RISK ASSESSMENT OF A PETROLEUM OIL STORAGE TERMINAL

Ph.D. THESIS

by

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INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE – 247 667, INDIA
MARCH, 2014

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A THESIS

Submitted in partial fulfilment of the
requirements for the award of the degree
of
DOCTOR OF PHILOSOPHY

in

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this thesis entitled **"RISK ASSESSMENT OF A PETROLEUM OIL STORAGE TERMINAL"** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Centre of Excellence in Disaster Mitigation and Management, Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out at the Centre during the period from August, 2008 to March, 2014 under the supervision of Dr. B. R. Gurjar, Associate Professor, Department of Civil Engineering, Dr. Rajat Agrawal, Assistant Professor, Department of Management Studies (both associated to the Centre of Excellence in Disaster Mitigation and Management), Indian Institute of Technology Roorkee, Roorkee, and Dr. S.R. Wate, Director, National Environmental Engineering Research Institute, Nagpur, India.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

(RAVI KUMAR SHARMA)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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Supervisor	**Supervisor**	**Supervisor**

Date:

The Ph.D. Viva-Voce Examination of Ravi Kumar Sharma, Research Scholar, has been held on ____.

Signature of

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ABSTRACT

In the last decade, major accidents have occurred in petroleum storage terminals around the world, e.g., Burchfield, UK (2005), Puerto Rico, USA (2009), and IOCL Jaipur, India (2009), which have drawn attention of expert groups as well as researchers working in the area of risk assessment. Irrespective of these accidents, many developed countries have already adopted legislations for risk assessment and consequence analysis taking risk as a criterion. Developing countries like India, however, couldn't develop comprehensive guidelines due to lack of centralized mechanism to collect and maintain industrial accident database / information pertaining to the causes, consequences and preventive measures. Moreover, quantitative risk assessment studies related to accidents in petrochemical industry and storage facilities are sparse in India.

It is necessary to study the mechanisms of risk assessment of petroleum industrial accidents to prevent or effectively tackle the emergencies in future. The consequences of major accidents provide only latent information as it is difficult to generate or simulate accident scenarios either through laboratory or field investigations. That is why a scientific analysis of the past accidents is necessary so that it can provide significant information to determine the most probable accident scenarios for new situations. Therefore, to fill the existing gape in the area of risk assessment of petrochemical storage facilities, the present research study has been carried out, which mainly focus on simulation and modeling of vapour cloud explosion (VCE) and large tank fire at a petroleum oil storage terminal. The study also includes the assessment of cumulative effects of explosion and fire on onsite and offsite population in terms of individual and societal risks. The results obtained from explosion fire modeling have been used to propose an appropriate emergency response plan based on electronic incident command system (e-ICS).

To make the research more application oriented, the simulation and modeling of VCE and large tank fire have been applied for post risk assessment of Indian Oil Corporation Ltd. (IOCL) depot, Jaipur (India) accident. During this accident, high intensity blast pressure waves were generated across the terminal followed by multiple tank fires that destroyed several buildings and caused fatalities in the immediate surroundings.

Significant learning has occurred from the IOCL, Jaipur accident. The typical methods and practices employed for the hazard identification and risk assessment of this site were unlikely to have identified the high overpressure generated at the time of accident. However, the research on recent accidents such as Burchfield, UK (2005) provides evidences on how the geometry of the terminal and vegetation in vicinity can generate the conditions for very high overpressure.

The IOCL Jaipur accident resulted in release of approximately 2000 tonnes of gasoline when a 15 m high storage tank outlet valve leaked for approximately 80 minutes before the ignition of flammable mixture. A large and homogeneous flammable cloud covering an area of 180,000 m^2 was formed due to very low wind speed and neutral or stable weather conditions. The overpressure in excess of 200 kPa (2 bar), due to one of the major VCEs, was generated across most of the site, which was not uniformly distributed throughout the terminal (Chapter 4). The directional indicators point to the source of the detonation being in the Pipeline Division area in the north east corner of the site.

Subsequently, massive explosion immediately triggered the intense multiple tank fires. The large tank fire modeling reveals that the calculated flame height $(H/D)_{max,calc}$ lies between 0.9 and 1.5, which is within the observed range. The estimated surface emissive power ranges between 27 and 123 kW/m^2, as evaluated by adopting various models (*SFM, MSFM, TZM and TRSMFM*) for large-scale tank fires (Chapter 5). The irradiances (E_r) are calculated with a point source model and validated by the DNV Norway-based risk assessment PHAST 6.51 software. The modelled parameters of large tank fires showed a maximum percentage error of 25% with the observed values.

The assessment of individual and societal risk associated with the effects of explosions and fires gives the maximum individual risk level as 10^{-4} per year at a distance of around 100 m from the release point. The next individual risk level (i.e.10^{-5} per year) has reached up to a distance of 280 m within the terminal boundary. The maximum individual risk to offsite people is 6.8×10^{-5} per year. The individual risk values for onsite and offsite people falls within the acceptable range. F/N curve indicating societal risk falls in the ALARP (“As Low As Reasonably Practicable”) region where risk can be controlled with additional precautionary measures (Chapter 6). Thus, the total risk at the terminal does not lie in the unacceptable region but in ALARP region where substantial measures for risk reduction were needed. The consequences in and around the terminal might be high due to improper implementation of essential precautionary measures.

Accidents such as studied in this thesis may result in huge loss of lives and property, along with widespread environmental damage due to improper coordination and communication in handing the emergency. To address this issue, an automated networking system, named as the electronic - Incident Command System (e-ICS) has been proposed taking into account the results obtained from simulation and modeling of the Indian Oil Corporation Limited (IOCL) Jaipur storage terminal accident (Chapter 7). At the end, recommendations based on the lessons learnt from this study for improving safety aspects of petroleum storage terminals have been made in terms of appropriate preventive and mitigation measures with respect to future accidents (Chapter 8).

This is expected that overall methodology of simulation and modeling of vapour cloud explosion (VCE) and large tank fire proposed in this thesis followed by estimation of individual and societal risks can help the regulatory agencies to enhance and strengthen safety measures at petroleum oil storage terminals to prevent accidents and/or mitigate the consequences. The approach evolved and applied in this study can also be used for emergency response planning at petroleum oil storage terminals.

ACKNOWLEDGEMENT

This thesis has been carried out in the context of a doctoral program on “Risk Assessment of Petroleum Oil Storage Terminal Accident” at the Indian Institute of Technology Roorkee, India. A number of people and organizations have provided necessary help and support for the completion of this thesis and it gives me great pleasure to thank all of them.

I express my deep sense of gratitude to Dr. B. R. Gurjar, Associate Professor, Department of Civil Engineering, IIT, Roorkee, for enabling this opportunity to work under his kind supervision. I am very thankful for his continuous technical guidance and scientific discussions. A very sincere thank and deep appreciation to Dr. Rajat Agrawal, Assistant Professor, Department of Management Studies, IIT- Roorkee, for his guidance and suggestions on different topics of interest.

I would like to thank especially Dr. S. R. Wate, Director, National Environmental Engineering Research Institute (NEERI), Nagpur. I am very grateful for his expert suggestions, numerous discussions on various topics and his purposeful way of working which always motivated and supported me.

I would also like to thank Mr. Santosh Ghuge, Scientist, Environmental Impact and Risk Assessment Division, NEERI, Nagpur for providing excellent support and co-operation for conducting Quantitative Risk Assessment (QRA) modeling. I thank Rohit Wankar and Nitesh V Kirnake for their cooperation and great assistance.

Also, I wish to thank Dr. Ajay Gairola , Head Center of Excellence in Disaster Mitigation and Management, IIT Roorkee, and Prof. D. K. Paul, Emeritus Fellow and formerly Head of Center of Excellence in Disaster Mitigation and Management, for their constant moral support and encouragement for my work. I also thank Dr. Santosh Rangnekar, Head, Department of Management Studies for providing the facilities of Management Department, IIT Roorkee.

I am thankful to Ajay Nagpure, Pralhad Walvekar, Vijaya for the excellent cooperation and friendly support. I am also very thankful to Tahir Husain for his assistance.

It gives me great pleasure to thank my mother who has always been a constant source of inspiration and encouragement to me in all my endeavors. I thank my brother for his love, friendship and patience throughout all these years.

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NOTATIONS, SYMBOLS AND ABBREVIATIONS

a_{sz}		area fraction of smoke zone
A	[m^2]	area of the hole,
$\bar{A}_F$	[m^2]	time averaged flame area
$\bar{A}_{\mathrm{LS}}$	[m^2]	time averaged flame area of yellow luminous spots
A_P	[m^2]	pool area
C_D		discharge coefficient
C_S	[m/s]	sound velocity
C_0	[m/s]	speed of sound in air
C/H		carbon to hydrogen atomic ratio in fuel
D	[m]	pool or tank diameter
E_c	[kJ/kg]	heat of combustion of flammable gas,
E_{TNT}	[4680 KJ/kg]	heat of combustion of TNT
E_r	[kW/m^2]	irradiance at the horizontal distance Δy from flame surface
F_P	[m^{-2}]	point source view factor
$Fr_{\mathrm{f}} \equiv \frac{\bar{m}_f''}{\rho_{a\sqrt{gD}}}$		fuel Froude number
g	[m^2/s]	gravitational constant
h_L	[m]	liquid head above the hole
H	[m]	height of the combustion zone
H_{cl}	[m]	height of the hot, clear burning zone not obscured by black smoke
$\bar{H}/D$	[m]	time-averaged relative height of the visible flame
$(H/D)_{max}$	[m]	maximum relative height of the visible flame
ΔH_c	[kJ/kg]	Heat of Combustion
H_{cl}	[m]	height of the hot, clear burning zone not obscured by black smoke
$\Delta\ H_c$	[J/kg]	Specific heat of combustion

ΔH_v	[kJ/kg]	latent heat of vaporization
k_g	[m/s]	mass transfer coefficient
L_P	[m]	pool length
LFL	[% v/v]	lower flammability limit
m	[Kg/s]	mass of discharge rate
m_{mass}	[kg/s]	evaporation rate per unit area,
m^*	[-]	dimensionless mass burning rate of fuel
$\bar{m}_f''$	[kg $s^{-1}m^{-2}$]	mass burning rate
$\bar{m}_{f,max}''$	[kg $s^{-1}m^{-2}$]	maximum mass burning rate
MW		molecular mass
M	[kg]	mass of fuel in the cloud
P	[bar]	atmospheric pressure,
P^0	[bar]	maximum overpressure,
P_g	[k Pa]	gauge pressure,
P^{sat}	[-]	saturation vapour pressure of the liquid
q^0	[bar]	maximum dynamic pressure,
Q	[kW]	heat release rate of the fire
$\bar{Q}_\mathrm{c}$	[kW]	heat of combustion
SEP	[kW/m^2]	surface Emission Power of the flame
R_g	[J/K /mol]	ideal gas constant,
t	[s]	time
T_a	[K]	ambient temperature
T_f	[K]	average surface emission temperature of the flame
T_L	[K]	temperature of the liquid
UFL	[% v/v]	upper flammability limit
U	[m/s]	shock wave velocity
u_w^*	[m/s]	wind velocity
U_9^*		dimensionless wind speed measured at a height of 9m
u_F	[m/s]	actual (absolute) flame front velocity with partial
u^*		dimensionless wind speed
V_1	[m^3]	volume of the unburnt gas or flammable volume of the hemisphere gas cloud before ignition

V_0	[m^3]	fume volume or expanded volume of the gas cloud after ignition m^3
$\bar{V}_{a,max}$	[m/s]	maximum burning velocity
ϑ	[m/s]	release velocity,
W		equivalent mass of TNT
x	[m]	distance from the point source to the targe

Greek symbols

α		adiabatic exponent
η_{rad}		radiative fraction of the fire
η		empirical explosion efficiency (unitless)
β		correction factor referring to the optical path height
$k\beta$		mean beam length corrector-flame attenuation coefficient product
τ_a		atmospheric transmissivity
ε_1		isobar expansion ratio
$\bar{\varepsilon}_F$		effective emissivity of the (gray) flame
ε_F		flame emissivity
σ	[$kWm^{-2}K^{-4}$]	Stefan-Boltzmann-constant
ρ	[Kg/m^3]	Density of the liquid,
ρ_0	[Kg/m^3]	Density of the unburnt gas orthe gas cloud before ignition
ρ_1	[Kg/m^3]	Density of the fumes (burntgas) or density of the gas cloudafter ignition
ρ_a	[kg/m^3]	Ambient density
ρ_f	[kg/m^3]	Density of fuel

Subscripts

a	ambient conditions
act	actual quantity (i.e., the luminous flame is partly obscured by black smoke)
calc	calculated or predicted quantity
cl	hot, clear burning zone of the height or height H_{cl}

exp	experimental quantity
hs	hot spots
kβ	mean beam length corrector extinction coefficient product, m^{-1}
la	Laminar
LS	yellow luminous spots
ma	maximum SEP, i.e. the flame is not obscured with black smoke
max	maximum value of a quantity
P	pool
SA	area of black smoke
sp	parcel of black smoke
SZ	zone of black smoke

Abbreviations

3G	Third generations of mobile telecommunications
BPCL	Bharat Petroleum Corporation Limited
CFD	Computational Fluid Dynamics
e-ICS	Electronic Incident Command System
EMCS	Emergency Management Computation Systems
EOC	Emergency Operations Center
ERP	Emergency Response Plan
ERP	Emergency Response Planning
ERT	Emergency Response Team
FLACS	Flame Acceleration Simulator
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HF	High Frequency
HPCL	Hindustan Petroleum Corporation Limited

IC	Incident Commander
ICS	Incident Command System
IOCL	Indian Oil Corporation Ltd
IRSR	Individual Risk and Societal Risk
MoPNG	Ministry of Petroleum and Natural Gas
MOVs	Motor Operated Valves
MSFM	Modified Solid Flame Model
PPEs	Personal Protective Equipment
QRA	Quantitative Risk Assessment
SCBA	Self Contained Breathing Apparatus
SEP	Surface Emission Power
SFM	Solid Flame Radiation Model
SOP	Standard Operating Procedure
TRM	Two-zone Radiation Model
TRSMFM	Thermal Radiation for Single and Multiple Tank Fires Model
TSV	Thermal Safety Valve
UHF	Ultra High Frequency
UVCE	Unconfined Vapour Cloud Explosion
VCE	Vapour Cloud Explosion
VHF	Very high frequency

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Oil and gas sector which deals with processing and storing of crude oil, petroleum products and petrochemicals is a core sector of the economy and therefore has a significant role in the nation’s economic development. This sector has strategic significance and plays a crucial role in addressing country’s energy concerns, and there by influence decisions on all other spheres of the economy. This sector has been witnessing a steady growth due to intensified exploration and production activities in India. The oil refining activities have grown at a steady pace in India, which may make it a refinery hub in the coming years. Besides this, rapid urbanization in many parts of the country has resulted in increased fuel outlets, storage inventories and capacities, and the evacuation of oil and gas through pipelines. Due to increase in such activities, the safety concerns while handling hazardous chemicals have become a major and critical factor in the oil and gas industries. Since most of the oil and gas are highly inflammable, the impact of an accident can cause complete destruction and severely affect the surrounding population or facilities. Such accidents result in loss of material and lives, and also damage the environment. It is, therefore, necessary to examine and assess the sequence of events comprehensively and develop an understanding of the underlying mechanisms to amicably address the prevention, mitigation and land-use planning issues related to petrochemical industries.

The progression and consequences of major accidents provide only latent information as it is difficult to generate or simulate accident scenarios either through laboratory or field investigations. That is why a scientific analysis of the past accidents is to be carried out because it can provide significant information to determine the most probable accident scenarios for new situations. However, it should be noted that the risk assessment techniques have intrinsic boundaries with respect to fully rebuilding past-accident situations due to the complexities introduced by event interactions and multi component or multiphase systems encountered in real situations. Thus, it is imperative that the oil and gas industries need to be very conscious and should not be negligent in adopting stringent safety measures while handling these petrochemicals.

1.2 GLOBAL CONCERNS

Over the previous decades, increasing awareness of the hazards posed by accidental fuel releases has stimulated worldwide research into the formation, evolution, combustion and explosion of fuel clouds and their consequent effects. Accidental release of flammable substances into the atmosphere is, therefore, one of the main concerns in modern industry, where a wide range of hydrocarbons are used on a large scale. A typical cause of such a release is partial or total loss of containment followed by depressurization of a high-pressure storage vessel or pipeline. Vapour fuel clouds from accidental releases may ignite, burn, explode or detonate. The consequent pressure waves, high-speed fragments, fires, and fireballs may cause severe human casualties and property losses. In the last decade, major accidents at Buncefield, UK (2005), Puerto Rico, USA (2009), and Jaipur, India (2009) show the destructive potential of such incidents at terminals and tank farms. A wide range of similarities has been observed among these accidents most importantly the one related to Vapour Cloud Explosion (VCE) followed by the massive fire. Since only the Buncefield and Jaipur accidents investigation reports have been published till date, most of the factors leading to overpressure in the other accidents can be arbitrated only on the basis of postulations of the same or the information collected from newspapers and magazine articles.

1.3 INDIAN SCENARIO

The industrial accident like Bhopal Disaster (1984) in India was a significant blow not only to the commercial sector but also to the national economy. In the recent years, major petrochemical industries accidents like Indian Oil Corporation's Ltd. (IOCL) Jaipur terminal (2009), IOCL Navi Mumbai terminal (2011), IOCL Hazira, Surat, Gujarat terminal (2013), and HPCL Refinery Visakhapatnam (2013) forced the regulatory organizations and scientific groups to be greatly concerned about the proper safety measures to avoid such calamities in the future. Such incidents have not only caused huge financial losses and disruption of oil supply but also led to the loss of human lives and widespread damage to the surrounding environment. The risk posed by such industrial accidents rises as the density of industries and human population increases. This is particularly prominent in industrial areas of developing countries like India where lack of resources for proper spatial planning, the close proximity of residential neighborhoods and vulnerable communities to potentially hazardous industries, difficulty in sharing information among the administrative bodies and inadequate training of responders make the matter more alarming. Thus, the practice of quantitative risk assessment (QRA) is to be encouraged in developing countries like India so that it can enable the industries, decision makers and stakeholders to assess the relative impacts of various industrial hazards.

1.4 MOTIVATION AND NEED FOR THE STUDY

Petrochemical industries process hazardous chemicals which have the potential to cause major accidents in case of equipment failure or human error. As most of such industries are situated adjacent to densely populated urban or rural locations (particularly in developing countries), it is significant to study the mechanisms of accidents that may take place and the damage they may cause so that mitigative measures can be taken before any tragedy occurs. Additionally, in modern industries, the probability of “chain of accidents” or cascading/domino effect has been increasing. This type of study, therefore, can contribute towards evolving strategies for cleaner and safer functioning of these industries.

1.5 OBJECTIVES AND SCOPE

The present study has the following main objectives:

- Quantification of industrial process risk to the individual or the surrounding population through fire and explosion modeling pertaining to a petroleum oil storage terminal.
- Validation of fire and explosion models with the real scenario.
- Delineation of Emergency Management Plan (EMP) based on electronic - Incident Command System (e-ICS).

The additional outcome of this study would be to illustrate what the industry can learn from recent major accidents and thereby take appropriate measures to prevent major accidents in the future. Lessons learnt from the past accidents are important for the future safe operations of process equipments and oil storage tanks. The flowchart of Fig. 1.1 shows the different stages of the study focused on the accident that occurred in the petroleum oil storage terminal of IOCL, Jaipur, India.

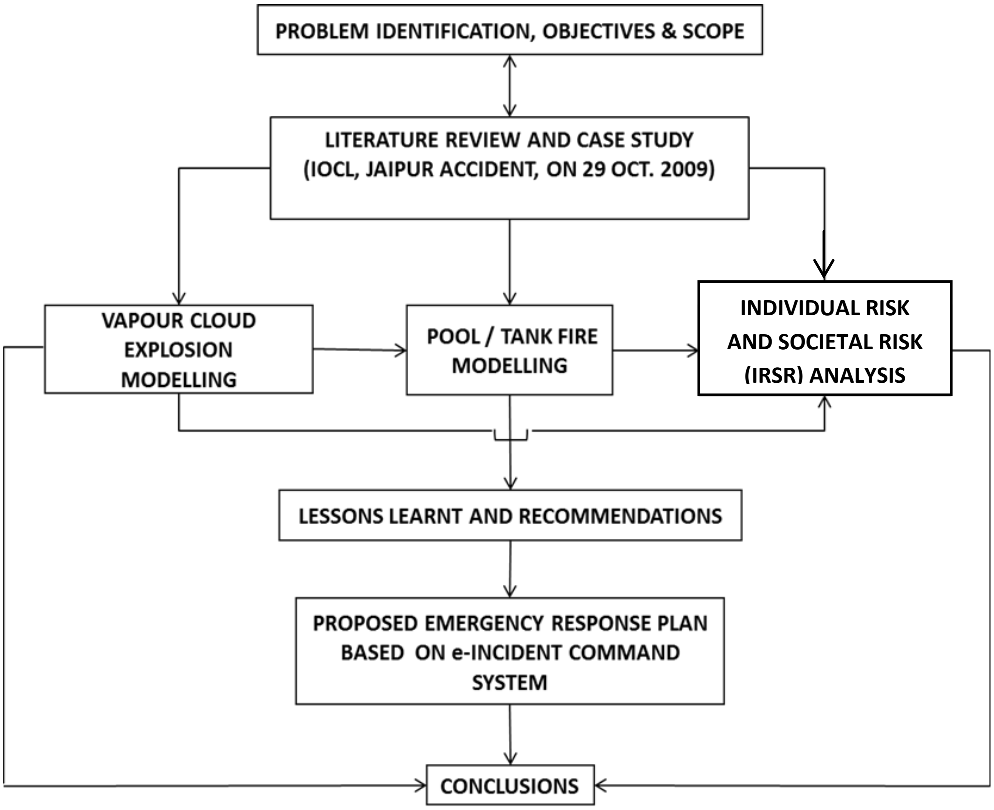


Fig. 1.1 Flow chart showing different stages of the study

1.6 METHODOLOGY

Risk assessment is the determination of quantitative or qualitative value of the risk to a concerned situation and a recognized threat (also called hazard). Quantitative risk assessment (QRA) requires the calculation of two components of risk- the magnitude of the potential loss and the probability of the accident (CCPS, 2000). The methodology adopted for this research is shown in the form of a flowchart in Fig. 1.2.

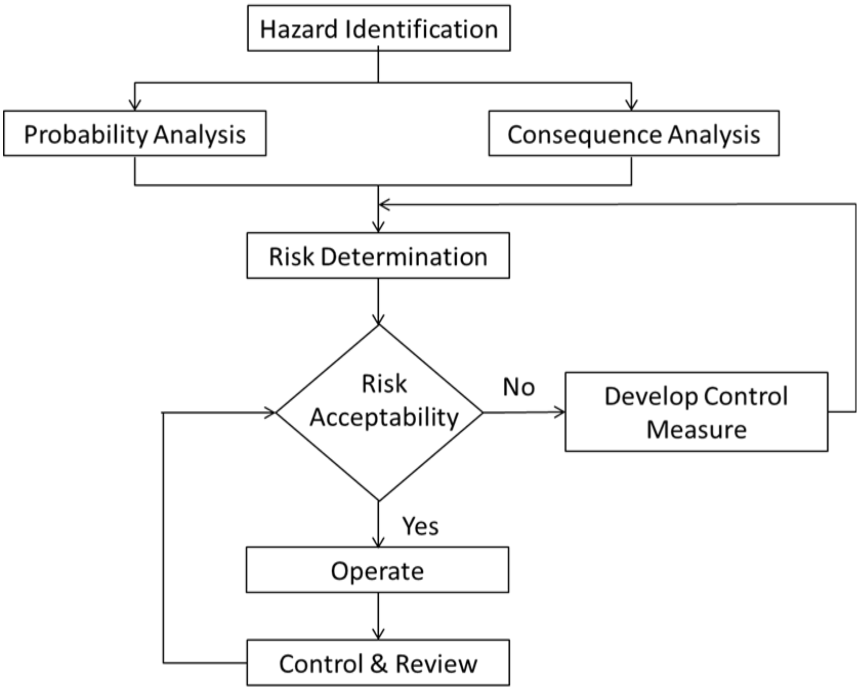


Fig. 1.2 Quantitative risk assessment methodology

1.7 ORGANIZATION OF THE THESIS

The thesis has been divided into nine chapters. The organization / structure of the thesis is given below.

Chapter 1 introduces the risk associated with petrochemical process and storage industries. Global concerns with regard to the major petrochemical accidents and the Indian scenario are touched upon. This also includes the broad objectives, scope and methodology of QRA.

Chapter 2 consists of a review of the significance of the “domino effect” in risk assessment studies. The areas covered under literature search include the past accident analysis in chemical process industries which confers great importance to identifying their triggers (causes), sequences, and their consequences. The main purpose of the work is to get a better understanding of the causes of hazardous event escalation, their consequences and mitigation measures that can prevent transforming minor accidents into disasters.

Chapter 3 describes the overview of the site, tank storage facilities and other associated facilities of Indian Oil Corporation Ltd (IOCL), Jaipur, which is the focus of our case study. This chapter also describes the timeline of Events of IOCL Jaipur accident, which occurred on 29th October, 2009.

Chapter 4 illustrates the vapour cloud explosion (VCE) modeling and its evidences at IOCL Jaipur. The mechanisms that are reviewed comprise high-speed turbulent combustion, quasi-detonations, and fully developed detonations.

Chapter 5 presents the various semi-empirical mathematical models that have been used to study large-scale pool and tank fire characteristics. The analysis concentrates on the discussion and evaluation of the flame height, temperature as well as thermal radiation of the IOCL Jaipur accident.

Chapter 6 describes the initial step towards the quantification of individual and societal risks related to the large-scale oil storage terminal that can help in managing associated hazards and their effects. In this chapter, attempts have been made to make reasonable assumptions to provide a more realistic estimate and analysis of the risk.

Chapter 7 presents the Emergency Response Planning (ERP), which is an integral and essential part of the safety and loss prevention strategy and comprises of the actions taken to manage, control and mitigate the immediate effects of an accident. This chapter highlights the need, structure and development of an automated networking system, called the e-Incident Command System (e-ICS), for improving coordination and communication in petrochemical industrial accident response planning and management.

Chapter 8 enumerates the lessons learnt from Jaipur IOCL and past accidents and thus their use to improve hazard identification and risk assessments of similar incidents. Consequently, the recommendations have been made under two categories, viz, for immediate implementation and secondly for planned implementation.

Chapter 9 contains conclusions of the present research work along with future scope. The research work carried out in this thesis has focused on risk assessment of petroleum oil storage site with an aim to utilize the findings for deploying appropriate preventive measures so as to reduce and mitigate hazards posed by such facilities.

CHAPTER 2

LITERATURE REVIEW AND ANALYSIS

2.1 INTRODUCTION

As this study focuses on “Risk Assessment of a Petroleum Oil Storage Terminal” incorporating a case study of Indian Oil Corporation Limited – IOCL’s Jaipur (India) terminal accident with domino effect, this chapter presents a detailed review of relevant literature. The domino effect has been responsible for several catastrophic accidents that have occurred in petro-chemical processes and the storage industry. The consequences of these accidents are at various levels and may affect not only the industrial sites but also people, economy and the environment. The destructive potential of such accidents is widely recognized but scarce attention has been paid to this subject in the scientific and technical literature (Jayanty, 1997; Mohan and Gurjar, 2004; Cozzani et al., 2006; Darbra et al., 2010; Abdolhamidzadeh et al.; 2011; Hassanien et al., 2011; Kadri et al., 2012). In the area of risk assessment, the domino effect has been documented in the technical literature since 1947 (Kadri et al., 2012). However, no well-assessed procedures have been developed for the quantitative assessment of risk caused by the domino effect. Therefore, the assessment of domino accidental events remains an unresolved problem. Moreover, there is widespread uncertainty in the escalation criteria and in the identification of the escalation sequences that should be considered in the analysis of domino scenarios, either in the framework of quantitative risk assessment or in land-use planning. The probability of domino effects is relatively high due to the development of industrial plants, proximity of such facilities to other installations, their inventories and the transportation of hazardous substances (Kadri and Chatelet, 2013).

The severity of domino accidents has caused concern in the legislation and in technical standards aimed at the assessment and prevention of accident escalation. Therefore, the European legislation widely recognized the assessment of domino hazards since the first “Seveso” Directive (Directive 82/501/EEC), which was adopted in 1982. Currently, these requirements have been extended to the assessment of possible ‘‘domino’’ scenarios both on-site and off-site. Such requirements are compulsory for industrial sites falling under the obligations of the ‘‘Seveso-II’’ Directive (Council Directive 96/82/EC) as amended by Directive 2003/105/EC (Major Accident Hazards Bureau, 2005). Therefore, the domino effect is a significant concern in risk analysis. A good understanding of the main hazards and features of this phenomenon can help identify additional safety measures, such as minimum safe distances between certain types of equipment.

In spite of the relevant attention dedicated in the legislation, there is no well-accepted approach to date for the analysis of domino effect related hazards. Several authors have analysed the categories involved in domino accidents. Bagster and Pitblado (1991) and Khan and Abassi (2001) analysed the probability of occurrence and adverse impacts of such ‘domino’ or ‘cascading’ effects. Cozzani and Salzano (2004a, b) studied the contribution of a blast wave as a primary event and assessed the overpressure threshold values for damage to equipment caused by blast waves originating from primary accidental scenarios. Reniers et al. (2005a) analysed the efficiency of current risk analysis tools for preventing external domino accidents. They proposed a meta-technical framework for optimizing the prevention of external domino accidents (Reniers et al., 2005b; Deshpande, 2011). Cozzani et al. (2007) emphasized the significance of combining inherent safety criteria with conventional active and passive protection. Antonioni et al. (2009) developed a methodology for quantitatively assessing the contribution of domino effects to overall risk in an extended industrial area. Subsequently, several technical standards have introduced preventive measures, such as safety distances, thermal insulation or emergency water deluges, etc. to control and reduce the probability of domino events. However, a relevant uncertainty exists in the threshold values assumed in such assessments (Cozzani et al., 2006; Cozzani and Salzano, 2004a; Deshpande, 2011).

In view of above, the domino effect is an important aspect of risk assessment because the understanding of main hazards and features of the phenomenon can be used to introduce additional safety measures. The past accident analysis in chemical process industries bestows great importance on identifying their triggers, sequences, and consequences. Retrospection can provide pointers for developing accident prevention strategies.

Due to its importance, the compilation and analysis of 262 past accidents involving domino effects have been carried out in this chapter to study their behaviour. The analysis reveals that explosions were responsible for domino effects in almost 57% of the cases, followed by fires (43%). Explosions and fires can cause subsequent accidents, and their physical effects can trigger a domino sequence (Gupta, 2003). The severity of the ensuing scenario can considerably increase the influence of a domino effect. A historical analysis of domino effects carried out by Darbra and Casal (2004) show that 59.5% of accidents in seaport areas were due to fires, 34.5% were explosions and 6% were toxic clouds. The assessment carried out in the present study shows that 63% of domino accidents have occurred in process plants, whereas 20% in storage terminals and 15% during transportation of hazardous materials. Storage areas, which usually contain large amounts of hazardous materials, are also common settings for domino effect scenarios. The domino effect sequences were analysed using relative probability event trees. The most frequent sequences were i) explosion→ fire (26%), ii) fire→ explosion (20.3%), and iii) fire→ fire (12%). In the last decade, three major petroleum storage area accidents occurred in Buncefield, UK (2005), Puerto Rico, USA (2009), and Jaipur, India (2009) (Mishra et al., 2013). In addition to this, Amuay refinery accident occurred in Venezuela on the 25 August 2012 (Mishra et al., 2014).

Few authors have analysed historical surveys of the domino effect. For example, Abdolhamidzadeh et al. (2011) have presented an inventory of 224 major process industry accidents involving ‘domino effect’. Darbra et al. (2010) examined 225 accidents involving the domino effect, which occurred from 1961 to 2007. The aspects analysed included the accident scenario, the type of accident, the materials involved, the causes and consequences, and the most common accident sequences. Kourniotis et al. (2000) examined a set of 207 major chemical accidents that occurred between 1960 and 1998, 114 of which involved a domino effect according to their criteria. Ronza et al. (2003) performed a survey of 828 accidents in port areas and constructed relative probability event trees to analyse the sequence of the 108 accident scenarios in which a domino effect was observed. This paper addresses the development of revised criteria to assess the possibility of escalation of accidental scenarios, resulting in domino accidental events. The main purpose of the study was to obtain a better understanding of the causes of hazardous event escalation and mitigation measures that prevent transforming minor accidents into disasters.

2.2 DEFINITIONS AND EVENTS OF DOMINO EFFECTS

There is no universally accepted definition of the term ‘domino effect’ in the context of accidents in the chemical process industries to date. Most of the scientists define the situations wherein a loss of containment accident in a process unit becomes the trigger of one or more loss of containment accidents in the same or adjacent process units.

Lee defines the domino effect as “*a factor to take into account of the hazards that can occur if leakage of a hazardous material can lead to the escalation of the incident*” (Lees, 2005).

Delvosalle (1996) considers all of the aspects and define domino accidents as “*a cascade of events in which the consequences of a previous accident are increased both spatially and temporally by the following ones, thus leading to a major accident*”

The AIChE-CCPS (American Institute of Chemical Engineers - Centre for Chemical Process Safety) defines a domino effect as “*an incident that starts in one item and may affect nearby items by thermal, blast or fragment impact, causing an increase in consequence severity or in failure frequencies*” (CCPS, 2000).

A recent definition provided by Cozzani and Salzano (2004a) is: “*a domino accidental event will be considered as an accident in which a primary event propagates to nearby equipment, triggering one or more secondary event resulting in overall consequences more severe than those of the primary event*”.

Therefore, these definitions are used as a framework for the selection of accidents. Based on these definitions one can say that a relatively minor accident can initiate a sequence of events that causes damage over a larger area and lead to several severe consequences, which is typically referred as a *domino effect*.

According to Reniers (2010), domino effects are classified into two categories: single-company (internal) domino effects and multi-company (external) domino effects. Internal domino effects signify an escalation accident occurring inside the boundaries of one chemical plant. In external domino effects, one or more secondary accidents occur outside the boundaries of the plant where the primary event occurs. Although external domino effects often have more severe consequences than internal domino effects, this phenomenon has received less attention from prevention managers in existing chemical clusters. The reason for this relatively extraordinary observation is threefold (Reniers, 2010). First, they are less frequent; second, their modelling is highly complex; and third, they are difficult to investigate because several companies are involved. The analysis of technical literature and case histories concerning past accidents shows that all of the accidental sequences, where a relevant domino effect took place, have three common features namely event occurrence, their propagations and escalation vectors (Cozzani et al., 2006) as shown in Fig. 2.1 and discussed below.

