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Lessons Learned from Industrial Chemical Accidents: A Case Study of Indian Oil Corporation (IOC) Terminal, Jaipur, India

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Abstract

Fire and explosion hazards in industrial storage units have gained a considerable attention in recent years. Indian Oil Corporation (IOC) storage terminal accident in Jaipur, India, is a recent example of Vapor Cloud Explosion (VCE) and fire accidents preceded by Buncefield (2005) and Puerto-Rico (2009). On 29th October 2009, a leak of gasoline occurred in the IOC storage terminal. Long delay of 80 minutes in ignition led to a huge vapor cloud covering an area of 180,000 m^2 over the entire installation and subsequent ignition triggered strong VCE with intensity more than 200 kPa. Eleven people lost their lives, more than 150 people were injured and a property loss of approximately U.S. $60 million was reported. The Individual and Societal Risk has been quantified and found that risk does not lie in the unacceptable region, but in the As Low As Reasonably Practicable (ALARP) region where substantial measures for a risk reduction were needed.

The incident has left many safety issues behind which must be repeatedly addressed. It reveals that adequate safety measures were either underestimated or not accounted seriously. This article highlights the aftermaths of IOC incident and addresses challenges put forward by it. Furthermore, a comparative study is performed between such incidents to analyze the similarities and how they could have been avoided. Therefore, electronic-Incident Command System (e-ICS) based 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.

Introduction

Despite of up to date safety know-hows, industries all over the world still confront frequent explosion and fire hazards [1–3]. The accidents may occur due to different reasons extending from malfunctioning of an installed mechanical device to mistake committed by any personnel. The subsequent consequence of such failure results in abrupt release of stored fuels forming vapor cloud around a facility. Depending on flammability and the availability of an ignition source, such a vapor cloud may lead to a massive explosion which has been referred as Vapor Cloud Explosion (VCE) in the process safety literature [1–5]. In the last decade many of such major accidents in storage sites are reported [6]. There have been two large-scale incidents viz, Puerto Rico, (USA) in 2009 and Buncefield (UK) in 2005 which have exhibited striking similarities with Indian Oil Corporation Limited (IOCL), Jaipur, (India) storage terminal accident [7-9]. A wide range of similarities in VCE and subsequent fire have been observed among these accidents. Only the Buncefield and IOCL, Jaipur investigation reports have been published till date [1, 3]. One expects that the overpressure generation as a result of such VCE often lie in the range between 20 and 50 kPa [4,5]. Such overpressures are possible to evaluate by the existing models in the open literature. But, the peak side on overpressure estimated after the IOCL, Jaipur accident [9] of >200 kPa was not expected based on the existing knowledge on VCE. There are lists of parameters required to be considered behind this excessive overpressure generation. Some of them like congestion in the form of trees and bushes can have a significant contribution on the Deflagration to Detonation Transition (DDT) [10-14]. The intensity of disaster due to explosion becomes severer when DDT is seen as a result. Hence, a careful review of the safety measures related to conditions favoring the generation of excessive overpressure are necessary to be executed.

In the second part of this paper, safety distance estimation from after explosion scenario which is very often a large pool fire is presented. Strength of explosion, number of tanks and surrounding conditions could lead to single or multiple fire. Subsequent explosions also lead to the engulfment of surrounding tanks / containers and contribute towards a violent fire. Whenever such a scenario has occurred the seen consequences were even worse. The affected area can be of the order of a few meters to several kilometers depending on the magnitude of the incident. Large-scale accidents have a potential to harm the on-site and off-site population. In the third part, paper presents an assessment of Individual Risk and Societal Risk (IRSR) associated with the cumulative effects of explosions and fires. However, the total risk at the IOCL, Jaipur accident does not lie in the unacceptable region, but in the As Low As Reasonably Practicable Region (ALARP) where substantial measures for a risk reduction were needed. The consequences in and around the terminal were high, which might be due to the failure or absence of certain precautionary measures. Moreover, according to Buncefield Major Incident Investigation Board (BMIIB) [1], 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. 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.

Successively, 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 [15]. 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.

Brief summary of the major accidents

An introduction of major accidents occurred during the last decade are presented in this section. There might be other causalities but we limit our discussion only up to: a. Buncefield (2005), b. Puerto Rico (2009) and c. IOCL, Jaipur (2009).

