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Types of accidents occurring in chemical process industries and approaches to their modelling

by

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Abstract

Accidents in chemical process industry cause significant lossessin terms of human health, life, property and environmental pollution. An accident starts with loss of containment of one or other hazardous substance resulting in fire, explosion, or dispersion of toxic material. The severity of an accident depends both on the scale of the accident and nature of impacted surroundings. This paper presents an overview of the types of accident that occur in chemical process industry, their damage potential, and how the likely impacts are forecast.

Keywords: Chemical process industry, accident forecasting, fire, explosion, toxic release

1. Introduction: accidents in chemical process industries

Accidents in process industries began in the era of alchemy when flammable and/or toxic substances began to be used in creating new products. With industrialization occurring rapidly in the aftermath of industrial revolution, accidents in chemical process industries (CPI) rose in frequency of occurrence and degree of severity around the world (Khan and Abbasi 1997a, b, c; 1998 a, b, c, d; 1999a, b; 2001a, b, c, d; 2002; Abbasi *et al.*, 2010; 2013). In parallel with the advancement in science and technology, chemical process industries have to contend with ever new hazardouschemicals and processes thereby continuously increasing the risk of accidents. The exponential increase in the global population has also added tothe probability of the harm any accident may cause. Even those industries which were earlier situated in remote areas far from human dwellings now find themselves being enveloped by residential colonies. Thus the risk posed by probable accidents continues to grow(Abbasi and Abbasi 2005; 2007 a, b, c; 2008; Tauseef *et al.*, 2010; 2011 a, b; Vasanth *et al.*, 2013).

A major accident has been defined as "an occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operationof any establishment and leading to serious danger to human health and/or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances" (Casal, 2008; CCPS, 1999).

Analysis of past accidents reveals that 57−73% of them were caused by technical and engineering failures which include piping system failure, contamination, weakening of construction material, corrosion and erosion, mass transfer, heat transfer, and failure of control system (Duguid, 2001; Nivolianitou *et al.*, 2006; Prem *et al.*, 2010; Kidam and Hurme, 2012). Organizational failures (23%) andunknown causes account for 23% and 4% of the pat accidents.