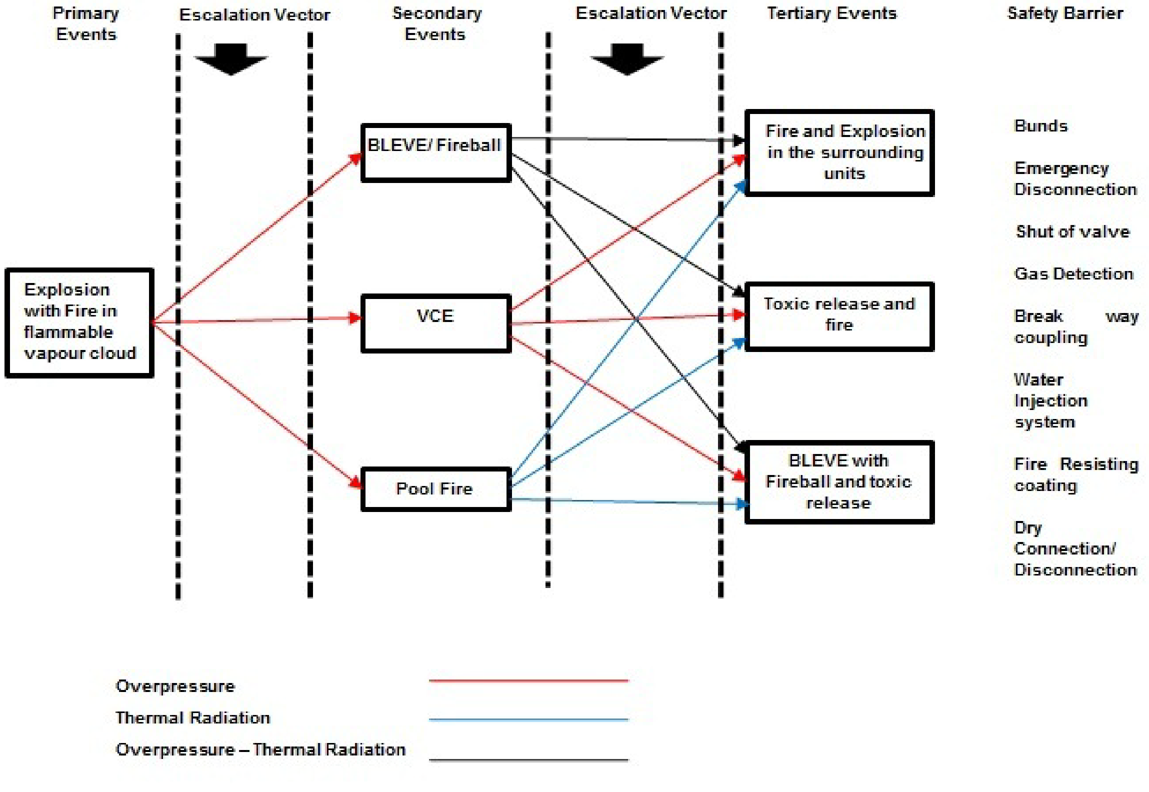


Fig. 2.1 Domino sequences that may be triggered by an initiating event explosion.

- A “primary” event (fire, explosion), which triggers the domino effect.
- The propagation of the accident enhanced by the effect of escalating vectors by which “secondary” accidents are triggered as a result of the primary event.
- An “escalation” vector that enhances consequence effects and propagations with secondary accidents having higher severity than the primary one.

Thus, it is important to understand that the propagation sequence is relevant only if it results in an ‘escalation’ of the primary event, i.e., triggered by an ‘escalation vector’ originating from the primary scenario. By these definitions, all knock-on accidents including the accidents that occur within a single process unit would fall under the umbrella term ‘domino effect’ (Abdolhamidzadeh, 2011).

2.2.1 Collection of Information on Domino Events

To study the historical analysis of domino accidents, one of the critical tasks is to establish the criteria for differentiating domino accidents from non-domino accidents. The hurdles involved in interpreting records of past accidents create difficulties in conducting past accident analysis (PAA) for stand-alone accidents and an increased level of difficulty for the PAA of domino events. Therefore, it is important to develop the most appropriate definition for the domino effect. There are certain well-known difficulties associated with the task of obtaining records of past accidents (Van Der Schaaf and Kanse, 2004; Korvers and Sonnemans, 2008; Abdolhamidzadeh, 2011), as listed below:

a) a well-established mechanism was not developed for reporting and maintaining records of domino accidents that occurred in many countries, particularly in the previous century;

b) industries and governments intended to under-report the accidents to reduce liability;

c) integral inaccuracy of several available records; for example, explosion and fire accidents were often recorded in a generic sense, and in several situations it was difficult to identify the specific event type;

d) contradictory descriptions of the incident and incompetence of assessment leading to an inability to resolve the uncertainty due to lack of unassailable evidence;

e) indistinct documentation of sequence of accidents in an incident.

In developing countries, the lack of proper documentation and inventory of accidents obscure the involvement of the domino effect. Hence, there is no method to confirm whether the accident had involved a ‘domino effect’. To classify a series of accidents as a domino event, it is necessary to establish that the event conforms to the definition of a domino effect. Usually incomplete and imprecise records of the past accidents create complications to determine whether more than one process unit was involved in an incident involving multiple accidents. We conducted this study recognising these limitations and surveyed the records of the following sources:

- MARS (Major Accident Reporting System), 2013
- FABIG (Fire and Blast Information Group)
- Abdolhamidzadeh (2011)
- Lee's (2012)

In present literature review, only accidents that occurred over the past 50 years were considered. Accidents that occurred prior to 1961 were excluded, as they happened in a technological environment in which safety measures and risk planning were not comparable with those currently in place. This, although, has reduced the number of accidents studied but increased the quality and significance of the sample.

2. 3 MAJOR CHEMICAL ACCIDENTS WORLDWIDE

Major chemical accidents are consistent with trends in industries for developing untapped and technologically challenging sources of hydrocarbons. Further, even with developments in engineering practice and hazard awareness, a decade-wise analysis demonstrates that large losses continue to occur. There are a number of good examples where the industry does appear to have learnt from incidents and made improvements on a global basis. Corporations involved in the hydrocarbon processing industry are becoming additionally sophisticated in their risk assessment and risk management approaches and practices. There may, however, be several cultural barriers to learning from these major incidents. These barriers are identified as time, litigation, fear of adverse publicity, internal procedure, disclosure of confidential information, and commitment (of both companies and individuals).Such barriers are specific to the developing world (Kletz, 1993). This study increases the awareness of domino accident losses across the industry and provides a resource from which lessons can be learnt. Table 2.1 summarizes the major catastrophic domino accidents worldwide with the largest losses. In this study, the large property damage losses have been grouped by type of facility into five categories: refineries, petrochemical plants, gas processing plants, storage terminals/distribution, and upstream.

Table 2.1 Major chemical accident events in the last 25 years*

Date	Plant Type	Event type	Location	Property Loss (US $ million)	Injuries / Fatalities
07/07/1988	Upstream	Fire/ Explosion	North Sea, UK	1600	165/--
19/03/1989	Upstream	Fire/Explosion	Gulf of Mexico, United States	750	7/--
23/10/1989	Petrochemicals	Explosion/Fire	Pasadena, USA	Over 1000	100/25
29/09/1998	Natural gas plant	Explosions/ Fires	Longford, Victoria, Australia	13000	--/2
25/12/1997	Gas Processing	Fire/Explosion	Sarawak, Malaysia	430	--/--
25/06/2000	Refinery	Vapour cloud explosion	Mina Al-Ahmadi, Kuwait	600	50/5
13/05/2000	Firework factory	Explosion/fire	Enschede The Netherlands	-	1000/22
21/09/2001	Petrochem	Explosion/ Fire	Toulouse, France	610	3000/ 30
19/01/2004	Gas Processing	Fire /Explosion	Skikda, Algeria	580	74/ 27
23/03/2005	Refinery	Fire/Explosion	Texas, United States	1500	170/15
11/12/2005	Petroleum	Fire /Explosion	Hertfordshire, England	1443	43/0
12/09/2008	Refinery	Hurricane	Texas, United States	750	--/--
23/10/2009	Refinery	Fire /Explosion	Bayamon, Puerto Rico	<6.4	--/--
29/10/2009	Petroleum	Explosion/Fire	Jaipur, India	32	150/11
02/04/2010	Refinery	Fire/Explosion	Washington, United States	-	4/--
21/04/2010	Upstream	Fire/Explosion	Gulf of Mexico, USA	590	--/--
6/01/2011	Refinery	Fire/Explosion	Fort McKay, Albert, Canada	600	--/--
25/08/2012	Refinery	Explosion/Fire	Venezuela	1000	100/50
18/04/2013	Fertilizer Plant	Explosion/Fire	Texas, USA	-	100/15
23/08/2013	Refinery	Explosion/Fire	Visakhapatnam, India	-	14/37

*(Sources: MARS, 2013; FABIG ; Abdolhamidzadeh, 2011; Lee's, 2012; Mishra et al., 2014; http://zeenews.india.com/news/andhra-pradesh/ap-govt-to-issue-notice-to-hpcl-over-fire-in-vizag-refinery_874083.html)

2.4 STATISTICAL ANALYSIS OF DOMINO ACCIDENTS

2.4.1 Distribution of Accidents over the Last Five Decades

As shown in Table 2.2, there has been a significant increase in the number of accidents over the years from the 1960s up to 2010 with the exception of the 1991-2000 decade. This increase can be attributed to two main reasons. First, the chemical industry has undergone continuous expansion: more and larger process plants and storage areas have been created that are more prone to fire and explosion hazards. Second, access to information about accidents has improved gradually over the time. A considerable number of accidents that occurred during the 1960s and before were not recorded and the information were lost.

The number of fatalities has also been increasing every decade with the exception of the 1991-2000 decade. The decade from 1981-1990 showed an exceptionally high number of fatalities due to two of the biggest accidents. The Mexico City accident in 1984 led to 650 deaths, which is higher than 60% of the total fatalities in that decade. This decade had the worst industrial accident - Bhopal gas tragedy in 1984, but it is not factored in the computations because it was not of the domino kind (Gupta, 2002). Even during the years 2001–2010, two major accidents in Neyshabur and Zahedan (Iran) had higher than 45% of the total fatalities in that decade. Thus, one or two major accidents in a decade have typically led to the highest number of fatalities. Major accidents, which are found to be domino in nature, should be controlled at the initial stages to minimize the fatalities. Despite the number of accidents, the domino effect has received much less attention than other aspects of risk assessment.

Since 2001, the number of accidents has decreased every year (Fig. 2.2) except in the year 2009. This decreasing trend could be due to increasing automation of industries, new strict regulations and prompt action in the case of emergencies.

Table 2.2 Domino accidents and fatalities per decades (1961-2013)

Decades	Number of Accidents (263)	Percentage	Number of fatalities (2650)	Percentage	Per accident death rate
1961-1970	31	12	76	2.9	3
1971-1980	40	15	305	11.7	8
1981-1990	57	22	1058	40.6	19
1991-2000	44	17	146	5.6	3
2001-2010	82	31	897	34.5	11
2011-2013	9	3.4	168	6.2	18.6

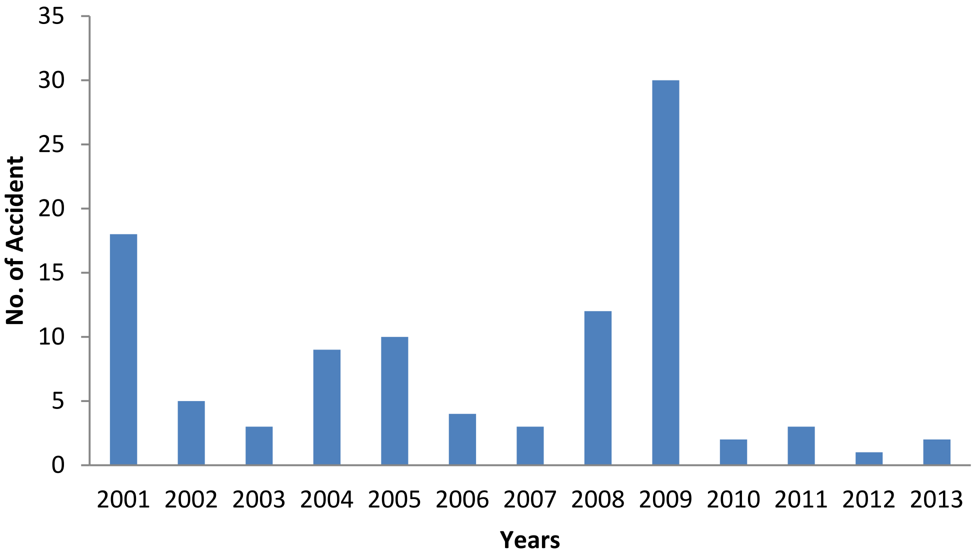


Fig. 2.2 Trends in the frequency of major accidents over the last decade

2.4.2 Location-specific accidents

Accidents were divided into the following categories according to the country in which they occurred:

- the European Union (~ 12%, France, Italy and Germany have a large number of domino accidents than the rest of EU Nations);
- other developed countries (~ 65%, United States, Canada, Australia, UK, Russia);
- the rest of the world (~ 23%, Asia and North African countries).

A certain degree of bias may exist because preference was given to information on accidents that occurred in Europe and the United States. This is because most of the institutions that manage the databases used in the study are based in these countries and the information on them is generally more exhaustive.

It has been observed that more than 75% of accidents involving domino effects are recorded from developed countries as illustrated in Table 2.3. The large scale of process plants and associated storage and transportation facilities in developed countries could be the major contributor to the high percentage, while some loss of data in the rest of the world must be considered. Data on the number of accidents are mostly obtained from the organizations of developed countries and could be the reason for high percentages. The possible loss of data in developing countries could contribute to the lower percentage. Data from developing countries may also be incomplete. However, the available data seems to be enough to show the overall trend.

Table 2.3 Domino accidents in various parts of the world

Countries	Number of accidents (252)	%	Remark
USA	135	53.7	Developed Countries: Total: ~77%
Europe	31	12.4	
UK	14	5.6	
Canada	7	2.8	
Australia	5	2.0	
Russia	3	1.0	
Asia	54	21.5	Developing Countries Total: ~23%
North African countries	3	1.0	

2.4.3 Substances in Most Accidents

Most of the domino accidents involved more than one substance. Although the number of substances involved in accidents is higher, only the substance involved in the primary accident is categorically mentioned. In domino accidents, the substance in the primary event may involve other substances in secondary or further events leading to the involvement of a large number of substances in some of the worst accidents. A relatively small number of accidents involved only one substance. Flammable substances were involved in most of the accidents (89%) and were the substances most frequently found in domino accidents (Darbra et al., 2010).

In most of the domino accidents, flammable substances were involved. The analysis of 125 domino accidents as shown in Table 2.4 Illustrate that Crude oil is by far most frequently involved (34 cases, 27%) followed by propane (15%), LPG (14%), gasoline was found in 12% cases and diesel oil involved 5%. Ethylene, chlorine, hydrogen and methanol were involved in the same number of accidents (3.2 % each one).

Table 2.4 Materials involved in major domino accidents

Substance	No of accidents (125)	%
Crude Oil	34	27
Propane	19	15
LPG	17	14
Gasoline	15	12
Vinyl chloride	7	6
Diesel oil	6	5
LNG	6	5
Ethylene oxide	5	4
Ethylene	4	3.2
Chlorine	*4*	3.2
Hydrogen	4	3.2
Methanol	4	3.2

2.4.4 Types of Industries

All chemical accidents have been categorized according to the types of industries, such as process plants, storage terminals and transportation. It has been observed that most of the accidents (63%) are from process plants followed by 20% in storage terminals and 15% due to transportation. The percentage-based distribution is shown in Fig. 2.5. Process plants could have the highest percentage of accidents due to the elevated operating conditions of reactants and the complex nature of reactions involved. The probability of domino accidents in process plants could also be high due to the congestion of equipment and their connectivity. Storage terminals and transportation of chemicals are at risk due to large amount of chemicals retained at one place.

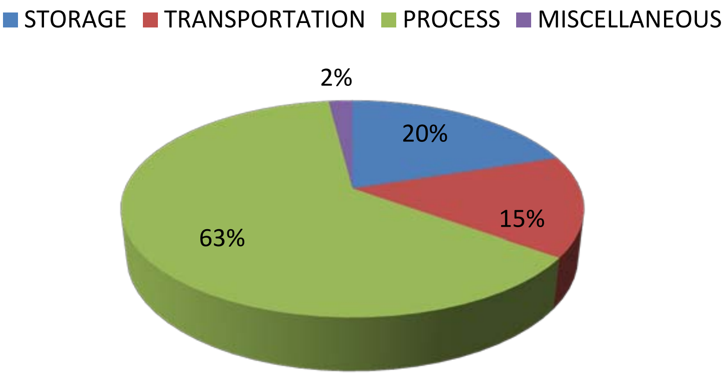


Fig. 2.3 Percentage of major domino accidents in various types of industries

2.4.5 Causes

The cause of the primary accident is a significant aspect of the analysis of domino effect accidents. The Major Hazard Incident Data Service reported several generic causes: external events, human error, impact failure, mechanical failure, instrument failure, violent reaction (runaway reaction), upset process conditions and services failure (MHIDAS, 2007). Although some of the generic causes for accidents are self-explanatory (for example, violent reaction), the accidents due to human error have greater complexity because other causes, such as violent reaction or mechanical failure could also be a result of human error.

Of all the external causes, accidents (fire and explosion) in other plants were the most frequent types. When the primary event was an explosion, it was typically impossible to ascertain from the information available whether it was the blast wave or the fragment projection that caused the secondary accident. When human error was the generic cause of the accident, general operations, general maintenance, overfilling and procedural failures were the main specific causes. The specific causes are shown in Fig. 2.4.

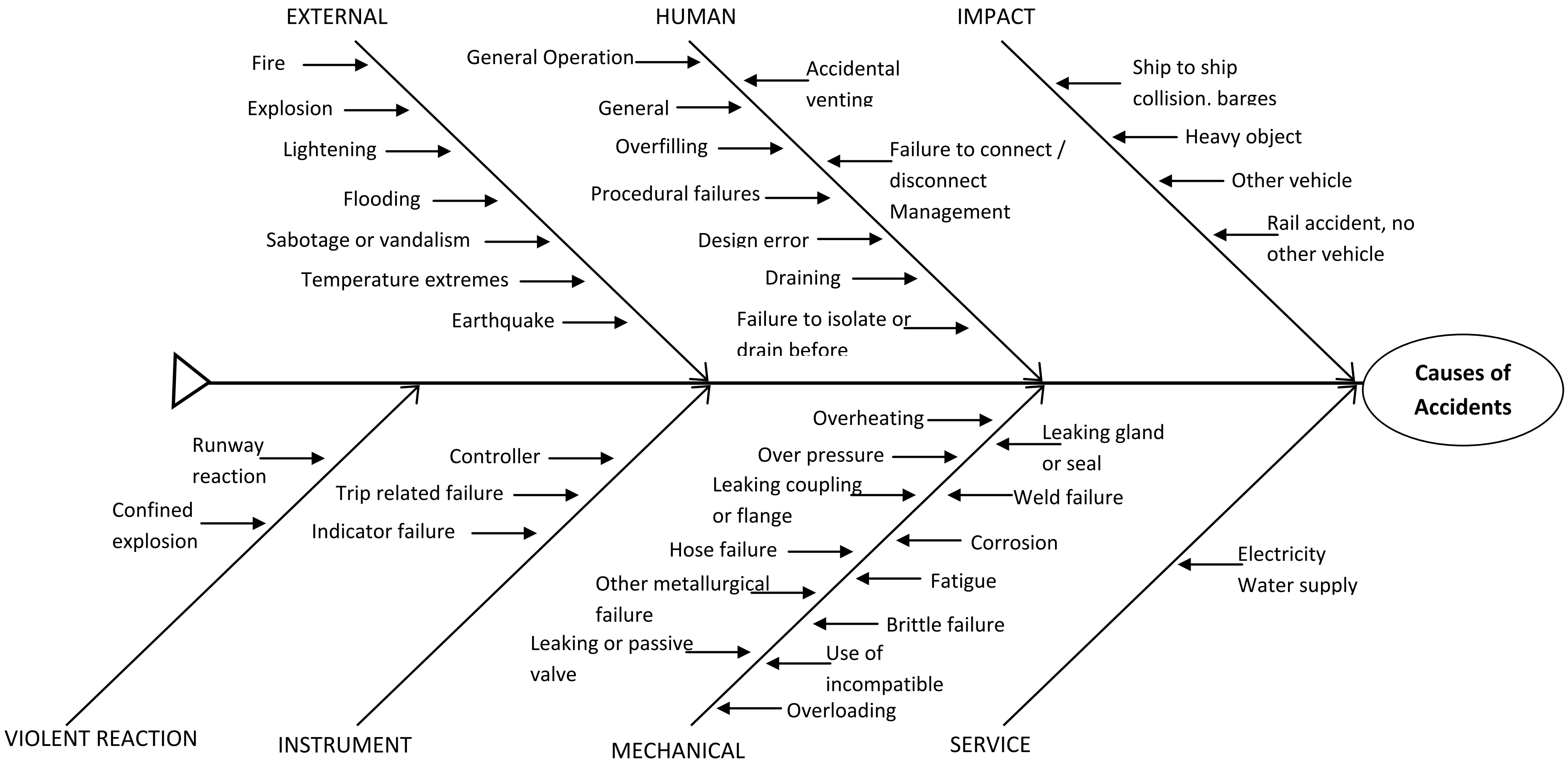


Fig. 2.4 Fish born diagram of domino accident causes

2.5 THE DOMINO EFFECT METHODOLOGY

The methodology proposed here for evaluating the potential for a domino effect involves a three-stage procedure as illustrated in Fig. 2.5. This staged approach has an increasing degree of complexity. In any hazard analysis, it is initially prudent to evaluate whether it is possible to demonstrate acceptability on the basis of the "consequences" being tolerable or non-hazardous (i.e. acceptable) followed by a second stage that considers whether the "probability or frequency" is tolerable. The third stage involving risk assessment is only necessary if it is not possible to show that the site separation was acceptable from a consequence and a frequency viewpoint. If it is still not possible to demonstrate risk tolerability at the third stage, then it will be necessary to investigate and include risk mitigation measures. This approach is reflected in the proposed methodology for domino assessment as illustrated in Fig. 2.5, where

Stage 1 includes an assessment of the maximum hazard ranges for sites A and B and an evaluation of whether these hazard zones extended to susceptible critical plants on their site,

Stage 2 includes an assessment of whether the frequencies of all incidents affecting critical plants exceed some notional threshold value, and

Stage 3 includes a combined Quantified Risk Assessment for both sites.

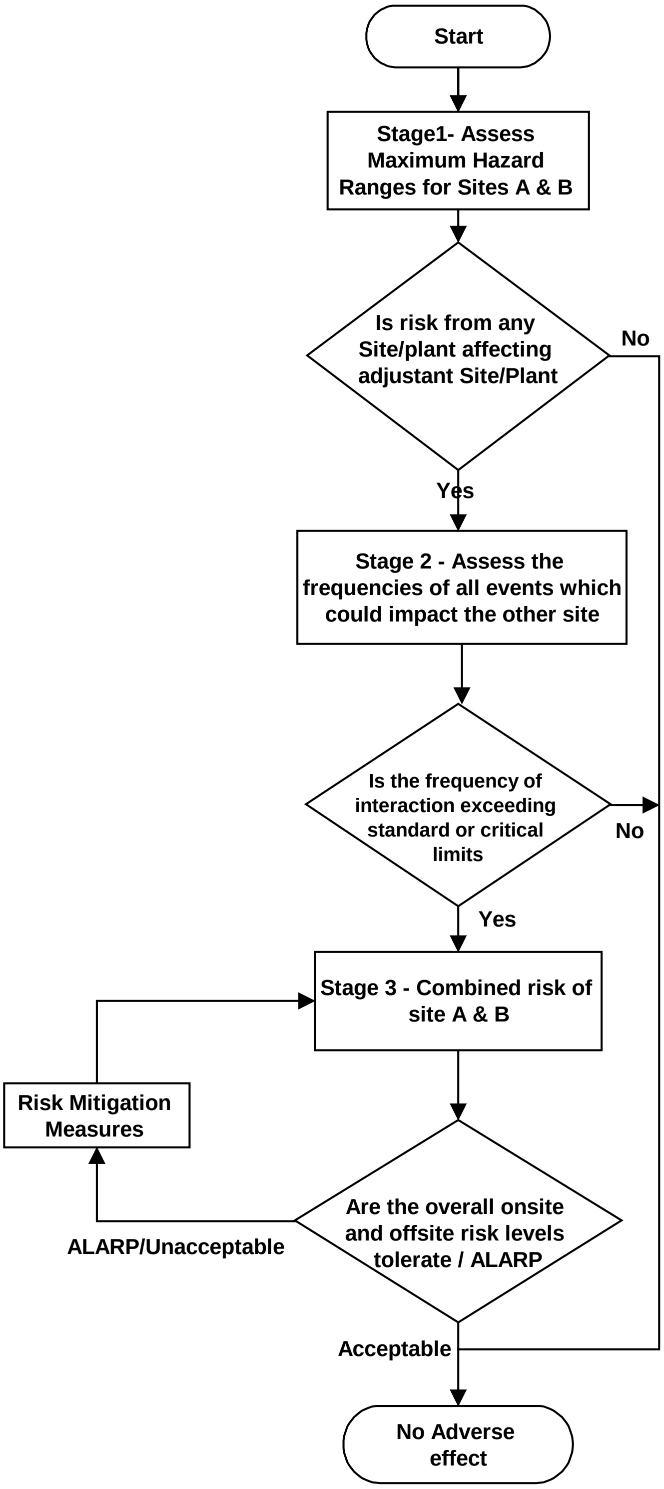


Fig. 2.5 Overall domino assessment methodology

2.5.1 Input Data for Analysis

Accurate data are necessary to evaluate the correct effects of any accident. If additional and accurate data are available, the prediction of impacts will have higher reliability. The information and data required for the domino assessment methodology are listed below.

- A layout of the site
- Locations of units in the layout which may generate primary events of concern
- Operating conditions of all processes
- In-plant and surrounding population data
- Probable ignition sources in the plant and weather data
- Analysis of the primary events with respect to failure frequencies and consequence analysis
- Effects of primary events at adjacent facilities due to overpressures, heat radiations and toxic releases
- Assessment of secondary events
- Analysis of factors which led to a domino effect

2.5.2 Identification of Escalation Vectors

After the identification of primary accidental events, the escalation vectors associated with each scenario should be defined (step 2 in Fig.2.1). The propagation of the primary event due to the escalation vectors and its effects typically generate at least one secondary target. Thus, the physical effect due to the primary event that caused damage to the exposed individuals is often different from that responsible for escalation. Therefore, it is crucial to understand that each accidental scenario should be associated with a “vulnerability vector” (used to estimate the damage to the exposed individuals) and to one or more ‘escalation vectors’.

Any scenario can generate the three following escalation vectors. Escalation vectors and criteria (Cozzani at el., 2006) for the primary and probable secondary scenarios shown in Table 2.5 are:

- heat radiation and/or fire impingement,
- overpressure, and
- toxic release.

Table 2.5 Escalation vectors and criteria for the primary and probable secondary scenarios

Primary scenario	Escalation vector	Escalation criterion	Expected secondary scenarios
Mechanical explosion	Fragments, over pressure	16 kPa	Pool fire, Jet fire, BLEVE, toxic release
Confined explosion	Overpressure	Fragment impact	All
BLEVE	Fragments, over pressure	Fragment impact	All
VCE	Overpressure, fire impingement	16 kPa	All
Pool fire	Radiation, fire impingement	15 kW/m2	All
Jet fire	Radiation, fire impingement	15 kW/m2	All
Flash fire	Fire impingement	LFL	Tank fire
Fireball	Radiation, fire impingement	Engulfment	Tank fire
Toxic release	-	-	-

Therefore, the selection of credible escalation scenarios based on reliable models for equipment damage is a central issue to allow the assessment and the control of risk due to domino accidents.

2.6 DOMINO SEQUENCES

The accidents have been classified into three different types: explosion, fire, and release of material. However, the “release” category is not available as an incident type for some accidents. Although the general information might suggest that a leak or release has occurred, most accidents are initiated by a loss of containment. The sequence of each accident is represented schematically by constructing a relative probability event tree whose branches indicate the different accident scenarios (Figs. 2.6 and 2.7). The probability of occurrence of each sequence of accident was determined by a simple statistical procedure. The number of accidents and the relative probability of occurrence are shown for each branch. The figures illustrate the probability of occurrence with respect to the level immediately above. The values at the end of every branch represent the overall probability of occurrence of the specific accident sequence relative to all possible events.

The relative probability event tree is shown in Fig. 2.6, which includes explosion, fire and release as primary events. Based on the total number of accidents analysed, 47% started with an explosion while 34% started with a fire and 19% with the release. Almost 50% of release accidents led to fire as the secondary event and 61% converted into explosion, with 9% converting into fire and toxic release as a tertiary event. Explosion as a secondary event was followed by fire in 57% of the cases and another explosion in 13% of the cases.

However, ‘release’ as a primary event is typically ignored and loosely described in the databases if it is not followed by another accident. In addition, the description of some accidents suggests that in many cases of ‘fire’ or ‘explosion’ there was probably a previous release that was not recorded in the database. Therefore, ‘release’ as a primary event could be considered misleading.

If “release” is not considered a primary event, the corresponding secondary events become primary events and the tree can be rearranged as shown in Fig. 2.7. Once ‘release’ has been removed, the primary events are explosion (57% of cases) and fire (43%). In the case of fire as a primary event, the secondary events were explosion (65% of cases), another fire (29%), and a toxic gas release (6%). Fire or toxic release as a secondary event did not lead to any tertiary event. Even in case of explosion as secondary event the probability of a tertiary event is low with only 20% chance for fire.

Explosion as a primary event can lead to fire as a secondary event in 53.6% and explosion in 40.7% of cases. Of the 85% of these fires and explosion, secondary events do not convert to any tertiary event. The conclusion from this event tree analysis is that the possibilities of formation of any tertiary event are very low. Of the 246 accidents considered, the majority of accidents (~85%) are involved in only one domino effect (primary plus secondary accidents). Thus, we can conclude that the chances of an accident converting into a tertiary event are very low. Fig.2.7 indicates that the probability of explosion and fire as primary events are almost one-half, with explosion having a slightly higher chance. This trend of equal possibility of fire and explosion has been observed for secondary events with only 6% chance for toxic releases.

Considering the event tree in Fig. 2.7 as the most representative one, the most frequent first-level sequences starting from the primary event (and sometimes followed by a tertiary accident) were explosion→fire (relative probability: 0.3), fire→explosion (relative probability: 0.23) and fire→ fire (relative probability: 0.12). The most frequent second-level sequence was explosion→ fire→explosion (relative probability: 0.09). Globally, the most frequent final domino sequences (indicated by the values at the end of each branch) were explosion→fire (26%), fire→explosion (20.3%) and fire→fire (12.6%).

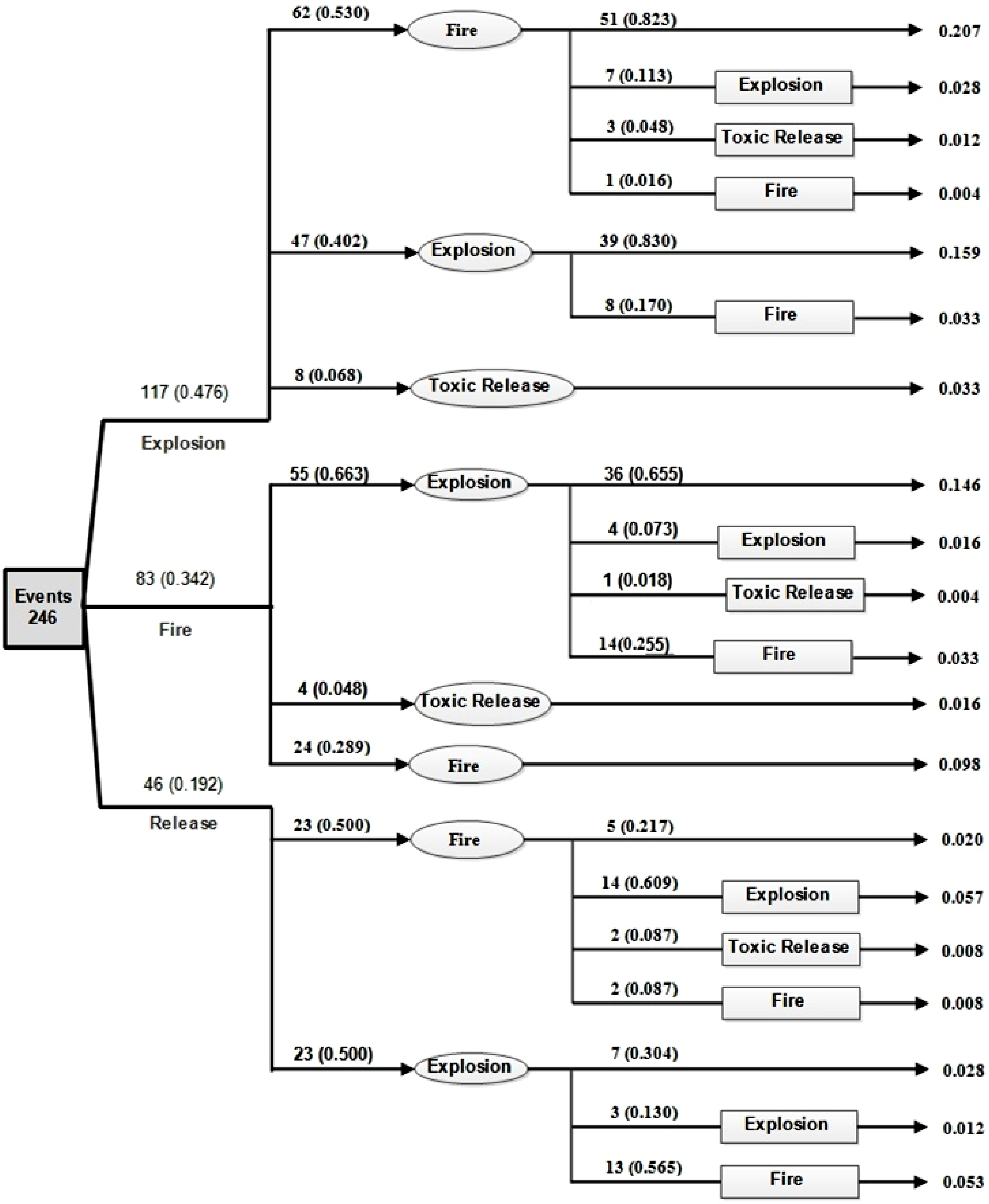


Fig. 2.6 The relative probability of the tree showing diverse domino effects sequence with release on the basis of 246 accidents

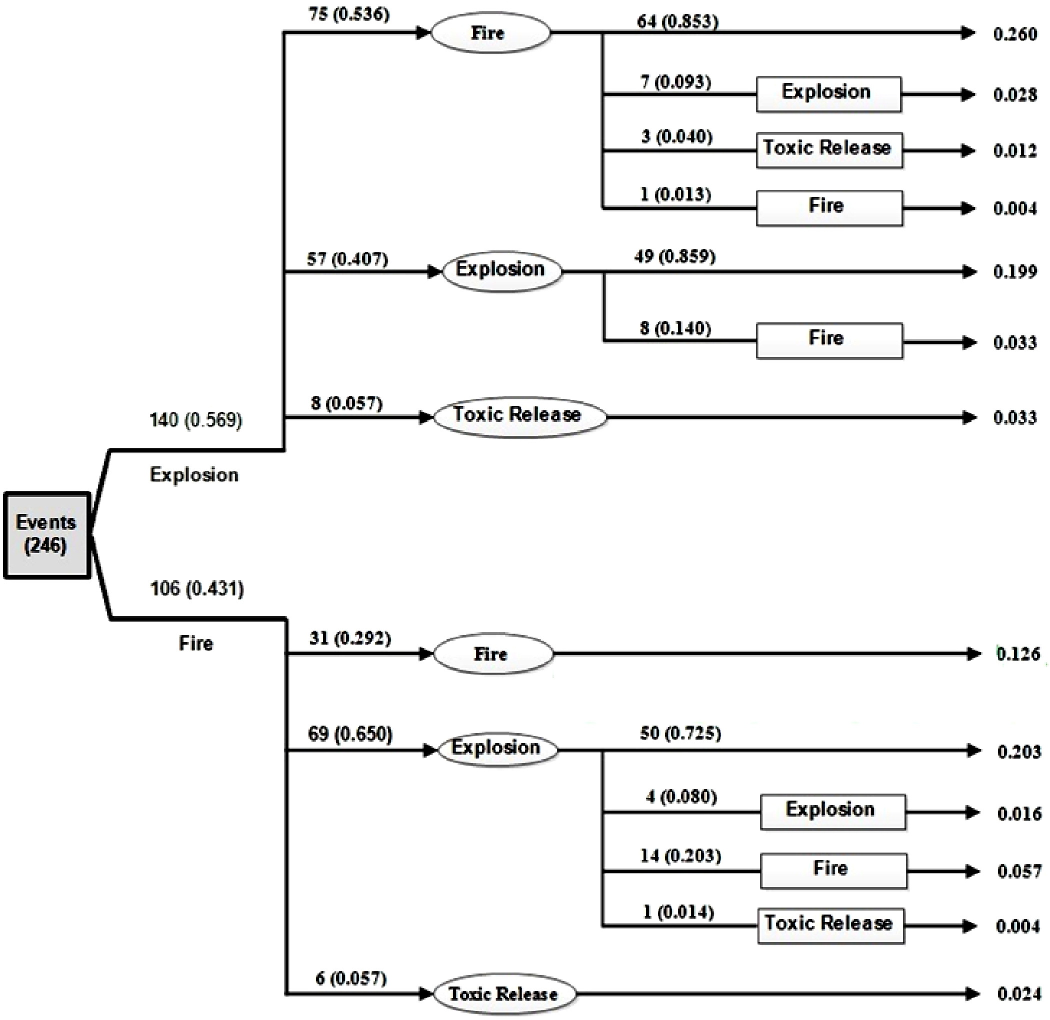


Fig. 2.7 The relative probability of the tree showing diverse domino effects sequence without release on the basis of 246 accidents

2.7 CONCLUSION

Domino effect accidents have been noticed in the tragic history of many past accidents and a more realistic way of addressing intrinsic risks of chemical and petrochemical plants. Assessment of domino accidents is a difficult task due to the involvement of more than one flammable substance and secondary or tertiary events. Due to the complex nature of such accidents, very few studies on its analysis have been published. The present review and analysis of published literature has led to records of 262 major domino events spread over five decades. The domino accidents have been summarized indicating the number of fatalities, locations, involvement of substances and domino sequences.