Buncefield (2005, UK)

On the early morning of 11 December 2005 one tank (912) at Buncefield storage depot started receiving excess amount (more than its capacity) of unleaded petrol leading to an overflow of the tank and subsequent collection of petrol in the bund [1]. The scenario is shown in Fig. 1. The failure of automatic safety switch alarm allowed the tank 912 to fill at a rate of more than twice of that in normal operation [1]. By calculating the overpressure of liquid in tank 912 from the following relation between pressure drop and flow rate of an incompressible fluid, $\Delta p \propto V^2$, it reveals that the tank was overflowing at a liquid overpressure of 2.2 times of the pressure under normal operating conditions. It is likely that this liquid overpressure certainly contributes towards magnitude of formation of vapor cloud under stable wind conditions [1] and subsequent explosion (gases) overpressure. The existing understanding on the overpressure of a vapor cloud explosion rather underestimates the reported intensities of overpressures at Buncefield. One would have estimated an average value of overpressure of 5 kPa [4,5] for such vapor cloud explosion which simply does not represent the devastating recorded (determined from damage analysis) overpressure of >200 kPa [4,5]. The diameter of the vapor cloud was estimated to be about 391 m and the high speed rotating machines in the pump house are postulated to be the potential source (initial) of ignition [1,4,5]. The effect of overpressure could be felt as far as 2 km from the center of explosion [1]. Fortunately, no fatalities took place though light and serious injuries could not have been avoided.

Fig. 1. Buncefield accident (2005, UK) [1]

Puerto Rico (2009, USA)

A similar scenario to Buncefield accident was seen on 23 October 2009 at Caribbean Petroleum Corp., Bayamon, USA, where also an uncontrolled flow of petroleum products mainly gasoline led to the formation of a vapor cloud and finally resulted in heavy explosion overpressures (Richter scale 2.8) [2]. The scenario is shown in Fig. 2. The investigation report currently being exercised by the Chemical Safety Board of the USA and thus many details on this accident are not available to date [2]. The feedback of eyewitnesses/ evidences also supports the similarity to the Buncefield disaster [2].

Fig. 2. Puerto Rico, USA (2009) storage fire accident [2].

IOCL, Jaipur (2009, India)

On 29 October 2009, a petrol terminal in the Indian Oil Corporation (IOC) in Sitapura industrial state (near Jaipur) caught fire following an explosion and continued to rage until a week [3] (Fig. 3). The oil industry safety directorate of India has investigated the incident [3]. They found potential similarities with Buncefield except the ignorance/ mistakes done by personnel which were additional reasons reported behind the IOC, Jaipur accident. However, from a scientific point of view the occurrence was similar to the above mentioned two incidents. The overflowing of a tank, formation of vapor cloud in still air (low wind speeds), ignition triggered by the pump/generator station and finally the spreading of fire over the other tanks [3].

Fig. 3. Sitapura, India (2009) storage fire accident [3].

Accident and Its Aftermath

The IOC, Jaipur, India, incident was one of the major petroleum storage terminal accidents in India. During transfer operations through 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 so-called hammer blind valve of Tank 401-A over a period of 80 min before ignition of the resulting flammable mixture. The total amount of gasoline released was 2,000 metric ton, which resulted in a formation of 81 metric ton of vapor cloud covering an area of 180,000 m^2 [9]. Subsequently, the ignition of a flammable mixture had resulted in massive explosions and intense fires. A series of powerful explosions was 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 [3].

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, which were found up to 2 km from the terminal [3]. After one of the major explosions there was a fire that engulfed 11 large storage tanks. The fire burned for a week, destroying most of the site. The vegetation around the storage facility was completely consumed by the fire. The management of IOC had taken a considered decision to allow the petroleum products to burn out to avoid further possibilities of accident in the installation thus ensuring safety of the public.

Casualties

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 5,000 people in the nearby surrounding area had to be evacuated from their homes [3]. This makes it one of the most fatal accidents that have occurred during the last decade in the petroleum industry.

Hazard criteria

In general, a storage site for flammable liquids is designed as per the standard norms prescribed by the regulating bodies. However, some industries have their own hazard mitigation plans. In either case, consequences arise from explosion and fire must be addressed. Most importantly, the damage to people and vicinity which may be caused by the explosion overpressure [4,5] or/and by thermal radiation [16-17] from fires are required to be specified before installation and operation. Technically, explosion refers to vapor cloud explosion or gas explosion and fire refer to single/multiple large pool fires in this article. This will be discussed as follows.

