.009
99	3	2	3	4	12	0.009
100	5	5	3	3	16	0.012
					1375	

Experts identified from major accident hazard industries (MAH) were requested to express their opinion. Experts were selected from different fields, such as design, installation, maintenance, operation and management of chlor-alkali and similar process industries. Experts from regulatory organizations such as petroleum and explosives safety organization (PESO), Government of India and Department of factories and boilers, Kerala state and academicians with background in process safety were also approached for their opinion. Table 5.2 attached to the questionnaire was discussed with all the 100 experts, who were interviewed. A weighting factor is used to represent the relative quality of the response of different experts. Scores are assigned for different heads such as ‘Title’, ‘Experience’, ‘Educational qualifications’ and ‘Age’. Higher scores are assigned for highly experienced and highly qualified experts. High scores are also assigned for higher designations. Higher scores are also assigned for the higher age. This is due to the fact that as the age increases, the experience and perception of a person are found to be improved. This is true up to an age of around 70. In the present study interviews were conducted with experts who are in service and who had retired during the last five years. The weighting factors obtained on the basis of interviews with 100 experts were determined as shown on Table 5.3. For expert i, weighting score is calculated as sum of Title score, Experience score, Age score and Educational qualification score. Then weighting factor of the expert i is estimated by dividing the weighting score of i^{th} expert by sum of weighting score of the all the experts.

$$f_{VH}(x) = \begin{cases} 0 & x \le 0.8 \\ \dfrac{x-0.8}{0.1} & 0.8 < x \le 0.9 \\ 1 & 0.9 < x \le 1 \end{cases}$$

$$f_{H}(x) = \begin{cases} \dfrac{x-0.6}{0.15} & 0.6 < x \le 0.75 \\ \dfrac{0.9-x}{0.15} & 0.75 < x \le 0.9 \\ 0 & otherwise \end{cases}$$

$$f_{M}(x) = \begin{cases} \dfrac{x-0.3}{0.2} & 0.3 < x \le 0.5 \\ \dfrac{0.7-x}{0.2} & 0.5 < x \le 0.7 \\ 0 & otherwise \end{cases} \qquad ----------- (5.2)$$

$$f_{L}(x) = \begin{cases} \dfrac{x-0.1}{0.15} & 0.1 < x \le 0.25 \\ \dfrac{0.4-x}{0.15} & 0.25 < x \le 0.4 \\ 0 & otherwise \end{cases}$$

$$f_{VL}(x) = \begin{cases} 0 & x > 2 \\ \dfrac{0.2-x}{0.1} & 0.1 < x \le 0.2 \\ 1 & 0 < x \le 0.1 \end{cases}$$

5.3 CONVERSION OF LINGUISTIC TERMS INTO FUZZY NUMBERS.

Since the experts applied natural linguistic terms to judge failure probability of the basic events that lead to a chlorine release, a numerical approximation system was proposed to systematically convert linguistic expressions to their corresponding fuzzy numbers by Chen and Hwang [26]. Eight different types of conversion scales have been suggested for the purpose. In this paper, one of the conversion scales (Fig. 5.3) is used to represent the expert's opinion corresponding to the membership functions of different linguistic terms. The linguistic terms 'very high', 'high', 'medium', 'low', and 'very low' are represented as *VH, H, M, L,* and *VL* respectively and the corresponding membership functions are given in Equation (5.2) . They are also represented in Fig. 5.3.

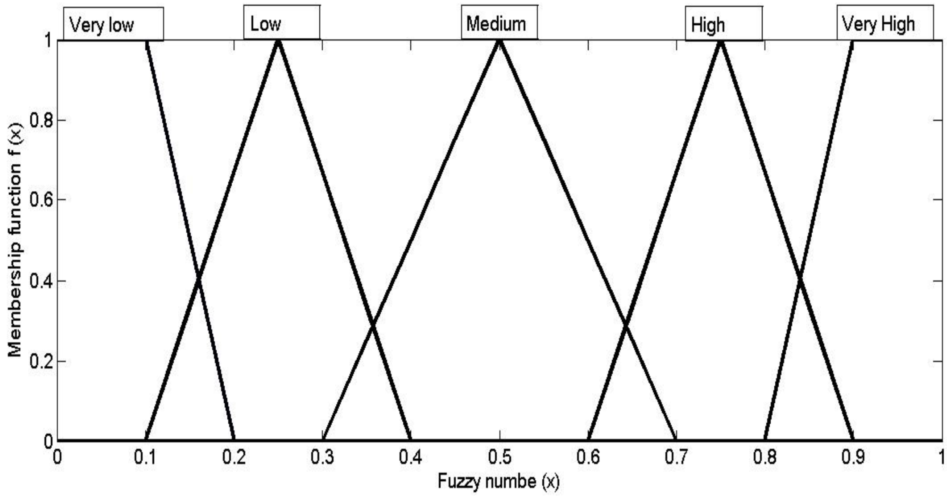


Fig. 5.3 Fuzzy membership functions for various linguistic expressions

Although there can be different opinions on probability of the basic events, it is necessary to aggregate the opinion into a single one. There are various methods to aggregate fuzzy numbers. One of the methods is linear opinion pool [Equation (5.3)] proposed by Clemen and Winkler [27].

$$M_i = \sum_{j=1}^{n} w_j A_{ij}, i = 1,2,3,.........m ------(5.3)$$

where A_{ij} is the linguistic expression of a basic event i given by expert j. m is the number of basic events and n is the number of experts. w_j is a weighting factor of the expert j and M_i represents combined fuzzy number of the basic event i. Based on the extension principle of fuzzy set theory [25], M_i is also a triangular or trapezoidal fuzzy number. Using α-cut of different membership functions of Equations. (5.2) and (5.3), the total fuzzy number for the opinion of 100 experts could be obtained as another fuzzy number represented by Fig. 5.4 and the corresponding expression is $\left[(0.1339\alpha + 0.3097), (0.6140 - 0.1427\alpha)\right]$.

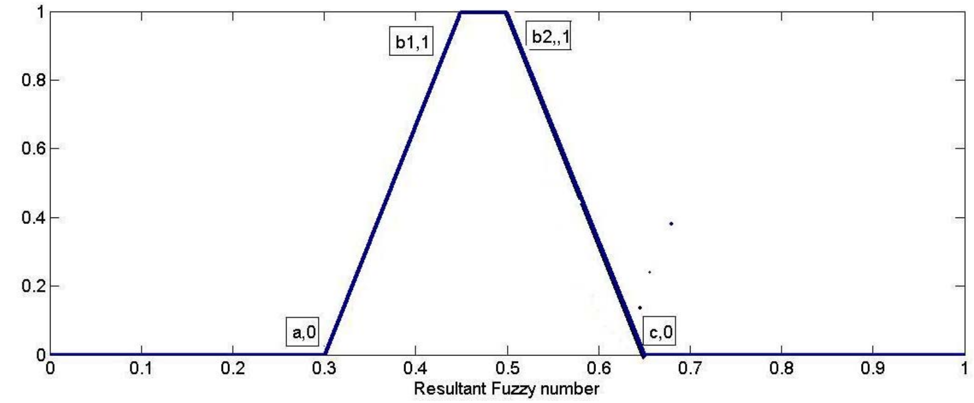


Fig. 5.4 Aggregate fuzzy number for the opinion of 100 experts

5.4 CONVERTING FUZZY NUMBER INTO FUZZY POSSIBILITY SCORE

When fuzzy ratings are incorporated into a FTA problem, the final ratings are also fuzzy numbers. In order to determine the relationship among them, fuzzy number must be converted to a crisp score, named fuzzy possibility score (FPS). FPS represents the most possibility that an expert believes in the occurrence of a basic event. Many investigators have proposed fuzzy ranking methods that can be used to compare fuzzy numbers. Of these, left and right fuzzy ranking method proposed by Chen and Hwang [26] is used here. The left and right utility score of fuzzy number N may be achieved with the help of Fig. 5.5 and the corresponding expressions are given by Equations (5.4) and (5.5).