The number of accidents over five decades has been increasing due to the expansion of chemical industries and improvements in accessing information on accidents. In addition, we observed that one or two major accidents in a decade led to a higher number of fatalities in last five decades. More than 75% of domino accidents occurred in developed countries, which seems rational due to a large number of industries located there. There is also the possibility of loss of data regarding accidents in developing countries, thereby leading to a lower percentage. However, the review and analysis has also shown that domino accidents in underdeveloped countries have higher severity compared with countries that are technologically more advanced.

Event trees of the analysed accidents have indicated that fires and explosions are the primary domino effect events. Thus, precautionary measures should be adopted while handling flammable materials, which are the most common substances in domino accidents. The most frequent sequences are explosion→fire, fire→ explosion and fire→fire. The results show that the quantitative assessment of escalation hazard is a key tool to understand the credible and critical domino scenarios in complex industrial sites. Therefore, significant efforts should be devoted to improving safety in such operations, especially in storage facilities where most transfer operations are performed.

Past accident analysis enables an understanding of how accidents occur and provides useful inputs for the development of loss prevention strategies, and therefore, it is an important component of loss prevention Research and Development (R&D) activities. Consequence analysis in the case of domino accidents is a complex task as no clear guidelines for identifying it are available. The escalation criteria described in this chapter may represent an initiating point in quantifying risk of domino effects. The probability of an initiating event and event trees thereof can lead to a computation of the frequency of each sequence, which can simplify the domino effect risk analysis procedures.

The domino effect is an important aspect in risk analysis, as knowledge of the main hazards and features of this phenomenon can be used to identify additional safety measures. However, risk assessment techniques have intrinsic limitations due to the complexities introduced by event interactions and multi component or multiphase systems encountered in real situations. Thus, it is imperative to study the risk assessment of major past accidents and thereby to take appropriate measures to prevent major accidents in the future.

CHAPTER 3

DEVELOPMENT OF CASE STUDY OF IOCL JAIPUR ACCIDENT

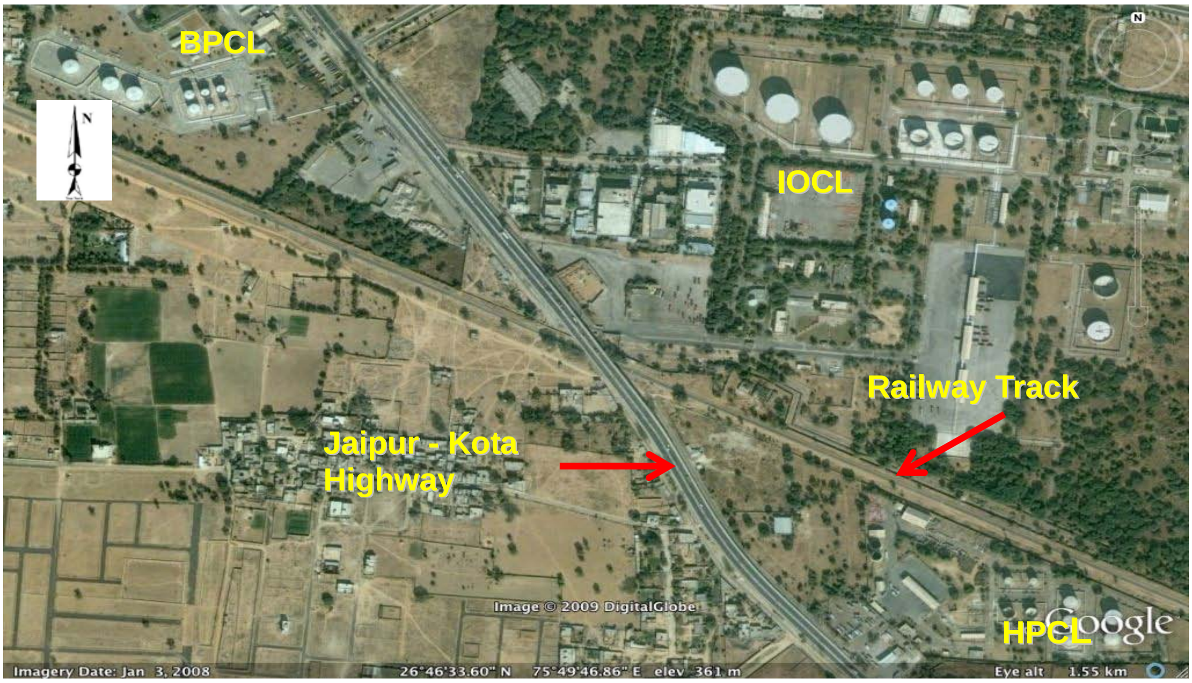
3.1 INTRODUCTION

An uncontrolled loss of containment and ignition of a flammable vapor cloud mixture can result in devastating consequences, e.g., intense fires and explosions with an influence over several kilometers. Depending on flammability and the availability of a potential source of ignition such a vapor cloud may lead to a severe explosion which is referred to as Vapor Cloud Explosion (VCE). In the last decade, many of such major accidents at petroleum storage sites have been reported (Mishra et al., 2013). The first accident took place at Buncefield (MIIB, 2011) (UK) in 2005, the second one was in Puerto Rico (Chemical Safety Board, USA, 2011) (USA) in 2009, and the third one was in IOCL Jaipur (India) in 2009 (MoPNG, 2010). In addition to this, Amuay refinery accident occurred in Venezuela on the 25 August 2012 (Mishra et al., 2014). A wide range of similarities has been observed among these accidents, most importantly the VCE followed by the massive fire.

On Thursday, 29th October 2009, at 19:30 hrs, a series of explosions in rapid succession was followed by fires that engulfed 11 large fuel storage tanks - a significantly high proportion of the IOCL Jaipur oil storage and transfer depot at Sitapura industrial area, India. Subsequently, the depot was completely destroyed and widespread damage was caused to the neighbouring properties. This devastating accident resulted in 11 fatalities and injuries to more than 150 people. About 5000 people had to be evacuated from their homes in the adjacent area. The fire burned for 11 days, destroying most of the site and emitting a large plume of smoke. The cost of the incident in terms of damage to property and loss of business is estimated to be approximately USD 60 million. In the aftermath of the incident, the Ministry of Petroleum and Natural Gas Committee (MoPNG) was formed to oversee the investigation.

3.2 OVERVIEW OF THE IOCL SITE

At the time of the incident, the IOCL Sanganer Marketing Terminal had been in operation for almost 12 years and was spread over an area of approximately 120 acres. It is located at Sanganer, about 6 km from Jaipur airport, on Jaipur-Kota highway. The location was chosen at Sanganer as the site was far away from the then residential localities of Jaipur city and at that time there were no neighbouring industries or factories located within few kilometers of the site boundary at that time. Subsequently, a large industrial area was developed by the State Government all around the terminal area which progressively became densely populated. Two oil storage terminals of Bharat Petroleum Corporation Limited (BPCL) and Hindustan Petroleum Corporation Limited (HPCL) are also located about 1 to 1.5 kms from IOCL terminal and solely dependent on supplies from IOCL. An overall view of the site, at a time before the incident, (taken from Google Earth), is shown in Fig. 3.1. Some of the key features of the site are shown in this google earth image. A plot plan of the site is given in Fig. 3.2. The pipeline division of IOCL occupied an area in the North West corner of the overall site, as indicated in Fig. 3.2. The pipeline division area contained a number of other buildings including a separate control room.



(Source: Google Earth, Last access, 30 June 2011)

Fig. 3.1 The site of IOCL Jaipur terminal, BPCL and HPCL terminal at a time before the incident

(Source: Google Earth, Last access, 30 June 2011)

Fig. 3.2 The IOCL Jaipur site showing site boundary (Red), the Pipeline Division area (Purple) and car park/storage building (Blue)

3.3 TANK STORAGE FACILITIES DURING THE FIRES

The IOCL Jaipur terminal contained 11 large storage tanks of gasoline, diesel, and kerosene. Additionally, there were five underground tanks, each of 70 m^3 capacity, for storage of gasoline and anhydrous alcohol. The terminal receives different types of fuel such as gasoline, kerosene oil and diesel by through Koyali–Sanganer product pipeline systems (MoPNG, 2010). The terminal also used to receive and distribute lube oils in drums through trucks.

Table 3.1 StorageTank Facilities (MoPNG, 2010)

S.No.	Material stored	Nominal Capacity (m^3)	Nos.	Height (m)	Diameter (m)	Type	Tank Nos.
1	Gasoline	6,110	3	15	24	Floating Roof	401-A/B/C
2	Gasoline	8,400	2	15	28	Floating Roof	409- A/B
3	Kerosine	5,080	3	20	18	Cone Roof	402 A/B/C
4	Diesel	20,000	3	20	36	Cone Roof	403 A/B/C
	Total Capacity	**1,10,370**					

3.4 OTHER ASSOCIATED FACILITIES

The entire area, confined by trees and buildings, was enclosed by a compound wall of 3m height. The major function of the site was storing and distribution of fuel through pipeline to the neighbouring depots of other oil companies i.e. HPCL and BPCL. The depot delivered petroleum products through tank trucks to retail outlets and also supplied lube oil to local market. All storage tanks, buildings, and roads including the rows of trees and hedges are also shown in the Fig. 3.3. Besides the main technological facilities, the following buildings and structures were located within the ambit of the terminal.

- Control Room (CR)
- Administrative Building
- Business Community Centre (BCC)
- Truck Loading Facility (TLF)
- Tank Farm Management System
- Diesel Generator (DG)
- Pump House (PH)
- Fire water pump house
- Terminal Canteen

The majority of these buildings associated with the main terminal, were located in the South West corner of the site nearer to the main site entrance.

The major facilities associated with the terminal at the time of accident were as follows:

- **Pump House**

  The pump house accommodates 9 pumps, three dedicated to each of the products i.e. (Gasoline, Diesel and Kerosene). These pumps are generally electrically driven centrifugal type.

- **Truck Loading Facility (TLF)**

  Thirty loading gantries were provided for truck loading. These consisted of 30 loading bays with 33 loading points.

- **Exchange Pit**

  For pipeline transfers at the south battery limit, an exchange pit is provided consisting of two isolation valves (HOV) with a hammer blind type valve for positive isolation, on each of the product transfer pipelines.

- **Control Room**

  The control room consisted of digital screens and other instruments including emergency shutdown provision for the entire installation.

- **Business Community Centre (BCC)**

  This terminal also had the Business Community Centre (BCC), which housed the corporate Entrepreneur Resource Planning (ERP) system. BCC was provided with a Diesel Generator (DG) to provide necessary power backup, which was designed to start on auto mode in case of power failure in BCC.

3.4.1 Pipeline Division

Pipeline division consisted of the following:

3.4.1.1 Control room

A separate control room for pipeline division housed supervisory control and data acquisition (SCADA) panel along with the tank details which indicated all tank levels from the Tank Farm Management System (TFMS).

3.4.1.2 Pumping facilities

The booster pumping station for crude oil consisting of two diesel driven pumps were located in the pump house of pipeline division.

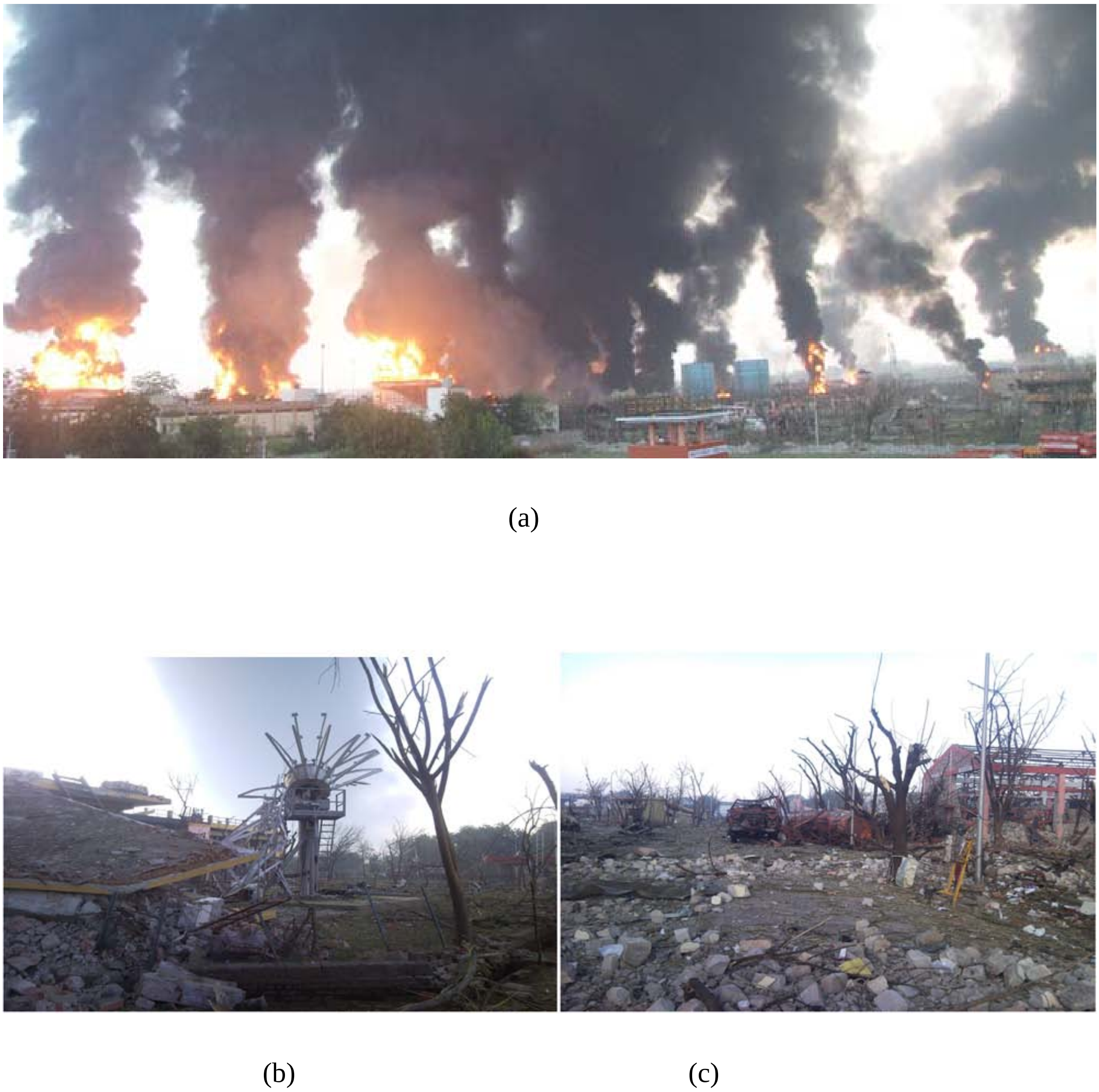
(Source: Google Earth, 2011)

Fig. 3.3 Pre-accident arial view of IOCL Jaipur terminal tank storage site and the immediate neighbourhood

3.5 TIMELINE OF EVENTS

In the evening hours of October 29, 2009, the Indian Oil Corporation Limited's Petroleum Oil Lubricants (POL) Terminal at Sanganer in Jaipur was preparing to transfer kerosine and gasoline to the neighboring Bharat Petroleum Corporation Limited (BPCL) Terminal, a routine operation for these installations. The chronology of events that led to the accident presented here has been summarized from various reports and sources such as MoPNG Committee (2010), Media news (2009), Sharma et al. (2013), which are listed below.

- At approximately 6:10 pm, during the process of preparing Tank 401-A for pumping, a huge leak occurred from a 'Hammer Blind Valve' on the tank outlet.
- The leak continued for about 80 minutes. It was estimated that gasoline, of the order of 2000 tonnes, were released from the tank prior to ignition.
- The post incident analysis indicates that the flammable vapor cloud covered much of the IOCL site i.e 180,000 m^2 with an average height of about 2m.
- Possible identified ignition source in the car parking and control room triggered the flammable vapor cloud.
- Eventually, a big explosion occurred at 7:30 pm, measured 2.3 on the Richter scale, and was one of the most intense accidental explosions in recent times. Buildings in the immediate neighbourhood had damages with window pane breakages up to a distance of 2km. The first explosion was followed by further explosions leading to multiple tank fire, which involved 9 tanks containing different materials immediate after the explosion. This was followed by additional 2 tank explosions due to effect of highly intense heat radiation caused by fire in 9 tanks. Thus, 11 large storage tanks of various sizes exploded and caught fire that resulted in the complete destruction of the facilities and buildings within the premises of the terminal as shown in Fig. 3.4.
- Half an hour later at 8:00 pm, the fire turned into uncontrollable flames of 12m height affecting buildings up to 1 km away from the site.
- At 9:00 pm the entire area was evacuated. By 10:00 pm all the 11 containers exploded and each turned into an inferno.



(a)

(b) (c)

Fig. 3.4 (a) The IOCL terminal site view during the incident, and (b) and (c) terminal site view over pressure damage.

3.5.1 Injuries and Fatality

Eleven people lost their lives in the accident (six from IOCL and five outsiders) and more than 150 peoples were injured. In addition to this, about 5000 people in the nearby and surrounding area had to be evacuated from their homes (MoPNG committee, 2010). As reported, This is one of the most fatal accidents that have occurred during the last decade in the petroleum industry.

3.6 PROBABLE CAUSES OF THE ACCIDENT

The following are the identified possible immediate critical factors of the Jaipur accident:

- Non-observance of normal safe procedure that involves a sequence of valve operation during line up activity, and an engineering design that permitted the use of a manually operated ‘Hammer Blind Valve’, which failed.
- Absence of site specific written operating procedure.
- Absence of Operating Personnel in Vital area (the Control Room and Field).
- Absence of remotely operated shutdown valves and lack of understanding of hazards, risk and consequence.
- Absence of On-site and Off-site Emergency Measures immediately on loss of containment.
- Inadequate mitigation measures such as the absence of personal protecting equipments and fire fighting equipments.

With a view to evolve better understating of risk and consequences analysis of petroleum storage facilities, the case study developed in this chapter has been taken as the base in subsequent chapters related to the modelling and analysis of VCE, pool fire, and individual and societal risk assessment of various events that led to this devastating accident.

CHAPTER 4

ASSESSMENT OF VAPOUR CLOUD EXPLOSIONS

4.1 INTRODUCTION

The petroleum refineries and storage terminals deal with the flammable materials that can give rise to Vapour Cloud Explosions (VCEs). Much of the processing and storage of petroleum products are done under higher than ambient pressure. This implies that loss of confinement will lead to rapid release rates. Vapour fuel clouds from accidental releases may ignite, burn, explode, or detonate. The consequent pressure waves, high-speed fragments, fires, and fireballs may cause severe human casualties and property losses (Baker et al., 1983; Lees, 1996a). Recently, an inventory of the past domino accidents (Abdolhamidzadeh et al., 2011) reveals that explosions are the most frequent cause of major domino accidents (57%), where VCEs have been the most frequent cause (84%).A study of 225 accidents involving domino accidents made by Darbra et al. (2010) shows that storage areas are the most probable starters of major domino accidents (35%) followed by process plants (28%). VCEs are, therefore, considered as a major hazard in industrial plants where large amounts of flammable materials are stored or processed (Maremonti et al., 1999). In fact, many VCEs which occurred in the last decades in fuel storage areas caused almost total destruction of the plant. Major accidents at Newark, New Jersey, 1983; Naples, Italy, 1985; Pasadena Texas 1989; Saint Herblain, France, 1991; Sri Racha, Laem Chabang, Thailand, 1999; Buncefield, UK 2005; Puerto Rico, USA, 2009; and IOCL Jaipur, India, 2009 are examples of how dangerous releases of hydrocarbons into the atmosphere can be (Abbasi et al., 2010, Mishra et al., 2013). Besides this, recently a massive VCE occurred at Amuay refinery, Venezuela, 2012 (Mishra et al., 2014).

Accidental release of flammable substances into the atmosphere is one of the main dangers in modern industry, where a wide range of hydrocarbons are used on an increasing scale. These range from minor innocuous leaks to catastrophic releases (like the ones occurred at IOCL Jaipur, India). A typical cause of such a release is partial or total loss of containment, followed by depressurization of a high-pressure storage vessel or pipeline

(Makhviladze and Yakush, 2002).The impact can also have a very wide range, from causing temporary malfunctioning of a small component of an equipment to the demolition of an entire installation. The highest property damage (PD) from a VCE reported till this date is the one that occurred in Pasadena Texas (USA) in 1989. It is estimated that the cost to rebuild the plant was around 869 million USD (based on 2002 USD market value) (Marsh, 2003).The business interruption (BI) cost in this case was about 700 million USD.

In order to assess the likely consequences it is essential to properly identify the different events of accidents on the basis of their distinct attributes. Only with a proper understanding of the nature and the mechanism of each event can the consequence modeling be done effectively. This Chapter examines the analyses of the VCEs occurred at the IOCL (Jaipur, India) fuel storage terminal in 2009, which is one of the most intense accidental explosions in recent times. This followed the release of approximately 2000 tonnes of gasoline, when a 15 m high storage tank outlet valve was leaked for about 80 min before ignition of the resulting flammable mixture. The ensuing explosion overpressures in excess of 200 kPa (2 bar) were generated across most the site, which, however, was not uniformly distributed throughout the terminal (Sharma et al., 2013; Johnson, 2011). The directional indicators point to the source of the detonation being in the Pipeline Division area in the north east (NE) corner of the site. The ensuing explosion was of a severity that had not been observed previously in a major hazard assessment of this type of facility in India. The accident caused eleven fatalities, six on the IOCL site and five off-site, and economic loss of 55 million USD. It was, therefore, imperative to investigate the event comprehensively and develop an understanding of the underlying mechanisms to inform future prevention, mitigation and land-use planning issues. With this view, the most probable explosion mechanisms and the evidence for them at IOCL Jaipur have been examined in this chapter. Mechanisms that are reviewed in this chapter include, i) high-speed turbulent combustion, ii) deflagration, and iii) fully developed detonations. The acceleration of turbulent flames and the transition to detonation phenomena are of particular importance. On the basis of quantification of maximum overpressure generated at various facilities within the terminal, a number of conclusions are drawn and suggestions made for further research.

4.2. DEFLAGRATIONS AND DETONATIONS

Explosions can be divided into detonations and deflagrations. In order to assess the implications of the findings, it is worthwhile to consider briefly the differences between deflagrations and detonations in relation to the generation of damaging overpressures.

4.2.1 Deflagrations

The primary characteristics of a vapour cloud explosion involving a deflagration are as follows:

- Deflagration literally means fast burning. It consists of a moving exothermic reaction zone sustained by heat flow from hot reaction gases to unreacted material by conduction, convection, and radiation (Eckhoff, 2005; Lee, 1996a; Lees and Mannan, 2005; NFPA 921, 2008).
- A pressure front is generated by the flame, which moves through the cloud at high speed, typically over 200 m/s (for comparison, the ambient speed of sound is about 340 m/s). The flame generates pressure because of the inertia of the unburnt mixture in front of the flame, in much the same way that any object moving at high speed through air generates a pressure wave in the front area (Johnson, 2010).
- The high propagation rates in deflagrations occur either through a mechanism of pressure-driven acceleration due to increased heat transfer and higher reaction rate under confinement or through flame acceleration in gases as a result of turbulence generation in the still unreacted gas ahead of the flame. The turbulence increases the burning surface area and thickens the flame.

An important aspect of deflagrations is that the high flame speeds are dependent on the continued presence of obstacles. Once the flame passes into an open area it rapidly decelerates. Therefore, pressure generation is limited to regions with repeated obstacles and the magnitude of the pressure wave produced by the explosion decreases with propagation away from the congested region. The rate at which the observed pressure decays will depend to some extent on the nature of the actual explosion.

4.2.2 Detonations

The key properties of a detonation, as compared to a deflagration are:

- In a detonation, the energy transfer to initiate a reaction in the fresh substance is caused by compression in a shock wave, and hence, the propagation velocity is supersonic (Crowl, 2003; Lees, 1996b; Martin et al., 2000; Qiao and Zhang, 2010). Because of the high velocity of the wave, the reactions and the conversion of the substance into a hot mass of expanding gas take place over a very short time, so a shock wave that we perceive as a bang is produced in the ambient air.
- The shock front compresses the fuel-air mixture and thus raises its temperature. In a detonation, the temperature increase by the sudden compression starts the reaction. Energy released in the combustion process maintains the magnitude of the shock front.
- For mixtures of hydrocarbons and air initially at atmospheric pressure, the initial shock front typically has a magnitude in excess of 20 bars. The detonation front travels at speeds of the order of 1800 m/s (Johnson, 2010)
- The influence of both fuel type and concentration has been indicated in peer reviewed publication (Bull et a., 1981).

Ranges of overpressure for detonation are higher than those for deflagration. Only an upward propagating flame ensues from deflagration near the explosion limit (Abbasi et al., 2010). Because of these features, detonations are more destructive than deflagrations for a given quantity of explosive.

4.3 EVENTS LEADING TO VAPOUR CLOUD EXPLOSION

In the evening hours of 29th October 2009, during routine operation of plant, personnel at IOCL’s Jaipur terminal were preparing to transfer kerosene and gasoline to the neighbouring Bharat Petroleum Corporation Limited (BPCL) Terminal, which is a routine operation for these installations. During this operation, an accidental release of gasoline took place leading to series of VCEs followed by multiple tank fires. The timeline of events has already been described in Chapter 3 (section 3.5). Outline of events leading to a massive VCE is given in Fig.4.1 (MoPNG Committee, 2010; Media news , 2009; Sharma et al., 2013).

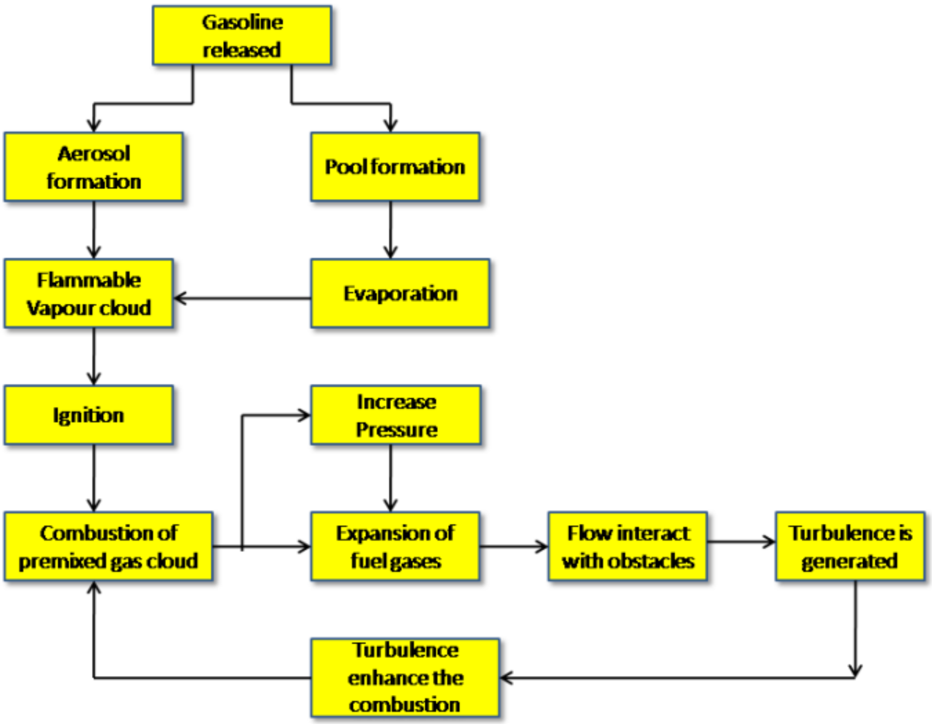


Fig. 4.1 An outline of events leading to a vapor cloud explosion (VCE) scenario at the Jaipur IOCL depot

4.4. EVALUATION OF VAPOUR CLOUD EXPLOSION

The present analysis is carried out using the DNV Norway based PHAST 6.51 software for the estimation of release rates. The release is subsequently examined to identify potential dispersion scenarios. In turn, the dispersion scenarios are analysed to determine the largest explosive transient vapour cloud and the resulting overpressure impacts on the various facilities. The analysis reveals the influences of vapour cloud dispersion on the explosion overpressure.

In the present analysis, the first event (i.e. the accidental release) has been analysed and then the modeling up to the VCE and transition to detonation, the final event, has been carried out to identify all the possible consequences of explosion.

4.4.1. The Release Rate

As reported by the Independent Inquiry Committee (MoPNG, 2010), the initiating event of the sequence was caused by the accidental releases of gasoline from the 0.25 m diameter outflow tank valve (i.e. manual operated Hammer Blind Valve). This resulted in the leakage of huge amounts of flammable liquid. The released gasoline formed a liquid pool within the tank dyke and the continuous evaporation from the pool, formed a dense vapour cloud which stratified on the ground, whose dispersion was partially hindered by the various facilities located in the surrounding area.

In the first case, the mass discharge rate from the valve was determined by Eq. 4.1 (Crowl and Louvar, 1990). This assumed fraction is represented by a discharge coefficient, C_D, and accounts for the pressure due to the liquid head above the hole h_L.

$$m = \rho\vartheta A = \rho A \mathrm{C_D}\sqrt{2\left({}^{\mathrm{g}P_g}/_{\rho} + \mathrm{g}h_L\right)}, \tag{4.1}$$

where m is the mass discharge rate, ϑ the fluid velocity, A is the area of the hole, ρ is the density of the liquid at 30°C and P_g the gauge pressure at the top of the tank (for a tank open to the atmosphere $P_g = 0$), and g is the gravitational constant. The density of gasoline is 740 kg/m^3 at NTP and the liquid head above the hole is 14 m. By using Eq. 4.1 the estimated mass discharge rate or release rate is 323 kg/s.

For liquids that are accelerated during the release, such as in a jet, a common approach is to assume an isentropic path. If the liquid temperature is less than the normal boiling point, the flash fraction is zero (CCPS, 2000).

4.4.2 The Evaporation Rate

The calculation of the vapour mass involved in the explosion is crucial for assessing the consequences of such accidents. The evaporation rate per unit area m_{mass} can be calculated by considering the pool area and liquid falling into the pool. The vaporization rate for this situation is not as high as for flashing liquid or boiling pools, but can be significant if the pool area is large. A typical approach is to assume a vaporization rate of the form Matthiesen (1986) as illustrate in Eq. 4.2

$$m_{mass} = \frac{MW k_g A_P P^{sat}}{R_\mathrm{g} T_L} \tag{4.2}$$

where, MW is the molecular weight of the evaporating material (86.18 for gasoline), k_g is the transfer coefficient, A_P is area of the pool (exposed area for evaporation was 5114 m^2), P^{sat} is the saturation vapour pressure of the liquid (60 kPa), R_g is the ideal gas constant, and T_L is the temperature of the liquid.

As far as the pool evaporation term is concerned, the mass transfer coefficient can be computed as in Eq. 4.3:

$$k_g = 0.002 \times v^{0.78}\ L_P^{-0.11} = 1.7 \times 10^{-3} \qquad (4.3)$$

where, ϑ is the wind velocity at a height of 10 m from the ground and L_P is the pool length. The gasoline evaporation rate has been estimated as 17 kg/s by using Eq. 4.2. It is estimated that in 80 minutes of uncontrolled release resulted in about 81 tonnes of gasoline, which might have formed an adequate vapour cloud of gasoline for a massive explosion.

4.4.3 Vapor Cloud Explosion Model

A consequence in the form of a VCE can be seen as a combination of many factors. The overpressures generated due to VCE (with regard to the incidents considered here) are primarily influenced by the following parameters:

- Amount of fuel and its flammability,
- Degree of confinement/congestion,
- Source and strength of ignition, and
- Weather conditions.

Thus the strength of a VCE depends on a range of parameters as listed above. Some of them are related to the geometry (e.g., size), the degree of confinement and amount of turbulence generated by obstructions. Others are related to the gas mixture, like composition, location and quantity. However, most of the empirical models developed to date typically consider the above four parameters. This is to be noted that absence of a single factor can alter the probabilities and extent of occurrence to a great extent.

4.4.3.1 TNT Equivalence model

TNT equivalence model is used to estimate the effects of gas explosion. It is easy to use as it does not require the vapour cloud size or the space conditions as input parameters. In this model, the energy released from an explosion is assumed to equate to a mass of TNT that would give an equivalent amount of energy. TNT is a standard explosive against which other explosive types are compared. TNT is used as a standard due to the availability of lot of experimental data on the overpressures that are generated by the explosion of a certain amount of TNT. Once an equivalent amount of TNT has been estimated, the explosion characteristics and the possible damages are derived from the large amount of data available from TNT explosions. Equivalent mass of TNT that would produce the same effect as explosion is given in Eq. 4.4.

$$W_{TNT} = \frac{W_{gas}\eta\ \Delta H_{C(gas)}n}{\Delta H_{C(TNT)}} \tag{4.4}$$

where, W_{TNT} is equivalent mass of TNT (kg), η is the explosion yield which is the quotient between the energy in the shock wave and the theoretical energy available in the explosion. Generally η is in the range of 1-10 % for most explosions on the basis of calculated value of the total quantity of vapour in the cloud. W_{gas} is the total mass of flammable material in the cloud (kg), $\Delta H_{c(gas)}$ is the lower heat of combustion of the material (kJ/kg) and $\Delta H_{c(TNT)}$ is the heat of combustion of TNT, which is approximately 4680 kJ/kg. It is estimated that in the reported 80 minutes of uncontrolled release, about 81 tonnes of gasoline might have escaped, which would have generated an adequate vapour cloud of gasoline to cause an explosion with the equivalence of 38 tonnes TNT.

4.4.3.2 Estimation of maximum peak overpressure

In the present study, the estimation of the maximal peak overpressure ΔP_{max} by an unconfined vapour cloud explosion (UVCE) and by a (partially confined) VCE was mainly focussed. Hailwood et al. (2009) have reported that the course of a UVCE should be treated as a deflagration (when ΔP_{max}< 1 bar) or as a detonation (when ΔP_{max}> 1 bar). While taking this into account, a formula can be derived for a spherical pressure waves for an unconfined and partially confined vapour cloud explosion between the flame front velocity u_F and the maximum peak over-pressure ΔP_{max} estimate by Eq. 4.5.

$$\Delta P_{max}/P_a = \frac{2\alpha\left(1 - {}^{1}/_{\varepsilon_1}\right)^2 \left({}^{u_F}/_{c_s}\right)^2}{1 + \left(1 - {}^{1}/_{\varepsilon_1}\right) {}^{u_F}/_{c_s}} \tag{4.5}$$

Where, the expansion ratio ε_1(measure of the energy release rate) is determined from Eq. 4.6:

$$\varepsilon_1 \equiv {}^{\rho_0}/_{\rho_1} \equiv {}^{V_1}/_{V_0} \tag{4.6}$$

The range of $\varepsilon_1 \approx 7$ to 8 (Engelhard, 1997) for stoichiometric hydrocarbon-air mixtures.