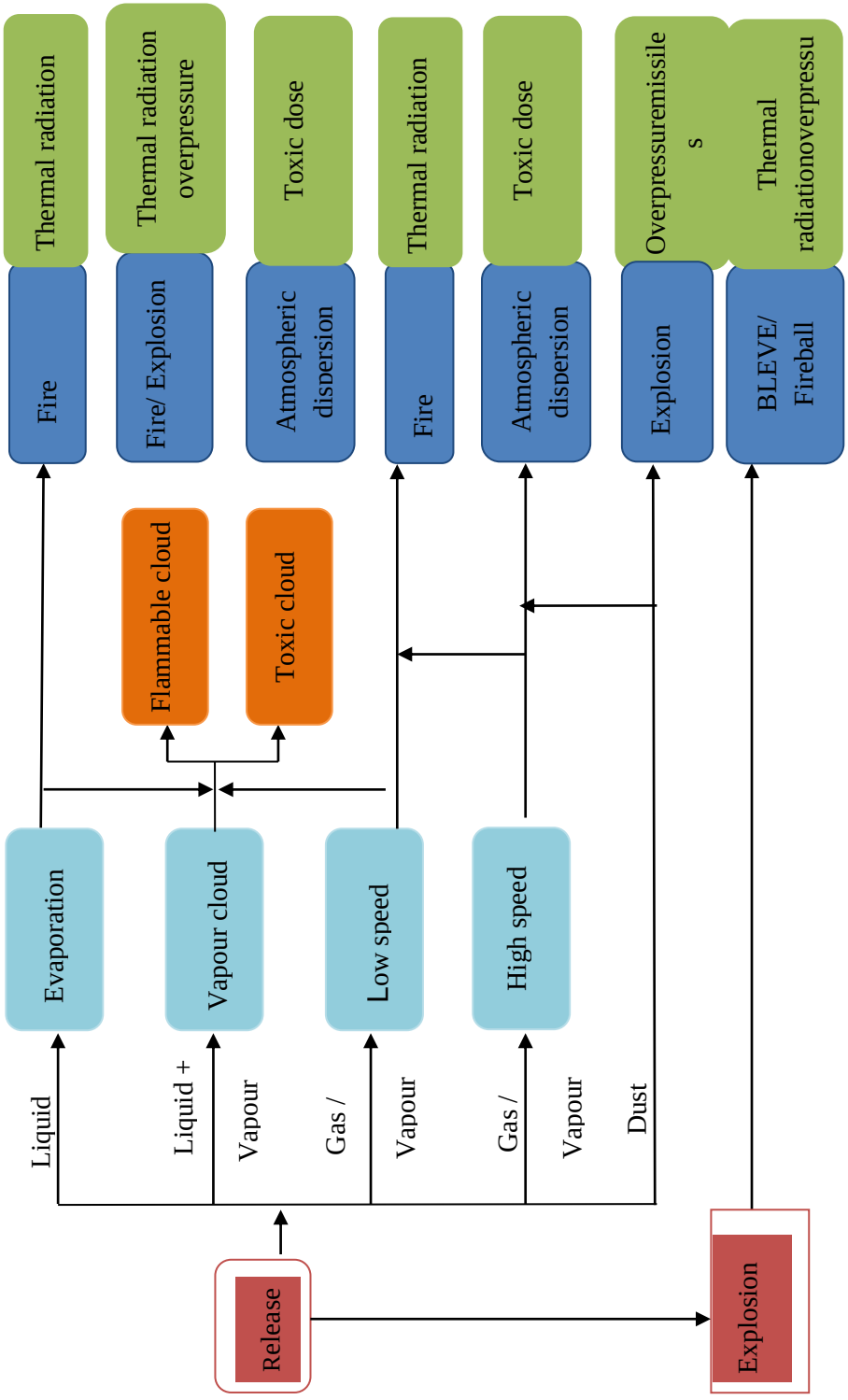

Figure 1: Major accidents: simplified schema (Rosas and Casal, 2011)

Any major accident involvesthe release ─ instantaneous or over a relatively short period - of significant amountsof energy or of one or more hazardous materials (Casal, 2008). After initiation, an event can follow different paths and various accidentalscenarios can be reached depending on the nature of accident and the nature of the surroundings it effects. This has been shown in Figure 1 through a simplified scheme, adapted from Rosas and Casal, (2011).

By an estimate, 59% of all CPI accidents involve fires, 35% involve explosions, and 6% comprise toxic lacks (Gomes-Mares, 2008). Very often, more than one of these accident types occur, either simultaneously or one after another (NPTEL, 2006, Casal, 2008; Abdulhamidzadeh *et al.,* 2010; 2011). A fire may lead to an explosion and *vice versa*; and they in turn may cause more fires or explosions with or without toxic release.

2.Types of explosions in chemical process industry

According to Lees (2005) an explosion is a sudden and violent release of energy accompanied by the production of loud noise. The violence of the explosion depends on the rate at which energy is released during the explosion. When the release is rapid enough the energy is dissipated as a pressure or shock wave which has potential to injure living systems and damage assets such as buildings and the environment. Lesser number of explosion occur in the process industries than fire but when they do occur, they inflict much greater loss of life and damage than fire, anestimated 67.7% against 30.2% losses caused by fires and 2.1% by toxic releases (Lees, 2005; Abbasi, 2009).

Abbasi *et al.,* (2010) have presented a scheme for the classification of explosions in process industry. According to the authors there are "three kinds of energy associated with all explosions: physical, chemical, and nuclear. Of these, only the first two are encountered in process industries as also in day-to-day existence".

2.1 Physical explosion

Abbasi *et al.,* (2010) further observe that "a physical explosion occurs when the accumulated energy is suddenly released in a rapid physical change such as the expansion of a compressed gas or the flash vaporization of a superheated liquid by a failure of the containment".This energy can produce a shock wave and accelerate vessel fragments accelerating. If the contents are flammable it is possible that ignition of the released gas could result in additional consequence effects(www.fedoa.unina.it).