$$\mu_L(N) = \frac{(1-a)}{\left[1+(b1-a)\right]} \text{--------}(5.4)$$

$$\mu_R(N) = \frac{c}{\left[1+(c-b2)\right]} \text{--------}(5.5)$$

If the left and right scores are available, then the total fuzzy possibility score could be calculated using Equation (5.6)

$$FPS = \frac{\left[\mu_R(N) + \left(1-\mu_L(N)\right)\right]}{2} \text{----------}(5.6)$$

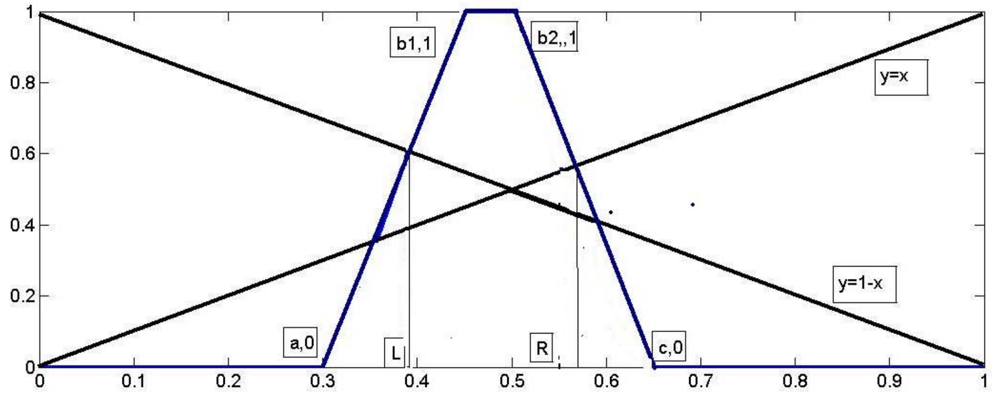


Fig. 5.5 Left and right utility score of aggregate fuzzy number for FFTA

5.5 TRANSFORMING FUZZY POSSIBILITY SCORE INTO FUZZY FAILURE PROBABILITY (FFP)

In the fault tree of chlorine release, the probabilities of the basic events are obtained by the expert judgment and fuzzy logic discussed earlier. In order to ensure compatibility between real numbers and fuzzy possibility score, the fuzzy possibility score must be transferred to fuzzy failure probability.

Fuzzy failure probability was defined by Onisawa, [28] as

$$FFP = \begin{cases} \dfrac{1}{10^k} & FPS \neq 0 \\ 0 & FPS = 0 \end{cases} \qquad ----------(5.7)$$

where

$$k = \left[\frac{(1-FPS)}{FPS}\right]^{\frac{1}{3}} \times 2.301--------(5.8)$$

Similarly failure probability of all the basic events could be generated using the above-mentioned step. If probabilities of all the basic events are known, the failure probability of the top event can be calculated.

5.6 TWO DIMENSIONAL FUZZY LINGUISTIC TERMS

Whenever we collect data, the expert expresses his opinion as well as hesitation. In real life problems, one can model an expert's opinion more precisely by two dimensional linguistic terms which accounts for one's confidence and hesitation. In this paper two dimensional linguistic terms (l_1, l_2) are used to represent the expert's opinion and hesitation. Hence l_1 denotes the opinion and l_2 denotes the hesitation. When an expert says 'very high' with 'little' hesitation or 'very low' with 'high' hesitation, then one can represent these as two dimensional linguistic terms (very high, little), (very low, high). The linguistic terms used here for the degrees of hesitation are 'very high', 'high', 'little' and 'no hesitation'.

5.6.1 Conversion of two dimensional linguistic terms

A two dimensional linguistic term can be converted into two dimensional fuzzy number using triangular fuzzy number. It is also possible to convert the degree of hesitation into triangular fuzzy number**.**

5.6.2 Scores of two dimensional fuzzy numbers

Let (M, H) be a two dimensional fuzzy number. Then the scores of two dimensional fuzzy number T is given by Equation (5.9).

$$T = \left(\frac{1 + R(M) - L(M)}{2}\right), \left(\frac{1 + R(H) - L(H)}{2}\right) - - - - - - - - (5.9)$$

Where [L (M), R (M)] and [L (H), R (H)] are left and right scores of opinion and hesitancy fuzzy number respectively**.**

5.6.3 Two dimensional fuzzy scores of basic events

Two dimensional fuzzy score of each basic event is the sum of the products of the weighing factors of the expert and their corresponding two dimensional fuzzy numbers.

5.6.4 Crisp scores of basic events using TDFFTA

Let two dimensional crisp scores be M (A_i), H (A_i) for each basic event. The score of opinion and hesitancy variables can be obtained by using equation (5.4), (5.5) and (5.6).

The crisp score T (A_i) of each basic event = membership score M (A_i) – y [hesitancy score H (A_i)], where

$$y = \frac{\text{minimum difference of scores in opinion variable}}{\text{number of hesitancy variable}}$$