Evaluation and analysis of an accident

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

The release rate

As reported by the Independent Inquiry Committee [3], the initiating event of the sequence was caused by the accidental releases of gasoline from the 0.25 m diameter outflow pipe. This resulted in the leakage of substantial amount of flammable liquid. In the first case, the mass discharge rate from the Hammer Blind Valve was determined by the Equation (1) [18]. This assumed the fraction is represented by a discharge coefficient, C_D, and accounts for the pressure due to the liquid head above the hole, h_L.

$$m = \rho\vartheta A = \rho A C_D \sqrt{2\left({gP_g}/{\rho} + gh_L\right)} \qquad (1)$$

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. (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 [19].

The Evaporation Rate

The calculation of the vapour mass involved in the explosion is crucial for assessing the consequences of such accidents. A more accurate result can be obtained by computing the evaporation rate of gasoline during the accidental release.

The evaporation rate per unit area *m* mass can be calculated by considering two contributions that are derived, respectively from pool area and from the 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. Atypical approach is to assume a vaporization rate of the form [20]:

$$m_{mass} = \frac{MW k_g A_P P^{sat}}{R_g T_L} \qquad (2)$$

where MW is the molecular weight of the evaporating material, k_g is the transfer coefficient, A_P is the area of the pool, P_{sat} is the saturation vapour pressure of the liquid, 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:

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

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

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. 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.

The Formation and Size of the Flammable Cloud

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 [21].

- 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 [3].

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 [22]. In the case of the IOC 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 [22]. 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[22]. 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 Risk 6.7 [23] software 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 [9]. The wind direction at the time of incident was 340° (NNW direction), with a stability class of D. Fig. 4 shows the vapour cloud dispersion with a varying concentration of material, towards the south east (SE) direction using DNV Norway based Phast Risk 6.7 software [23]. 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.

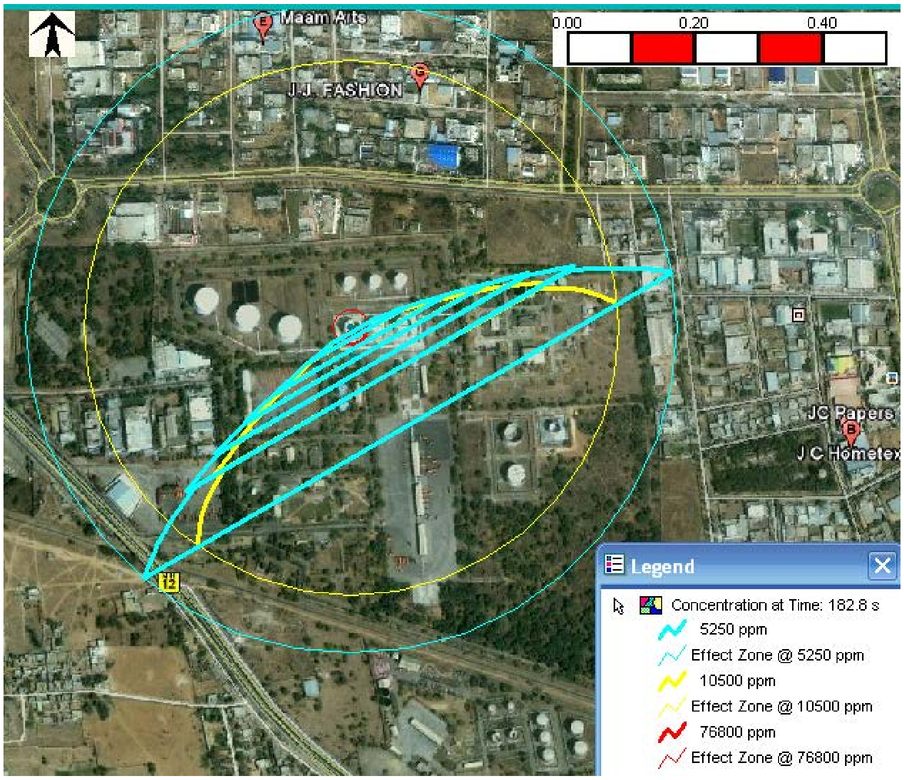

Fig. 4 Dispersion of vapour cloud in SE direction by using Phast Risk 6.7

Vapor Cloud Explosion (VCE)

A consequence in 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:

1. Flammability and quantity of fuel
2. Degree of confinement/congestion
3. Source and strength of ignition
4. Weather conditions.