The other important parameters of the VCE are the shock wave velocity, maximum dynamic pressure and the maximum reflected overpressure (Lee, 1980). The shock wave velocity in air, U, is calculated by using Eq. 4.7.

$$U = C_0 + \left(1 + {}^{6P^0}/_{7P}\right)^{1/2} \tag{4.7}$$

where, C_0 is the speed of sound in air, and P and P^0 are atmospheric pressure and maximum overpressure, respectively. The estimated shock waves velocity which is generated due to massive explosion travel with a speed of 488 m/s (Sharma et al., 2013).

Dynamic pressure q^0 refers to the transformation of kinetic energy of the wind generated due to explosion into pressure energy when encountering a solid surface in its path. For explosion in air, the maximum dynamic pressureq^0can be expressed as Eq. (4.8) (Lee, 1980).

$$q^0 = \frac{5}{2}\frac{(P^0)^2}{7P + P^0} \tag{4.8}$$

Lastly, it is important to consider the maximum overpressure due to wave reflection. When the pressure wave hits a solid surface not parallel to the propagation direction, a reflection is produced and the reflected pressure varies not only with the value of P^0 but also with the angle of incidence. The maximum overpressure takes place when the pressure wave hits on a surface perpendicular to the direction of propagation.

$$\left(P^{o}\right)_{r}=2P^{o}\left(\frac{7P+4P^{o}}{7P+P^{o}}\right) \tag{4.9}$$

where, $(P^{o})_{r}$ is the overpressure produced on a surface perpendicular to the direction of propagation as a consequence of the reflection and r denotes the ‘reflected’ overpressure. Eq. (4.9) shows that the maximum reflected overpressure is at least double $P^{0}$and could become 8 times greater. However, for weak explosion P^{0} can be smaller as compared to atmospheric pressure. The calculated dynamic pressure and reflected over pressure with respect to maximum overpressure (>1 bar) are 0.32 bar and 2.7 bar, respectively (Sharma et al., 2013). The damage caused by this explosion resulted in further loss of containment and the subsequent fires involved a number of fuel storage tanks on the site

4.5 THE RELEASE SCENARIO OF FLAMMABLE MATERIAL

The nature of the liquid release plays an important role in determining the extent of the vapour cloud and the quantity of aerosol droplets that may entrain in the vapour cloud (Mannan, 2011). Major accidents usually start with a loss of containment (Casal, 2008). The flammable liquid released from a hole in the tank near the ground produces a relatively low volume of vapour and liquid droplets compared to liquid release from height (Kletz, 1986).

As described in the MoPNG committee report (MoPNG, 2010) on the IOCL Jaipur depot, at the time of the incident the floating roof tank 401-A held 4500 tonnes gasoline. Approximately, 2000 tonnes of gasoline was released when the 15 m high tank outlet ‘Hammer Blind Valve’ leaked for 80 min, before the flammable mixture ignited (Sharma et al., 2013). The leak resulted in a jet of gasoline directed upward from the valve. The estimation indicated that the gasoline would have been released (0.25 m diameter valve) at the rate of 1656 m^3/hr by a high-velocity jet of 10 m/s, with an angle of 10°-15° to vertical, which may have reached a height of 5 m before spilling back to the ground approximately 5 m away (Sharma et al., 2013). The gasoline escape resulted in an upwards direction from the valve and cascaded into the bund (Fig. 4.2). This type of liquid drop from a height due to jet formation would have contributed to the formation of a large vapour cloud, which covered almost the entire IOCL storage terminal site.

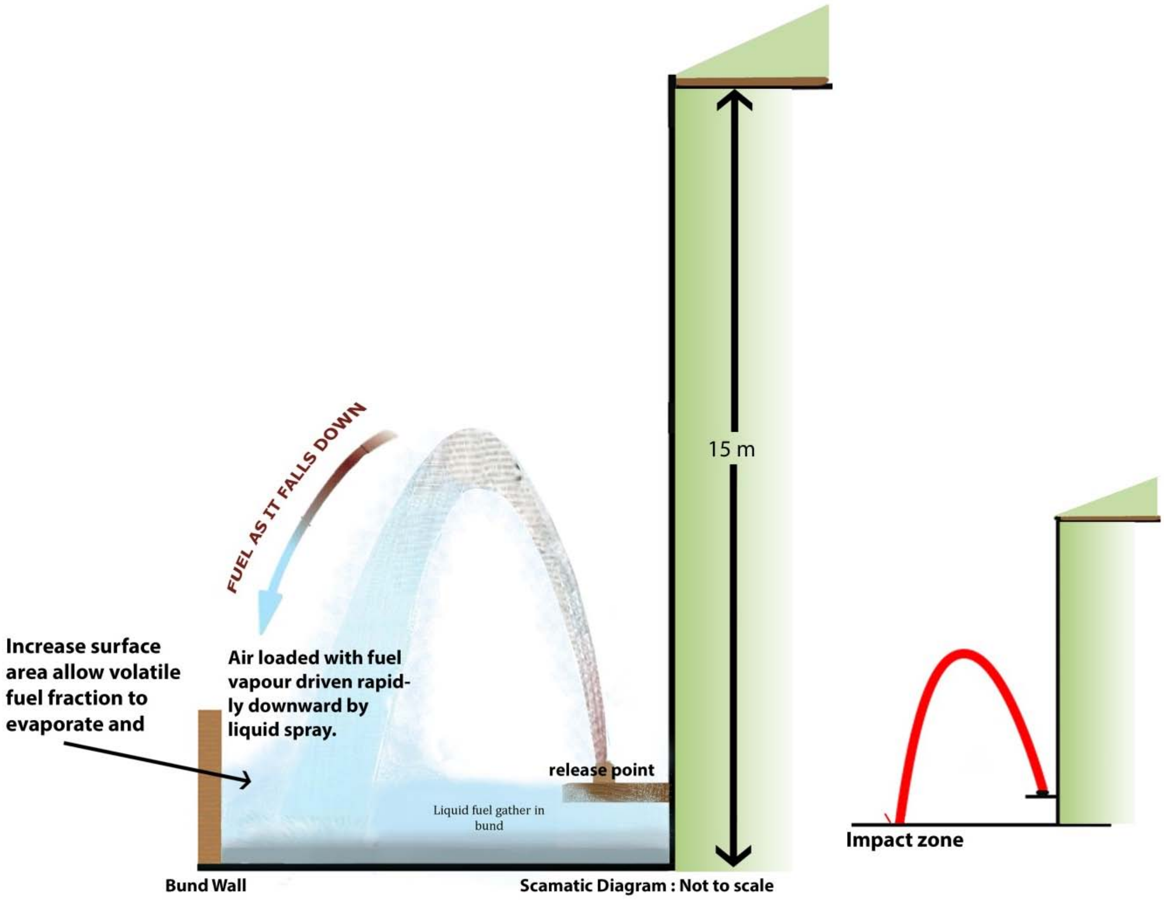


Fig. 4.2 Liquid flow during leakage of a tank from the hammer blind valve.

4.5.1 Formation of Aerosol Mix Vapour Cloud Droplets

When high flash point fuel is released under pressure, jet breakup and aerosol formation occurs (Di Benedetto et al., 2010). In present case, it is possible that close to the bund, micrometre-sized droplets of gasoline were present in the cloud because of droplet splashing and mechanical breakup during the jet cascade. In the case of a jet release, the cloud is a mixture of aerosols and vapours. The mechanism of the gasoline release and drop from height leads to the formation of a large vapour cloud. Most of the vapour is formed due to the entrainment of aerosol droplets into the vapour by the time the release hits the ground (Koshy et al., 1995; Mannan, 2011). This might have been the mechanism behind the formation of the large quantity of vapour cloud at the IOCL Jaipur storage terminal.

Johnson (1999) reported that the liquid exiting the orifice is broken up, either i) due to drag forces between the liquid and the ambient air or ii) by the action of the expansion and acceleration of the liquid as it flashes after exiting the orifice. As the intermingling sprays of the released liquid fall on the ground, large scale liquid strings are formed, which start dividing into large droplets. Based on the empirical model of Bai et al. (2002), the initial liquid fragments rapidly shatter to form a range of secondary droplets. This can lead to the formation of aerosol droplets of various sizes. Droplets of this size would have quite rapidly fallen out of the air under the action of gravity. Some size reduction may have taken place due to collisions and aerodynamic forces following the initial impingement. In addition, further size reduction would have occurred through evaporation (Gant and Atkinson, 2011; Franco, 2010). There would have also been the formation of aerosol droplets of various sizes.

Some of the droplets in the dispersing vapour current may have been deposited as the flow passed through nearby hedges, and the lighter hydrocarbon fractions in the droplets may have continued to evaporate (Kumar, 2008). While the phenomenon described above was occurring at the IOCL Jaipur depot, air was drawn into the liquid cascade and vapour was produced by the liquid evaporating and mixing with the air. The high ambient temperature of 30°C, low wind speed of 1.5 m/s, and long delay prior to ignition facilitated the formation of a vast cloud of vapour and mist with a 400 µm droplet diameter. Some liquid droplets remained suspended in the vapour flow as it impacted the dike or other tanks within the dike. It is likely that the splash zone at the base of the tank was a kind of supplementary area where vapour and very finely divided liquid were vigorously mixed for a significant period of time. Certainly, given the composition and properties of the released fluid, there would have been vaporisation. Due to the drop from height and the droplet formation, the vaporisation rate was enhanced. Given the release of 2000 tonnes of gasoline from Tank 401-A and the release scenario described above, the formation of the cloud of the size that did form was expected.

4.6 THE FORMATION AND SIZE OF THE FLAMMABLE CLOUD

The formation of a large vapour cloud was the precursor to the first explosion. The strength of the explosion and the subsequent overpressure depends on the amount of flammable mixture (which is a function of the amount of released fuel), the release duration, and the height of the jet before falling to the ground. The formation of large vapour clouds may be due to the following factors, which increase the cloud size for dense and neutrally buoyant vapour clouds (Ian Herbert, 2010).

- Still wind conditions.
- Delayed ignition potential increase due to better control over ignition sources.
- Ease/speed of detecting loss of containment.
- Significant delay in arresting the release (that increases the radius of the impact zone).

The nearest meteorological measurements indicate that on evening of the day of the accident, the weather was calm and stable, with an air temperature close to 30°C and 25% humidity. The weather on the evening of the release was Pasquill stability category D, with a 1.5 m/s wind speed (MoPNG committee, 2010).

The amount of air entrained into the cascade by momentum exchange is sensitive to the liquid mass density, which, in turn, requires knowledge of the width of the spray zone (Bradley et al., 2012; Mohan et al., 1995). In the case of the IOCL Jaipur incident, the vapour cloud formation was favoured due to air entrainment, dispersion from the falling strings of gasoline and evaporation of the gasoline in the bund. Additionally, the topography of the surrounding land and the blocking due to undergrowth, storage tanks and the plant affected the spreading of vapour cloud.

However, the vapours would have spread as a gravity current, mixing with air at the leading edge and top surface of the cloud, whereas the lower part would have remained stratified and fuel rich. It seems reasonable to suggest that the centre of the cloud would be deeper and richer in fuel than the edges (Bradley, 2012). Once initiated, the flame would flash through the flammable regions, leaving the rich mixture to burn more slowly as diffusion flames. The flammable limit corresponding closely to the top of the mist layer may not hold and needs to be justified by the thermodynamics of the local cloud composition and atmospheric humidity (Bradley, 2012). Complete appreciation of the mechanism of this cloud formation has proved difficult to achieve. Thus, the source term for the vapour dispersion contains many uncertainties and inherent difficulties.

The estimation using PHAST 6.51 shows that the total area of the cloud was of the order of 180, 000 m^2 and extended to a distance of almost 500 m, with an estimated height of 2 m over most of the area (Sharma et al., 2013). The wind direction at the time of incident was 340° (NNW direction), with a stability class of D. Fig. 4.3 shows the vapour cloud dispersion with a varying concentration of material, towards the south east (SE) direction using DNV Norway based PHAST 6.51 software. The estimated cloud boundary was based on the combination of the overpressure and directional indicator observations combined with the knowledge that the site wall would tend to retain the cloud within the site. It was a massive cloud, both absolutely and compared with the clouds observed in other incidents, and the cloud size is an important reason why the explosion was so large. With regard to the development of the vapour cloud, the height of the cloud is also important. This study was undertaken to understand how the vapour cloud spread over such a large area and to provide data that could be used for explosion modeling studies.

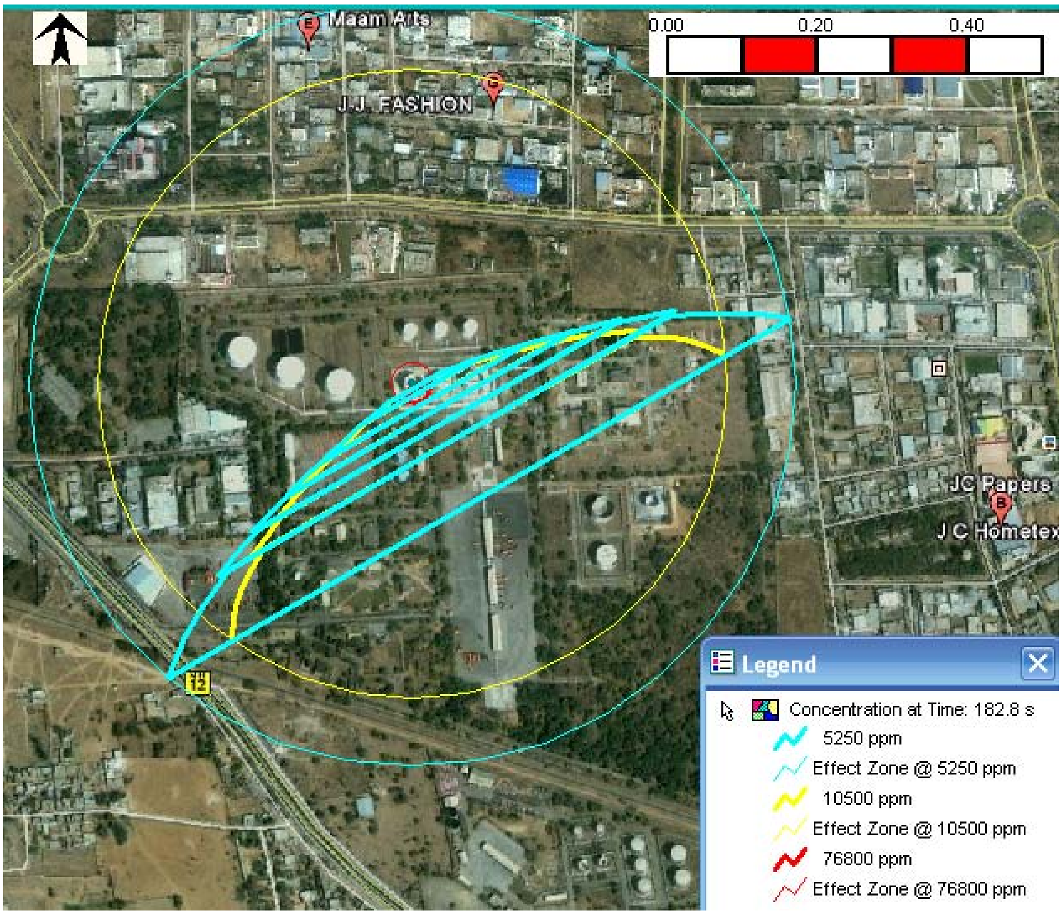


Fig. 4.3 Dispersion of vapour cloud in SE direction by using PHAST 6.51

4.7 IGNITION

In an earlier analysis (MoPNG Committee, 2010), a piece of non-flame proof electrical equipment in the Administrative Block or from a vehicle being started in the installation area was considered to be a possible ignition source. These were within the vapour cloud from an early stage. A flammable mixture would have built up inside of these potential areas. There is a possibility that either of potential ignition sources may have caused an internal explosion, providing a significant energy ignition source. By the time ignition occur, a partially dispersed fuel cloud can contain zones in which the fuel is mixed with air. Ignition can cause burning in both the premixed and diffusion flame mode, as well as high-speed deflagration (especially in partially confined or congested areas) that can lead to vapour-cloud explosion and, possibly, detonation. The flame speed may have been enhanced by the aerosol fuel mist (Lawes and Saat, 2011) and also by the turbulence generated in the gas ahead of the flame as it propagated through confining trees and undergrowth (Leal and Santiago, 2004).

4.8 DEFLAGRATION

Gas masses that are released into the atmosphere can form, together with the ambient air, ignitable gas-air mixtures (flammable gas clouds), and the subsequent ignition can cause burning in both the premixed and diffusion flame modes as well as high-speed deflagration. The highly non-uniform distributions of concentration and/or temperature in the premixed zone can cause the initiation of gas-dynamic waves, fast deflagration, and even detonation (Bartenev and Gelfand, 2000; Makhviladze and Rogatykh, 1991). Deflagration can lead to detonation if the gas cloud explosion takes place in an enclosed space and near geometric structures, such as buildings, congested parts of installations or rows of trees. The turbulence generated by obstacles and confining boundaries accelerates the flame by accelerating the gas flow ahead of it. This turbulence leads to an increase in the turbulent burning velocity, which in turn creates more turbulence in the unburnt gas ahead of the flame front (Hailwood et al., 2009). Large turbulent burning velocities can create a strong impulse wave ahead of the flame coupled with a pressure and temperature increase. This further increases the root mean square (r.m.s.) turbulent velocity, which in turn increases the turbulent burning velocity, further accelerating the flame. This run-away feedback mechanism is eventually countered by partial quenching of the flame because of the increasing flame stretch rate and a volume packing limit to the flame surface density (Bradley et al., 2012). As a result, there is a maximum value of the ratio of turbulent to laminar burning velocity, u_t/u_l. This ratio is a function of the Markstenin number for strain rate and the dimensionless group, u_lL/ v, where L is the turbulent integral length scale and v is the kinematic viscosity (Bradley, 2012). Chao and Lee (2003) measured such turbulent flame speeds in ducts that are closed at one end and packed with cylindrical rods to accelerate the flame. These flame speeds also depended upon the blockage ratio.

At the IOCL Jaipur site, the vapour cloud explosion could not have been caused by deflagration alone given the widespread presence of high overpressures and directional indicators in open areas. However, the area exhibiting high overpressures included many open regions, without trees, bushes or pipe work. Many of the indicators were in open areas, providing evidence inconsistent with the vapour cloud explosion that occurred as a result of deflagration only. In these areas, deflagration would not be sustained, and the overpressures would have decayed. The overpressure damage evidence is, therefore, not consistent with the vapour cloud explosion that only involves deflagration. This evidence included damage due to overpressure to steel drums, steel boxes, vehicles, tanks and buildings. Much of this evidence has a close similarity to the evidence observed in the Buncefield incident. The evidence is not consistent with overpressure generation in one particular area producing a pressure wave that decays as it propagates away from the source and across the site. The over-pressure computed in the south direction of the site on the control room and Business Continuity Centre (BCC) Buildings were of the order of 15 kPa. Additionally, over-pressures on the car parking and Administration building were 16 kPa and 17 kPa, respectively (Sharma et al., 2013), whereas the over-pressure on the canteen was 23 kPa.

4.9. RESULTS AND DISCUSSIONS

4.9.1. Estimation of Consequence Modeling

Most hydrocarbons when accidentally released in a pressure-liquefied or refrigerated condition are initially cold and dense. They either partly condense by themselves or cause condensation of the water vapour in the air into which they mix. They can be seen as a white cloud at low level just before an explosion (Abbasi et al., 2010). In present case, a vast release of gasoline had formed a flammable aerosol mix vapour cloud that spread over a wide area before it ignited, exploded, and set fire to a considerable number of tanks. View of the plant site during the incident is shown in Fig. 4.4. A similar kind of accident had occurred in December 2005 at the Buncefield fuel depot in the UK due to overflowing of gasoline from a tank.

Most flammable material releases are confined within the plant by the presence of obstacles. Hence, the cloud dimensions and contours are usually determined by the configuration at the installation, and the normal depth of clouds varies from 1 to 2 m. However, the release of gas or fuel oil in open terrain, as in the case of accidents in storage terminals, causes the cloud to spread over a very large area. Previous incidents have shown that these vapour clouds can travel several hundreds of metres. In these cases, flash fires are more possible and may lead to explosions that occur due to delayed ignition (Koshy et al., 1995).

(Source: Roy, 2011)

Fig. 4.4 Jaipur IOCL terminal site during the major fires that followed the explosion

The accident at IOCL Jaipur (India) occurred due to the release of gasoline from a 250 mm hole outflow pipes the result of the failure of a hammer blind valve on the delivery line of tank 401-A for about 80 minutes. The estimation by using PHAST 6.51 software indicates that the gasoline would have been released at the rate of 336 kg/s while the calculated value of release rate by using Eq. (4.1) is 323 Kg/s. The percentage error between estimated and calculated release rate is 3.9%. The high-velocity jet of 10 m/s with an angle of 10°–15° to vertical might have reached a height of about 5 m before spilling back on the ground around 5 m away. Therefore, a leak resulted in a jet of gasoline directed upwards from the valve. The total amount of gasoline released was estimated at about 2116 tonnes. This resulted in a pool covering the tank dyke of 6400 m^2, whereas, the exposed area for evaporation was 5144 m^2 and the rate of gasoline evaporation due to buoyancy was obtained as 17 kg/s. Eighty minutes of continuous release resulted in the formation of 81 tonnes of vapour cloud of gasoline. The high ambient temperature of 30°C, very low wind speed (1.5 m/s), stability class "D", 25% Relative humidity and long delay prior to ignition - all these factors facilitated the formation of a vast cloud of vapour and mist having a 400-µm droplet diameter. Thus, the vapour generated during this period was about 81 tonnes and posed a great hazard due to the delay in ignition. The total area of the cloud was of the order of 180,000 m^2 and extended to a distance of almost 500 m with an estimated height of about 2 m over most of the area (Sharma et al., 2013). The MoPNG (2010) stated that the gasoline was composed of 36.5% pentane and 63.5% hexane, which could have increased the rate of vapour generation. The main components of the gasoline vapour cloud were probably butane and pentane (Atkinson et al., 2008).

4.9.2 Factors Affecting the Explosion

Sufficiently delayed and strong ignition after an accidental release of hydrocarbons generally leads to either a flash fire in an open area or a VCE in a confined area. The strength of the gas explosions mainly depends on geometric factors (size, confinement, and obstructions generating turbulence), gas mixture factors (composition, reactivity or nature, and quantity of fuel), and ignition source (location and strength) (Qiao and Zhang, 2010).

As previously stated, the vapour cloud in the Jaipur IOCL accident had covered the almost area of the plant facilities (as shown in Fig.4.3). The simulated impact of the subsequent explosion and fire was indicative of the damage that was observed on site. Estimates show (see section 4.9.1) that the facilities covered by the vapour cloud would have been vulnerable in the event of an explosion. These include the plant, other buildings, truck loading facilities, fire water system, and portions of the pipeline terminal. Excluding the area immediately adjacent to the release source, the concentration of the vapour cloud was within the range of the upper flammability limit (UFL) and lower flammability limit (LFL) of gasoline. The distances of the UFL and LFL mixes of the vapour cloud were estimated at 15.54 m and 375 m, respectively.

4.9.3 Estimation of Overpressure

For an explosion to occur, several conditions must be fulfilled. First, the substance released must be flammable. Second, there must be a certain delay in ignition, because if ignition occurs immediately, a jet fire scenario is realized. Third, the vapour cloud must reach a minimum size. If there is a significant delay in ignition, it is possible that a sufficiently large size cloud of fuel-air mixture will develop. Fourth, part of the fuel-air cloud must be within the upper and lower flammability limits. Finally, the presence of turbulence is required. This turbulence can be produced either by the release mode in the case of a jet or by interaction of the cloud with obstacles that create a partial confinement (Casal, 2008).

If the release is from a pressure-liquefied state, the initial behaviour may be similar to that of a heavy gas even if at normal temperature and pressure the substance is lighter than air. This may be due to its initially low temperature, entrapped liquid droplets (condensed fuel vapour or water mist due to high humidity), and high release density. The resultant vapour cloud is, therefore, likely to hug the ground initially due to negative buoyancy, before slowly rising and moving away. This potential for a spillage of so-called cold gasoline resulting in a vapour cloud explosion has also been recognized (Kletz, 2006).

Any delay in arresting the release increases the radius of the impact zone. Dispersion of the dense vapour cloud in Jaipur IOCL accident release was favoured by the conditions described in section 4.6. The strong source of ignition that subsequently triggered the explosion could have been from one of the non flame proof electrical equipment or from a vehicle being started at the installation (MoPNG, 2010). The shock waves which are generated due to massive explosion travel with the velocity of 488 m/sec. Scenarios were analyzed to identify the largest explosive transient vapour cloud that built up after the accidental release and to quantify the potential overpressure due to the VCE that was experienced by the various facilities. The estimated maximum overpressure in this scenario is about >1.0 bar whereas the calculated dynamic pressure and reflected over pressure for maximum overpressure are 0.32 bar and 2.7 bar, respectively. The damage caused by this explosion resulted in further loss of containment and the subsequent fires involved a number of fuel storage tanks on the site.

4.9.4. Effect of Barricades on Explosion

The presence of obstructions, such as vessels, pipe racks, supporting structures, buildings, and trees, enhances the overpressure of an explosion (Koshy et al., 1995). In present case, very severe damage has been reported within a short distance from the release point. In extreme cases, the entire plant is destroyed, including the control rooms, business continuity centre, terminal office building, terminal pumping station, piping, and vessels, as shown in Fig. 4.5.

(Source: Google Earth, 2011b)

Fig. 4.5 Jaipur IOCL terminal site after the incident.

4.9.5. Effect of Overpressure

A shock wave can be regarded as a jump-like discontinuous increase in pressure, temperature, and material velocity that propagates through a medium with the material velocity in the direction of the front. Therefore, the propagation velocity of a shock front is principally higher than that of a sound wave. The transfer of shock wave energy from one material to another is optimal at equal acoustic impedance (product of density and sound velocity). Hence, most of the energy of a shock wave in air is reflected upon hitting a solid or liquid surface. An explosion in the air near the ground results in higher pressure at the ground surface by reflection than in free air at the same distance from the source (Abbasi, 2010).

It should be noted that the minimum overpressure to cause significant damage and take human lives is far below the maximum pressure rise of typical explosions. Pekalski et al. (2005) reported that overpressures of only 10% of the typical maximum explosion pressure cause severe damage. The effects of blast wave overpressures on structures are given in Table 4.1. Personal injuries caused by blast waves arise both directly from interacting with the overpressure and indirectly from being struck by flying debris or a collapsing structure.

Table 4.1 Extent of damage as a function of the overpressure of the shock waves (Assael and Kakosimos, 2010, Crowl, 2003).

Description of damage	**Side-on overpressure (bar)**
Glass Panes	
Fracture 5%	0.007 – 0.01
Fracture 50%	0.014 - 0.03
Fracture 90%	0.03- 0.06
Buildings	
Movement of tiles	0.03 – 0.05
Destruction of doors and window frames	0.06 – 0.09
Destruction of wall construction 50-70%	0.35 – 0.8
Near total demolition	0.8 – 2.6
Pillars	
Destruction	0.8 – 2.6
Large trees	
Destruction	0.5 – 1.0
Railway cars	
Derailment limit	0.8 – 1.9
Rupture of oil storage tanks	0.2- 0.3
Steel frame building distorted and pulled away from foundation	0.2

The results of the overpressure study by PHAST 6.51 software were used in the determination of the overpressures associated with various facilities and buildings located within the terminal area. Moreover, they were validated by site-specific studies for reasonable and acceptable reasons, as listed in Table 4.2.

Table 4.2 Peak overpressures calculated by PHAST 6.51 simulation and estimated by analysis of observed damage.

Observation point	**Damage analysis**		
	Observed damage	**Approximate Distance (m)**	**Approximate Overpressure (bar)**
Pump house	Damaged	134	0.52
Lubricant yard	Damaged	147	0.45
Canteen	Partially Damaged	210	0.23
Diesel generator building	Partially Damaged	231	0.2
Administration building	Walls & Ceiling Damaged	252	0.17
Car parking	Damaged	265	0.16
Control room	Partially Damaged	273	0.15
Truck loading facility	Damaged	273	0.15
Shed roof	Totally blown out	277	0.15
Business continuity centre	Ceiling & Walls Damaged	280	0.15
Glass	Destroyed	up to 2 km	0.01
Window frames	Destroye	up to 2 km	0.01
Tank401-B	Partly deformed	33	1.0
Tank 401-C	Roof collapsed inward	77	1.0
Fire water tanks	Roof blown out	134	0.52
Tanks 402-A, B & C	Heavily deformed	48, 67, & 96	1.0
Tanks 403-C	Heavily deformed	79	1.0
Tanks 403-B	Heavily deformed	147	0.43
Tank 403-A	Heavily deformed	210	0.23
Tank 409-A	Deformed	306	0.13
Tank 409-B	Deformed	327	0.11

The level of pressure damage is illustrated in Figs. 4.6 and 4.7. Lees (1980) observed that the exact shape of the pressure profile in the initial moment depends on the type of explosion. In any case, at a certain distance from the point of the region of positive pressure (overpressure) is usually followed by a rarefied zone, in which there is a weak negative pressure with respect to the atmosphere, which generally does not exceed 0.25 bar absolute. In spite of this, its destructive effect can be very significant, due to the fact that the buildings and facilities are generally not designed to resist greater within than without.


(a) (b)

Fig. 4.6 (a) High level of over pressure damage at Terminal main building and (b) view of the damaged car parking

A large industrial building belonging to Genus Industries, located very close to the western boundary wall of IOCL terminal and approximately 290 – 300 m from the release point, was extensively damaged and collapsed from west to east. The MoPNG (2010) reported that three employees of this factory were killed and a large number (about 45 persons) were injured. Other large industrial buildings very close to the eastern boundary wall were extremely damaged. All trees and bushes close to the south end of the area, except for a very few, were totally denuded of leaves, snapped at different heights, because of the effect of the blast.

4.9.6 Assessment of Vapour Cloud Explosion Hazards

A number of aspects of the IOCL explosion at Jaipur (India) stand out as important issues for the assessment of vapour cloud explosion. Series of powerful explosions were heard up to 20 miles (32.2 km) away as the fire spread from one tank to another. The impact of one explosion measured 2.3 on the Richter scale (MoPNG, 2010). As a result of the powerful explosion, about 1.7 km of the 3 km boundary wall collapsed. There was extensive pressure damage to a number of buildings, vehicles, instruments, and lubricating oil drums located within the vapour cloud. Most of the damage indicated that approximate overpressures were in excess of 2 bar.

This evidence included overpressure damage to steel drums, steel boxes, vehicles, tanks and buildings. Overpressure damage was recorded photographically and, where required, the location at which the photograph was taken was noted. The damage observed are shown in Fig.4.6 and 4.7.

(a) (b) *(Source: Roy, 2011)*

Fig. 4.7 (a) Damaged Vehicles and (b) lube oil drums due to extensive over pressure of vapour cloud explosion

4.10 DEFLAGRATION TO DETONATION TRANSITION

Unlike deflagration, detonation is self-sustaining and propagates across the open areas if the vapour cloud concentration is within the detonable limits (which are generally similar to the flammable limits for common hydrocarbons). As a result, the directional indicators would be more widespread (Johnson, 2011). A critical condition for a transition from deflagration to detonation (DDT) in a duct caused by attaining a maximum turbulent burning velocity should be high enough for the gas velocity ahead of the flame to generate a shock wave sufficiently strong (Bradley et al., 2008). These waves resulted in increased pressure and temperature behind them to cause auto ignition of the compressed reactants between the shock wave and the flame. Thus, detonation cannot occur without a sufficient maximum turbulent burning velocity and auto ignition. However, due to heterogeneity in the vapour cloud, auto ignition will first occur at the most reactive hot spot, within a restricted reactivity gradient (Johnson, 2010). This may create a confined shock wave, which triggers earlier auto ignition throughout the remaining reactants (Hailwood et al., 2009). Therefore, high speeds of change of the heat release rates can produce intense sound waves. The condition for the coupling of a sound wave and a chemical reaction front needed for the development of a detonation is that the confined reactivity gradient generates an auto ignition velocity that is close to the speed of sound (Bradley et al., 2012). Thus, the final flame velocity produced by the turbulent flame acceleration process depends on various parameters, including the mixture composition, the dimensions of the enclosure, and the size, shape, and the distribution of the obstacles.

In the IOCL Jaipur accident, estimated peak overpressures in excess of 200 kPa (2 bar) were generated across most of the site, with a 488 m/s shockwave velocity that was not consistent throughout the site (Sharma et al., 2013). The event was caused by an explosion in one area of the site, producing a decaying blast wave that propagated across the site. The overpressure damage and the directional indicator evidence are not consistent with *only deflagration* event in a ‘congested’ region. Directional indicators are generated by the flow from the expanding combustion products behind a detonation front. In this situation, they would point in the direction of the detonation propagation rather than in the opposite direction. Some of the directional indicators may be due to the effects of blast wave propagation away from the detonating cloud.

In the IOCL Jaipur site, the most probable cause of the detonation was a flame entering either the pipeline area control room or the pipeline pump house located at north east corner of the site, causing a confined or partially confined explosion that might have initiated a detonation as it vented from the building (Johnson, 2011). The damage of the pipeline control room building and Pipeline pump house are shown in Figs. 4.8 and 4.9. As shown in Fig. 4.8, damage to the south side of the building was much more severe than on the north side of the building, where there was a complete collapse of the building, indicating the propagation of waves towards the pipeline division from the south side. Fig. 4.9 shows the damage to the pump house from the south side. Trees bent towards the northeast direction, as examples of directional indicators, are also shown in Fig.4.10.

(a) (b) *(Sorce: Johnson, 2011)*

Fig .4.8 Damaged control room in the Pipeline Division area (a) north side, (b) south side

(Source: Johnson, 2011)

Fig. 4.9 Damaged Pipeline pump house from the south of the building

There are two probable descriptions that can validate the pipeline control room damage.

- There is a clear dividing line between the high pressure damage to the south side and the lower level of damage on the north side. This finding is also supported by the apparent lack of damage to the trees on the north side of the control room that can be seen in Fig. 4.8a.
- It is notable that the collapse of the roof downwards on the south side (Fig. 4.8b) does not appear to be consistent with an internal explosion that vented outwards from the north side building. The flames venting from the building might have resulted in a transition to detonation and the high external pressure could have pushed the partially failed roof downwards. This description could be considered to be physically plausible.

The directional indicators point to the source of the detonation being located in the Pipeline Division area in the northeast corner of the site, as illustrated in Fig. 4.11. The arrows indicate the approximate directions indicated for each area of the site (Johnson, 2011).

(Source: Johnson, 2011)

Fig. 4.10 Directional indicators: Trees bent towards the pipeline Division located in north east direction

(Source: Johnson, 2011)

Fig. 4.11 Overview of the directional indicators and estimated cloud boundary (yellow line)

There was a confined explosion in the control room that could have eventually led to a transition to detonation in the vapour cloud on the south side, or it could have enhanced flame propagation towards the pipeline pump house further to the south, with a detonation being initiated by an explosion in this building. This hypothesis can be supported because at the downwind side, the wind flow reattaches to the ground and the mean velocity remains lower than it is on the upwind at the same height above the ground. All along this wake, turbulence is higher than the upwind side values. Thus, flammable material near a building can have higher concentrations in the building wake than in the absence of the building. Enhanced turbulence accelerates flames near and far downwind of the building. The directional indicators would then be produced by a combination of asymmetric propagation of the detonation combined with direct overpressure effects.

A deflagration to detonation transition due to trees along the north wall of the pipeline division has not been considered because there were no dense bushes at a lower level and some gaps were found in the tree line. These gaps in the tree line might have decelerated the transition. Whereas, in the case of the Buncefield analysis, the possibility of the detonation occurring as a result of flame acceleration in trees does not appear to be consistent with the evidence, and it was found that directional indicators could be explained by a detonation propagating through the low lying vapour cloud **(**Johnson, 2010**)**. The evidence obtained from the IOCL Jaipur site has a high degree of consistency with the observations made following the Buncefield incident, both in terms of overpressure damage and directional indicators. Table 4.3 lists some of the important details concerning the accidents.