Depending on the situations that cause physical explosion, this event can be categorized either as a boiling liquid expanding vapour explosion (BLEVE) or as a rapid phase transition explosion (RPTE).

The boiling liquid expanding vapour explosion (BLEVE)

BLEVE is among the most fearsome of accidents that can occur wherever a pressure liquefied gas (PLG) exists.The PLG can be CNG, LPG, and other petrochemicals which are used in

pressure liquefied form(Abbasi and Abbasi, 2007). But it is not at all necessary that a substance must be flammable in order to suffer a BLEVE; even pressure liquefied water can suffer BLEVE (Abbasi and Abbasi 2007a; 2008).

A BLEVE is caused by a sudden release from confinement of a liquid at a temperature above its boiling point. The sudden decrease in pressure results in explosive vaporisation of a fraction of the liquid, and a cloud of vapour and mist are formed, with accompanying blast effects. If the material is flammable fire ball IS formed. The primary cause is usually an external flame impinging on the shell of a vessel above the liquid level weakening the container and leading to sudden shell rupture.

Figure 2: Boiling liquid expanding vapour explosions (BLEVE's) triggered by earlier vapour cloud explosions (VCEs) at Feyzin (France) (accidentsoilandgas.blogspot.in), top and San Juan (Mexico), bottom (devastatingdisasters.com/san-juanico-1984/).

A BLEVE poses the following hazards: (1) fireball with thermal radiation with some rainout forming pool fires, (2) missiles and (3) overpressure from shock waves. Past experience has shown that whenever there is BLEVE; the thermal radiation of the fireball and the over pressure, do severe damage (DMI, 2015). Visulas of some major BLEVE accidents are presented in Figure 2.

The rapid phase transition explosion (RPTEI)

A rapid phase transitionexplosion (RPTE) may occur when cryogenic liquids are accidentally exposed to hotter environment, for example liquefied natural gas (LNG) spilled on or in water (Abbasi, *et al.*, 2010). This occurs when a volatile liquid comes into contact with another liquid of a higher temperature. Therefore, energy is transferred from the hotter liquid to the colder volatile liquid. So the liquid rapidly changes phase to vapour, the large increase in volume (due to the vapour generation) causes a localised pressure increase which gives rise to an air or waterborne blast wave.

2.2 Chemical explosion

A chemical explosion involves energy derived from a chemical reaction. Explosions of a vessel due to combustion of flammable gas, and explosion of a reactor caused by decomposition of reaction products in a runaway chemical reaction, are examples of accidents involving chemical energy. Several sub-categories falling under chemical explosion are:

- Vapour cloud explosion
- Condensed phase explosion,
- Dust explosion
- Aerosol explosion.

Vapour cloud explosion (www.ijetae.com)

Vapour cloud explosion (VCE) is one of the biggest hazards in chemical process industries (Baker, 1999). When a large quantity of flammable gas or vapour is accidentally released in to atmosphere it may form a vapour cloud and if it then meets a source of ignition (such as a spark) it could produce a vapour cloud explosion. The damage caused by a vapour cloud explosion is mostly due to the overpressure that is created from the fast expansion of the combustion products. Past accidents have revealed that, because of strong blast, VCEs cause heavy damage to people, equipment and facilities (CCPS, 1999), often setting off a chain of accidents. Four visuals associated with VCE-related damage are presented in Figure 3.

A uniquely bothersome attribute of a VCE is that a vapour cloud may drift some distance from the point where the leak has occurred before exploding. Thisattribute of the VCputs to risk even those areas that are lying far away from the industry where the vapour cloud had formed (Tauseef *et al.*, 2011).

Figure 3: Damage caused by vapour cloud explosion at Flixborough (top left) (devastatingdisasters.com/san-juanico-1984/), PEPCON (top right) (damninteresting.com/the-pepcon-disaster/), BP refinery (bottom left) and Jaipur (bottom right) (nbcnews.com/id/33800042/ns/world_news).