Most of the empirical models developed to date are typically based on the above four parameters. Absences of a single factor alter the probabilities and extent of occurrence to a great extent. For example, if a vapor cloud is formed at a location but could not find a source of ignition so it may not be harmful or a situation where the wind speed is high and the vapor are carried away thus minimizing the risk of accumulation [4–6, 10]. Many of such possibilities exist and a careful review of permutation and combination is required for the risk assessment studies. There has been significant study done in the past and recently to establish common conclusions on the resulting overpressure from IOC, Jaipur VCE [9]. While many of them report that the excessive overpressure was not usual for the common understanding on VCE till date a number of papers also indicate the likeliness of such high overpressure generation [5,6]. Regardless of which is true we try to examine the possible applicability of available models today. There are three different methods considered in the relevant literature to estimate the overpressure for a VCE. Each of them is briefly described below.

TNT equivalent method

A common approach for determining the damage caused by a given explosion consists in estimating the "TNT equivalency", i.e. the mass of TNT that would produce the same degree of damage [24]. The main features of TNT and other high explosives have been extensively studied and are therefore reliable references. Since significant experimental data on the explosion characteristics of TNT are available it is easier to extrapolate the scenario with TNT. The following Eqs. (4) and (5) describe the same.

$$W = \frac{\eta M E_c}{E_{TNT}} \quad (4)$$

$$Z^* = \frac{R}{W_{TNT}^{1/3}} \quad (5)$$

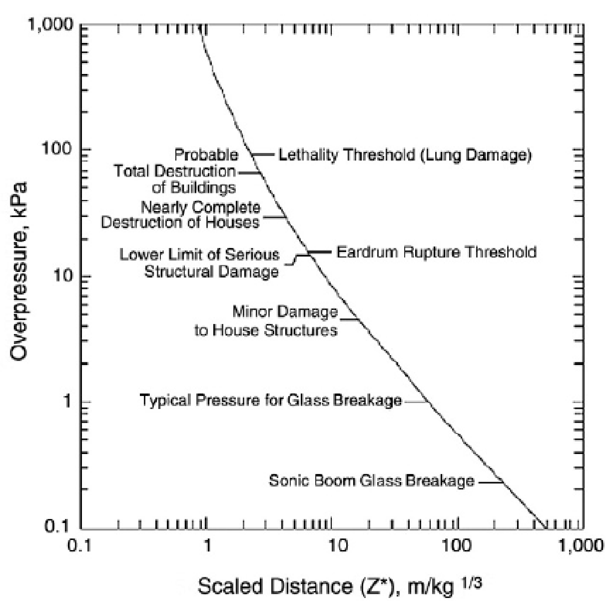

Fig. 5. Overpressure produced by a VCE vs. scaled distance [24].

where W is the equivalent mass of TNT, η is an empirical explosion efficiency, M is the mass of hydrocarbon, E_c is the heat of combustion of flammable gas, and E_{TNT} is the heat of combustion of TNT. Eq. (4) has a yield factor η which depends on the degree of congestion on the site. Typical values based on experience for η are between 3% and 5%. However, for stoichiometric proportions and heavily congested area a value of 20% is specified [14, 25-27]. In Eq. (5), R (m) is the distance from the centre of explosion. The estimation of on side overpressure can be made with the help of plot for pressure on site vs. scaled distance Z^* (m kg$^{-1/3}$) as shown in Fig. 5. For the sake of initial estimation this method could be utilized. For example when this method is applied to IOC Jaipur it estimates an overpressure of ~9 kPa at a distance of 2 km from the source of explosion provided the yield factor is 20%. Even when the lowest value of yield factor is considered, i.e., 3% .

The biggest drawback of this method is that it is not applicable to overpressures of >100 kPa and small distances Z^* as the local pressure developed in case of TNT is much higher than that in case of flammable gas explosion waves which travels to a larger distance. Therefore, for far field regions it does not estimate the overpressure correctly. When this method is applied to IOCL Jaipur accidents it estimates the overpressures (at 300 m) to be 13 kPa, respectively, depending on the mass of flammable fuel responsible for explosion.