5.7 SENSITIVITY ANALYSIS OF FAILURE PROBABILITY VALUES

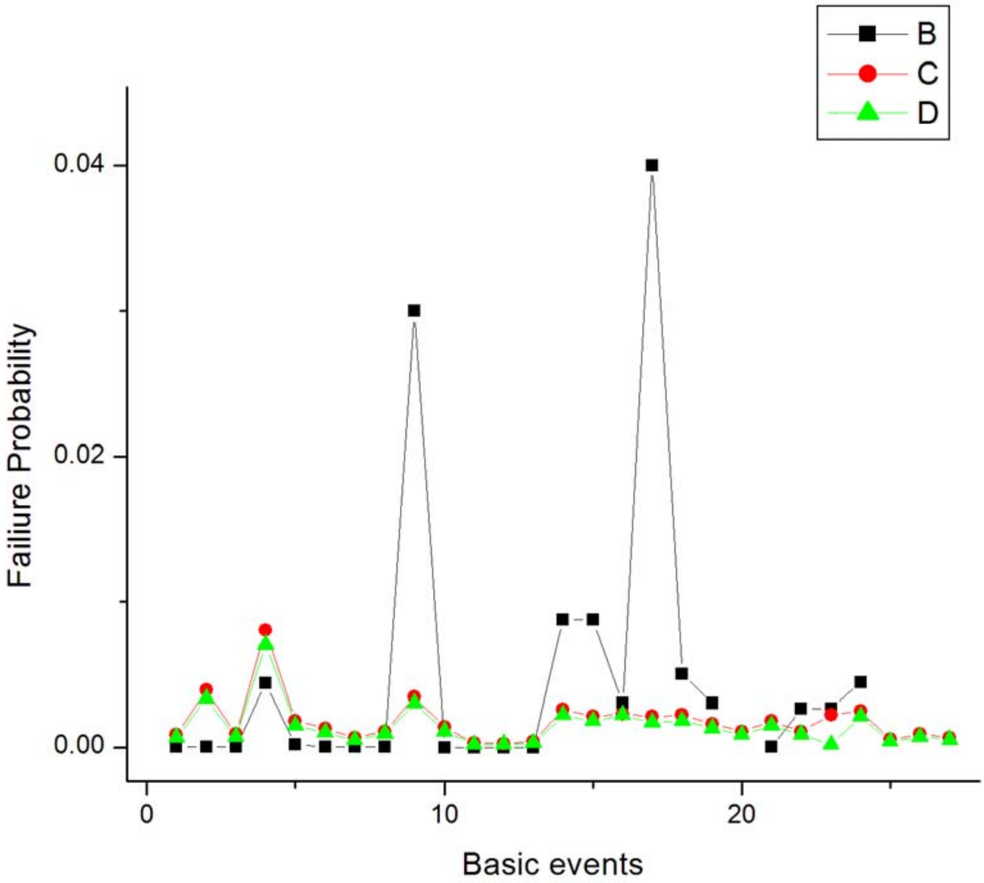
The probability value of chlorine release provides an idea about the chances of release of chlorine. Sensitivity analysis is used to evaluate the impact of each basic event on the top event probability. Sensitivity analysis is carried out by eliminating each basic event from the fault tree and estimating the top event probability.

5.8 RESULTS AND DISCUSSION

Failure probability values are obtained using fuzzy logic and expert elicitation and are shown in Table 5.4. Failure probability values of basic events obtained from the internationally published data are compared with those generated using fuzzy logic and TDFFTA are presented in Table 5.4 and Fig. 5.6. It is observed that the failure probability values obtained from published data are generally lower than the values generated using fuzzy fault tree analysis (FFTA) under Indian conditions. This may be attributed to the tropical climatic conditions, inconsistent service conditions and unsystematic operating and maintenance practices. The probability of chlorine release estimated using published data and generated data using FFTA are 0.02793 and 0.07969 per year respectively. Sensitivity analysis of the basic events reveals that flange leak due to gasket failure and pipe rupture due to corrosion play a very important role in chlorine release. Table 5.5 and Fig. 5.7 show the failure probability values obtained from TDFFTA for different hesitation grades. It is observed from the Tables 5.4 and 5.5 that the values obtained for ‘no hesitation’ grade is the same as those obtained from FFTA. The difference between FFTA values and TDFFTA values narrows down when the hesitation grade changes from ‘very high’ to ‘little’. The relative percentage difference [100 x (FFTA-TDFFTA)/ FFTA] with respect to the results obtained form TDFFTA is carried out and is presented in the Table 5.6.

Table 5.4 Failure probability values of basic events that lead to chlorine release

Sl. No.	Basic event Number	From Published data	Using fuzzy FFTA	Using TDFFTA
1	B1	$8.76\text{x}10^{-6}$	$8.57\text{x}10^{-4}$	$6.75\text{x}10^{-4}$
2	B2	$8.76\text{x}10^{-6}$	$3.90\text{x}10^{-3}$	$3.30\text{x}10^{-3}$
3	B3	$8.76\text{x}10^{-6}$	$9.23\text{x}10^{-4}$	$7.32\text{x}10^{-4}$
4	B4	$4.38\text{x}10^{-3}$	$8.00\text{x}10^{-3}$	$7.00\text{x}10^{-3}$
5	B5	$1.75\text{x}10^{-4}$	$1.80\text{x}10^{-3}$	$1.50\text{x}10^{-3}$
6	B6	$8.76\text{x}10^{-6}$	$1.30\text{x}10^{-3}$	$1.00\text{x}10^{-3}$
7	B7	$1.00\text{x}10^{-5}$	$6.60\text{x}10^{-4}$	$5.12\text{x}10^{-4}$
8	B8	$1.00\text{x}10^{-5}$	$1.10\text{x}10^{-3}$	$9.32\text{x}10^{-4}$
9	B9	$3.00\text{x}10^{-2}$	$3.40\text{x}10^{-3}$	$3.00\text{x}10^{-3}$
10	B10	$1.00\text{x}10^{-6}$	$1.40\text{x}10^{-3}$	$1.10\text{x}10^{-3}$
11	B11	$1.00\text{x}10^{-9}$	$2.89\text{x}10^{-4}$	$1.95\text{x}10^{-4}$
12	B12	$1.00\text{x}10^{-8}$	$2.59\text{x}10^{-4}$	$2.00\text{x}10^{-4}$
13	B13	$1.00\text{x}10^{-8}$	$3.78\text{x}10^{-4}$	$2.66\text{x}10^{-4}$
14	B14	$8.76\text{x}10^{-3}$	$2.60\text{x}10^{-3}$	$2.20\text{x}10^{-3}$
15	B15	$8.76\text{x}10^{-3}$	$2.10\text{x}10^{-3}$	$1.80\text{x}10^{-3}$
16	B16	$3.00\text{x}10^{-3}$	$2.30\text{x}10^{-3}$	$2.00\text{x}10^{-3}$
17	B17	$4.00\text{x}10^{-2}$	$2.10\text{x}10^{-3}$	$1.70\text{x}10^{-3}$
18	B18	$5.00\text{x}10^{-3}$	$2.20\text{x}10^{-3}$	$1.80\text{x}10^{-3}$
19	B19	$3.00\text{x}10^{-3}$	$1.60\text{x}10^{-3}$	$1.30\text{x}10^{-3}$
20	B20	Not available	$1.10\text{x}10^{-3}$	$8.55\text{x}10^{-4}$
21	B21	$8.76\text{x}10^{-6}$	$1.80\text{x}10^{-3}$	$1.50\text{x}10^{-3}$
22	B22	$2.63\text{x}10^{-3}$	$1.10\text{x}10^{-3}$	$8.84\text{x}10^{-4}$
23	B23	$2.63\text{x}10^{-3}$	$2.20\text{x}10^{-3}$	$1.80\text{x}10^{-3}$
24	B24	$4.40\text{x}10^{-3}$	$2.50\text{x}10^{-3}$	$2.10\text{x}10^{-3}$
25	B25	Not available	$5.33\text{x}10^{-4}$	$4.03\text{x}10^{-4}$
26	B26	Not available	$8.99\text{x}10^{-4}$	$7.10\text{x}10^{-4}$
27	B27	Not available	$6.71\text{x}10^{-4}$	$5.19\text{x}10^{-4}$