Condensed phase explosion

As noted by Abbasi *et al.*, (2010), certain industrial liquids or solid products of high energy density on catching fire can generate pressure waves of energy and speed high enough to cause an explosion even in an unconfined space. These materials are routinely found in the explosive or munitions industry but can also be found in the chemical process industry. Examples include organic peroxides, acetylene compounds, and nitration mixtures. The hazard can occur in processes if some unwanted and highly sensitive substance is accidentally allowed to concentrate resulting in blast and fragment effects" (CCPS, 2010).

Dust explosion

Any combustible material can burn rapidly when in a finely divided form. If such a dust is suspended in air in the right concentration, it can become explosive (ann-srv.asianewsnet.net). Ignition of the particles can be from variety of sources such as open flame, mechanical and electrical sparks, friction or other type of heating, such as by an unprotected lamp or even by self-heating of the dust settled in a layer in e.g. a dryer. The reactivity of a dust increases, up to a limit, with the decrease in particle size, increase in surface area to mass ratio, decrease in

moisture content, and increase in combustion energy. Their explosion strength is of the same order of magnitude as those of explosive gases (Abbasi and Abbasi 2007b).

Aerosol or mist explosion

An aerosol explosion differs from vapour cloud explosion in the role played by the liquid droplets contained in an aerosol. Their presence enhances the probability of the cloud getting into the flammable range. Once a flame is initiated it generates a blast which in turn can interact with particles ahead of the flame stripping off a micro-mist due to drag. This fine mist can react very intensively when it is reached by the flame. This can make the explosion more violent (Abbasi *et al*, 2010).

3.Fires in chemical process industry

Fire is a chemical reaction in which a substance combines with oxygen and heat is released (Lees, 2005). Usually fire occurs when a source of heat comes into contact with a combustible material. Fuel, oxygen and heat are three essential conditions for a fire to occur which is called as fire triangle. If one of the conditions is missing, fire does not occur and if one of them is removed, fire is extinguished (Lees, 2005).

As stated earlier, fire is the most frequently occurring event in the process industries causes more serious accidents than explosion or toxic release, lthough the accidents in which the greatest loss of life and damage occur are generally caused by explosion (Lees, 2005). According to an estimate of Darbra *et al.*, (2004) 59.5% of accidents involve fire, 34.5% account for toxic dispersion. Another estimate concerning process plants and the transportation of hazardous materials by Planas *et al.,* (2009) pegs the accidents involving at fire 47% of all.

In process plants, fire normally results from a leakage or spillage of fluid. Larger leaks may occur from vessels, pipes or pump failures while the smaller ones occur from flanges, sample and drain points, and other small bore connections. Often a small fire may trigger an explosion which may than cause a much bigger fire (Lees, 2005). The types of firesthatmay occur are:

- Jet fire
- Pool fire
- Flash fire
- Fireball

3.1 Jet fire (Cheremisinoff, 2006; Khan and Abbasi 1999)

Jet flames can occur in chemical process industries, either by design in the case of intentional disposal of unwanted gas in flares or by accident. When a storage tank or a pipeline containing liquefied or compressed gas is somehow punctured or ruptured during an accident, it discharges gas at high speed in the direction away from the rupture, all the while entraining and mixing with air. When the gas is flammable and encounters an ignition source, a jet flame of considerable length may form. For chemicals that are liquid under ambient conditions, no gas jet will form.

Liquid or vapour might leak out through puncture or break, but will not blow out(Cheremisinoff, 2006; Khan and Abbasi 1999).

Scenarios involving jet flames are not easy to handle, since a large jet flame may have a substantial 'reach', sometimes up to 50 meters or more (www.aidgc.org.au). Such flames could bring about serious harm but will generally affect a limited area.

3.2 Pool fire

Pool fire occurs when a flammable liquid spills onto the ground and is ignited. A pool fire begins typically with the release of flammable material from process equipment or storage. If the material is a liquid, stored at a temperature below its normal boiling point, the liquid will collect in a pool. The geometry of the pool is dictated by the surroundings. If the liquid is stored under pressure above its normal boiling point, then a fraction of the liquid will flash into vapour, with a portion of the unflashed liquid remaining to form a pool in the vicinity of the release.The primary effects of pool fires are due to thermal radiation from the flame source.