Baker and Strehlow method

This method is based on the Mach number MW (flame velocity), reactivity of fuel and level of congestion and confinement [5, 28]. The Eqs. (6), (7) and (8) for maximum overpressure P_{max}, dimensionless average side on pressure $\bar{P}_s$ and the scaled distance $\bar{R}$ are

$$P_{max} = 24\frac{M_W^2}{(1+M_W)} \quad (6)$$

$$\bar{P}_S = \frac{P_{max}}{P_a} \quad (7)$$

$$\bar{R} = R\left(\frac{P_a}{E_1}\right)^{1/3} \quad (8)$$

When a medium reactivity, a Mach number M_W of 0.55, a total available energy E_1 (J) and a high level of congestion are assumed an overpressure of 50 kPa results. The $\bar{P}_S$is plotted against $\bar{R}$ in Fig. 6. The same overpressure values are also estimated for the other two accidents when a Mach number of 0.55 is assumed (generally valid for hydrocarbons).

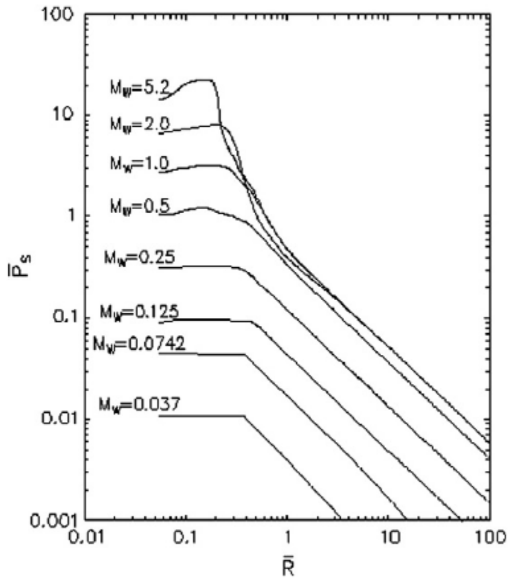

Fig. 6 Overpressure produced by a VCE vs. scaled distance [24]

TNO (multi energy method)

This is the most widely used method in Europe [5, 29]. The challenge in this method is to determine an appropriate explosion source strength. The Eq. (9) describes the maximum overpressure as follows:

$$P_{max} = 0.84 \left(VBR \frac{L_f}{D}\right)^{2.75} S_L^{2.7} D^{0.7}/84 \qquad (9)$$

Where P_{max}: maximum overpressure in kPa; *VBR*: Volume Blockage Ratio (%); L_f: flame path length (m); *D*: average obstacle diameter (m); S_L: laminar burning velocity of flammable mixture (m/s).The dependence of dimensionless overpressure Eq. (7) on distance Eq. (8) is shown in Fig. 7. When applied this method to IOCL, Jaipur with *VBR* 4%, L_f=50 m, *D* =0.3 m and S_L =0.46 m/s for hexane [3] it estimates the overpressure to be >2000 kPa.

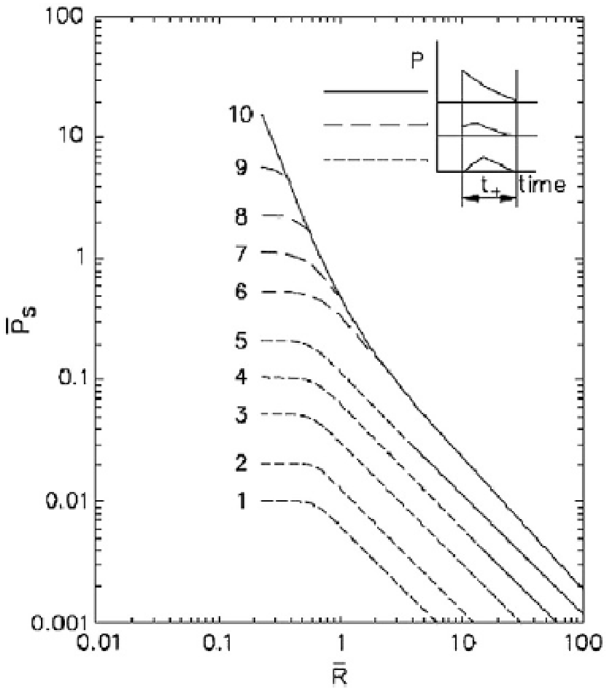

Fig. 7. Overpressure produced by a VCE vs. scaled distance [29].

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 focused. Hailwood et al., [30] reported that the course of a UVCE should be treated as a deflagration (ΔP_{max} < 1 bar) or as a detonation (ΔP_{max} > 1 bar). When 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} is determined from Eq. 10.

$$\Delta P_{max}/P_a = \frac{2\alpha(1-1/\varepsilon_1)^2(u_F/c_s)^2}{1+(1-1/\varepsilon_1)u_F/c_s} \quad (10)$$

Where, the expansion ratio ε_1(measure of the energy release rate) is determined from Eq. 11:

$$\varepsilon_1 \equiv \rho_0/\rho_1 \equiv V_1/V_0 \quad (11)$$

The range of $\varepsilon_1 \approx 7$ to 8 [31] 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 [32]. The shock wave velocity in air, *U*, is calculated by using Eq. 12.

$$U = C_0 + \left(1 + {}^{6P^0}/_{7P}\right)^{1/2} \quad (12)$$

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 [9].