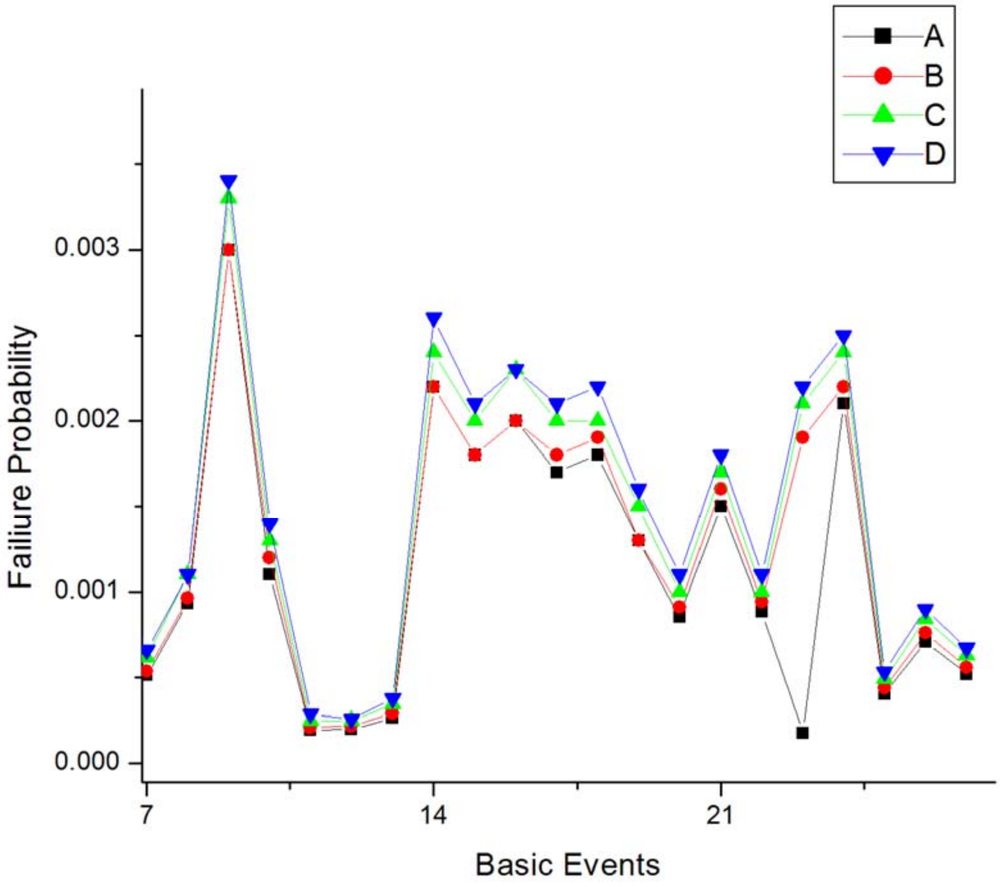


B - **Internationally published data**
C - **Generated data using FFTA**
D - **Generated data using TDFFTA**

Fig. 5.6 Comparison of failure probability values generated using different methods.

Table 5.5 Comparison of failure probability values based on different hesitation grade.

BE	Very high	High	Little	No
B1	6.75×10^{-4}	7.07×10^{-4}	8.02×10^{-4}	8.57×10^{-4}
B2	3.30×10^{-3}	3.40×10^{-3}	3.70×10^{-3}	3.90×10^{-3}
B3	7.32×10^{-4}	7.66×10^{-4}	8.65×10^{-4}	9.23×10^{-4}
B4	7.00×10^{-3}	7.20×10^{-3}	7.70×10^{-3}	8.00×10^{-3}
B5	1.50×10^{-3}	1.50×10^{-3}	1.70×10^{-3}	1.80×10^{-3}
B6	1.00×10^{-3}	1.10×10^{-3}	1.20×10^{-3}	1.30×10^{-3}
B7	5.12×10^{-4}	5.36×10^{-4}	6.14×10^{-4}	6.60×10^{-4}
B8	9.32×10^{-4}	9.66×10^{-4}	1.10×10^{-3}	1.10×10^{-3}
B9	3.00×10^{-3}	3.00×10^{-3}	3.30×10^{-3}	3.40×10^{-3}
B10	1.10×10^{-3}	1.20×10^{-3}	1.30×10^{-3}	1.40×10^{-3}
B11	1.95×10^{-4}	2.09×10^{-4}	2.50×10^{-4}	2.89×10^{-4}
B12	2.00×10^{-4}	2.20×10^{-4}	2.50×10^{-4}	2.59×10^{-4}
B13	2.66×10^{-4}	2.94×10^{-4}	3.47×10^{-4}	3.78×10^{-4}
B14	2.20×10^{-3}	2.20×10^{-3}	2.40×10^{-3}	2.60×10^{-3}
B15	1.80×10^{-3}	1.80×10^{-3}	2.00×10^{-3}	2.10×10^{-3}
B16	2.00×10^{-3}	2.00×10^{-3}	2.30×10^{-3}	2.30×10^{-3}
B17	1.70×10^{-3}	1.80×10^{-3}	2.00×10^{-3}	2.10×10^{-3}
B18	1.80×10^{-3}	1.90×10^{-3}	2.00×10^{-3}	2.20×10^{-3}
B19	1.30×10^{-3}	1.30×10^{-3}	1.50×10^{-3}	1.60×10^{-3}
B20	8.55×10^{-4}	9.12×10^{-4}	1.00×10^{-3}	1.10×10^{-3}
B21	1.50×10^{-3}	1.60×10^{-3}	1.70×10^{-3}	1.80×10^{-3}
B22	8.84×10^{-4}	9.43×10^{-4}	1.00×10^{-3}	1.10×10^{-3}
B23	1.80×10^{-3}	1.90×10^{-3}	2.10×10^{-3}	2.20×10^{-3}
B24	2.10×10^{-3}	2.20×10^{-3}	2.40×10^{-3}	2.50×10^{-3}
B25	4.03×10^{-4}	4.38×10^{-4}	4.93×10^{-4}	5.33×10^{-4}
B26	7.10×10^{-4}	7.61×10^{-4}	8.41×10^{-4}	8.99×10^{-4}
B27	5.19×10^{-4}	5.59×10^{-4}	6.30×10^{-4}	6.71×10^{-4}



A- Very high hesitation
B- High hesitation
C- Little hesitation
D- No hesitation

Fig. 5.7 Comparison of failure probability values for different hesitation grades.