Table 4.3 A summary of the facts of major incidents that have similarities with the Jaipur IOCL gasoline release accident

Location of Accident & Date	**Storage Capacity (m^3)**	**Cause**	**Delayed in ignition (min.)**	**Quantity Released (tons)**	**Cloud Cover (m^2)**	**Explosion Overpressure (bar)**	**Intensity on Richter Scale**	**Fire Lasted (days)**	**Loss**			
									Death	**Injured**	**Damages (tanks destroyed / total tanks)**	**Economic Loss ($)**
Buncefield UK, Dec. 2005	273×10^3	Overfilling	40	300	12×10^4	≈ 1.3	≈ 2.4	≈ 4.5	Nil	43	22/41	1.5×10^9
IOCL Jaipur, India, Oct. 2009	110×10^3	Leakage	80	2000	18×10^4	> 2	≈ 2.3	≈ 11	11	150	11/11	55×10^6

4.11 CONCLUSIONS

Vapour cloud explosions are highly complex phenomena whose destructive potential depends on not only the flammable mass involved but also the cloud dispersion and the reactivity of the gaseous mixture. The concentration, size, and location of the vapour cloud play important roles in VCE, which is evident from IOCL terminal Jaipur (India) accident assessed in this chapter.

The severity of the Jaipur IOCL plant explosion was high, even though the site was not highly congested. The severity of explosion in such an unexpected surrounding has been successfully explained using the current knowledge of VCEs and information available in the open literature. The modelling of the vapor cloud formation and dispersion corroborates the observations by plant personnel that gasoline vapours had enveloped almost the entire area of the facility. This implies that the facilities covered by the vapour would have been vulnerable in the event of a fire. These include the non-plant buildings, Truck Loading Facilities (TLF), fire water system, and portions of the pipeline terminal. In the event that the prevailing weather conditions and the turbulence of a cloud permitted sufficient mixing with air, an unconfined vapour cloud explosion (UCVE) occurred when a source of ignition was encountered.

Both in terms of overpressure damage and directional indicators, the evidence obtained from the IOC Jaipur site is consistent with the observations made during the Buncefield incident. The observed damage at the site can be explained in terms of high-speed deflagrations and transition to detonations. The Norway based DNV PHAST 6.51 software was used in the determination of the overpressures associated with various damaged facilities and to validate the extent of the damage that had occurred. High pressure up to1.0 bar was found only in the immediate vicinity of the more confined section of the plant. This range of overpressure reached in the south (S) and south-west (SW) direction of the terminal. Though the pressure decreased rapidly with increasing distance, explosions of such an extent still caused considerable glass breakage at distances up to 2 km.

While the overpressures in excess of 200 kPa (2 barg) were generated across almost the entire site (most probably in north east direction) but it was not uniformly distributed across the site. The overpressure damage and the directional indicators show that the flammable vapour cloud covered almost the entire site. The vapour cloud explosion could not have been caused by deflagration alone due to the widespread high overpressures and the directional indicators in the open areas. The overpressure pressure damage and directional indicators show that the source of the detonation was in the Pipeline Division area in the northeast corner of the site. Flame entering into the pipeline division area caused a confined or partially confined explosion, which then led to detonation as it vented from the building. The possibility of detonation due to the line of trees along the north wall of the pipeline division has been ruled out because it is not deep at lower levels, and there were some gaps in the tree line. It is significant to note that the overpressure damage and direction evidence observed in the IOCL Jaipur explosion are characteristic of a vapour cloud explosion in dense low lying clouds, where a detonation has been initiated and has been observed in previous incidents. During this study a dire need for more such analytical studies of similar major chemical accidents was felt to better validate the models proposed in the literature to represent such complex physical phenomena.

CHAPTER 5

ANALYSIS OF GEOMETRIC AND RADIATIVE CHARACTERISTICS OF HYDROCARBON TANK FIRES

5.1 INTRODUCTION

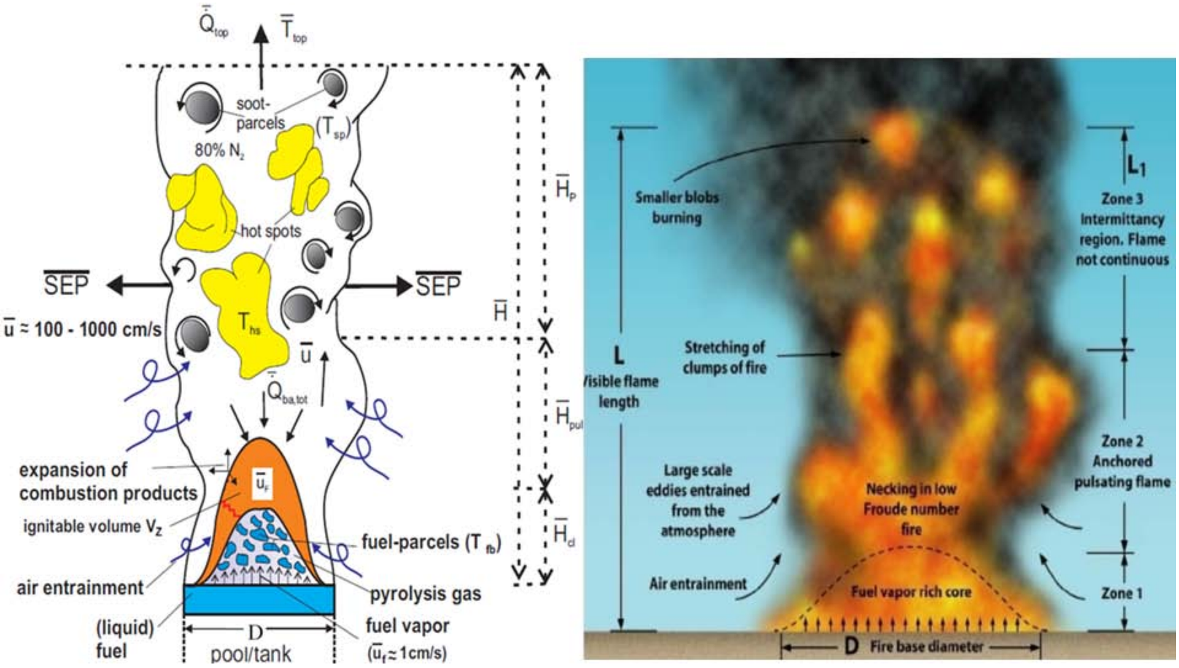
Storage tanks at refineries and depots contain large volumes of flammable and hazardous materials. A hydrocarbon tank fire or pool fire is relatively a frequent accident that may lead to unexpected consequences to the surrounding facilities at the installation including damage to the environment and fatal injuries or fatalities. Evidence shows that the majority (approximately 42%) of all accidents in chemical processing industries involve pool fires (Abdolhamidzadeh et al.; 2011). Pool fire hazards from accidentally released flammable fuels are one of the main concerns in the processing industry. Pool and/or tank fires can be very large, persistent and difficult to douse. In the last decade, there have been three large-scale fuel storage tank fire accidents that have exhibited striking similarities. The Buncefield oil storage depot accident in the UK on 11 December 2005, the Caribbean Petroleum Corporation fuel depot accident in Puerto Rico, USA on 23 October 2009, and the Indian Oil Corporation Ltd (IOCL) accident in Jaipur, India on 29 November 2009 (Mishra et al., 2013; Sharma et al., 2013). In addition to this, Amuay refinery accident occurred in Venezuela on the 25 August 2012 (Mishra et al., 2014). These accidents demonstrate not only the large-scale destruction of the surroundings and serious environmental implications but also underline the necessity of appropriate measures to prevent such devastating accidents (Pitblado, 2010). Therefore, learning from the past accidents is important for the future safe operations of storage tanks.

The hazard calculation of such accidents involves measurements of the mass burning rate, flame geometry, flame temperature and, more importantly, emitted radiation by the flame. The thermal radiation evaluation plays a significant role in assessing the resistance of equipments in the proximity of fire and verifying the possibility of domino effects. To avoid too conservative results, imposing anti-economic geometric constraints, for example, in terms of spacing, a realistic scenario evaluation is needed.

This chapter concentrates on the assessment and evaluation of the flame height and temperature as well as the thermal radiation of the IOCL Jaipur incident (MoPNG committee, 2010). In the analyses of the accidental hydrocarbon pool (or tank) fires and their domino effects, the evaluation of the flame extent and temperature are of the utmost importance. Because the pool fires have thermal radiation effects, employees' safety zones need to be addressed on the basis of flame characteristics and heat radiation intensities. In this chapter, various semi-empirical mathematical models have been used to study large-scale pool and tank fire characteristics.

5.2 CHARACTERISTICS OF POOL FIRES

Large-scale tank or pool fires in refineries and storage depot accidents are characterised by turbulent non-premixed fires burning over a horizontal pool of vaporising flammable material (Raj, 2007; Fay, 2006). Due to the turbulence, flames undergo a significant fluctuation, and fireballs are formed on the top. The heat is transferred from fire to the pool of flammable material by convection and radiation, which may lose or receive heat by conduction from liquid substrate under the liquid layer. Therefore, once the fire has reached the steady state, there is a feedback mechanism that influences its vaporisation rate and consequently the size and other characteristics of the fire. Schalike et al. (2011) reported that pool fires can be divided into two or three non-continuous zones, as shown in Fig. 5.1, which can be calculated -albeit with large uncertainty. The luminous clear burning zone (H_{cl}) is just over the pool rim with hot spots. This zone is not covered with black smoke and has the largest surface emissive power $\overline{SEP}_{\mathrm{cl}}^{\mathrm{ma}}$ of the fire. In the pulsation zone (H_{pul}), the flame front is still connected to the flame basis but it is a less efficient combustion zone of the flame. In this zone, the formation of black soot can occur due to large eddies of air intake with radial and axial pulsation. In the top region i.e. the plume zone (H_{P}), a non-continuous segregated flame is observed. The flame temperature and axial velocity decrease in this zone due to the continued air entrainment.



(a) (b)

Fig. 5.1 Existence of three zones in a turbulent buoyant diffusion flame (5.1 (a), Schalike et al., 2011; 5.1 (b), Raj, 2007)

5.2.1 Tank Fire Accident Scenarios

Potential tank fire scenarios that can be developed in a tank accident are presented in LASTFIRE (2001) (Fig. 2): The initial pool fire is of the following types:

- Rim seal fire
- Spill on roof fire
- Full surface fire
- Bund or Dyke fire
- Pontoon explosion
- Boil over

Among these, the most intense are the full surface fire and boil over.

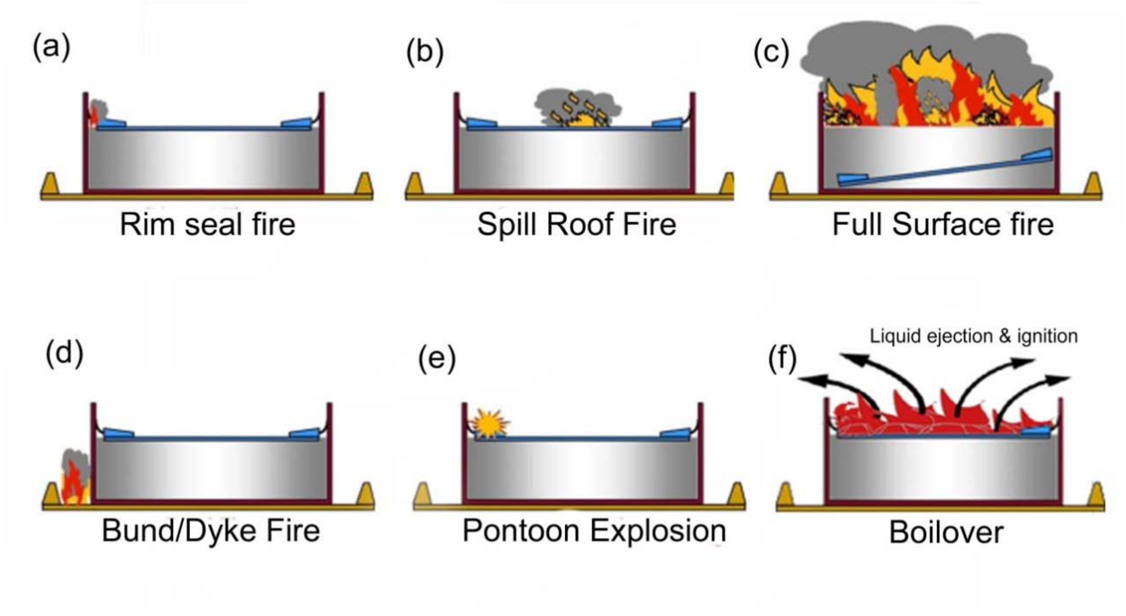


Fig. 5.2 Potential tank fire scenarios

5.2.1.1. Rim seal fires

A rim seal fire occurs when the seal between the tank shell and roof has lost and vapours find ignition in the seal area. The flammable vapour cloud can occur in various parts of the seal depending upon the seal design.

5.2.1.2. Spill on roof

A ‘‘Spill on roof’’ fire occurs when a hydrocarbon spill on the tank roof is ignited but the roof maintains its buoyancy. In addition to this, flammable vapours escaping through a roof fitting or tank vent can be ignited.

5.2.1.3. Full surface fires

A full surface fire is one where the tank roof has lost its buoyancy and some or the entire surface of liquid in the tank is exposed and then involved in the fire.

5.2.1.4. Bund fires

A fire in a bund is any type of fire that occurs within the containment area outside the tank shell. The flammable mixture of hydrocarbon vapour and air exists in any of the above potential scenarios but fire will only result if there is an ignition source providing for sufficient energy to initiate combustion. The fire risk that characterizes a fixed roof atmospheric storage tank is the sum of pre-risks associated with the rim seal fire scenario.

5.3 FIRE SCENARIO AT IOCL JAIPUR

Accidental fire in process plants is often a pool fire or a tank fire, like the one occurred at IOCL Jaipur in India on October 2009 (MoPNG, 2010). The effect of heat release from a large flame is as intense as a thermal radiation on people and surrounding objects and can produce fatal injuries or damage buildings or parts of the plant. The IOCL Jaipur accident is a result of leakage of a very large mass of gasoline (m_f = 2000 t), which led to a major fire of 11 days duration and involved all the 11 tanks (Sharma et al., 2013) as shown in Fig. 5.3. The expansion of the fire to the neighboring tanks happened without explosions due to the high thermal radiation. For large, black, smoky hydrocarbon fires, the estimation of the critical thermal separation distance is not only dependent on the total fire but also on the height of a hot and clear burning zone. Additionally, for multiple tank fires, as occurred in Jaipur, there is a considerable increase in the mass burning rate, the flame height, the surface emissive power, as well as the thermal separation distance (Liu et al., 2009).

Fig. 5.3 IOCL Jaipur tank fire during the incident (MoPNG, 2010, Roy, 2011)

5.3.1 Selection of Typical Damage Images

To understand and illustrate the postulated scenarios, a selection of typical damage images from the IOCL Jaipur incident is shown in Figs. 5.4- 5.6.

(a) (b)

Fig. 5.4 Damaged tanks after the accident (a ,b)

(a) (b)

Fig. 5.5 Warehouse and crushed drums on the loading bay (Johnson, 2011)

(a) (b)

Fig.5.6 (a) Covered storage area to the north of the warehouse (Johnson, 2011) and (b) Damaged depot pumping station (MoPNG, 2010)

5.4 FLAME CHARACTERISTICS AND OF POOL FIRES

The pool fire characteristics are given below, which have been used to estimate the flame height, flame temperature and thermal radiation.

5.4.1 Mass Burning Rate

The time averaged mass burning rate $\overline{m}_f^{''}$ can be calculated by multiplying the time averaged burning velocity and the liquid density of fuel. The equation for the mass burning rate is given below:

$$\overline{m}_f^{''} = 10^{-3}\,\Delta H_c/\Delta H_{\mathrm{v}} \tag{5.1a}$$

This equation is valid for a wide range of gaseous and liquid fuels (Vela, 2009).

For the maximum mass burning rate, the following equations are used (Vela, 2009).

$$\overline{m}_f^{''}(D) = \overline{m}_{\mathrm{f,max}}^{''}\left(1 - e^{-k\beta D}\right) = \overline{m}_{f,max}^{''}\varepsilon_{\mathrm{F}} \tag{5.1b}$$

$$\overline{m}_{\mathrm{f}}^{''}(D) = \rho_{\mathrm{f}}\,\overline{\mathrm{V}}_{\mathrm{f,\ max}} \approx 1.27\times 10^{-6}\,\Delta H_c/\Delta H_{\mathrm{v}}\left(1 - e^{-k\beta D}\right)\rho_{\mathrm{f}} \tag{5.1c}$$

The estimated maximum mass burning rate $\overline{m}_f^{''}(D)$ for large tank gasoline fire is 0.055 kg/m^{2}s. As reported by various authors, the $\overline{m}_f^{''}(D)$ of gasoline in a large tank in fire ranges from 0.055 to 0.083 kg/m^{2}s (Chatris et al., 2001; Munzo et al., 2004)

5.4.2 Flame Geometry

The geometry of a flame depends mostly on flame pool diameter, flame length, mass burning rate, temperature and the flame radiative properties. These properties are characteristically taken as averaged in time. The measurements derived from different assessments for the influence factors and the geometry of large flames is shown below.

5.4.2.1 Relative flame height

The flame height is generally taken as the maximum visible height or the time-averaged visible height (Rew et al., 1997). The time-averaged relative ($\overline{H}/D$) and maximum relative ($(\overline{H}/D)_{\mathrm{max}}$) visible flame height are dependent on the Froude number (Fr_f) and the dimensional wind velocity ($\bar{u}_W^*$) that can be estimated by the following correlations (Hailwood et al., 2009) :

$$\bar{H}/_{D} = a\, Fr_f^b \bar{u}_W^{*c} \tag{5.2a}$$

and

$$\left({}^{H}/_{D}\right)_{max} = a\, Fr_f^b \bar{u}_W^{*c} \tag{5.2b}$$

There are more correlations with many empirical parameters, such as a, b, and c, which are given in Table 1 (Vela, 2009).

Table.5.1 Parameters for determination of dimensionless visible flame heights used in Eq. (5.2a, b) (Munoz et al., 2007).

Correlation	**a**	**b**	**C**	**Comment**
Munoz 1	8.44	0.298	-0.126	Measured on gasoline and diesel pool fires: $(\mathrm{H}/\mathrm{D})_{\max}$
Munoz 2	7.74	0.375	-0.096	Measured on gasoline and diesel pool fires: $(\bar{H}/D)$

The height of the visible flame is a function of the pool diameter and the burning velocity. For the IOCL Jaipur incident, an assessment of the maximum, visible and relative flame heights of gasoline tank fires was conducted assuming that the ‘c’ parameter in Eq. (5.2b) was zero because there was no wind effect. The modified equation can, therefore, be written as:

$$(H/D)_{max} \approx a\mathrm{Fr}_f^b = \mathrm{a}\left(\frac{\bar{\tilde{m}}_f}{\rho_{a\sqrt{gD}}}\right)^b \tag{5.3a}$$

Thus, the estimated $(H/D)_{\max}$ ratio for the gasoline tank fire (with *D = 24 m*) is 1.5. For a large hydrocarbon pool fire where *D ≥ 9m,* the time-averaged relative flame height ($\bar{H}/D$) is calculated using Eq. (5. 2a) (Hailwood et al., 2009) and Table.1 that can be approximated as below:

$$(\bar{H}/D)_{\mathrm{calc}} \approx a\mathrm{Fr}_f^b = 7.74\left(\frac{\bar{\tilde{m}}_f}{\rho_{a\sqrt{g\,D}}}\right)^{0.375} = 0.9 \tag{5.3b}$$

With $\overline{m''}_{f,max}$ (D=24 m) ≈ 0.055 kg/ (m^2s) for a gasoline pool fire, ρ_a = 1.29 kg/m^3, and the parameters a and b from Table 1, the calculation based on Eq. (5.3a, b) results in

$$0.9 \leq (H/D)_{max,calc} \leq 1.5 \qquad (5.3c)$$

An empirical relationship was observed between the maximum and average flame height. Thus, a single correlation could be used to estimate both dimensions (Muñoz et al., 2004):

$$(H/D)_{\mathrm{max}} \approx 1.6\,\bar{H}/D \qquad (5.4)$$

The empirical relationship in Eq. (5.4) was considered valid for the IOCL Jaipur tank fires.

5.4.2.2 Height of the clear burning zone by MSFM

In the Modified Solid Flame Model (*MSFM*), $\overline{SEP}^{ma}_{\mathrm{MSFM}}$ $(D,\eta) \equiv \overline{SEP}^{ma}_{\mathrm{cl}}$, $\overline{H} \equiv \bar{H}_{cl}$ and $\bar{\eta}_{rad} \equiv \bar{\eta}_{rad,\mathrm{cl}}$. Thus, the relative height of the hot clear burning zone (yellow luminous), $\bar{H}_{\mathrm{cl}}/D$, which is not covered with a black smoky layer, can be calculated by Eq. (5.5a) (Hailwood et al., 2009):

$$\bar{H}_{cl}\,(D)/D = \frac{\bar{\eta}_{rad,\mathrm{cl}}(D)\overline{m}''_{\mathrm{f,max}}(-\Delta H_c)}{4\overline{SEP}^{ma}_{cl}} \qquad (5.5a)$$

Eq. (5.5a) is valid only for gasoline and kerosene fires. Within the extent of the *MSFM* exponential correlation between $\bar{\eta}^{\mathrm{exp}}_{\mathrm{rad}}$ and the pool diameter (Schmitz et al., 2012), the following relationship is valid:

$$\bar{\eta}_{\mathrm{rad,cl}}(D) = \bar{\eta}^{\mathrm{exp}}_{\mathrm{rad}}(D) \;=\; 0.35\,\mathrm{e}^{-0.05\mathrm{D}},\ \text{when}\ \overline{SEP}^{\mathrm{ma}}_{\mathrm{cl}} \approx 100\ \mathrm{kW/m^2} \qquad (5.5b,c)$$

Eq. (5.5a) with Eq. (5.5b, c) results in the following equation (5.5d):

$$\bar{H}^{\mathrm{MSFM}}_{\mathrm{cl}}/D = 2.5\ \times 10^{-3}\,\bar{\eta}^{\mathrm{exp}}_{\mathrm{rad}}(D)\overline{m}''_{f,max}\,(-\Delta H_c) \qquad (5.5d)$$

For a large tank gasoline fire, $\overline{m}''_{\mathrm{f,max}}\,(-\Delta H_c)$ ≈3630 kW/m^2 (Muñoz et al., 2004).

$\overline{H}_{\mathrm{cl}}^{\mathrm{MSFM}}/D \approx 2.1 \times \mathrm{e}^{-0.05\mathrm{D}} = 0.6$ (5.5e)

The $\overline{SEP}_{cl}^{ma}$ defines the relative height $\overline{H}_{cl}/D$ of the clear burning zone, as well as radiative fraction of the fire $\overline{\eta}_{red,cl}\ (D)$.

5.4.2.3 Height of the clear burning zone by considering (C/H) ratio

The modelling of the clear flame length has been proposed by Pritchard and Binding (1992) and Ditali (1992). It was reported that the height of the clear flame varied by approximately 30% of the maximum flame length for fires up to 25 m in diameter and to 0% for fire diameters of 5 m or more. The hydrocarbon fuel has a major role in the production of smoke within the fire affecting the height of the clear flame. The (*C/H*) ratio is used to illustrate the saturation of a hydrocarbon fuel and the tendency to generate soot.

- ***Pritchard and Binding Correlation:***

Pritchard and Binding (1992) used the *C/H* ratio to characterise the effect of the fuel type in the correlation of the clear flame height by Eq. (5.6a).

$$H_{Cl}/D = 11.404\ (m^{*})^{1.13}(U_9^{*})^{0.179}(C/H)^{-2.49} \approx 0.3 \quad (5.6a)$$

where the C/H ratio for gasoline is 0.43

$m^{*}$and U^{*} can be calcutated by Eqs. 5.6b and 5.6c respectively

$m^{*} = m^{"}/\rho_a\ (\mathrm{g}D)^{1/2}$= 6× 10^{-3} and (5.6b)

$$U^{*} = U/\left(\frac{\mathrm{g}}{m^{"}\ D/\rho_a}\right)^{1/3} \approx 0.5 \quad (5.6c)$$

- ***Ditali Correlation*:**

Ditali et al. (1992) produced a similar correlation (Eq. 5.7) based on a separate set of experiments, with a lower dependency on the (C/H) ratio.

$$H_{\mathrm{cl}}/D = 12.4\ \left(m^{"}\right)^{0.61}D^{-0.6}(C/H)^{-0.15} \approx 0.4 \quad (5.7)$$

Comparison of the above two correlations with clear flame data shows that the Pritchard and Binding correlation provides a better prediction than the Ditali correlation (Rew et al., 1997). Hence, the Pritchard and Binding correlation represents the best available method for predicting clear flame height.

The estimated maximum, relative, and clear burning zone flame heights using the above correlations for the IOCL Jaipur incident are illustrated in Table 5.2.

Table.5.2 Flame Heights for gasoline tank (*D* = 24 m) on fire in IOCL Jaipur Accident

$(\boldsymbol{H/D})_{\textbf{max obs,Jaipur}}$	**1.0 – 1.7**	**Ref.**
$(H/D)_{max}$	1.5	(Hailwood et al., 2009)
$(\bar{H}/D)_{\text{calc}}$	0.9	(Hailwood et al., 2009)
$\bar{H}_{\text{cl}}^{\text{MSFM}}/D$	0.6	(Hailwood et al., 2009)
H_{Cl}/D	0.3	(Pritchard and Binding, 1992)
H_{cl}/D	0.4	(Ditali et al., 1992)

The $(H/D)_{max}$ ratio computed by the Munoz correlation is 1.5, whereas the observed value lies in between 1.0 and 1.7. Thus, the calculated value is within the observed value. The average value of $(\bar{H}/D)_{\text{calc}}$ is 0.9. The clear burning zone heights (H_{Cl}/D) were obtained by various models such as the *MSFM*, Pritchard and Binding, and Ditali models. The Pritchard and Binding and Ditali models use (*C/H*) ratios to indicate the saturation of the hydrocarbon fuel. The *MSFM* model gives a maximum value of 0.6, whereas the Pritchard and Binding and Ditali models predict 0.3 and 0.4, respectively. This trend shows that the flame height in the Jaipur incident case was unusually large.

5.5 FLAME TEMPERATURE

The flame temperature is a function of time and height, as described by Planas and Casal (1998). The correlation used for the flame temperature is given by the following equation (Eq. 5.8):

$$\mathrm{T}_f(t,h) = \frac{10^4 . t}{(34+210 \times \mathrm{H}+8.51\times \mathrm{t})} + 298 \tag{5.8}$$

In the IOCL Jaipur accident, the estimated flame temperature of the gasoline tank (*D = 24m*) was approximately 1230K, which lies within the range (1100K-1240K) reported by various researchers for large-scale gasoline pool fires (Mudan, 1984; Koseki, 1989; Babrauskas, 1983; Croce and Mudan, 1986; Chuna et al., 2009).

5.6 SURFACE EMISSION POWER (SEP)

A key parameter for the estimation of the thermal radiation of tank or pool fires is the Surface Emissive Power (*SEP*) (Gawlowski et al., 2009; Munoz et al., 2007; Raj, 2007; Fay, 2006). It is usually defined as the heat flux due to thermal radiation at the surface of the flame in kW/m^2 (Engelhard, 2005). The flame surface area (A_F) should be considered in the calculations of *SEP* because it depends on the geometry of the flame. The thermal radiation, *SEP*, of a tank or pool fire can be calculated using the radiation models, such as the Solid Flame Model (*SFM*), the Modified Solid Flame Model (*MSFM*), the Two-zone Radiation Model (*TRM*) and Thermal Radiation for Single and Multiple Tank Fires Model (*TRSMFM*). These models consider the effect of heat feedback enhancement on *SEP*.

5.6.1 Solid Flame Radiation Model (*SFM*)

In this model, the flame is considered as a cylinder with the circular base having a homogeneous temperature around the flame as shown in Fig. 5.7. This model can also be considered as a single-zone radiation model, with no black soot portion, having a high emissivity of $\bar{\varepsilon}_{\mathrm{F}} \approx 0.95$, just like optically thick flames. The time-averaged maximum surface emissive power $\overline{SEP}_{SFM}^{ma}$ is calculated using the Eq. (5.9a) as given by Engelhard (2005).

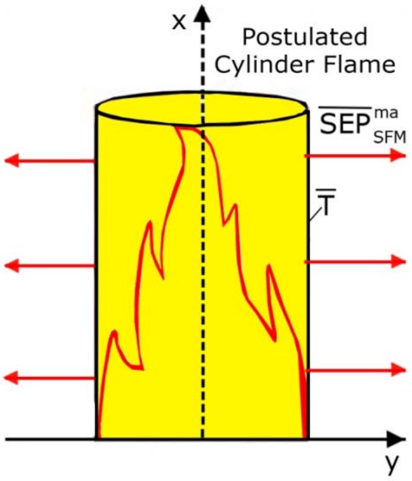


Fig. 5.7 Solid flame radiation model: The flame is equally radiant cylinder (Hailwood, 2009)

$$\overline{SEP}_{\mathrm{SFM}}^{\mathrm{ma}} = \bar{\varepsilon}_{\mathrm{F}}\, \sigma\, (\mathrm{T}_f^4 - \overline{\mathrm{T}}_{\mathrm{a}}^4) \neq f(Df) \tag{5.9a}$$

With the calculated flame temperature of 1230 K from Eq. (8), the surface emissive power is estimated as below:

$$\overline{SEP}^{\mathrm{ma}}_{\mathrm{SFM}} = 123 \text{ kW/m}^2 \qquad (5.9\text{b})$$

SFM is used to compute the maximum surface emissive power of a specific pool or tank fire (Mc Grattan et al., 2000, Engelhard, 2005).

5.6.2 Modified Solid Flame Model (*MSFM*)

In this model, the flame is divided into two parts: a luminous part where the flame can be clearly seen with high emissive power and an upper part where dark smoke covers the flame with sudden bursts of luminous flames, as shown in Fig. 5.8. The moving border between these two parts depends on the fuel, pool diameter, and oxygen content of the burning zone (Raj, 2007). Especially for large pool diameters, an alternative equation for the time-averaged maximum surface emissive power $\overline{SEP}^{ma}_{MSFM}$ (D, η) is proposed by Munoz et al. (2007) (Eq. 5.10a).

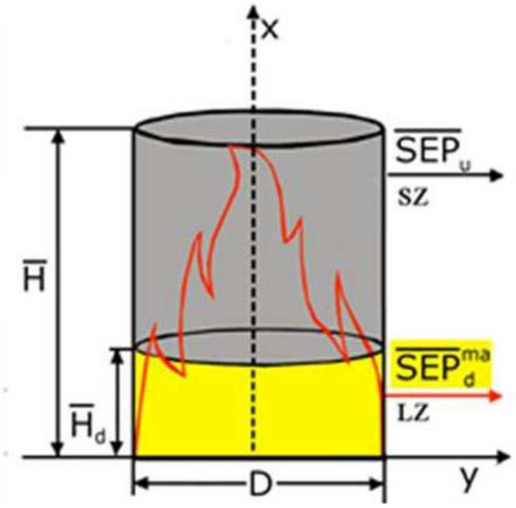


Fig. 5.8 MSFM: the flame is divided into a clear luminous zone with a high radiation (LZ) and a non-radiating soot zone (SZ) (Hailwood et al., 2009)

$$\overline{SPM}^{ma}_{\mathrm{MSFM}}\ (D,\eta) = \frac{\overline{\eta}_{\mathrm{rad}}(D,\eta)\overline{m''}_{\mathrm{f}}\ \ (-\Delta H_c)}{4\overline{H}\ (D)/D} \qquad (5.10\text{ a})$$

Mc Grattan et al. (2000) found an exponential relationship between η_{rad} and pool diameter (Eq. 5.10b):

$$\eta_{rad} = 0.35\, e^{-0.05D} \tag{5.10b}$$

MSFM is a two-zone radiation model where the *SEP* of the lower clear burning zone (*LZ*) is denoted by $\overline{SEP}_{\mathrm{cl}}^{ma}$ (Eq. 5.10c), whereas the *SEP* for upper black soot zone (*SZ*) is denoted by $\overline{SEP}_{\mathrm{u}}$. The *SEP* of two zones, depending on the area fraction of the smoke zone ($\bar{a}_{\mathrm{SZ}}$), can be calculated according to Eq. (5.10d) (Rew et al., 1997) :

$$\overline{SEP}_{\mathrm{cl}}^{\mathrm{ma}}(D) = \overline{SEP}_{\mathrm{max}}\,(1 - e^{-kD}) \tag{5.10c}$$

$$\overline{SEP}_{\mathrm{act}} = (1 - \bar{a}_{\mathrm{SZ}})\overline{SEP}_{\mathrm{cl}}^{\mathrm{ma}} + \bar{a}_{\mathrm{SZ}}\overline{SEP}_{\mathrm{SZ}} \tag{5.10d}$$

From a hazard prediction point of view, the summation of thermal radiation from black soot and radiation from the luminous spots on an equivalent area basis is used to reach an average emissive power for the fire. If we consider two assumptions of 35% and 65% for the surface area covered with black smoke and the remaining part with luminous spots, the time average emissive power is given by the following expressions (Eqs. 5.10e - 5.10f):

$$\overline{SEP}_{\mathrm{act}} = 0.65\,[140] + 0.35\,[20] = 98\ \mathrm{kW/m^2} \tag{5.10e}$$

$$\overline{SEP}_{\mathrm{act}} = 0.35\,[120] + 0.65\,[20] = 55\ \mathrm{kW/m^2} \tag{5.10f}$$

where, gasoline-pool fires show: 1) $\bar{a}_{\mathrm{SZ}}$= 0.35 and $\overline{SPM}_{\mathrm{MSFM}}^{\mathrm{ma}}$ =140 kW/m^2 for Eq. (5.10 e) and

2) $\bar{a}_{\mathrm{SZ}}$= 0.65 and $\overline{SPM}_{\mathrm{MSFM}}^{\mathrm{ma}}$ =120 kW/m^2 for Eq. (5.10 f), and the $\overline{SEP}_{\mathrm{SZ}}$ = 20 kW/m^2 for Eqs. (5.10e,f) with k ≈ 2.0.

5.6.3 Two-zone Radiation Model (*TRM*)

As illustrated in Fig. 5.9, most hydrocarbon fuel fires become optically thick when the diameter is approximately 3 m or larger. Although the thermal radiation from black soot is low, the hot spots appearing on the flame surface due to turbulent mixing have a higher emissive power. Corresponding to the empirical radiation model according to Mudan (1984) for sooty pool fires and the time-averaged surface emissive power, the following Eq. (5.11a) is to be used:

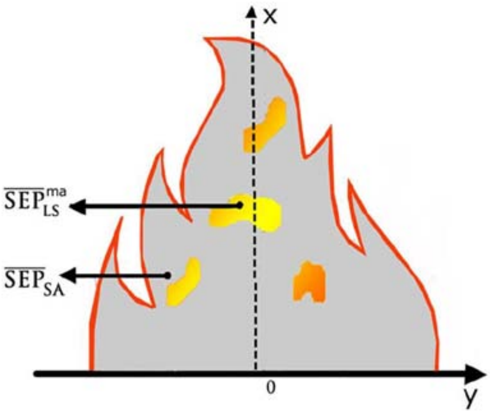


Fig.5.9 Two zone radiation model (Mudan, 1984)

$$\overline{SEP}_{act}(D) = \overline{SEP}_{LS}^{ma}\bar{a}_{LS}(D) + \overline{SEP}_{SA}\,(1 - \bar{a}_{LS}\,(D)) \tag{5.11a}$$

where, the area fractions are estimated by Eq. (5.11b).

$$\bar{a}_{\mathrm{LS}}(D) = \bar{A}_{\mathrm{LS}}/\bar{A}_{\mathrm{F}} = 1 - \bar{a}_{\mathrm{SA}} = e^{-sD} = \mathrm{e}^{-0.12D} \tag{5.11b}$$

According to Mudan and Croce (1998), a uniform surface emissive power of flames for smoky hydrocarbon fuels can be determined by Eq. (5.11c). Although the thermal radiation from black soot is low, the hot spots appearing on the flame surface due to turbulent mixing have a higher emissive power.

$$\overline{\mathrm{SEP}}_{\mathrm{act}}(D) = \overline{\mathrm{SEP}}_{\mathrm{LS}}^{\mathrm{ma}}\mathrm{e}^{-sD} + \overline{\mathrm{SEP}}_{\mathrm{SA}}\,(1 - \mathrm{e}^{-sD}) \tag{5.11c}$$

$$\overline{\mathrm{SEP}}_{\mathrm{act}}(D) = 140\,\mathrm{e}^{-0.12D} + 20\,(1 - \mathrm{e}^{-0.12D}) = 27\ \mathrm{kW/m^2} \tag{5.11d}$$

Mudan and Croce (1998) proposed an actual $\overline{SEP}_{act}(D)$ averaged over the flame surface based on the means $\overline{SEP}_{LS}^{ma}$ = 140 kW/m^2 $\neq \eta(D, \eta)$ and $\overline{SEP}_{SA}$ = 20 kW/m^2 $\neq \eta$ (D, η). For larger pool fires with $D \geq 20$ m, $\overline{SEP}_{act}$ $(D) \approx 20\,(1-e^{-0.12D})$ is also valid so that for larger pool and tank fires, the hot and luminous spots [right side first in Eqs. (5.11a, c)] are eliminated.