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. (13) [32].

$$q^0 = \frac{5}{2}\frac{(P^0)^2}{7P + P^0} \quad (13)$$

where q^0 is the maximum dynamic pressure. 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 the overpressure experienced and that which takes places on a surface parallel to the direction of propagation.

$$\left(P^o\right)_r = 2P^o\left(\frac{7P + 4P^o}{7P + P^o}\right) \quad (14)$$

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. 14 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 [9]. 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.

Deflagration-to-Detonation Transition (DDT)

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 [33]. 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 [34].

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 [33]. The damage of the pipeline control room building and Pipeline pump house are shown in Figs. 8 and 9. As shown in Fig. 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. 8 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. 10.

(a) (b)

Fig. 8 Control room in the Pipeline Division area (a. north side b. south side) [33]

Fig. 9 Damaged Pipeline pump house from the south of the building [33]

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. 8a.

- It is notable that the collapse of the roof downwards on the south side (Fig. 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. 11. The arrows indicate the approximate directions indicated for each area of the site [33].

Fig. 10 Directional indicators: bent tree (towards the northeast direction) towards the pipeline division

Fig. 11 Overview of the directional indicators and estimated cloud boundary (yellow line) [33]

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 [11]. 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 1 lists some of the important details concerning the accidents.

Table.1 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}
IOC Jaipur, India, Oct. 2009	110×10^{3}	Leakage	80	2000	18×10^{4}	> 2	≈ 2.3	≈ 11	11	150	11/11	6×10^{6}

Fire hazard criteria

Hazard from a fire is generally defined in terms of emitted thermal radiation to the people and objects [16]. The fires in the considered accidents burn in form of large pool fires. The diameter of a pool can range in the order of some meters. In the open literature a significant amount of work has been reported on thermal radiation characteristics of different hydrocarbon pool fires [16-17, 28, 35]. The hydrocarbon in the considered accidents was primarily gasoline. The amount of thermal radiation emitted by a large gasoline pool fire (D = *24 m*) at different distances is shown in Fig. 12.With the assumption that thermal radiation from the surface of a turbulent fire ($D \gg 1$ *m*) is saturated one can estimate the safety distance. There are several methods described in the literature [1]. We will also use them for the accidents described above.

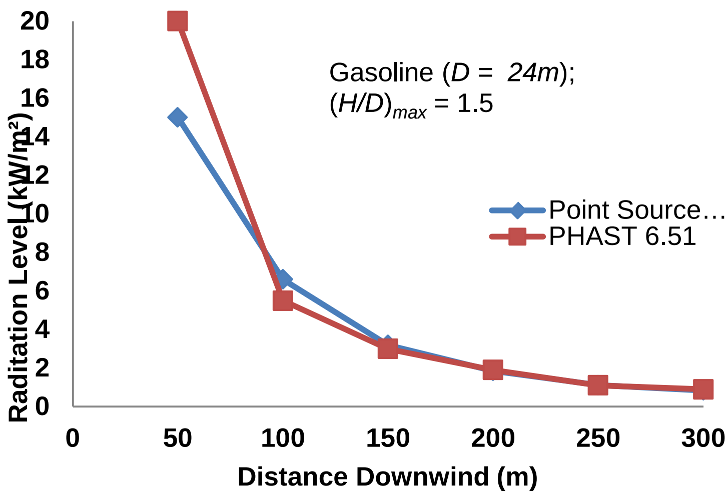

Fig. 12 Thermal radiation variation with relative from a fire

Flame characteristics and modelling of pool fires

The pool fire characteristics, like the following description of the consequence model given below, have been used to estimate the flame height, flame temperature and thermal radiation.