Table 5.6 Uncertainty analysis for TDFFTA

Sl. No.	Basic event Number	(Using fuzzy FFTA)	(Using TDFFTA)	Relative percentage difference
1	B1	$8.57x10^{-4}$	$6.75x10^{-4}$	21.23
2.	B2	$3.90x10^{-3}$	$3.30x10^{-3}$	15.38
3	B3	$9.23x10^{-4}$	$7.32x10^{-4}$	20.69
4	B4	$8.00x10^{-3}$	$7.00x10^{-3}$	12.50
5	B5	$1.80x10^{-3}$	$1.50x10^{-3}$	16.66
6	B6	$1.30x10^{-3}$	$1.00x10^{-3}$	23.08
7	B7	$6.60x10^{-4}$	$5.12x10^{-4}$	22.42
8	B8	$1.10x10^{-3}$	$9.32x10^{-4}$	15.27
9	B9	$3.40x10^{-3}$	$3.00x10^{-3}$	11.76
10	B10	$1.40x10^{-3}$	$1.10x10^{-3}$	21.43
11	B11	$2.89x10^{-4}$	$1.95x10^{-4}$	32.53
12	B12	$2.59x10^{-4}$	$2.00x10^{-4}$	22.78
13	B13	$3.78x10^{-4}$	$2.66x10^{-4}$	29.63
14	B14	$2.60x10^{-3}$	$2.20x10^{-3}$	15.38
15	B15	$2.10x10^{-3}$	$1.80x10^{-3}$	14.29
16	B16	$2.30x10^{-3}$	$2.00x10^{-3}$	13.04
17	B17	$2.10x10^{-3}$	$1.70x10^{-3}$	19.05
18	B18	$2.20x10^{-3}$	$1.80x10^{-3}$	18.18
19	B19	$1.60x10^{-3}$	$1.30x10^{-3}$	18.75
20	B20	$1.10x10^{-3}$	$8.55x10^{-4}$	22.27
21	B21	$1.80x10^{-3}$	$1.50x10^{-3}$	16.67
22	B22	$1.10x10^{-3}$	$8.84x10^{-4}$	19.64
23	B23	$2.20x10^{-3}$	$1.80x10^{-3}$	18.18
24	B24	$2.50x10^{-3}$	$2.10x10^{-3}$	16.00
25	B25	$5.33x10^{-4}$	$4.03x10^{-4}$	24.39
26	B26	$8.99x10^{-4}$	$7.10x10^{-4}$	20.58
27	B27	$6.71x10^{-4}$	$5.19x10^{-4}$	22.65

(V.R. Renjith et.al. J. Haz. Mater. 183 (2010)pp108)

5.9 CONCLUSIONS

FTA is one of the many quantitative hazard identification tools used extensively to assess the safety and reliability of the complex systems in refineries, chemical process plants and many other industries. In conventional FTA probability of failure of basic events must be known in advance. These are, in general, obtained from the international database which may not be exactly applicable to Indian conditions. Therefore the failure probability values obtained here are different from the available values. The differences in the operating procedures as well as climatic factors contribute to the variations. The sensitivity analysis of probability of failure of basic events pin-point the areas where more attention is required for preventing chlorine release. Two dimensional fuzzy fault tree analyses is an effective tool for expert elicitation where hesitation is to be included for accuracy. This study reveals that, flange leak due to gasket failure and pipe rupture due to corrosion play a very important role in the probability of release of chlorine. This has been substantiated by the extensive analysis carried out by correlating the data and expert opinions from the concerned industry. This method could be extended to all complex chlor- alkali industry as the basic events identified here are more or less common to all chlor- alkali units. The above method may be applied for refineries, petrochemical, fertilizer and pesticide industries.

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Chapter **6**

SUMMARY AND CONCLUSIONS

Consequence analysis is gaining importance in the industrial disaster mitigation and management decisions. 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 modelling shows that the hazardous distances for certain chemicals extended up to 90 meters which might prevent effective fire fighting in case of a pool fire. The domino effects on adjacent tanks are also found to be significant in many cases. The consequence calculations have been made for explosion scenarios also. A maximum threat zone of 560 meters is observed in the case of cyclohexane. From the dispersion modelling, it is found that, the hazardous inventory, wind speed, wind direction and air temperature are the deciding factors for the large 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 deciding the location of rehabilitation centres and the local emergency control rooms (in case of offsite emergency plan).

This research work explored the concept of analyzing human vulnerability to chemical accidents in the vicinity of an industrial area. A geographical information system-based methodology for mapping vulnerability is proposed for the Udyogamandal area. Vulnerability assessment helps screening key nodes for prioritizing risk management, especially for protecting risk targets against environmental risks. Knowledge of the spatial distribution of physical and social vulnerability, as well as the overview of the total vulnerability are useful for preparing a better disaster management and mitigation strategy to reduce the risk in the areas under consideration. This work integrates 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 in the areas surrounding industrial belts.

FTA is an effective way to assess safety and reliability of complex systems, in which fuzzy is an objective issue due to unavailability and vagueness of failure probability data related to the basic events. A methodology to handle fuzzy problems in FTA has been provided in this dissertation by combining expert elicitation with fuzzy set theory. In conventional FTA, probability of failure of basic events must be known in advance. These are, in general, obtained from the international database which may not be exactly applicable to Indian conditions. Therefore the failure probability values obtained here are different from the available values. The differences in the operating and maintenance procedures as well as climatic factors at different geographic locations contribute to the variations. The sensitivity analysis of the probability of failure of basic events pin-point the areas where more attention is required for preventing chlorine release. Two dimensional fuzzy fault tree analysis has been proposed for balancing the hesitation factor involved in the expert elicitation. Two dimensional fuzzy fault tree analyses is an effective tool for expert elicitation where hesitation is to be included for accuracy. This study reveals that, flange leak due to gasket failure and pipe rupture due to corrosion play a very important role in the probability of release of chlorine. This has been substantiated by the extensive analysis carried out by correlating the data and expert opinions from the concerned industry. This method could be extended to all complex chlor- alkali industry as the basic events identified here are more or less common. The above method may be applied for refineries, petrochemical, fertilizer and pesticide industries. The method given in this dissertation can reduce the error in conventional fault tree analysis followed in India.

All our activities in society, economy, administration, management, engineering, medicine and science take place in a complex world where generally complexity arises from uncertainty in the form of ambiguity. Humans have addressed problems featuring complexity and ambiguity subconsciously since they could think; these ubiquitous features pervade most social, technical, and economical problems faced by the human race. The only way for computers to deal with complex and ambiguous issues is through fuzzy logical thinking, systemizing, controlling and deciding procedures.

Research contribution

- An attempt has been made to generate Indian version of failure probability values using fuzzy logic and expert elicitation.
- Introduced two dimensional fuzzy fault tree analysis (TDFFTA) instead of Fuzzy fault tree analysis (FFTA) to incorporate hesitation during expert elicitation.

Scope of future work

- Development of a real time model using GIS application for predicting vulnerability for better disaster management.
- Model used here (FFTA and TDFFTA) is applied for chlor-alkali industry. It can be extended to refinery, pesticide and fertilizer industries and one can generate the whole database of failure probability values for Indian conditions.