5.6.4 Thermal Radiation for Single and Multiple Tank Fires Model (*TRSMFM*)

For multiple tank fires, as occurred in the IOCL Jaipur incident, the interaction of neighbouring tank fires has a considerable effect on *SEP* of the individual tank fires due to heat feedback enhancement. To determine the surface emissive power of a flame, the flame surface area $A_F$has to be calculated. The thermal radiation, that is, the maximum surface emissive power SEP^{ma} (without by black soot), of a tank fire can be calculated with (Hailwood et al., 2009; Vela, 2009; Raj, 2007; Fay, 2006; Rew et al., 1997; Mudan and Croce, 1988).

$$SEP^{ma} = \eta_{rad}(D)\,\bar{Q}_{\mathrm{c}}/\bar{A}_F = 114\ \mathrm{kW/m^2} \tag{5.12a}$$

With

$$\bar{Q}_{\mathrm{c}} = \bar{m}_{\mathrm{f}}^{"}(-\Delta H_c)A_P \tag{5.12b}$$

For the cylinder flame area is given by:

$$\bar{A}_F = \pi D\bar{H}(D) + \pi D^2/4 \tag{5.12c}$$

The time-averaged $\bar{A}_F$ is determined from the instantaneous areaA_F, which is influenced by the flame fluctuations. According to Eq. (5.12 a), doubling of $m_f^{"}$, as a result of the interaction, brings about a doubling of the thermal radiation of the hot spots. These types of effects were investigated theoretically and experimentally by Gawlowski et al. (2009).

Table.5.3 Surface Emission Power (*SEP*) of a gasoline tank on fire in the IOCL Jaipur Accident

Models	**(SEP)**	**kW/m²**
SFM	$\overline{SEP}_{\mathrm{SFM}}^{\mathrm{ma}}$	123
MSFM	$\overline{SPM}_{\mathrm{MSFM}}^{ma}$ ($\bar{a}_{\mathrm{SZ}}$= 0.35)	98
MSFM	$\overline{SPM}_{\mathrm{MSFM}}^{ma}$ ($\bar{a}_{\mathrm{SZ}}$= 0.65)	55
TZM	$\overline{\mathrm{SEP}}_{\mathrm{act}}$	27
TRSMFM	SEP^{ma}	114

The analysis of the *SEP* in the Jaipur accident, estimated with various models, is illustrated in Table 5. 3, which indicates that a higher *SEP* ($\overline{SEP}_{\mathrm{SFM}}^{\mathrm{ma}}$ ≈123 kW/m^2) value was reached by *SFM*, where the flame is considered as a single luminous zone. In the case of multiple tank fires, the interaction of neighbouring tank fires, e.g., as during the Jaipur incident, has a considerable effect on the *SEP* (SEP^{ma} ≈ 114 kW/m^2) of the individual tank fires. In the later stage, the radiation from inside the flames is blocked by absorption of dense soot parcels. Subsequently, the effect of the sooty zone is calculated by *MSFM* with considerable assumptions ($\overline{SPM}_{MSFM}^{ma}$ ($\bar{a}_{SZ}$= 0.35) = 98 kW/m^2 and $\overline{SPM}_{MSFM}^{ma}$ ($\bar{a}_{SZ}$= 0.65) = 55 kW/m^2). In addition, the turbulent mixing phenomena also influences the *SEP* ($\overline{SEP}_{act}$ ≈ 27 kW/m^2), which can be estimated by *TZM*. Hottel (1959) reported that as the pool or tank diameter increases, the fire regime changes from laminar to turbulent. The different models used to predict the values of *SEPs* show a significant lack of accuracy to cover the most possible scenarios.

5.7 IRRADIANCE

The received thermal flux, i.e., the irradiance at any point, is calculated by a point source model, which assumes that heat radiation of the flame is irradiated from a point that equally disperses in a radial direction from the emission point as a sphere, as shown in Fig. 5.10. (Engelhard, 2005).

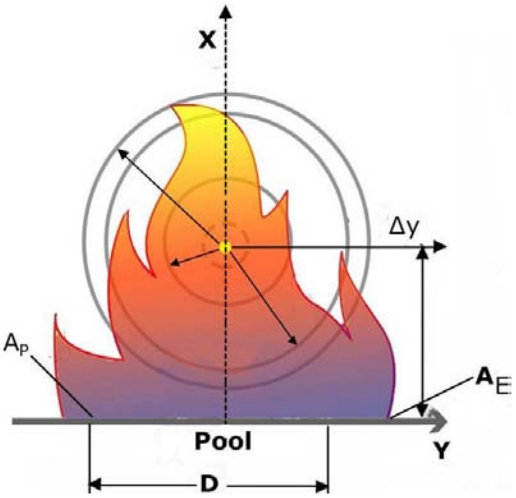


Fig. 5.10 Point source radiation model (Raj, 2005)

The point source radiation model (PSM) calculates the mean irradiance (received thermal radiation flux) by using following equation (Eq. 5.13a) (CCPS, 2000):

$$E_r = \tau_a \bar{\eta}_{rad} m_f \Delta H_c A_F F_P \tag{5.13a}$$

The view factor F_P is calculated according to the fundamental relation of view factor with respect to distance (Eq. 5.13b):

$$F_P = 1/4\pi x^2 \tag{5.13b}$$

The *PSM*, however, has only a very limited range of validity. In particular, in the near field, great uncertainties exist.

In the IOCL Jaipur accident, the mean irradiance E_r versus distance was calculated for the gasoline tank (*D* = *24*) fires with the point source (*PS*) radiation model and was validated with the DNV Norway-based risk assessment PHAST 6.51 Software estimation, as shown in Fig. 5.11. The percentage error between the estimated and calculated irradiance is 17% at a 100 m distance.

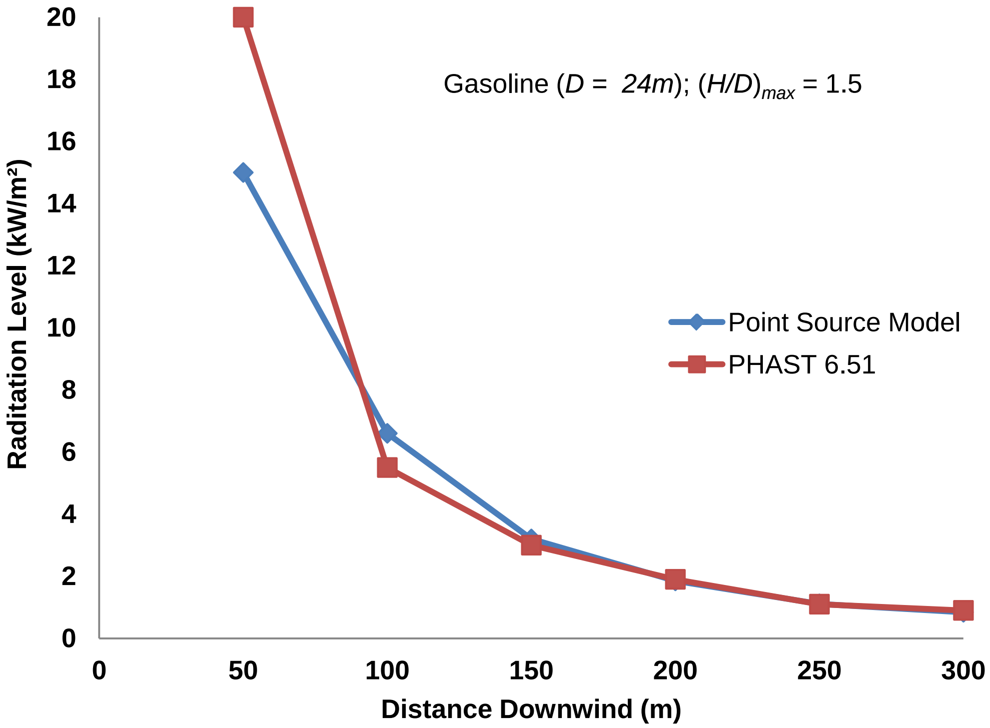


Fig. 5.11 Estimation of the received thermal flux from a gasoline (*D* = 24) tank fire with the point source model and PHAST 6.51 software

From the above figure, it is observed that the radiation intensities at various distances from the flame computed by the point source model and PHAST 6.51 software are nearly identical. There is a difference of 20 to 25% in values at nearer distances, whereas the effective values at higher distances are almost equal.

5.8 PREVENTIVE MEASURES IN OIL DEPOT

Fuel storage terminals and installations should be subjected to a quantitative risk assessment (QRA) through fire modelling to identify high hazard locations. The available fire risk reduction measures are grouped into the following main categories as shown in the following fishbone diagram (Fig. 5.12).

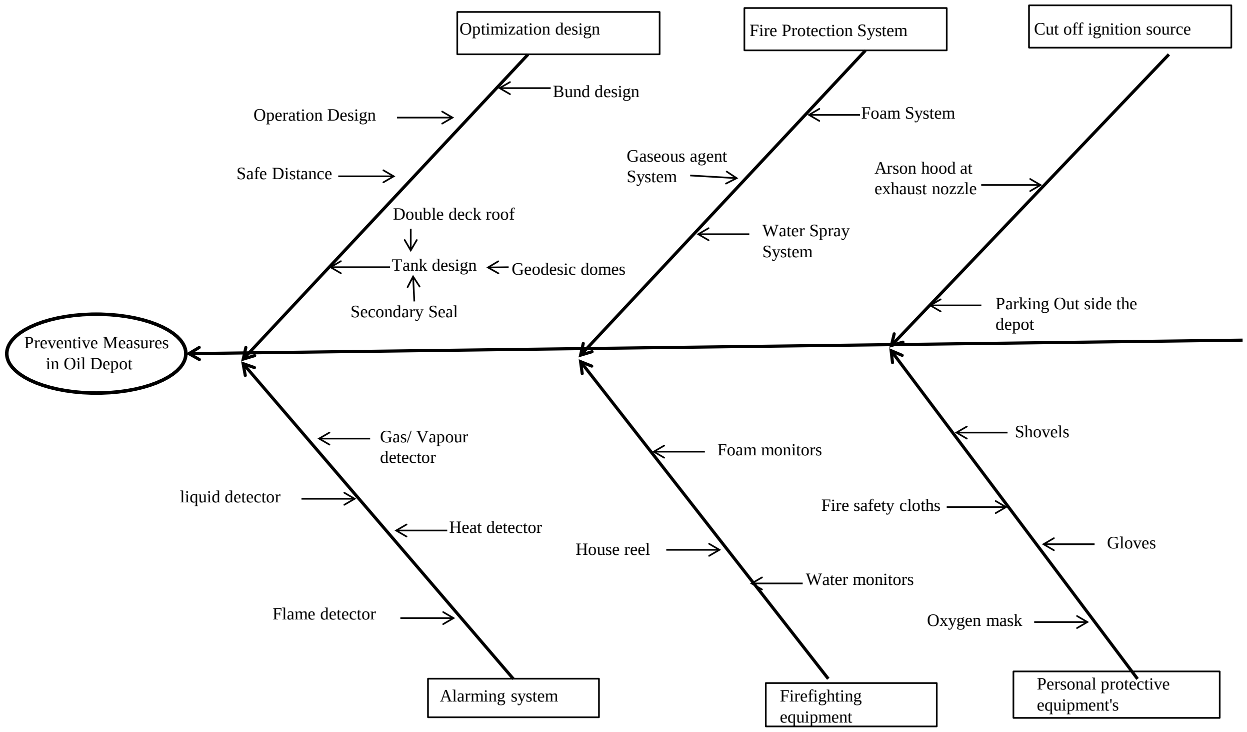


Fig. 5.12 Fishbone diagram of pool or tank fire prevention

5.9 CONCLUSIONS

Large-scale pool fires of liquid hydrocarbons show fundamentally different characteristics, e.g., generally much higher mass burning rates, large flame heights and high irradiances. To measure, calculate and study the fire characteristics, simulations and modelling of hydrocarbon large-scale pool fires were performed using various models. The present simulations are based on the assumption of a complete combustion without wind influence.

The computed mass burning rate and flame temperature, based on the data collected, are within the ranges reported in the peer-reviewed literature. The modelling analysis of the Jaipur accident revealed that the height to diameter ratio $(H/D)_{max}$ lies between 0.9 and 1.5. This ratio is approximately 1.6 times the average value and lies well within the observed values. For the computation of the clear burning zone, the Pritchard and Binding correlation results in better values than the Ditali and *MSFM* models.

The surface emissive power from a tank fire was calculated by changing the percentage of black smoke and luminous spots covering the flame. Four models namely (*SFM, MSFM, TRM, TRSMFM*) were used to predict the values of *SEPs* that showed a most likely fire scenarios occurred during the accident. The irradiance at various distances based on the point source model were compared with the DNV Norway-based risk assessment PHAST 6.51 Software estimations with a maximum percentage error of 25%.

A physical explanation of the Jaipur accident with regard to the relative flame heights *H/D* and thermal radiation (*SEP, E*) is in principal possible, in particular when considering the effective consequence models including the observations regarding multiple tank fires. However, it is necessary to overcome the lack of field data, especially with regard to the *H/D, SEP*, and E_r for larger individual as well as multiple tank and pool fires for their more realistic characterization. Furthermore, continuous efforts are required to improve the large tank fire modelling to simulate real life scenarios coping with changes in technology and management of petrochemical storage terminals.

CHAPTER 6

INDIVIDUAL AND SOCIETAL RISK ANALYSIS

6.1 INTRODUCTION

Accidents at large-scale oil storage terminals have the potential to harm the on-site and off-site population, and destroy the terminal and surrounding buildings. Much attention needs to be given in designing, constructing and operating an installation that uses and stores large quantities of flammable materials. Any uncontrolled loss of containment and subsequent ignition of a flammable mixture can result in devastating consequences, including intense fires and explosions with an influence over several kilometres (Bradley et al., 2012). Strong pressure waves can propagate beyond the immediate vicinity and the ensuing fire can have devastating effects in the surrounding and downwind atmosphere. If the accident is severe, it can cause serious injuries or fatalities to surrounding people. Therefore, a detailed assessment and analysis of risk is required that can help determine adequate safety measures to avoid such fatal incidences or reduce their severe effects.

According to Buncefield Major Incident Investigation Board (BMIIB) (BMIIB, 2008), land use planning (LUP) is responsible to the risk on the site. BMIIB suggested that LUP should be based on the risk level and more attention should be paid to minimize the risk to the surrounding population. Center for Chemical Process Safety (CCPS) (CCPS, 2000) gives guidelines to estimate the individual and societal risk associated with different incident outcome cases from major petrochemical industrial accidents. If we do not consider injuries then the individual risk is defined as annual frequency of fatality of a given person by hazardous factors of fireand explosions. Time of presence of this worker/person in or around hazardous zones is taken into account during calculations of the individual risk. The societal risk characterizes the scale of a fire and explosion hazard in terms of number of people get injuries or die. In practice the societal risk is usually determined on fatality not less than 10 people.

This study is an initial step towards the quantification of individual and societal risks related to the large-scale oil storage terminal that can help in managing associated hazards and their adverse effects. In this chapter, an attempt has been made to make reasonable assumptions to provide a more realistic estimate and analysis of individual and societal risks due to fire and / or explosion at a petrochemical storage terminal.

6.2 METHOD OF ANALYSIS AND INPUT DATA

There are two kinds of risks to people, i.e., individual and societal risk. Evaluation of individual and societal risk is the key point for the probabilistic safety assessment of the storage terminal. The individual risk is defined as the probability of death per year of exposure to an individual at a certain distance from the hazard source. It is usually expressed in the form of iso-risk contours around the source of hazard (Jo and Crowl, 2008). Whereas, societal risk as "the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realisation of specified hazards" (Ichem, 1985). Societal risk is presented in terms of F/N curves, where N is the number of fatalities and F is the frequency of N or more fatalities. Many countries such as Australia, the Netherlands, Malaysia and UK employ numerical criteriain determining acceptability of risk in terms of safety zones. The ALARP principle is developed by the Health and safety Executive of the UK (HSE, 2001). It states that risk should be reduced to "As low as reasonable practicable" (ALARP) level. The ALARP principle divides risk into three bands: intolerable risk at the higher end, negligible risk at the low end, and the tolerable risk in between. As shown in Fig. 6.1. Maximum tolerable individual risk for workers is 10^{-3} per year whereas for members of public it is 10^{-4} per year. Risk in the middle region can be tolerated as long as all cost- effective measures to reduce risk have been put into place. The cost in reducing risk should not exceed the benefits gained in reducing risks. A process with risk in the tolerable risk region must demonstrate that the lowest risk has been achieved by taking into consideration cost versus risk reduction criteria.

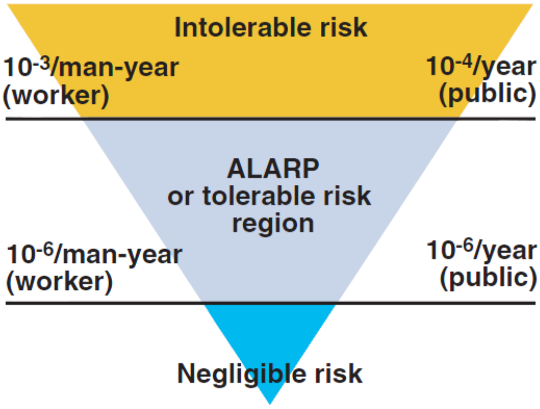


Fig. 6.1. The ALARP principle, developed in the UK (HSE, 2001)

In this chapter, individual and societal risks have been quantified and the hazard identification study results have been reviewed to generate a list of events for analysis. The overall method is comprised of the following steps:

- Identify probability and failure frequency categories of various instruments.
- Identify significant population groups of interest and their characteristics.
- Identify important events outcomes.
- Assess the consequences of event outcomes.
- Determine impacts of event outcomes at locations of interest.
- Estimate individual and societal risk.

Individual Risk at a geographical location *x, y* is given by AIChE/ CCPS (CCPS, 2000) as follows (Eq. 6.1):

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i} \tag{6.1}$$

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* (chance of fatality per year), *n* is the total number of incident outcome in the analysis from the industrial area. $IR_{x,y,i}$ can be estimated using the following equation (Eq. 6.2).

$$IR_{x,y,i} = f_i \times p_{f,i} \tag{6.2}$$

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

The societal risk of people affected by all incident outcome cases can be estimated using the following equation (Eq. 6.3) (Renjith and Madhu, 2010).

$$N_i = \sum_{x,y} P_{x,y}\, p_{f,i} \tag{6.3}$$

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

The risk assessment of the IOCL Jaipur accident has been carried out by using DNV Norway based PHAST RISK 6.51 software. The study involves analysis of the impact of overpressure due to vapour cloud explosions (VCEs) and the thermal radiation owing to tank fires on the surrounding people and facilities. The VCEs have the potential to cause significant knock-on effects. The effects of secondary events have also been included in the study. The results of the risk modelling show the severity of incidence in terms of individual and societal risk contours.

The following scenarios have been considered for the IOCL Jaipur accident:

- Failure of hammer blind valve (0.25 m) leading to the release of large amounts of gasoline
- Formation and propagation of aerosol particles and vapour, which covered an area of 1,80,000 m^2 (Sharma et al., 2013)
- Massive Vapour Cloud Explosion $>$ 2bar (Sharma et al., 2013)
- Tank fire on the surface of a tank roof
- Fire on a total cross-section surface of the tank
- Fire inside a dyke.

6.2.1 Ignition Source

Ignition source for the explosion could have been a spark from a non-flame proof electrical equipment in the administrative block or a vehicle being started in the installation (MoPNG committee, 2010). Probabilities of ignition of various sources at the terminal are given in Table 6.1.

Table 6.1 Probability of ignition for the on-site strength factor for hydrocarbon (CCPS, 2000)

Source	Probability of ignition
Furnaces, boiler, heaters	0.9-1.0
Substations	0.001-0.3
Office Buildings	0.1-0.2
Truck loading/unloading area	0.1-0.5
Cars	0.2-0.4
Construction Fabrication Shop	0.1-0.5

6.2.2 Assessment of the Population Group of Interest

The population groups of concern for risk assessment may include (Franks and Maddison, 2006):

- Different identifiable on-site groups of workers such as office workers, control room personnel and plant operators.
- Off-site population groups such as the residents of nearest area of housing or workers in adjacent industries.

The population in a residential area and average population density and that also include people on local roads have been determined based on a field survey conducted by the researcher. It is assumed that 70% of the population were out-door and 30% in-door as the incident had occurred in the evening hours. Population in various zones of the terminal and the surrounding areas is illustrated in Table 6.2 (also marked in Fig. 6.4).

Table.6.2 Population in various zones under study area (as mentioned in Fig. 6.4)

Zones	Approximate Population*	Population Density (m^{-2})
A	50	0.005
B	300	0.001
C	250	0.006
D	500	0.003
E	200	0.04
F	400	0.006
G	350	0.02
H	400	0.008

*population data is based on a field survey conducted by the researcher

6.3 RISK ACCEPTANCE CRITERIA

The level of risk in this study is quantified with an express purpose of comparing against typical acceptable risks. The acceptable risk levels can change with time and place. Although there are differences between the legislations adopted in the various countries (e.g., Canada, Malaysia, Australia, The Netherlands, and Hong Kong), there appears to be broad consensus on the tolerability of risk. The majority of the countries would accept risk levels for the public around 10^{-5} per year whilst the more stringent countries would set the tolerability level at 10^{-6} per year (Jonkman et al., 2003).In this regard, detailed guidelines available from United Kingdom (UK) (HSE, 2001)have been presented below.

6.3.1 United Kingdom Risk Regulations

In the UK the "Control of Major Accident Hazards" (COMAH) regulations are in line with the latest EU "Seveso-2" Directive (HSE, 2001). The regulations do not formally require a quantitative risk assessment, but the guidance notes make clear that in some circumstances quantification will help or could be asked for by the UK regulator - the Health and Safety Executive (HSE), and this is often done in practice.

To advise planning authorities on developments around industrial installations, the UK HSE has been developing risk acceptance criteria over the years. A comprehensive treatment of the subject of tolerability of risk was given in a report titled "Reducing Risks Protecting People”. The report repeated the concept and criteria as argued by the Royal Society in 1983 (Jonkman et al., 2003). It accepted the concept of tolerable Individual Risk as being the dividing line between what is just tolerable and intolerable and set the upper tolerable limit for workforce fatalities at 10^{-3} per year (1 in a thousand) for workers and 10^{-4} per year (1 in 10 thousand) for members of the public. A level at which risks might be broadly acceptable but not altogether negligible was set at 10^{-6} per year (1 in a million). The region in between these values would be controlled by the As Low As Reasonable Practice (ALARP) concept.

ALARP can be demonstrated in a variety of ways, depending on the severity of the worst case scenario. These are expressed in HSE guidance to Inspectors Consultation Draft September 2002. When a QRA is carried out, the F/N regions are defined as in the Fig. 6.2.

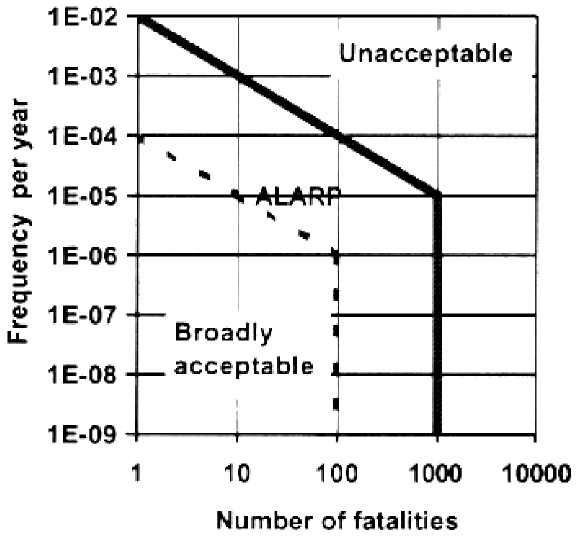


Fig. 6.2 United Kingdom Societal Risk Guidelines (risk to workforce and public) (HSE, 2001)

6.4 RESULTS OF THE RISK ASSESSMENTS

The typical results of evaluation of sizes of impact zones are shown in Figs. 6.4. It can be evaluated that the larger sizes of the impact zones are measured in the case of VCEs. The intensity of VCEs depends on the size of flammable mixture, composition and geometry of the terminal. In the present case, such severe situation was caused due to the 80 minute unabated releases of gasoline which formed a 81 tonne flammable mixture of aerosol-vapour clouds and covered an area of 180,000 m^2 (Sharma et al., 2013). The widespread pressure had damaged vehicles, instrument, drums and various surrounding buildings. Most of the damages were due to high overpressures in congested areas covered by many trees and due to geometry of the terminal. The directional indicators illustrated the detonation to be generated in the control room and the Pipeline Division area at north east (NE) direction of the terminal (Johnson, 2011).

6.4.1 Outcome Events of Concern (Event tree Analysis)

When determining possible event sequences and potential incidents, the quantitative risk analysis follows from the qualitative hazard identification. The main sources of potential release of hazardous material were identified and the initiating events that could cause such releases were determined. A complex analysis is usually based on the full range of possible incidents from all sources. The outcomes of an accident depend on the level of releases of hazardous material. For the purpose of quantitative risk assessment, it is necessary to define the event outcomes of concern using event tree analysis technique.

The methods of evaluation of impact parameters of accidents with fires and explosions as outcome scenarios have been considered in this study. One of the key issues at a risk analysis is a proper consideration of frequencies of initiating events, which determines the accuracy and reliability of the consequences. The IOCL Jaipur accident was due to the failure of manual operated valve which has a failure frequency of 10^{-4} per year (OGP, 2010). The subsequent formation of hydrodynamic wave and the release of a quantity of around 2000 tonnes of gasoline over the dyke have been taken into consideration while constructing the event tree. As the impact of accident was very severe, it is necessary to evaluate each possible event contributing to a risk value. Fig. 6.3 shows an event tree describing the series of events occurred at the site. The tree also shows the most possible effects of fire and explosion scenarios.

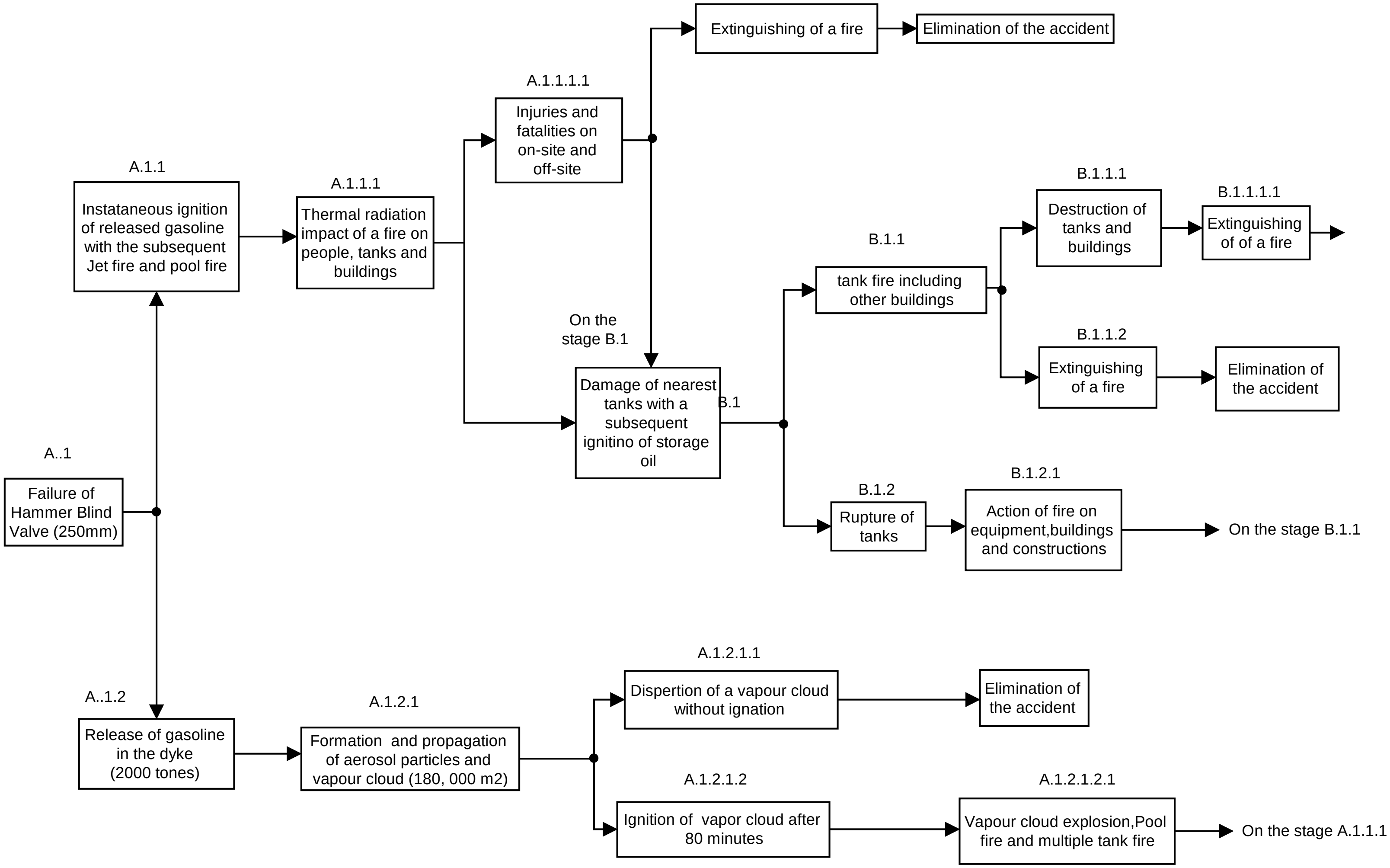


Fig. 6.3 Event tree diagram for IOCL Jaipur accident

6.4.2 Individual Risk

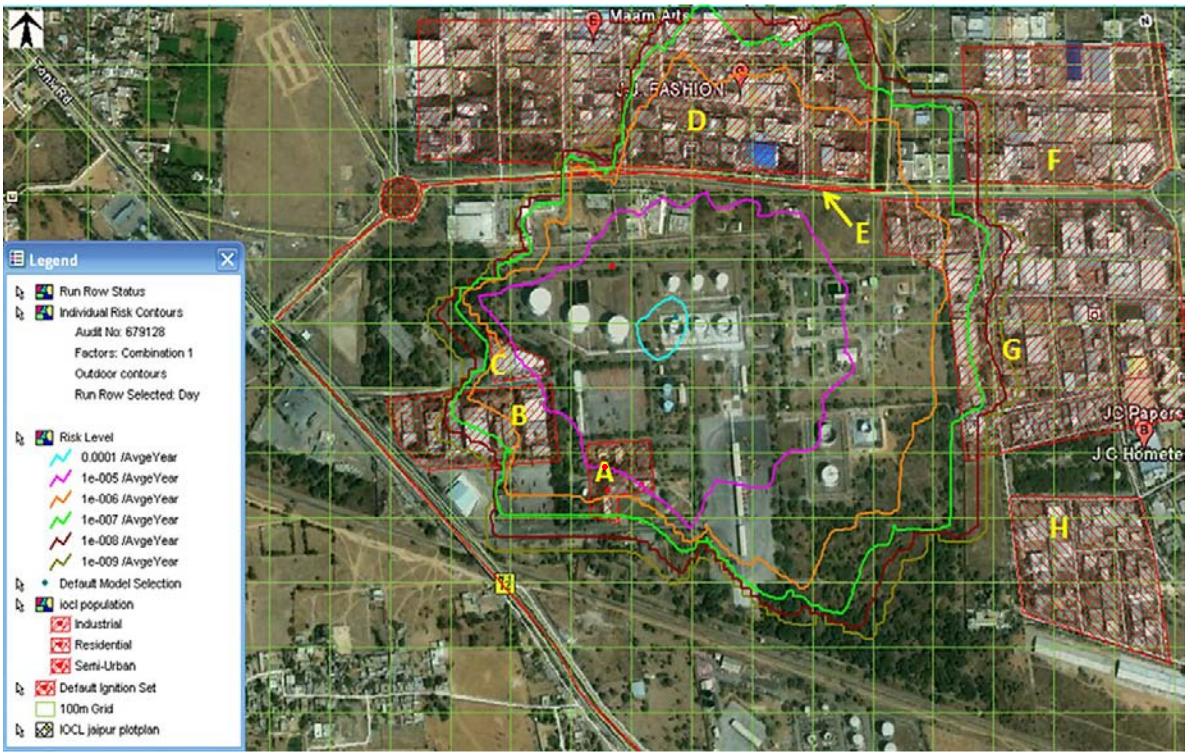
The severe impact of the accident was expected due to the formation of large amounts of air mixed flammable vapour cloud and subsequent fires on tanks. In the IOCL terminal, the peripheral distance from the released gasoline tank to adjacent tanks of gasoline, kerosene and diesel were 15 m, 55 m and 75 m, respectively. The maximum mass burning rate of the gasoline in most of the tank fires had been about 0.083 kg/m^2s (Muñoz et al., 2004).

Individual fatality risk levels reflect the cumulative risk implication of various events of varying consequences and likelihood of occurrence. The tolerable or acceptable value of the individual risk for personnel or industrial installations is not yet regulated by Indian standards and norms. Therefore, a comparison of the calculated risk values was made with the tolerable / acceptable risk values proposed by HSE UK guidelines. Maximum tolerable individual risk to site workers as per HSE UK guidelines is 10^{-3} per year whereas the same for the public is 10^{-4} per year (Kauer et al., 2002).

The individual risk has been computed by the DNV Norway based PHAST RISK-6.51 software for the territory of the terminal and the surrounding area. The individual risk contours with various risk levels have been presented in Fig. 6.4. The maximum risk level of 10^{-4} per year has been observed near the storage tank area at a distance of around 100 m from the release point. The next risk level i.e. 10^{-5} per year is at a distance of 280 m. These risk contours fall within the terminal boundary. In this case, risk at the terminal does not lie in completely unacceptable region as the level is not exceeding the value of 10^{-4} per year.

As the risk levels of 10^{-4} and 10^{-5} per year corresponds to the ALARP region, the risk in the terminal should have been minimized with more precautionary measures. The individual risk outside the terminal is more than 10^{-6} per year making it as an acceptable risk level.

As presented in Table. 6.3, the individual risk of the personnel associated with various buildings and facilities within the terminal is in the range of 1.9 -7.0 $\times 10^{-5}$ per year, which demonstrate that it is in the strict risk control zone. Individual risk values for personnel at various locations (illustrated in Fig. 6.5) outside the terminal are shown in Table. 6.4. The risk values are in the range from 1.0 $\times 10^{-8}$ – 6.8 $\times 10^{-5}$ per year. The risk level for the surrounding people was tolerable. Thus, the quantitative risk assessment demonstrates clearly that the safety precautionary measures were not effectively implemented in the terminal, which subsequently led to the severity of the accident. The results indicate that the incident could have been avoided / minimized by the proper implementation of safety measures. However, it seems that the failure of or absence of adequate precautionary measures (as discuss in Table 7.2) led to such a catastrophic accident.