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

Relative Flame Height

The flame height is generally taken as the maximum visible height or the time-averaged visible height [36]. The time-averaged relative $(\overline{H}/D)$ and maximum relative $((\overline{H}/D)$max) visible flame height are dependent on the Froude number (Fr_f) and the dimensional wind velocity $(\bar{u}_W^*)$ and can be estimated by the following correlations [30]:

$$\bar{H}/_D = a\,Fr_f^b \bar{u}_W^{*c} \quad (15)$$

and

$$\left({}^{H}/_{D}\right)_{max} = a\,Fr_f^b \bar{u}_W^{*c} \quad (16)$$

There are more correlations with many empirical parameters, including a, b, and c, which are experimental parameters and are given in Table. 2 [24].

Table. 2. Parameters for the determination of the dimensionless visible flame heights used in Eq. (15, 16) [37]

Correlation	a	b	C	Comment
Munoz 1	8.44	0.298	-0.126	Measured on gasoline and diesel pool fires: $(H/D)_{max}$
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. (17) was zero because there was no wind effect. The modified equation can therefore be written as:

$$(H/D)_{max} \approx a\mathrm{Fr}_f^b = \mathrm{a}\left(\frac{\overline{m}''_f}{\rho_{a\sqrt{gD}}}\right)^b \quad (17)$$

Thus, the estimated $(H/D)_{\mathrm{max}}$ ratio for the gasoline tank (D = *24m*) fire is 1.5. For a large hydrocarbon pool fire where $D \geq 9$ m, the time-averaged relative flame height $(\bar{H}/D)$ is calculated using Eq. (18) [30] and Table. 1 and approximates to

$$(\bar{H}/D)_{\mathrm{calc}} \approx a\mathrm{Fr}_f^b = 7.74\left(\frac{\overline{m}''_f}{\rho_{a\sqrt{g\,D}}}\right)^{0.375} = 0.9 \quad (18)$$

With $\overline{\mathrm{m}''}_{\mathrm{f,max}}$ (D=24 m) ≈ 0.055 kg/ (m2s) for a gasoline pool fire, ρ_a = 1.29 kg/m3, and the parameters a and b from Table 1, the calculation using Eq. (17, 18) results in

$$0.9 \leq (H/D)_{max,calc} \leq 1.5 \quad (19)$$

An empirical relationship was observed between the maximum and average flame height. Thus, a single correlation could be used to estimate both dimensions [38]:

$$(H/D)_{\mathrm{max}} \approx 1.6\,\bar{H}/D \quad (20)$$

The empirical relationship in Eq. (20) was also considered valid for the IOCL Jaipur tank fires.

Flame Temperature

The flame temperature is a function of time and height, as described by Planas and Casal [39]. The correlation used for the flame temperature is given by the following equation (Eq. 21):

$$T_f(t,h) = \frac{10^4 .t}{(34+210 \times H+8.51\times t)} + 298 \quad (21)$$

In the IOCL Jaipur incident, 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 [17, 40 - 43] .

Individual Risk and Societal Risk Assessment

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 BMIIB [1], land-use planning (LUP) is responsible for the level of risk on the site. BMIIB (2008) also suggested that LUP should be based according to the risk level and more attention should be paid to minimize the risk to the surrounding population. CCPS [19] gives guidelines to estimate the individual and societal risk associated with different incident outcome cases from major chemical industrial accident.

In this paper, an attempt has been made to make reasonable assumptions to provide a more realistic estimate and analysis individual and societal risks due to an explosion and/or fire at petroleum oil storage terminal. The release modeling has been carried out by classifying affected areas in and around the terminal, incorporating population density, and by focusing on the time sequence of events.

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 [44]. 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” [45]. 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 criteria in determining acceptability of risk in terms of safety zones. The ALARP principle is developed by the Health and safety Executive of the UK [46]. 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. 13. 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.

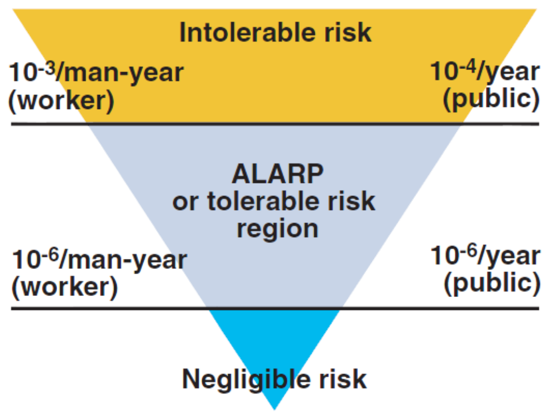

Fig. 13. The ALARP principle, developed in the UK (HSE, 2001)

Individual Risk at a geographical location x, y is given by AIChE/ CCPS [19] as follows (Eq. 22):

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i} \tag{22}$$

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. 23).

$$IR_{x,y,i} = f_i \times p_{f,i} \tag{23}$$

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. 24) [47].

$$N_i = \sum_{x,y} P_{x,y}\, p_{f,i} \tag{24}$$

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 6.7 software [23]. 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-one 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.