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Annexure A

SAMPLE WORK SHEETS FOR PHA

A1. Preliminary Hazard analysis in Ammonia storage plant

Accident	**System**	**Hazard**	**Safety relevant component**
Leak occurred in storage tank	Storage vessel	Formation of toxic vapour and dispersion of it outside the storage tank due to	
		-Corroded vessel	Vessel corrosion protection
		-Refrigeration failure	Inspection and standby arrangements
		-Insulation failure	Periodic inspection of insulation
		-Faulty safety valve	Safety valve

A2. Preliminary Hazard analysis in Chlorine storage plant

Accident	System	Hazard	Safety relevant component
Leak occurred in storage tank	Storage vessel	Formation of toxic vapour and dispersion of it outside the storage tank due to	
		-Corroded vessel	Vessel corrosion protection
		-Refrigeration failure	Inspection and standby arrangements
		-Insulation failure	Periodic inspection of insulation
		-Faulty safety Valve	Safety valve

A3. Preliminary Hazard analysis in LPG storage plant

Accident	**System**	**Hazard**	**Safety relevant component**
Vapour explosion	Storage vessel	Formation of an explosive atmosphere outside storage vessel due to	
		-Faulty safety Valve	Safety Valve
		-Corroded vessel	Vessel corrosion protection
		-Overpressure	Pressure gauge, temperature gauge, sprinkler system, safety valve
BLEVE	Storage	External fire	

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Annexure B

SAMPLE WORK SHEETS FOR HAZOP

Study Node : Pipe line from chlorine storage vessel to filling point

Parameter : Flow

Guide Word	Deviations	Causes	Consequences
NO	No flow of chlorine to the filling point	Tank empty	No significant hazard
		Outlet valve closed	Pressure build up in the storage tank and chances of leak
		Outlet line blocked	Pressure build up in the storage tank and chances of leak
		Leak/rupture of pipeline	Minor/major toxic gas release
LESS	Less flow of chlorine from the storage tank to the filling point	Partial opening of the out let valve	Chances of pressure build up in the storage line
		Minor leak in the pipeline	Minor release of chlorine to the atmosphere

Study Node : pressure indicates in the chlorine storage tank

Parameter: Pressure

Guide Word	Deviations	Causes	Consequences
NO	No pressure indicated by the pressure indicator	Faulty pressure gauge	Chances of pressure build up in the vessel leading to structural damage of vessel and chlorine release
		Isolation valve to the pressure gauge in the closed position	Chances of pressure build up in the vessel leading to structural damage of vessel and chlorine release
		Tank empty	No consequences
MORE	More pressure indicated by the pressure indicator	More pressure inside the storage tank	Chances of explosion due to pressure build up
		Vessel exposed to heat source	
		Outlet section of the storage tank blocked during transfer	
		Failure of safety relief valve	
		Fault in pressure line	

Study Node : Ammonia storage tank

Parameter : Pressure

Guide Word	Deviations	Causes	Consequences
MORE	More pressure in the storage tank	HIC 2703 fails to open HIC 2702 fails to close HIC 2704 fails to close More feed temperature Compressor failure External fire exposed to the storage tank Relief Valve failure	Pressure build up in the tank leads to leakage from the tank or .rupture of the tank: release of ammonia to atmosphere
LESS	Less pressure in the storage tank	Leakage Compressor fails to stop SV 2701 failure PS 2705 mal function	Chances of leakage from the inlet pipeline : Ammonia release to the atmosphere

Study Node : Ammonia storage tank

Parameter : Level

Guide Word	Deviations	Causes	Consequences
MORE	More level in the storage tank	HIC 2701 and HIC 2702 malfunction	Level rise in the tank leads to overfilling and leakage; ammonia release to the atmosphere
LESS	Less level in the storage tank	Leakage in the storage tank’ Transfer pump fails to stop	Release of ammonia to the atmosphere

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Annexure **C**

SAMPLE CALCULATIONS

Sample calculations for Table 3.6; Sl. No. 2

Mass burning rate

$$\frac{dm}{dt} = \frac{0.001H_c}{C_p\left(T_b - T_a\right) + H_{vap}}$$

where H_c - heat of combustion (J/kg), C_p - Specific heat at constant pressure (J/kg K), T_b - boiling point in (K), T_a - ambient temperature (K), H_{vap} - heat of vaporization (J/kg).

$$\frac{dm}{dt} = \frac{0.001(4.015\times 10^7)}{1696\left(353.1-306\right)+4.36\times 10^5}$$
$$= 0.07784$$

Total heat flux from a pool of radius "r" (meters)

$$Q = \frac{\left(\Pi r^2 + 2\Pi rH\right)\left[\dfrac{dm}{dt}\right]\eta H_c}{72\left[\dfrac{dm}{dt}\right]^{0.61} + 1}$$

where Q - total heat flux (W/m^2), H-flame height (m), η - efficiency factor (0.15 – 0.35).

Flame height

$$H = 84r\left[\frac{dm\!\!\left/\!{dt}\right.}{\rho_a\left(2gr\right)^{0.5}}\right]^{0.6}$$

where ρ_a - density of air (kg/m^3), g - acceleration due to gravity (m/s^2).

$$H = 84r\left[\frac{dm\!\!\left/\!{dt}\right.}{\rho_a\left(2gr\right)^{0.5}}\right]^{0.6}$$

$$H = 84\times 6.25\left[\frac{0.07784}{1.2\left(2\times 9.81\times 6.25\right)^{0.5}}\right]^{0.6}$$

$$= 24m$$

Total heat flux

$$Q = \frac{\left(\Pi r^2 + 2\Pi rH\right)\left[\frac{dm}{dt}\right]\eta H_c}{72\left[\frac{dm}{dt}\right]^{0.61} + 1}$$

$$Q = \frac{\left(\Pi(6.25)^2 + 2\Pi(6.25)24\right)\left[0.07784\right]\times 0.3\times 4.015\times 10^7}{72\left[0.07784\right]^{0.61} + 1}$$

$$= 6.176\times 10^7 W/m^2$$

Intensity of heat radiation

$$I = \frac{\tau Q}{4\Pi R^2}$$

where τ - transmissivity of air path, Q - total heat flux (W/m^2).

$$I = \frac{\tau Q}{4\Pi R^2}$$

$$I = \frac{1 \times 6.176 \times 10^7}{4\Pi (50)^2}$$
$$= 1.96\, kW / m^2$$

Sample calculations for Table 3.18 (Item No. 3)

$$W = \frac{\eta M H_c}{E_{TNT}}$$

where W - equivalent mass of TNT (kg), η - empirical explosion efficiency, M- mass of hydrocarbon (kg), H_c - heat of combustion of flammable substance (J/kg), E_{TNT} - heat of combustion of TNT (J/kg).

$$W = \frac{\eta M H_c}{E_{TNT}}$$

$$W = \frac{0.05 \times 8975 \times 4.594 \times 10^7}{4500 \times 10^3}.$$
$$= 4581.23 kg$$

$$Z = \frac{R}{W^{1/3}}$$

where Z - scaled distance in the graph, R- Radial distance from the surface of the fire ball (m), W - TNT equivalent (kg).