(Source: Google Earth, 2011)

Fig. 6.4 Individual Risk controls for the IOCL Jaipur incident

Table 6.3 Individual risk levels at various locations inside the terminal

Buildings and Facilities within the terminal	Distances from Release Point (m)	Individual Risk (per year)
Control Room	264	7.0×10^{-5}
Administrative Block	280	6.9×10^{-5}
Business Community Centre (BCC)	306	6.8×10^{-5}
Terminal Canteen	212	6.8×10^{-5}
Store	226	6.9×10^{-5}
Fire water pump house	125	4.0×10^{-5}
Lube warehouse	237	6.7×10^{-5}
Truck Loading Facility (TLF)	325	3.5×10^{-6}
Pump House	381	1.9×10^{-5}
Security Gate	368	6.8×10^{-5}

(Source: Google Earth, 2012)

Fig. 6.5 Individual Risk at different locations at outside the Terminal site

Table 6.4 Individual risk levels at various locations outside the terminal

Outside Locations*		**Distances from Release Point(m)**	**Individual Risk (per year)**
Genus Power Industries Ltd.	**(1)**	272	6.8×10^{-5}
Genus Power Industries Ltd.	**(2)**	296	6.8×10^{-5}
Global Art Exports Pvt.	**(3)**	369	7.0×10^{-5}
Shriram General Insurance (HQ)	**(4)**	166	7.0×10^{-5}
Power Substation area	**(5)**	220	4.7×10^{-6}
JVS Food PVT. LTD.	**(6)**	485	1.8×10^{-7}
Residential area (Adjacent to Sitapura water works)	**(7)**	550	1.0×10^{-8}
Jaipur Electrical Company	**(8)**	369	1.4×10^{-6}

*as point mentioned in Fig. 6.5

6.4.3 Societal Risk

The societal risk is presented as an F-N curve which is a plotting of cumulative frequency versus number of fatalities. The X-axis indicates the number of fatalities and the Y-axis gives the cumulative frequency (per year) of all the scenarios together. Fig. 6.6 shows an F/N curve for the incident delineating three regions viz. “Unacceptable”, “tolerable if ALARP” and “broadly acceptable”. Since the number of deaths and frequency cover several orders of magnitude, an arithmetic plotting is generally used for this purpose. To evaluate the societal risk, which reflects the acceptable individual risk criteria, it is significant to consider what the size of the population is, over which the risk must be shared.

Due to unavailability of India specific values, as a reference to determine criteria for socially acceptable safety level, the criteria used in foreign countries have been surveyed. According to HSE UK guidelines, acceptable frequency level is less than 1×10^{-4} per year, the buffer zone level lies in between 1×10^{-4} - 1×10^{-2} per year while unacceptable frequency level is higher than 1×10^{-2} per year (HSE UK, 2001). The F/N curve for the IOCL Jaipur accident is in the ALARP region. This region indicates that the risk to the surrounding population is tolerable if the precautionary measures are properly implemented. Failure in the periodical maintenance of the valves and properly implemented precautionary measures might have been the reason for this accident.

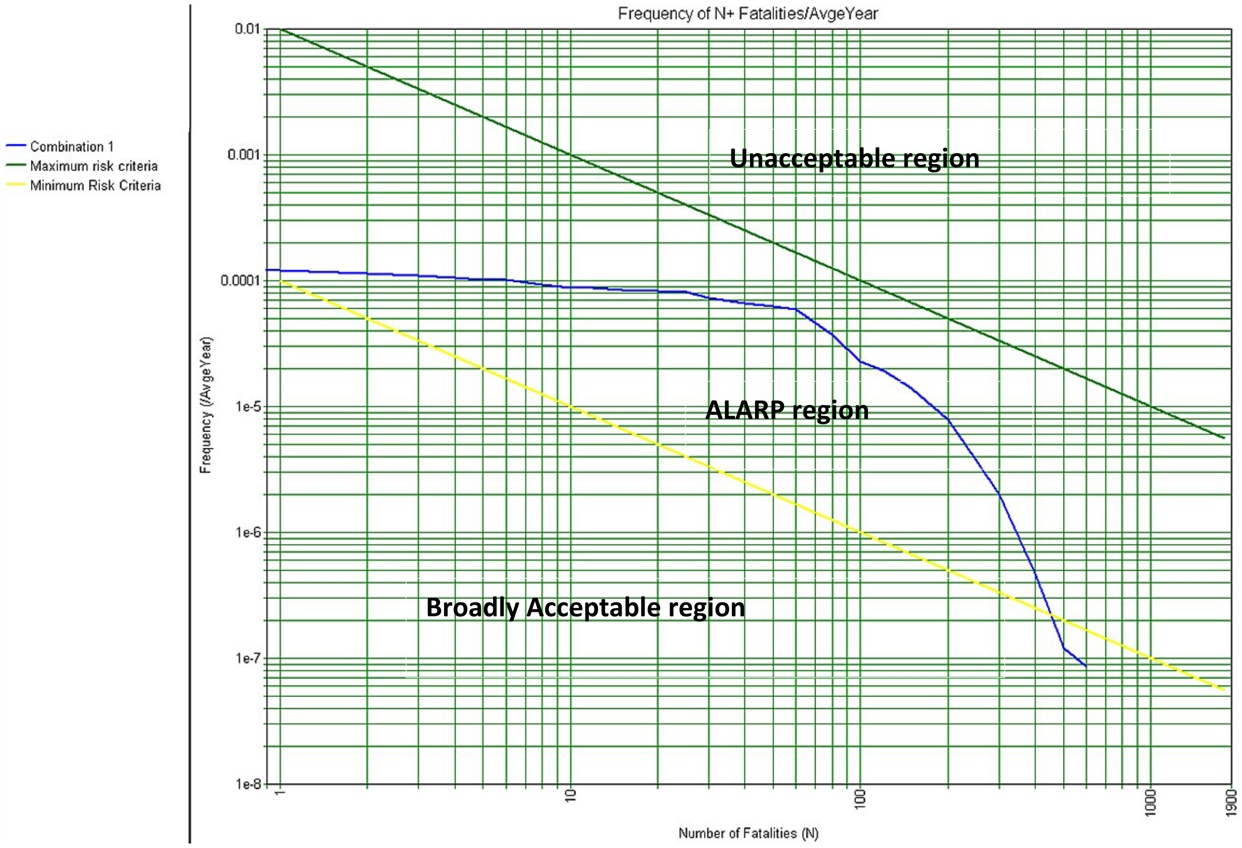


Fig. 6.6 F/N curve for Jaipur IOCL incident

6.5 CONCLUSIONS

In this chapter, quantitative risk assessment has been carried out. Individual and societal risks have been estimated as these are necessary for on-site and off-site design making. International methods suggested by HSE UK were used to assess and evaluate risk contours for accidents with fires, explosions. It is observed that the maximum estimated individual risk for terminal personnel is 10^{-4} per year which is below the maximum tolerable criterion (i.e. 10^{-3} per year). The risk contour of 10^{-4} per year extends up to the distance of 100m from the release point within the terminal boundary. Individual risk for members of the public outside the terminal at various location ranges from 6.8×10^{-5} - 1×10^{-8} per year, which is in the acceptable region. The F/N curve, indicating societal risk, falls in the middle zone known as ALARP region. This region indicates that the risk to the surrounding population is tolerable if the precautionary measures are properly implemented.

The individual and the societal risk estimates show that the risk levels to which population is exposed in and around the terminal do not exceed the tolerable limits proposed by the HSE UK standards and norms. The estimated risk at the terminal was under ALARP region where substantial measures for a risk reduction were needed. This infers that the failure in implementing adequate precautionary measures might have led to such high intense disaster. Precautionary measures like provision of firefighting facilities, sensing elements and continuous monitoring with alarm devices should have been done. Many countries, including Australia, Netherlands and UK, employ numerical criteria in determining acceptability in terms of safety. The authors feel that India, too, requires stringent guidelines to periodically assess the risks in such facilities to place appropriate safety measures so that disasters of above-discussed nature could be avoided and/or minimized.

CHAPTER 7

EMERGENCY RESPONSE PLAN THROUGH e-INCIDENT COMMAND SYSTEM

7.1. INTRODUCTION

As explained earlier, petroleum storage terminals normally have large storage tanks containing huge amounts of flammable chemicals. The occurrence of a tank accident in such facilities is probable and can lead to fire and explosions. Despite highly equipped process plants’ and storage sites' considerable efforts towards effective safety measures, it is still possible that an improbable event, or more likely an unforeseen series of events, may lead to a serious accident. In the last four decades, many serious accidents have occurred around the world at petroleum storage sites as a result of control system failure, incompatible reactions, human error, and other such reasons (Lin et al., 2003; Abbasi and Abbasi, 2005; Pasman and Suter, 2005). From the lessons drawn out of root-cause analyses we can infer that it is not sufficient to merely depend upon preventive measures but a timely, well-defined emergency response plan (ERP) must be designed and implemented to control an accident. The need for effective emergency planning has been reinforced in recent years by major accidents that occurred at Buncefield (UK) in 2005 (MIIB, 2011), Puerto Rico (USA) in 2009 (Chemical Safety Board, USA, 2011) and Jaipur (India) in 2009 (Sharma et al., 2013). As a consequence, an adequate ERP to deal with petroleum storage industry accidents has become a common concern throughout the world. An ERP implies that to prevent an accident from being exacerbated, an emergency system, safety equipment and manpower should be integrated along with proper evacuation planning. This integration is necessary to increase effectiveness and efficiency of response planning (Fitzgerald, 1996).

In the petroleum storage industry, emergency response planners have focused on designing better and safer equipment and self-contained self-rescuers, minimizing response time, increasing training of rescue teams, and emerging escape plans that comply with storage site safety regulations. Immediate and effective response to an accident site is, of course, necessary to reduce the severity of accidents, loss of life and the possibility of the loss of the future productivity of the storage site (Kowalski, 1995). Thus, the main focus in the management of emergencies has been on resources and logistics; in other words, having who and what you need, when and where you need it to encounter the crisis within an urgent time frame. ERP is required for various types of accidents to decrease the degree of hazards efficiently by effectively preparing, responding, and restoring normal conditions (Kowalski, 1995). Designing improved equipment along with the application of new technologies and focused training increases the efficiency of rescue operations. Additionally, modified technology has brought more efficient communication, such that personnel in the command centre have the opportunity to apprehend real time scenarios as precisely as the front line emergency workers. An effective communication system almost always curbs the severity of an emergency.

This chapter shows that information obtained from post risk assessment activities carried out on the IOCL Jaipur accident has generated significant data that is essential in emergency response planning. The data generated from the IOCL incident, considered to be crucial in framing on-site emergency plan of storage terminals, is also necessary for an off-site plan. According to the IOCL Jaipur incident analysis, when a leak occurred, staff at the plant site was unable to promptly deal with the critical situation due to unavailability of an effective plan with detail response mechanisms (MoPNG committee, 2010). Therefore, it can be said that a complete ERP must be effectively developed and distributed on the basis of the real scenario to prevent major incidents in the future. Predictive techniques enable major accident consequences to be assessed and thus aid in the development and implementation of mitigatory strategies incorporated in an ERP. This study outlines a suitable and effective ERP and demonstrates how the response to various emergency levels during an unexpected incident could be readily planned, controlled, and implemented.

7.2 LEARNING FROM THE PAST

A variety of accidents occur in process plants and storage terminals of petroleum products. These range from minor leaks to catastrophic releases leading to fire or explosion with the potential to threaten people, structures and surrounding environment. Despite all preventive arrangements, accidents do occur from which lessons can be learnt to further reduce the risk, provided that the lessons are extensively shared. Even with high quality safety arrangements and adherence to precautionary procedures, it is still possible that an improbable event, or more likely an unforeseen series of events, could lead to a serious accident. The main purpose of the post-accident assessment is to identify, from the emergency response operation, the weaknesses or strengths in the action plan and to make appropriate corrections in the plan. Therefore, an up-to-date ERP is required to tackle emergencies effectively. Predictive techniques enable major accident consequences to be assessed, and thus aid in the development and implementation of mitigatory strategies incorporated in an ERP. A list of major petroleum industrial accidents occurred during the last decade with the number of fatalities, injuries and property loss is given in Table 7.1.

Table 7.1 Major petroleum industrial accidents since 2000*

Date	Plant Type	Event type	Location	Property Loss (US $ million)	Injuries / Fatalities
25/06/2000	Refinery	Vapor cloud explosion	Mina Al-Ahmadi, Kuwait	600	50/5
21/09/2001	Petrochem	Petrochem Explosion	Toulouse, France	610	3000/ 30
19/01/2004	Gas Processing	Fire /Explosion	Skikda, Algeria	580	74/ 27
23/03/2005	Refinery	Fire/Explosion	Texas, United States	1500	170/15
11/12/2005	Petroleum	Fire /Explosion	Hertfordshire, England	1443	43/0
12/09/2008	Refinery	Hurricane	Texas, United States	750	0
23/10/2009	Refinery	Fire /Explosion	Bayamon, Puerto Rico	<6.4	0
29/10/2009	Petroleum	Explosion/Fire	Jaipur, India	32	150/11
02/04/2010	Refinery	Fire/Explosion	Washington, United States	-	4
6/01/2011	Refinery	Fire/Explosion	Fort Mckay, Albert, Canada	600	-
25/08/2012	Refinery	Explosion/Fire	Venezuela	1000	100/50
18/04/2013	Fertilizer Plant	Explosion/Fire	Texas, USA	-	100/15
23/08/2013	Refinery	Explosion/Fire	Visakhapatnam, India	-	14/37

**(Sources: MARS, 2013; FABIG ; Abdolhamidzadeh, 2011; Lee's, 2012; Mishra et al., 2014;* http://zeenews.india.com/news/andhra-pradesh/ap-govt-to-issue-notice-to-hpcl-over-fire-in-vizag-refinery_874083.html

7. 3 IOCL JAIPUR ACCIDENT

The IOCL Jaipur accident was first of its kind in India and the third one reported globally (MoPNG Committee, 2010). During gasoline transfer operations via a pipeline to another terminal a series of Vapor Cloud Explosions (VCEs) had occurred as a result of the uncontrolled release of gasoline from the 'Hammer Blind Valve' of Tank 401-A over a period of 80 minutes before ignition of the resulting flammable mixture. As explained in Chapter 3, the total amount of gasoline released was 2000 tonnes which resulted in a formation of 81 tonnes of vapor cloud covering an area of 180,000 m^2 (Sharma et al., 2013). Subsequently, the ignition of a flammable mixture had resulted in massive explosions and intense fires. A series of powerful explosions were heard up to 32 km away from the terminal. Seismological measurements reported that one of the VCE was equivalent to an earthquake with the intensity of around 2.3 on the Richter scale (MoPNG committee, 2010).

Due to such massive explosions, the entire installation was destroyed and the buildings in the immediate vicinity were heavily damaged. The associated blast wave caused windowpane breakages were found up to 2 km from the terminal. The one of the major explosions in rapid succession were followed by a fire that engulfed 11 large storage tanks. The fire burned for 11 days, destroying most of the site. The vegetation around the storage facility was completely consumed by the fire. Though fire services were rushed but no effective action was initiated as a considered decision was taken by IOCL, management to allow fire to burn till such time the products get completely burnt out to avoid further possibilities of accident in the installation thus ensuring safety of the public. The incident caused the fatalities of 11 people, 6 of which were company personnel. The assessment of ERP at the time of accident is given in Table 7.2

Table.7.2 Assessment of Emergency Response Plan at IOCL Jaipur Accident (MoPNG committee, 2010) on the basis of key elements of incident management (Leidner et al., 2009)

Elements	Assessment of Emergency Response at IOCL Jaipur Accident
Assets	Lack of emergency response plan and protocols
Response/ Infrastructure/ Resources	• Non-availability of vital Personal protective equipment (PPEs) like Self Contained Breathing Apparatus (SCBA), Safety Glasses, Oxygen Masks and Fire Suits • Inadequate fire fighting equipment/systems • Absence of on-site medical facilities like first-aid kit and ambulance • Outdated operational hardware and software • The automated shutdown system was out of order
Crisis response organizational structure	Complete lack of emergency as well as standard operating procedures. Organizational structure to share responsibilities were not framed
Informational Structure	Extremely poor information structure with lack of information dissemination among operators and official personnel
Coordination Structure	Two main divisions of the terminal, marketing and pipeline divisions, did not display coordinated emergency management
Collaborative Network	Even though the area had three major marketing terminals (IOCL, BPCL and HPCL), no collaborative efforts were made towards a sharing of fire-fighting facilities
Unity of Command	Pipeline transfer was being carried without any skilled supervision. Safety Officer was inexperienced and lacked requisite qualifications
Gaining stakeholder commitment	Operators and personnel were over-loaded indicating inadequacy of the work force. Also, there was a lack of commitment and sense of responsibility
Action	IOCL and local administration had no effective action plan to deal with the situation and the terminal burned for 11 days.
Agile Mobilizing	Non-availability of adequate resources led to a weak and inefficient response
Resolute informing	Not feasible due to shortage of VHF Sets and their improper usage
Leadership	• Inadequate leadership at terminal in-charge and state-level management • Poor leadership at supervisory level and ineffective leadership development program
Capability	Available resources and personnel were totally incapable of dealing with such major incidents
Ability to recognize the signals	Even after previous gasoline leakages in July, 2009 proper corrective measures were not implemented to reduce the possibility of more such accidents
Training & Preparedness	Periodic training to plant personnel and officers on plant safety and fire fighting facilities were not conducted
Risk Assessment	Risk Assessment to identify hazardous scenarios was not carried out. Thus the terminal staff was not aware of the worst-case scenarios and consequences thereof.

7. 4 OBJECTIVES OF EMERGENCY RESPONSE PLAN (ERP)

The main aim of an ERP is to provide a system and resources to deal with unseen events to protect people, property and the environment, and thus minimizing the severity of any accident. The objectives of ERP should be as comprehensive as possible. The main objectives of ERP are to:

- maintain a high level of preparedness.
- respond quickly and efficiently to limit the impact of an emergency.
- manage an emergency until the essential services arrive and take control
- support emergency services with information, knowledge, skill and equipment
- protect emergency responders, personnel and the community from harm

7. 5 COMPONENTS OF THE ERP

Safety procedures of petroleum storage plants encompass several layers of protection, control measures, shutdown systems, release absorption, accumulation of releases by dikes, and protection by barriers. These multi folds of protection are intended to prevent an event from propagating into severe consequences because of deviations from normal operating conditions. The emergency response is the last layer of protection, intended to control an event or to reduce the consequences if all other layers of protection fail. The emergency plan consists of the following major components:

- Risk Assessment in case of partial or full rupture of hazardous material incorporating worst case scenarios;
- Study of the availability of resources and capabilities, and determining needs;
- Development of on- and off-site emergency communication capabilities;
- Development of strategies to respond to fires and explosions, release of hazardous materials, rescue, evacuation, and emergency mitigation;
- Development of appropriate medical support infrastructure;
- Training of emergency teams, plant employees, and contractors;
- Development of procedures to assess the level of emergency;
- Development and execution of drills (involving neighbouring facilities and local communities);

- Development of drill-based improvement procedure;
- Study of emergency plans of neighbouring facilities and local community;

7. 6 EMERGENCY ALARM SYSTEM

Vapour clouds are primarily formed due to either uncontrolled overflow or accidental leakage of flammable material (Sharma et al., 2013). Therefore, installations must have adequate hydrocarbon detectors and alarm systems. Generally, high-level switches, two state detectors or CCTV monitoring is used to avoid overfilling or leakage (HSE, 2009). However, these means might be inefficient and lack reliability as prolonged inactivity of high-level switches and two state detectors may result in unrevealed faults and render them non-functional during an emergency. CCTV monitoring may not be useful in detecting small leaks. Although gas detectors might be available, they may be ineffective for detecting leaks due to complicated dispersion of gasoline vapour (Walsh and Kelsey, 2009). Liquid hydrocarbon detectors, however, may offer more reliable detection when they are installed near all potential leakage sources like tank dykes, tank manifolds and pump hose manifolds to detect escaping liquid. Still, there is a need for the development of advanced and automated detection systems to control leak at the earliest. For instance, high-level alarm from the radar gauge and from a separate tap off maybe provided.

7.7 EMERGENCY ANNOUNCING LEVEL

The Announcing Level (AL) is a significant part of ERP for all levels of emergencies. The AL has three stages, which can be treated as a standard for determining the level of accident. The appropriate responders will respond differently, depending on which of the three incident stages apply. Under the first, the commanding officer must arrive promptly at the incident site and collect information on the accident and decide whether the accident can be controlled and contained within the department or with the help of adjacent departments. Accidents of this level can be easily controlled through effective and prudent training (Tseng et al., 2008). In the second-stage, the incident commander should provide directions through telephone, cellular phone, internet, broadcast system, or any other suitable system to set up the Emergency Response Team (ERT). In the third-stage, the incident commander should coordinate with the local administration and civil authorities to control the off-site impacts and evacuation.

In the IOCL Jaipur accident case, it was found that the information did not flow in an effective way leading to a communication gap between office personnel (MoPNG committee, 2010). Therefore, training and effective communication are needed for all the activities, although emergency response tasks are unique due to a wide range of uncertainties and the urgency required in the emergency response (Ford and Schmidt, 2000; Shailendra and Gupta, 2005).

7.8 ELEMENTS OF ERP

7.8.1 Emergency Operations Center

The emergency operations center (EOC) is the nodal point of the entire emergency response process. The location, rules for activation and operational procedures of an EOC play a vital role in its effectiveness (Militello et al., 2007). In case of a fuel storage terminal, EOC should be separate from the operations control room and located close to the main entrance for easy access during an emergency. The distance of EOC from processing areas and storage is an important variable in its functionality. A location for the EOC should be identified in the plan, keeping alternate locations as back-up, if required. (BCERMS, 2000). EOC must be located at a safe distance from the incident to avoid accident effects. EOC should house a facility for a complete shutdown of the terminal, CCTV display units for the entire terminal, personal protective equipment (PPE), and ICS server along with the e-ICS connectivity unit. EOC should be immediately activated if the incident is not controlled by the on-site personnel. EOC should be easily activated from the control room. The planner should designate an alternate EOC, which may be located opposite to the EOC, in reference to the processing area. This will allow access to the alternate EOC in case access to the main EOC is not possible. The EOC should be manned in an emergency by the senior emergency coordinator, nominated senior works personnel, senior officers of the off-site services, and any nominated officers such as messengers. The Management (Response) team, which resides in EOC, generally has three responsibilities:

- Deciding the first line of direct supervision to field personnel
- Formulating the response strategy, tactical decisions and incident action plans,
- Sharing the command among responding functionaries such as firemen, police, medical and traffic officers.

7.8.2 Emergency Management Computation System

Emergency management computation systems (EMCS) are used for organization of information, estimation of severity of the incident by using source and dispersion models, and data collected from the field. This information is necessary to estimate the magnitude of the event, make decisions to announce an escalation and determine the need of evacuation for both onsite and offsite. Modern wireless networks, computation capabilities, and mobilization of computation systems make these systems extremely useful. Advanced process safety management packages with well-developed emergency management can be connected to weather stations, alarm systems, and local, state, and federal authorities.

7.9. EMERGENCY RESPONSE PROCEDURES

The emergency response team, personnel regimentation, rescue procedures and the assigned responsibilities for each rescue unit should correspond to the actual situation of the plant. In this approach, personnel can be mobilized quickly to take correct and effective action in an emergency, reducing losses to a minimum. Effective communication, training and sound knowledge can be utilized to handle accidents, thus enhancing the response capabilities. To deal with the issues of coordination, communication and human error in emergency response, an automated system like the Electronic Incident Command System (e-ICS) should be adopted. As per the directives of the Petroleum and Natural Gas Regulatory Board Regulations (2010), emergency response planning must incorporate some basic steps such as (1) Classification of Emergencies (2) Zone Mapping (Risk Assessment) (3) Resource Mapping (4) Organization of Response (5) Planning of Standard Protocols and (6) Assigning Roles & Responsibilities. Important steps involved in Emergency Response Procedures are described below.

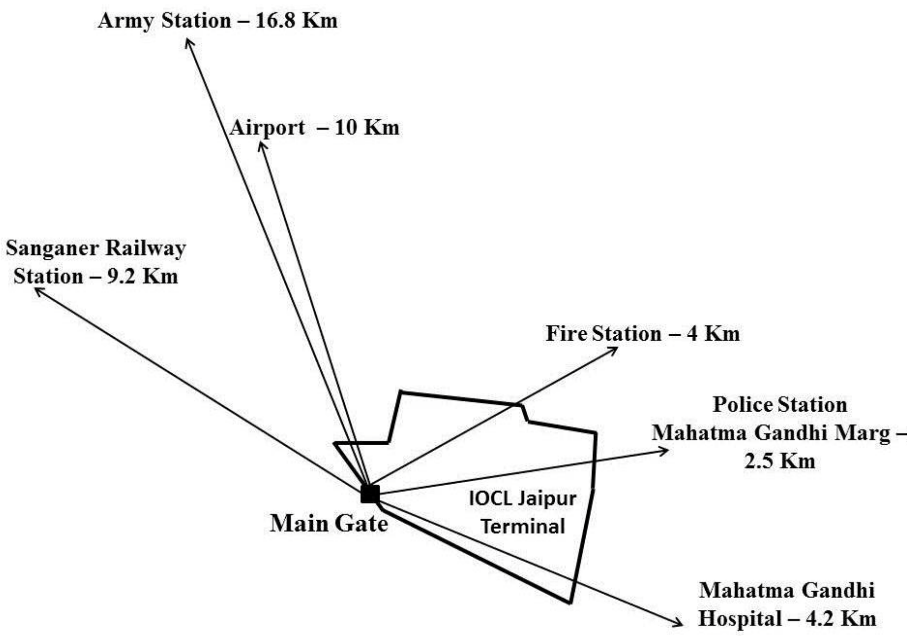
7.9.1. Zone Mapping

A zone map should be prepared to highlight the incident prone areas of the plant as it identifies sources for initiating action. The map should display the size of the onsite and off-site area within which human life would be seriously affected by the consequences of an incident. The mapping should also indicate the assembly point sites and emergency operations center. The site map must have 24 wind directions distinctly marked to facilitate easy access in case of emergencies.

Almost fifteen years ago, when the IOCL Jaipur terminal was set up, it had hardly any residential, commercial and industrial establishments around it. The installation ground area is very vast, comprising 105 acres for the marketing installation and 15 acres at the north-east (NE) corner for pipeline, interface manifold facility, control room and crude oil booster pump with auxiliaries. Over the years, the areas surrounding the terminal were occupied by industries. IOCL and local administration had no effective zone mapping of the site. Therefore, at the time of accident, IOCL had very weak contingency plans in place for dealing with such major incidents. This might be one of the reasons that the accident severely affected the onsite and offsite population and facilities.

7.9.2. Resource Mapping and Mobilization

As stated earlier, resource mobilization is all about having the manpower and resources at the right place at the right time to achieve an efficient and effective response in a minimal time frame. For rapid mobilization of resources, it is essential to ensure extensive resource mapping during emergency response planning (Keeney, 2004). Vital resources, in case of an accident in a petroleum industry, include fire-fighting units, safety equipment, transport, local police, medical facilities and army. The army is primarily responsible for relief, rescue and evacuation operations (Shivananda and Gautam, 2012). Incidents like the one in the IOCL Depot in Jaipur brought out the need for rapid mobilization of resources in an emergency response. Field survey and media reports state that the army and experts from Mumbai were called after more than twelve hours of tank fire, leading to a substantial delay in the response process. Delay in manpower and resource mobilization resulted into heavy socio-economic loss. Fig. 7.1 illustrates some of the major resources in the vicinity of IOCL Depot and the distance of these resources along the shortest land route.



(Note: Distances mentioned here are by road)

Fig. 7.1 Major resources in the vicinity of IOCL Terminal

7.9.3. Organization Network and Responsibilities

The management authority should regulate an ERP by setting up a control room, emergency control center, various response teams, rescue team, medical team and safety team. A complete ERP must be effectively developed and distributed to the appropriate personnel to prevent delaying corrective actions. Each ERT has its own responsibilities and duties. A commanding officer needs to be elected for overall planning. Incident Commanders should be adequately able to control and coordinate their subordinates and each individual involved in the response process must know the reporting hierarchy. The safety officer, liaison officer, information officer, and others should assist the Incident Commander in taking corrective actions. The proposed structure of the emergency response organization is illustrated in Fig. 7.2. According to the Jaipur accident analysis, when a leak occurred, the staff in the terminal could not promptly deal with the situation because a suitable plan and detailing response procedures had not been developed. Therefore, a complete ERP must be effectively developed and all concerned staff should be made aware of corrective actions to be taken in the emergency. Table.7.3 indicates the assignments of each staff member when an incident occurs. The plan should identify each responder's position, mission, duties and reporting relationship.

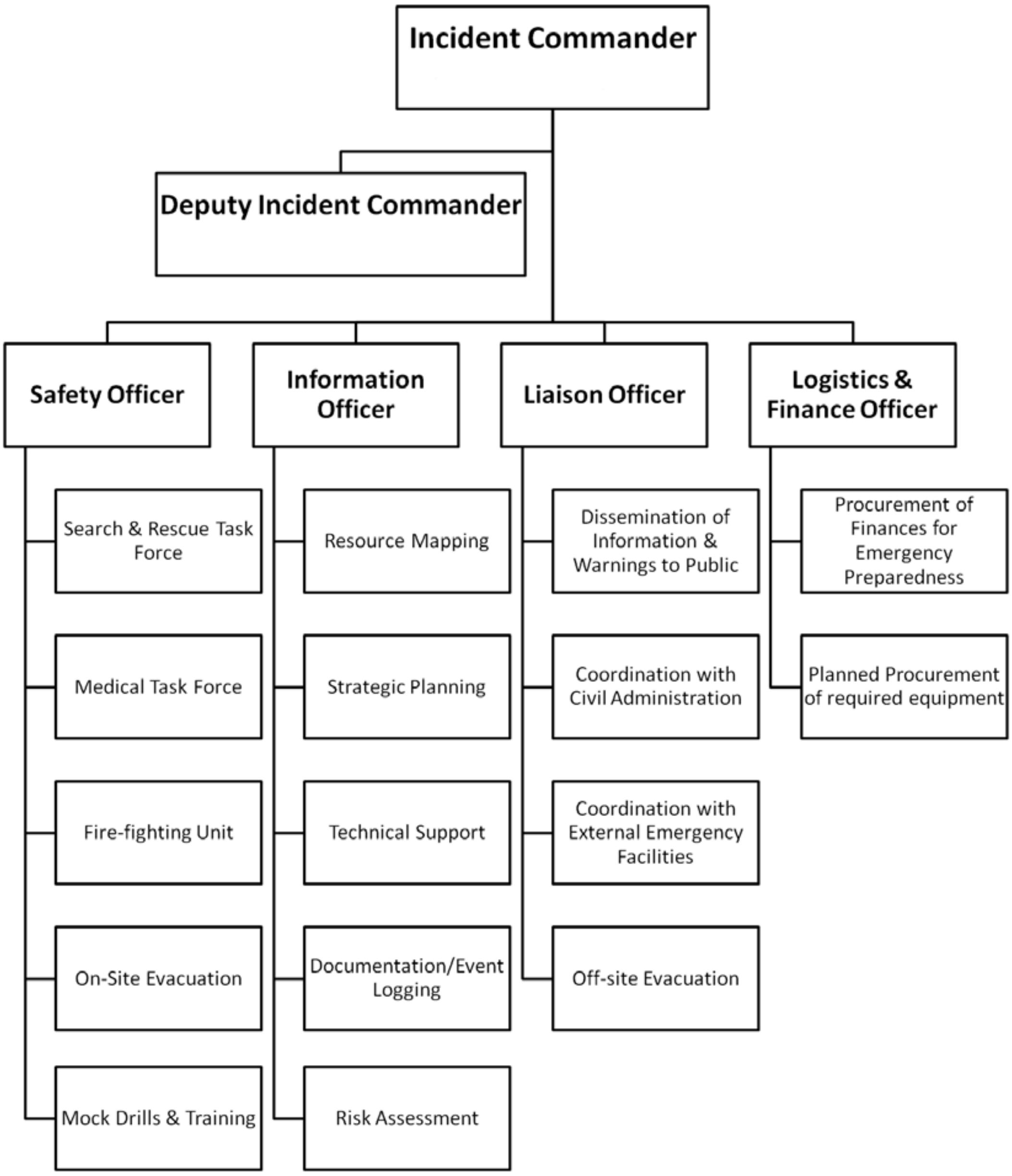


Fig. 7. 2 A proposed hierarchic organizational chart showing the responsibilities of the officers

Table. 7.3 Responsibilities of each related staff during an incident in a process plant

S.No.	Response organization	Assignment work
1.	Incident commander	• Executing and planning the emergency response actions • Assessing the situation’s hazard potential and coordinating teams • Issuing the evacuation order, if required, to the staff • Assigning manpower resources
2.	Deputy Incident commander	• Coordinate between the incident commander and other response teams to perform the task assigned to them • Coordinating the rescue team and offering the response measures
3.	Safety and security officer	• Safely guiding the support-personnel in the plant • On-site evacuating of the staff and vehicles • Supervising search and rescue operations • Assisting fire fighting operations
4.	Information officer	• Documenting rescue Mapping • Assisting the incident analysis • Reinforcing the role of technical members • Providing information to the media
5.	Liaison Officer	• Coordinating with district Administration, other Government offices and army for off-site evacuation
6.	Rescue team	• Protecting the staff and coordinating on-site evacuation • Arrange necessary resources for executing emergency rescues
7.	Logistics and Finance offices	• Providing a budget for the rescue process

The Incident Commander (IC) is responsible for the overall planning, management and coordination of the response mechanism. Importantly, in case of an emergency associated with fuel storage terminal IC decides upon the need for a complete shutdown of the terminal and the requirement or extent of evacuation. IC provides directives during response based on the technical inputs from the information officer. The Deputy Incident Commander takes charge in the absence of the IC. However, Deputy IC is individually responsible for closing of the units of the terminal to control the devastating extent of the incident. To minimise the level of confusion and uncertainty, it is very important that the roles and responsibilities of different officers and personnel are clearly specified and are religiously acknowledged.

7.10 RESPONSE MECHANISM THROUGH ICS

The concept of Incident Command System (ICS) was developed by the Fire fighting Resources of California Organized for Potential Emergencies (FIRESCOPE) program of the state of California, USA in 1980’s to respond to disastrous wild fires (BCERMS, 2000; NIMS, 2008; Martins, 2009). The ICS is an organizational structure employed by many companies and government agencies in British Columbia, Canada, in order to manage major emergencies (BCERMS, 2002). The ICS provides a management system that organizes the functions, tasks and staff within the overall emergency response. The ICS is a broadly applicable management system designed to allow effective, efficient incident management by integrating a combination of facilities, personnel, equipment, procedures, and communications operating within a common organizational structure.

The ICS organization is comprised of five functional sections: Incident Command (Commander), Operations, Planning, Logistics and Finance (BCERMS, 2002; NIMS, 2008). The ICS forms database that allows editing, managing, and archiving the ICS forms electronically on a computer network and functions as an Electronic Incident Command System (e-ICS). The e-ICS promotes communication and coordination. However, for the e-ICS to work, all responders must understand the system and their roles in it. The objective of the e-ICS is to maximize team efficiency by defining lines of communications, assigning responsibilities, expanding with new people and duties to ensure no one exceeds their capabilities.

7.10.1. Electronic Incident Command System (e-ICS)

Due to their complexity, uncertainty and uniqueness, disastrous situations differ considerably and require custom management approaches. However, the impact and influence of disasters on human life and behaviour remains similar (Othman and Beydoun, 2010). Thus, while dealing with issues of coordination and communication a generalized system can provide an effective response without delays. The Electronic Incident Command System (e-ICS) is an effective tool to deal with the major industrial accidents. This section illustrates the e-ICS system, shown in Fig. 7.3, developed by the authors to strengthen the effectiveness of ERP for petroleum storage sites in terms of multi-organizational coordination and integrated communication.