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 15m, 55m and 75m, respectively. The maximum mass burning rate of the gasoline in most of the tank fires had been about 0.055 kg/m^2s [38].

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 [48].

The individual risk has been computed by the DNV Norway based Phast Risk- 6.7 software for the territory of the terminal and the surrounding area. The individual risk contours with various risk levels have been presented in Fig. 14. The maximum risk level of 10^{-4} per year has been observed near the storage tank area at a distance of around 100m 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 [50].

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 led to such a catastrophic accident.

[Source: 49]

Fig. 14 Individual Risk controls for the IOCL Jaipur incident

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. 15 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 $1{\times}10^{-4}$ per year, the buffer zone level lies in between $1{\times}10^{-4}$ - $1{\times}10^{-2}$ per year while unacceptable frequency level is higher than $1{\times}10^{-2}$ per year [46]. The F/N curve for the IOCL Jaipur accident is in the ALARP region [50]. 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.

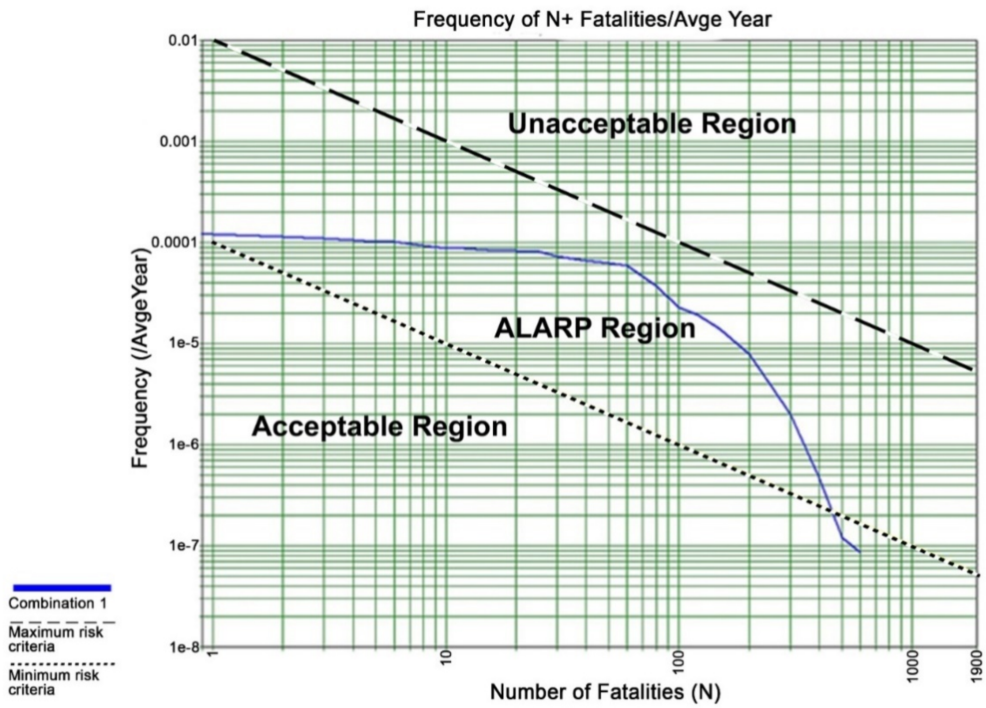

Fig. 15 F/N curve for Jaipur IOCL incident

Emergency Response Plan For Storage Terminals

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 [15]. 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. EMERGENCY RESPONSE PLAN (ERP) is required for various types of accidents to decrease the degree of hazards efficiently by effectively preparing, responding, and restoring normal conditions [15]. 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 study 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. 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.

Conclusions

The study carried out in this paper has focused on post-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. 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.

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.

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 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.

Flame characteristics like height and temperature have been computed to realize the intensity of fire. The consequence modeling also 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. 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. ALARP region indicates that the risk to the surrounding population is tolerable if the precautionary measures are properly implemented. 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.

Emergency Response Plan (ERP) to tackle such type of big accidents is an integral and essential part of a loss prevention strategy. The Emergency Operations Center (EOC) and

Emergency Management Computation System should be an important components of 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.

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