$$Z = \frac{R}{W^{1/3}}$$

$$Z = \frac{100}{(4581.23)^{1/3}}$$
$$= 6.021m$$

From the Fig 3.1 overpressure corresponding to 6.021m is 0.3kPa

Sample calculation for Table 3.23 (Item No. 2)

$$E_r = \tau_a E F_{21}$$

where E_r - emissive radiative flux received by a receptor (W/m^2), τ_a - transmissivity (dimensionless), E -surface emitted radiative flux (W/m^2), F_{21} - view factor (dimensionless).

$$E = \frac{RMH_c}{\Pi D_{\max}^2 t_{bleve}}$$

where E - radiative emissive flux (W /m^2), R - radiation fraction of heat of combustion (dimensionless), M - initial mass of fuel in the fire ball (kg), H_c - heat of combustion per unit mass (J/kg), $D_{\max}$ - maximum diameter of fire balls (m), t_{bleve} - duration of fireballs

$$\tau_a = 2.02\left(P_w X_s\right)^{-0.09}$$

where τ_a - atmospheric transmissivity (0-1), P_w -water partial pressure (N/m^2), X_s - path length distance from the flame surface to the target (m).

$$P_w = 1013.25(RH)\exp\left(14.4114 - \frac{5328}{T_a}\right)$$

where RH - relative humidity, T_a - ambient temperature (K).

$$F_{21} = \frac{H\left(D/2\right)^2}{\left(L^2 + H^2\right)^{3/2}}$$

where F_{21} - view factor, D - diameter of the fire ball

When the distance L is greater than D

$$F_{21} = \frac{L\left(D/2\right)^2}{\left(L^2 + H^2\right)^{3/2}}$$

$$D_{\max} = 5.8M^{1/3}$$

$$t_{bleve} = 2.6M^{1/6}$$

$$H_{bleve} = 0.75D_{\max}$$

where, M is the initial mass of the flammable material in kg.

Maximum diameter of fire ball

$$\begin{aligned} D_{\max} &= 5.8(8975)^{1/3} \\ &= 120.00m \end{aligned}$$

Duration of BLEVE

$$t_{bleve} = 2.6 \times (8956)^{1/6}$$
$$= 11.84s$$

Distance from the fire ball centre to ground (vertical distance)

$$H_{bleve} = 0.75(120)$$
$$= 90m$$

Water partial pressure

$$P_w = 1013.25(80)\exp\left(14.4114 - \frac{5328}{306}\right)$$
$$= 4035.7N/m^2$$

Transmissivity

$$\tau_a = 2.02\left(4035.6 \times 91\right)^{-0.09}$$
$$= 0.64$$

Surface emitted irradiative flux

$$E = \frac{0.4 \times 8975 \times 45940}{\Pi \times 120^2 \times 11.84}$$
$$= 308.06kW/m^2$$

View factor

$$F_{21} = \frac{90\left(60\right)^2}{\left(50^2 + 90^2\right)^{3/2}}$$
$$= 0.29$$

Radiation received by a receptor

$$E_r = 0.64 \times 0.29 \times 308.06$$
$$= 57.17 kW / m^2$$

TNT equivalent

$$W = 3.662 \times 105^{-5} V \left(\frac{P_1}{P_0} \right) R_g T_0 \ln \left(\frac{P_1}{P_2} \right)$$

$$W = 3.662 \times 105^{-5} \times 1^8.7 \left(\frac{27.58 \times 10^5}{1.01 \times 10^5} \right) \times 8.319 \times 10^3 \times 109.32 \times \ln \left(\frac{27.58 \times 10^5}{1.01 \times 10^5} \right)$$
$$= 55957.09 kg$$

Pressure of blast wave

$$P_b = P_s \left[1 - \frac{3.5(\gamma - 1)(P_s - 1)}{\sqrt{\left(\gamma T / M \right)(1 + 5.9 P_s)}} \right]^{-2\gamma / \gamma - 1}$$

where P_s - pressure at the surface of the vessel (bar abs.), P_b - burst pressure of the vessel (bar abs.), γ - heat capacity ratio of the expanding gas, M - molecular weight of the expanding gas, T - absolute temperature of the expanding gas (K).

$$P_b = P_s \left[1 - \frac{3.5(\gamma - 1)(P_s - 1)}{\sqrt{\left(\gamma T / M \right)(1 + 5.9 P_s)}} \right]^{-2\gamma / \gamma - 1}$$

$$688.7 = P_s \left[1 - \frac{3.5\left(1.4-1\right)\left(P_s-1\right)}{\sqrt{\left(1.4\times 300\!\!\left/_{29}\right.\right)\left(1+5.9\times P_s\right)}} \right]^{-2\times 1.4 \!\left/_{1.4-1}\right.}$$

$$P_s = 10.75\times 10^5\, N/m^2$$

Individual risk estimation

Probit equation for pressure effects of VCE

$$P_r = -77 + 6.91(\ln P^o)$$

Where P^o is the peak over pressure (Pa).

Here P^o is 150 kPa (from Table 3.26)

$$\begin{aligned} P_r &= -77 + 6.91(\ln 150000) \\ &= 5.35 \end{aligned}$$

From the probit table % fatality corresponding to 5.35 is 64%

Probit equation for heat radiation from pool fire

$$P_r = -36.38 + 2.56\ln(tq^{4/3})$$

Here t is the duration in seconds and q is the intensity of heat radiation in kW /m^2.

q (from Table 3.1) for first degree burn is 4.2 kW /m^2

Duration of exposure is assumed as 90 see

$$\begin{aligned}P_r &= -36.38 + 2.56\ln(90 \times (4200)^{4/3}) \\ &= 3.54\end{aligned}$$

Percentage fatality = 8%

Individual risk at x,y

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i}$$

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. $IR_{x,y,i}$, can be estimated using the equation.

$$IR_{x,y,i} = f_i p_{f,i}$$

where f_i is the frequency of incident outcome case *i,* from the frequency analysis and $p_{f,i}$ is the probability that incident outcome case *i* will result in a fatality at location *x, y,* from the consequence and effect models.

$$IR_{x,y,i} = f_i p_{f,i}$$

$$\begin{aligned}IR_{x,y(VCE-cyclohexane)} &= 1.2 \times 10^{-5} \times 0.64 \\ &= 7.6 \times 10^{-4}\end{aligned}$$

$$\begin{aligned}IR_{x,y(chlorine)} &= 7.96 \times 10^{-2} \times 0.15 \\ &= 1.194 \times 10^{-2}\end{aligned}$$

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i}$$

$$IR_{x,y} = (3.12\times10^{-7} + 3.00\times10^{-9})$$

$$IR_O = 3.15\times10^{-7}$$

Estimation of societal risk

$$N_i = \sum_{x,y} P_{x,y} p_{f,i}$$

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 incident outcome case i will result in a fatality at location x, y.

$$N_i = \sum_{x,y} P_{x,y} p_{f,i}$$

Here population density = 3000 per sq. Km

Probability wind in a particular direction is 40% (from the meteorological data)

Availability of people in that area during the incident outcome (70%)