The e-ICS is designed to be compliant with the Indian ICS Team Structure and involves the use of modern telecommunication technologies like GSM, GPS, 3G, Wi-Fi, etc. along with conventional technologies like UHF, VHF, HF and standard web access tools to facilitate information sharing through the mediums of text, voice, image and video. The entire e-ICS structure involves four components (1) the Partners (2) the Six Interfaces (3) the Early Warning System, and (4) the Server shown in Fig. 7.3.

Fig. 7.3 Components of e-ICS System

7.10.1.1. Partners

Once the accident information is received, the personnel involved in the Confirmation, Command, Tactical, and Support Nets as well as the beneficiaries (people of the affected community) constitute the partners of e-ICS. The primary objective of e-ICS is to facilitate coordination and communication among its partners and to build their trust in the system, so that protocols can be executed religiously to provide a coordinated response.

7.10.1.2. e-ICS Interfaces

The entire coordination and communication among the partners is an outcome of the complex network of the six interfaces namely (1) Wireless Interface (2) GSM Interface (3) Smartphone Interface (4) Satellite Interface (5) Web Interface, and (6) GPS Interface of e-ICS and their link with the partners and the server.

7.10.2 Proposed e-ICS System for Storage Terminal

The block diagram of e-ICS, highlighting the various components and the flow of information through the system is illustrated in Fig.7.4. The entire structure of e-ICS is based on four networks (1) Confirmation Net (Accident information),(2) Command Net (strategic functions), (3) Tactical Net (execution), and (4) Support Net (medical teams, fire fighters, etc.) (NIMS, 2008). The high level of efficiency ensured by the activation of these networks depends upon the phase of the incident and the announcing level. The optimal level of automation and the use of modern telecommunication advancements enable the e-ICS system to strengthen its framework by improving coordination, communication and minimizing errors in disaster responses**.**

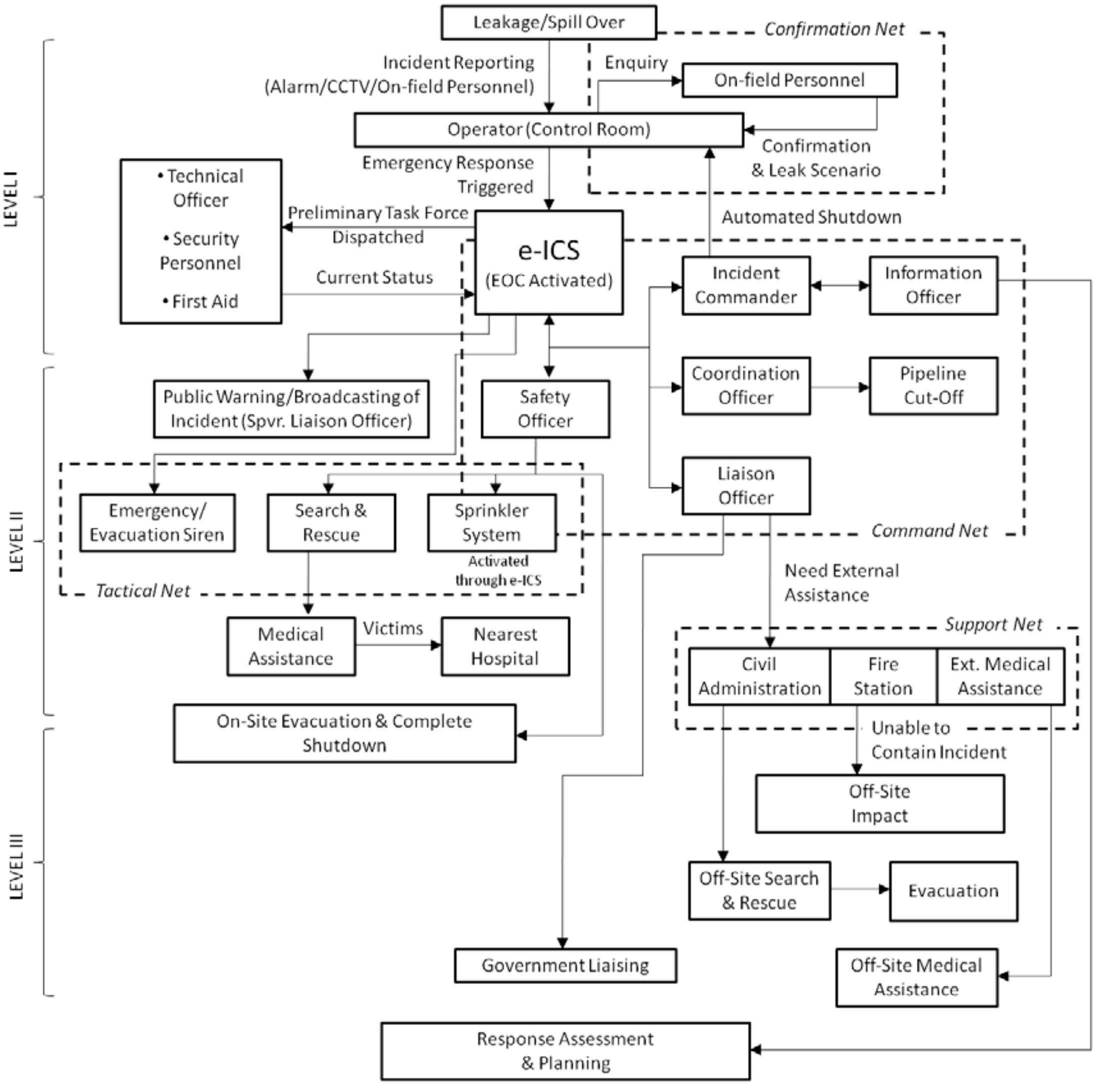


Fig. 7.4 A proposed structure e-ICS system for fuel storage terminals

7.10.2.1. Confirmation Net

The Confirmation Net is headed by the information officer and provides confirmation of the genuineness of the available information. It comprises the lower level staff deployed in the target area connected to e-ICS through either the wireless or the GSM interface. It promotes efficiency and avoids waste of resources and time in dealing with false information. The Confirmation Net is designed to prevent triggering of false alarms, which is essential to ensure the trust of the partners in the system. However, the response may be slightly delayed due to the introduction of an additional step.

7.10.2.2. Command Net

The e-ICS server disseminates, upon activation, incident information to the Incident Commander, Deputy Incident Commander, Information Officer, Safety Officer and the Liaison Officer that constitute the command network. Simultaneously, the preliminary task force is dispatched immediately to handle an emergency situation. Based on the information received from the information officer, the incident commander may order the complete shutdown of the terminal. The command net is the administrative constituent of the response mechanism and provides direction to emergency response.

7.10.2.3. Tactical Net

Tactical Net is headed by the safety officer and comprises various task forces involved in on-site emergency response i.e., the sprinkler system, the medical team, the search and rescue team, and the evacuation team. Air-foam based sprinkler systems are best suited for oil based fires. The e-ICS facilitates activation of the sprinkler system both automatically as well as manually. The tactical net is very important once it has been ascertained that the leak cannot be controlled and fire and or explosion is inevitable.

7.10.2.4. Support Net

In case the incident cannot be controlled by the on-site task forces and there is a risk of impacting the surroundings, the liaison officer may call for external support from the civil administration, fire-fighting services, medical teams and the army. These bodies constitute the support net which plays a vital role in level II and level III incidents. In case of a level III incident, the entire responsibility for the response lies with the civil administration and the support network as a whole. A coordinated response from the support net is crucial for early evacuation and medical assistance to minimise casualties.

7.11 PROPOSED EMERGENCY FACILITIES FOR STORAGE TERMINAL

The proposed emergency facilities for storage terminal are shown in Fig 7.5.

- Petroleum storage terminals should inform the members at the local crisis level, district crisis level and state crisis level of any sort of incidents, according to the provision under Chemical Accidents (Emergency planning, Preparedness and Response) Rules, 1996.

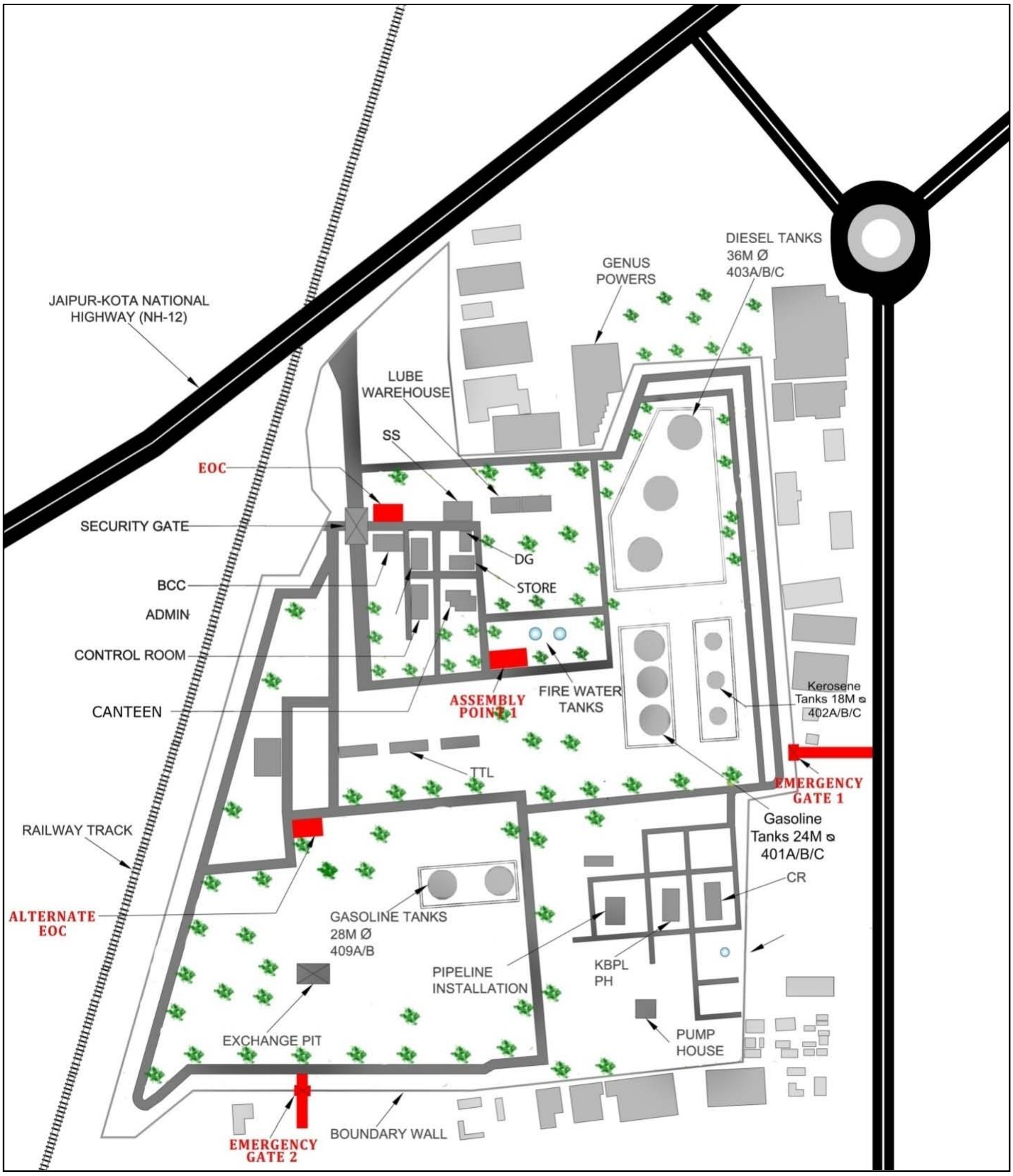


Fig. 7.5 Proposed (Red colour) emergency facilities in IOCL terminal

- Locations of assembly points in response planning shall be set up farthest from any likely hazardous events, where pre-designated persons from the works, contractors and visitors would assemble in case of emergency. A latest list of pre-designated employees by shift must be available at these points so that roll call can be taken. Pre-designated persons should take charge of these points and mark their presence as people arrive. Fig. 7.5 recommends locations of EOCs, assembly points and emergency gates for the IOCL storage terminal
- The emergency exit gate shall be away from the main gate and always be available for use for personnel evacuation during emergency.
- The control room should be located as far as practically possible from potential leak sources. Otherwise, the control room should be made blast-proof.

7.12 CONCLUSIONS

The Emergency Response Plan (ERP) for petroleum product storage terminals is an integral and essential part of a loss prevention strategy. The hierarchical response planning method provided in the present study is expected to be helpful in constructing an operable counter plan. All these tools, procedures, and training facilitate smooth coordination even for an ad hoc team facing unpredictable and highly variable incidents. All emergency response teams such as rescue team, information team, safety and security team, medical team, and government liaison and spokesperson need to comply with the designated responsibilities during ERP procedures. In this chapter, the significance of the extensively used ERP methodology in dealing with a hazardous situation for a petroleum storage terminal has been presented. The Emergency Operations Center (EOC) and Emergency Management Computation System have been recommended as important parts of the ERP.

The ICS is a "function" oriented approach to an emergency response. The ICS enables a rapid "modular" expansion of the response team to manage an escalating incident. The purpose of ICS is to reduce human error, chaos and confusion during emergency responses. ICS training to learn emergency procedures, effective communication systems, availability of emergency equipment and coordination between local authorities and industries are the key areas for effective emergency preparedness. Without training, even the best method of ICS may be in executable or undeliverable. The success of a system like e-ICS depends on relevance and accessibility of information and response timeliness provided by the system; whereas the acceptability is governed by behavioural tendencies of the users in terms of perceived task support, group coordination and personal biases. Therefore, applicability and feasibility of e-ICS needs to be further studied by applying it in realistic scenarios.

CHAPTER 8

LESSONS LEARNT AND RECOMMENDATIONS

8.1. LESSONS LEARNT

Preventing loss of containment is considered to be the first priority in refineries and petrochemical industries. However, the failure of liquid storage tanks or any process equipment can stem from inadequate design, construction, inspection and/or maintenance. Hazard reduction and prevention starts with the good design and construction, which is further strengthened by adequate safety measures, effective emergency response plans and disaster control / management strategies. In the case of Jaipur IOCL accident, the lack of back up for emergency shutdown from the control room and the absence of any emergency response plan allowed leakage of approximately 2000 tonnes of gasoline for 80 minutes which resulted into massive vapour cloud explosion and subsequent multi tank fires. The atmospheric conditions and availability of ignition sources play a major role in such accidents. This research describes the possible causes for the formation of huge flammable vapor clouds and its impacts on plant personnel and surrounding population in addition to other industrial facilities. The research also focuses on the validation of fire and explosion modeling and response plan in tackling industrial disasters. The sound knowledge of hazard identification, mechanisms of vapour cloud formation, and preventive measures to be adopted is useful to minimizing the effects of vapour cloud explosion and subsequent fire. Learning from Jaipur IOCL and past incidents can thus be used to improve hazard identification and risk assessments of similar accidents.

8.1.1 Lessons Learnt from QRA Studies

The lessons learnt from the IOCL accident, based on explosion and fire modelling studies, are highlighted below:

- It has been reported that improper design or maintenance of the ‘Hammer Blind Valve’ had led to the uncontrolled loss of gasoline in the form of a jet. Therefore, proper design, installation, operation and maintenance of all the equipments and valves are needed allied with a consistent maintenance to ensure their integrity.

- A probable ignition source which triggered an explosion and fire was suspected from a vehicle being started in the parking area of the terminal. Thus, it is felt that vehicle parking area should be outside the terminal to minimize number of ignition sources. It is also needed for automobiles entering into the terminal to load arson hood at exhaust nozzle.
- Poor lighting in the area while operating valves might have resulted in human error. Therefore, operations related to transfer of petroleum products should be carried out in daylight.
- This is also speculated that the failure of implementation of precautionary measures might have been a major reason for Jaipur accident. Precautionary measures like the installation of hydrocarbon detectors and high level alarm, and provision of medium expansion foam generators to arrest the vapor cloud formation should have been executed.
- One of the shift operators, who is quite experienced and well versed with the installation and its operations, was not on the plant site during the gasoline transfer process (MoPNG, 2010). Thus, it is felt that the physical presence of a supervisor must be mandatory to oversee the transfer pipeline and related operations.
- All terminal personnel including regular contractors and security personnel should be given periodic safety and fire fighting training in reputed training institutes.
- Continuous burning of the eleven tanks for eleven days reflected an inadequate leadership at the terminal and safety level management. Thus, site specific Standard Operating Procedures (SOPs) should be prepared to tackle emergency at terminal effectively. It is also needed to have a clear hierarchy underpinning various aspects pertaining to safety, environment and planning controls.
- Quantitative Risk Assessment (QRA) and safety audits should be carried out periodically to ensure proper implementation of risk mitigation measures.
- Facilities and installations with inherently high hazards should incorporate redundancy in safety systems and - their upkeep should be ensured at all times.
- Management must ensure that identified plans and actions pertaining to training, maintenance and timely inspections are being carried out.
- High degree of operational competence should be maintained at all times by building on the combined knowledge and experience of all the professional groups. The lessons learnt from all major accidents should be shared and widely disseminated in the entire Industry preferably through an appropriate website.

- A high priority on safety issues of senior and top management groups will send the right signals down the line to ensure safety and production.

8.1.2 Lessons Learnt from Failure of ERP

In addition to the above, the following lessons have been learnt on the basis of non effective Emergency Response action plan at the time of the accident, which subsequently increased the severity of the accident.

Land use planning: The original location of the IOCL Jaipur terminal, about 15 years ago, had hardly any industrial establishments around it. Many industries around the terminal have been set up over the years resulting in congested area. While setting up industries, various regulatory norms on industrial installations seem to have violated. Therefore, there is a need of proper coordination between local Land Planning Authorities and industries to minimize congestion and the impact of any accident.

Evaluation of the accident situation: It has been observed that IOCL had not effectively implemented contingency plans for tackling an accident. Even mock drills were not conducted periodically. Disaster Management Plan including on-site and off-site scenarios should have been available or implemented in handling such situations. This type of major accident was not envisaged by the terminal management and so it had very little time to control the accident.

Implementation of Quantitative Risk Assessment (QRA): QRA had not been carried out to find most hazardous locations in the terminal, worst-case scenarios leading to fire or explosion in case of any leakage, and the recommendations to be implemented in the event of an accident. Even safety audits were not carried out to ensure proper implementation of risk mitigation measures.

Improper utilization of communication equipment: Limited numbers of VHF handsets were available at the terminal site. Sufficient number of VHF handsets would have allowed response team members to communicate in an effective and continuous manner.

Inadequate emergency resources and untrained staff: During the time of the incident, the leakage area was fully enveloped by dense gasoline vapour. Non-availability of Self Contained Breathing Apparatus (SCBA), improper PPE (Personnel Protective Equipment) and lack of training in handling such an emergency led to the exacerbation of consequences. It was found that the security personnel were never trained for fire fighting equipment and safety equipment usage.

Ambiguous responsibilities of the person in-charge: The greatest problem at the time of IOCL accident was that members of terminal staff was not aware of their roles and responsibilities in tackling such an accident. Due to company transfer policies, new officers who joined the terminal just a few days before the accident had no experience or training to deal with such emergencies.

Delay of accident notification and reporting: Absence of adequate emergency management, incompetence at the supervisor level, lack of understanding of hazard potential, inadequate training of operators and managers and poor communication led to a delay in accident notification and reporting to senior level personnel. Even the senior level personnel at the terminal and state office were ignorant of similar major accidents, like that in Buncefield, UK.

Failure to execute the commander's instructions: It is reported that at the time of the incident, the Chief Manager had carried out several communications to various levels like security, his subordinates in the pipeline section, the control room and the Sr. Terminal Manager (Marketing). However, the instructions were not properly understood or followed. As staff failed to receive appropriate instructions, the chief manager could do little to control the development of the accident and ensure follow-up rescue operations.

8.2 RECOMMENDATIONS

As discussed and analysed in previous chapters, the Jaipur IOCL accident was of a serious nature that had severe consequences. Based on the present research study, the recommendations have been made under two categories; i) for immediate implementation, and ii) for planned implementation.

8.2.1 Immediate Measures

- Main emergency shutdown switch which should be located in the control room should also activate the Motor Operated Valves (MOVs) to close.

- Very high frequency (VHF) handsets should be provided to each member of the operating crew.
- The supervisor should be present to oversee the pipeline transfer line-up an drelated operation.
- Emergency procedures should be written and available to all personnel in the installation outlining the actions to be taken by each one during a major incident.
- Mock drills whenever conducted should include the full shut down system activation also.
- A system should exist for informing neighbouring industries about impending danger.
- The critical operating steps should be displayed on the board near the location where applicable.
- Control room should be manned on a continuous basis.
- The pipeline transfer should preferably be commenced during daylight.
- Personal protective equipments such as safety glasses must be worn while carrying out all operations
- All other Personal protective equipments (PPEs) should be available at operation sites and they should easily be identified.
- Hydrocarbon (HC) detectors should be installed near all potential leak sources of class ‘A’ and ‘B’ petroleum products, e.g., tank dykes, tank manifolds, pump house manifolds, etc.
- Medium expansion foam generators should be provided to arrest the vapour cloud formation from spilled volatile hydrocarbons.
- The security staff should be trained as first responders for fire fighting and rescue operations along with plant operating personnel.
- Manning level in the shift should be reviewed to have adequate coverage in the emergencies.
- Vehicles with spark ignition engine should not be allowed inside the Installation area except up to the Administrative Block and also to ensure ontinuous manning at the control room.

8.2.2 Measures For Planned Implementation

- Mannual operating hammer blind valve should be avoided as an equipment in the plant design. Only a closed system design should be adopted.

- All operational valves must be outside the dyke area.
- High level alarm from the radar gauge and high level alarm from a separate ??? should be provided.
- Piping design inside tank dyke area should ensure easy accessibility for any operations inside the dyke in the tank farm.
- Thermal Safety Valve (TSV) should be provided at the operating manifold (outside dyke).
- Tank Dyke Valves should be provided with position indicator (open or close) in control room and necessary hardware and instrumentation should be provided for this.
- A CCTV should be installed covering tank farm areas and other critical areas. The CCTV monitoring station should be provided both in the control room andin the Security cabin/office.

8.2.3 Process Safety Management

- The Terminal Managers should be trained in Hazard Identification techniques and be familiarized with risk assessment and risk mitigation methods.
- Quantitative Risk Assessment (QRA) on large sized installations should be carried out and recommendations made on the basis of model results should be implemented.
- Site specific “Standard Operating Procedure (SOP)” should be developed.

8.2.4 Plant Layout

- The control room should be located as much far away from potential leak sources as practically possible.
- Fire water tank and fire water pump house should be located far away from potential leak sources/tankage area.
- Buildings and structures should be located in the upwind direction (for the majority of the year) as far as practicable.
- All buildings which are not related to terminal operation should be located outside the plant area.This includes the canteen also, where any spark or open flame may exist.
- Congestion at the plant site because of buildings, structures, pipelines, trees etc. should be avoided. The location of these individual facilities should be decided based on Quantitative Risk Assessment.

- The emergency exit gate should be away from the main gate and alwaysbe available for use for personnel evacuation during an emergency.

8.2.5 Fire Fighting Facilities

- Wherever there is a cluster of terminals of different companies, an emergency response center equipped with advanced fire fighting equipment viz. fire tenders and trained manpower should be considered on cost sharing basis or on outsourcing basis.
- Sprinklers should also be provided in lube oil drum areas.
- During all operations, even after the general shift, a dedicated fire fighting team should be present.
- There should be a minimum level of manning maintained apart from the security personnel for monitoring the facilities even during non-operational hours.

8.2.6 Training

- For Supervisors, intimate knowledge of the operator’s job is essential and this should be ensured. In addition to this, Leadership Training should be provided on Manpower management and motivation, and also on communication, which should enable them to give proper task instructions to the operators.

- For Terminal Managers, safety training should include areas like
    - Basics of Safety Management System
    - Hazard identification
    - Risk Assessment and risk mitigation
    - Emergency preparedness and response
    - Crisis Management
    - Learnings from case histories

CHAPTER 9

CONCLUSION AND SCOPE FOR FUTURE RESEARCH

9.1 GENERAL

The research work carried out in this thesis has focused on risk assessment of petroleum storage site with an aim to utilize the findings for deploying appropriate preventive measures and delineating Emergency Response Plan (ERP) so as to reduce and mitigate hazards posed by such facilities. The present research work is, thus, useful for emergency response planning and risk management at such sites. For this purpose, modeling and simulation of vapour cloud explosion (VCE), large tank fire, and individual and societal risk have been carried out and applied for IOCL, Jaipur accident that occurred on 29th October 2009.

The following conclusions are drawn from the present research work:

9.2 VAPOUR CLOUD EXPLOSION STUDY

Vapour cloud explosions are highly complex phenomena whose destructive potential depends on not only the flammable mass involved but also the cloud dispersion and the reactivity of the gaseous mixture. Among those parameters, the concentration, size, and location of the vapour cloud play important roles, which is evident from IOCL Jaipur (India) accident assessed in this research work. The evidences obtained from the IOCL Jaipur site are consistent with the observations made during the follow-up study after the Buncefield incident both in terms of overpressure damage and directional indicators. The observed damage at the site can be explained in terms of high-speed deflagrations and transition to detonations. Overpressures in excess of 200 kPa (2 bar) were generated across the site within the terminal, which, however, was not uniformly distributed throughout the terminal.

The severity of the Jaipur IOCL plant explosion was unexpected given that the site was not highly congested. However, the severity of explosion has successfully been explained using the current knowledge of vapour cloud explosions and information available in the open literature. The modeling of vapour cloud formation and dispersion corroborates the observations by plant personnel that gasoline vapours had enveloped a large area of the facility. This implies that the facilities covered by the vapour would have been at risk in the event of a fire. These include the non-plant buildings, Truck Loading Facilities (TLF), fire water system, and portions of the pipeline division of terminal. The prevalent weather conditions and the turbulence of a cloud permitted sufficient mixing with air that likely led to an unconfined vapour cloud explosion (UCVE) when a source of ignition was encountered.

The overpressure damage and the directional indicators show that the flammable vapour cloud covered almost the entire site. The widespread high overpressures and the directional indicators in the open areas infer that the vapour cloud explosion might have not been caused by deflagration alone. The overpressure damage and directional indicators show that the source of the detonation most likely was in the Pipeline Division area in the northeast corner of the site. Flame entering into the pipeline division area might have caused a confined or partially confined explosion, which possibly led to detonation as it vented from the building. The possibility of detonation due to the line of trees along the north wall of the pipeline division has been ruled out because it is not deep at lower levels, and there were some gaps in the tree line. It is significant that the overpressure damage and direction evidence observed in the IOCL Jaipur explosion are characteristic of a vapour cloud explosion in dense low laying vapour clouds, which have also been observed in such past incidents.

9.3 LARGE TANK FIRE STUDY

Vapour cloud explosions led to a fire in one of the storage tanks. The fire immediately spread to surrounding all eleven tanks. The dimensions and characteristics of the fire need to be evaluated to study its impact on surrounding population and facilities. The fire attributes are modeled through various models. The $(H/D)_{max}$ ratio for tank fire, by the Munoz correlation, has computed as 1.5, whereas the observed value lies in between 1.0 and 1.7. Thus, the calculated value is within the observed value. The average value of $(\overline{H}/D)_{\mathrm{calc}}$ is 0.9. The clear burning zone heights (H_{Cl}/D) were obtained by various models such as the *MSFM*, Pritchard and Binding, and Ditali models. The Pritchard and Binding, and Ditali models use (*C/H*) ratios to indicate the saturation of the hydrocarbon fuel. The *MSFM* model gives a maximum value of 0.6, whereas the Pritchard and Binding, and Ditali models predict

0.3 and 0.4, respectively. This trend shows that the flame height in the Jaipur incident case was unusually large.

The estimated flame temperature of gasoline tank ($D = 24m$) was approximately 1230 K, which, lies within the range (1100 K-1240 K) reported by various researchers for large-scale gasoline pool fires.

The analysis of the Surface Emission Power (SEP) in the Jaipur accident, estimated with the help of various models (*SFM, MSFM, TRM, and TRSMFM*), indicates that a higher SEP ($\overline{SEP}^{\mathrm{ma}}_{\mathrm{SFM}}$ ≈123 kW/m^2) value was reached by *SFM,* where the flame is considered as a single luminous zone. In the case of multiple tank fires, the interaction of neighbouring tank fires, e.g., as during the Jaipur incident, has a considerable effect on the SEP ($SEP^{ma} \approx 114$ kW/m^2) of the individual tank fires. In the later stage, the radiation from inside the flames is blocked by absorption of dense soot parcels. Subsequently, the effect of the sooty zone is calculated by *MSFM* with considerable assumptions ($\overline{SPM}^{ma}_{MSFM}$ ($\bar{a}_{SZ}$= 0.35) $=$ 98 kW/m^2 and $\overline{SPM}^{ma}_{MSFM}$ ($\bar{a}_{SZ}$= 0.65) $=$ 55 kW/m^2). In addition, the turbulent mixing phenomena also influences the SEP ($\overline{SEP}_{act} \approx$ 27 kW/m^2), which can be estimated by *TZM*. Hottel (1959) reported that as the pool or tank diameter increases, the fire regime changes from laminar to turbulent. The different models used to predict the values of *SEPs* show a significant lack of accuracy to cover the most possible scenarios.

It is observed that the radiation intensities at various distances from the flame computed by the point source model and PHAST 6.51 software are nearly identical. There is a difference of 20 to 25% in values at nearer distances, whereas the effective values at higher distances are almost equal.

9.4 INDIVIDUAL AND SOCIETAL RISK ASSESSMENT

The IOCL Jaipur accident has the potential to harm the onsite and offsite population. It affected many people and caused death and injuries. The consequence modeling needs to be carried out to analyze its effect on each individual and surrounding population. Thus, individual and societal risk has been quantified considering population in and around terminal. It is observed that the maximum estimated individual risk for terminal personnel is 10^{-4} per year which is below the maximum tolerable criterion (i.e. 10^{-3} per year). This 10^{-4} per year risk contour falls up to the distance of 100 m from the release point within the terminal limits. The individual risk of the personnel associated with various buildings and facilities within the terminal is in the range of 1.9 - 7.0 $\times 10^{-5}$ per year, which demonstrate that it is in the strict risk control zone.

The F/N curve indicating societal risk falls in the ALARP ‘‘As Low As Reasonably Practicable’’ region. This region indicates that the risk to the surrounding population is tolerable if the precautionary measures are properly implemented.

The individual and the societal risk estimates show that the risk levels to which population is exposed in and around the terminal do not exceed the tolerable limits proposed by the HSE UK standards and norms. The estimated risk at the terminal was under ALARP region where substantial measures for a risk reduction were needed.

It is felt that India, too, requires stringent guidelines to periodically assess the risks in such facilities to place appropriate safety measures so that disasters of above-discussed nature could be avoided and/or minimized.

9.5 EMERGENCY RESPONSE PLAN THROUGH e-ICS

Such accidents results in huge loss of lives and property, along with widespread environmental damage due to improper coordination and communication in the emergency response. Therefore, effective Emergency Response Planning is required to tackle accidents of such huge intensity. Emergency Response Planning is an integral and essential part of the safety and loss prevention strategy and comprises of the actions taken to manage, control and mitigate the immediate effects of an incident.

- The Emergency Response Plan (ERP) for petroleum product storage terminals is an integral and essential part of a loss prevention strategy. The hierarchical response planning method provided in the present study is expected to be helpful in constructing an operable counterplan. All these tools, procedures, and training facilitate smooth coordination even for an ad hoc team facing unpredictable and highly variable incidents.

- All emergency response teams such as rescue team, information team, safety and security team, medical team, government liaison, and spokesperson need to comply with the designated responsibilities during ERP procedures.

- The Emergency Operations Center (EOC) and Emergency Management Computation System have been recommended as important parts of the ERP.

- The Incident Command System (ICS) is a "function" oriented approach to an emergency response. The success of system like e-ICS depends on relevance and accessibility of information and response timeliness provided by the system whereas the acceptability is governed by behavioral tendencies of the users in terms of perceived task support, group coordination and personal biases.

9.6 SCOPE FOR FUTURE RESEARCH

To enhance the fine time resolution and to use the user-defined functions of turbulence and kinetic energy for better validation of VCE in partially confined explosions, future research needs to be carried out on the effect of explosion and large pool fire modeling by using computational fluid dynamics (CFD). For example, the CFD explosion program FLACS (Flame Acceleration Simulator) can be used in such studies after validation. FLACS simulates the three dimensional development of explosions through clouds of vapour mixtures in complex geometries. It produces a time history of effects such as combustion progress, explosion pressure and explosion wind speed at all locations covered by the geometry model. These features or aspects of VCE with respect to time have not been studied in this thesis.

Continuous production of black smoke from large tank fires and emissions of the toxic gases from the combustion process create a potential environmental and health problem that is difficult to assess. Thus, there is scope to conduct a detailed research to estimate the height of the smoke plume, the ground-level concentrations of the air pollutants (e.g., smoke, SO_2, CO, PAHs, VOCs) and also to characterize health risk zones by comparing the ground-level concentrations with existing air quality standards . Furthermore, research studies can be carried out for the analysis of complexities of multi-component gasoline release, involving droplet break-up, air entrainment, and vapour cloud formation followed by dispersion in still air over uneven terrain.

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ANNEXURE –I

LIST OF PAPER PUBLICATIONS FROM THE PRESENT STUDY

International Refereed Journals

1. Sharma, R.K., Gurjar, B.R., Wate, S.R., Ghuge, S.P., Agrawal, R., 2013. Assessment of an accidental vapour cloud explosion: Lessons from the Indian Oil Corporation Ltd. accident at Jaipur, India, Journal of Loss Prevention in the Process Industries. 26, 82-90.

2. Gurjar, B.R., Sharma, R.K., Wate, S.R., Ghuge, S.P., Agrawal, R., Individual and Societal Risk Assessment for Large-Scale Oil Storage Terminal. (Ready for communication)

3. Sharma, R.K., Gurjar, B.R., Wate, S.R., Ghuge, S.P., Agrawal, R., Large hydrocarbon pool fires: Modeling of the geometric and the radiative characteristics (Ready for communication)

4. Gurjar, B.R., Sharma, R.K., Wate, S.R., Ghuge, S.P., Agrawal, R., A violent, episodic vapour cloud explosion assessment at the IOCL terminal in Jaipur, (Ready for communication)

5. Sharma, R.K., Gurjar, B.R., Wate, S.R., Ghuge, S.P., Agrawal, R., The Quantitative assessment of Chemical Accidents Involving Domino Effect: Main features and accident sequences, (Ready for communication)

6. Sharma, R.K., Gurjar, B.R., Wate, S.R., Ghuge, S.P., Agrawal, R., Emergency Response Plan through Incident Command System for Petroleum storage terminals, (Ready for communication)

International Conferences

1. Sharma, R.K., Gurjar, B.R., Wate, S.R., Ghuge, S.P., Agrawal, R., 2012 (29-31 March). The Indian Oil Corporation Ltd. Jaipur explosion and fire incident: causes, consequences and lesson learned, RDEIA- IACM international conference in NEERI, Nagpur.

2. Sharma, R.K., Gurjar, B.R., Agrawal, R., A violent, 2013 (15-17 February). Episodic vapour cloud explosion in fule storage area. International conference on Challenges in Disaster Mitigation and Management Strategies, Centre for Excellence in Disaster mitigation & Management, IIT Rooorkee, 2013.

National Conferences

1. Sharma, R.K., Gurjar, B.R., Gurjar, 2013. The Indian Oil Corporation Ltd (IOCL), Jaipur Explosion and Fire-Lessons Learned, Role of Infrastructure for Sustainable Development, Twenty-Eighth National Convention of Civil Engineers, Organised by The Institution of Engineers (India) Roorkee Local Center, IIT Roorkee Campus, Roorkee, 393-400

2. Sharma, R.K., Gurjar, B.R., Gurjar, (2013). Chemical and industrial accidents hazards in India: An Evaluation of their Causes and consequences and Mitigation strategied, 2nd India Disaster management Congress, 4-6 November 2009, 155-156.
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