% fatality due to that particular incident outcome – 0.15

$$N_i = (3000\times2.88\times0.7\times0.4)\times0.15$$

= 362 (Refer Table 4.5)

Sample calculation for Weighting factor (Refer Table No. 5.3 Sl. No. 7)

Weighting score = Title score + educational level score +Service time score + Age score

= 5+5+4+4

=18

Weighting factor = Weighting score/ total weighting score

= 18/1375

=0.013

$$M_i = \sum_{j=1}^{n} w_j A_{ij}, i = 1, 2, 3, ...m$$

From the mat lab code

Mi = (a,b1,b2,c)

Mi = (0.0748,0.1400,0.1985,0.322)

$$\mu_L(N) = \frac{(1-a)}{[1+(b1-a)]}$$

$$\mu_R(N) = \frac{c}{[1+(c-b2)]}$$

$$\mu_L(N) = \frac{(1-a)}{[1+(b1-a)]}$$

$$\mu_L(N) = \frac{(1-0.0748)}{[1+(0.1400-0.0748)]}$$

$$= 0.8686$$

$$\mu_R(N) = \frac{c}{[1+(c-b2)]}$$

$$\mu_R(N) = \frac{0.3222}{[1+(0.3222-0.1985)]}$$

$$= 0.2867$$

$$FPS = \frac{\left[\mu_R\left(N\right)+\left(1-\mu_L\left(N\right)\right)\right]}{2}$$

$$FPS = \frac{\left[0.2867+\left(1-0.8686\right)\right]}{2}$$

$$= 0.2091$$

Fuzzy Failure probability (FFP)

$$FFP = \begin{cases} \dfrac{1}{10^k} & FPS \neq 0 \\ 0 & FPS = 0 \end{cases}$$

where

$$k = \left[(1-FPS)/FPS\right]^{\frac{1}{3}} \times 2.301$$

$$k = \left[(1-0.2091)/0.2091\right]^{\frac{1}{3}} \times 2.301$$

$$= 3.5868$$

$$FFP = \frac{1}{10^k}$$

$$= \frac{1}{10^{3.5856}}$$

$$= 2.596 \times 10^{-4}$$

(Refer Table 5.4, Sl. No. 12)

Scores of two dimensional fuzzy number

Let (M, H) be a two dimensional fuzzy number. Then the scores of two dimensional fuzzy number T is given by.

$$T=(\frac{1+R(M)-L(M)}{2}),(\frac{1+R(H)-L(H)}{2})$$

Where [L (M), R (M)] and [L (H), R (H)] are left and right scores of opinion and hesitancy fuzzy number respectively**.**

Crisp scores of basic events using TDFFTA

Let two dimensional crisp scores be M (A_i), H (A_i) for each basic event. The score of opinion and hesitancy variables can be obtained by using equation (5.4), (5.5) and (5.6).

The crisp score T (A_i) of each basic event = membership score M (A_i) – y [hesitancy score H (A_i)], where

$$y=\frac{\text{minimum difference of scores in opinion variable}}{\text{number of hesitancy variable}}$$

y= 0.1917/4 (from Fig. 5.4) =0.0639

Tot al score = membership score – y (hesitance score)

= 0.3036 – 0.0639 (0.5646)   = 0.2675

$$k=\left[(1-0.2675)/0.2675)\right]^{\frac{1}{3}}\times 2.301$$
$$=3.218$$

Estimate FFP similar to that of previous calculation

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LIST OF PUBLICATIONS

International Journals

[1] V.R. Renjith, G. Madhu, V. Lakshmana Gomathi Nayagam, A.B. Bhasi. *Two dimensional fuzzy fault tree analysis for chlorine release from a chlor-alkali industry using expert elicitation*,, **Journal of Hazardous Materials**, **Elsevier publication.** (Accepted, doi; 10.1016/j.jhazmat.2010.06.116).

[2] V.R. Renjith, G. Madhu, *Consequence analysis for accidental release of flammable and toxic materials from storage installations in an industrial belt, south India – a case study,* **Journal of Safety Science**, **Elsevier publication**. (Under review).

[3] V.R. Renjith, G. Madhu, *Explosion modelling of hazardous materials for a better industrial disaster management plan*, **American Journal of Environmental Science**, **Science publication**. (Under review).

[4] V.R. Renjith, G. Madhu, V. Lakshmana Gomathi Nayagam, *Quantitative Risk assessment of chlor- alkali industry using fuzzy logic and expert elicitation,* **American Journal of Environmental Science**, **Science publication**. (Under review).

[5] V.R. Renjith, G. Madhu, *Individual and societal risk analysis and mapping of human vulnerability to chemical accidents in the vicinity of an industrial area,* **International Journal of Applied Environmental Science, Research India Publication .** *(communicated).*

Conferences

[1] V.R. Renjith, G. Madhu, *Explosion modelling of hazardous materials stored in Udyogamandal industrial area*, PETROSAFE 2007, National conference on hydrocarbon safety (23-25 April 2007), Kochi, India

[2] V.R.Renjith, G. Madhu, V. Lakshmana Gomathi Nayagam "*Fault tree analysis of chlorine release from a major accident industry using fuzzy logic*", National conference on fuzzy theory and applications (22-24 January 2009), St. Xavier's College Tirunelveli, India.

[3] V.R. Renjith, G. Madhu, *Quantitative risk assessment of chlorine release from a chlor-alkali industry*, Twenty fifth National Convention of Chemical Engineers (9-10 October 2009), Kochi, India.

[4] V.R. Renjith, G. Madhu, V. Lakshmana Gomathi Nayagam, *Application of fuzzy logic and expert elicitation in fault tree analysis*, National conference on Recent trends in Fuzzy and discrete Mathematics (19-21 November 2009), Aluva, India.

[5] V.R. Renjith, G. Madhu, *Explosion modelling hazardous materials for a better industrial disaster management plan,* International Conference on disaster management and mitigation.(16-18 December 2009), Dindigal, India.

[6] V.R. Renjith, G. Madhu, V. Lakshmana Gomathi Nayagam, *Quantitative Risk assessment of chlor alkali industry using Fuzzy logic and Expert elicitation,* International Conference on disaster management and mitigation. (16-18 December, 2009), Dindigal, India.

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Curriculum Vitae

Renjith V.R. was born in Cherthala, Alappuzha district of Kerala, India in 1975. He graduated with a B.Tech Degree in Mechanical Engineering from Govt. College of Engineering, Trivandrum under Kerala University in 1996. He completed his M.Tech Degree in Industrial Safety Engineering from NIT Trichy with first rank and gold medal in the year 2005. Since 1998, he is working in Cochin University of Science and Technology, Cochin, India. Now he is working as Reader in Safety and Fire Engineering Division, School of Engineering, Cochin University of Science and Technology. His teaching and research interest includes fire modelling, explosion modelling, dispersion modelling, effects modelling, fault tree analysis, fuzzy fault tree analysis, event tree analysis, HAZOP, FETI, disaster management, vulnerability analysis, safety in on & offshore drilling, and safety audit.

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