3.3 Flash fire (www.bioline.org.br; www.greatislandpowerproject.com)

When a volatile, flammable material is released to the atmosphere, a vapour cloud forms and disperses (mixes with air). If the resultant vapour cloud is ignited before the cloud is diluted below its lower flammability limit (LFL), a flash fire may occur (Rew et al, 1996). The combustion normally occurs within only portions of the vapour cloud (where mixed with air in flammable concentrations), rather than the entire cloud. The major impact of flash fires is due to the heat effect from thermal radiation jepardising objects in the nearby vicinity of the flash fire or in the path of the flash fire whether on land or water (Ashe and Rew, 2003; *www.bioline.org.br; www.great islandpowerproject.com*).

3.4 Fireball (Khan and Abbasi 1999d; archive.org)

A 'Fireball' is an event which results from a BLEVE in which an immediate ignition of the pressurized and liquefied fuel occurs. The fireball is generally far more serious than the other fires (ILO, 1993). It is usually related to the sudden loss of containment of a pressurized liquefied fuel (Lees, 2005). The two-phase cloud can bum only on its outer surface as inside there is no oxygen. This phenomenon has a short duration from a few seconds to few minutes, but the thermal radiation intensity is very strong. The destructive ability of fire ball is very high as the heat load generated by it is of the order of 1000 kJ/m^2 (Khan and Abbasi, 1997).

4. Toxic gas release (Lees, 2005; arshadahmad.wordpress.com; response.restoration.noaa.gov;

The third type of hazard in chemical process industry after fire and explosion is release of toxic chemical. It usually involves the emission of material from containment followed by vaporization and dispersion of the material. The toxic gases can spread to the surrounding community through venting and flares as well as from accidental release following fires and explosion. The most tragic example of toxic release is the Bhopal incident that killed several thousand persons and

injured several times more. The accidental release of a volatile chemical can present a threat to life and health far from the point of release. Some chemicals are toxic by inhalation; others can pose a fire hazard when it is flammable. The hazard presented by a toxic substance depends on the conditions of exposure and on the chemical itself. It can range from a sudden brief exposure at high concentration to prolonged exposure at low concentrations over a working lifetime (CCPS, 1999).

5. Approaches to model process industry accidents

Several empirical, analytical, and computational methods and models have been developed to assess the severity of possible accidents described above. Summaries of these attempts are presented in Table 1-7.

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Table 1: Models commonly used to forecast the size, duration, and heat load, generated by BLEVE-related fireballs (Lees, 2005; www.questconsult.com; bleve.totalsafety.nl; tdx.cat; archive.org; www.eng-consult.com)

Author/source	Description	Range of validity	Limitations/strengths
Hardee and Lee(1973)	Based on experiment on propane, proposed this empirical model to estimate diameter of propane fireball: $D = 5.55M^{1/3}$ Where, D is the diameter of the fireball (m) Mis the mass of fuel (kg)	This model applies to the fireball following the rupture of a vessel containing a liquefied flammable gas.	*Strengths:*Assumption of all the available fuels participating in the fireball generation leads to conservative results.
Fay and Lewis (1977)	Fay and Lewis (1977) developed empirical models based on that experiments on hydrocarbons. For fireball diameter they gave the formula $D = 6.36\ M^{0.325}$ Where, D = diameter of fireball (m) M= initial fuel mass(kg) For the duration the fireball they developed the expression: $t_d=2.57\ M^{0.167}$ Where, $t_{d=}$ fireball duration, seconds M is the initial mass of the fuel	These models are applicable to fireball formed from a compact, stationary cloud of pure fuel vapour ignited at the edge.	*Strengths:*Assumption of all the available fuel participating in the fireball reaction leads to conservative result.
Hasegawa and Sato(1977)	Hasegawa and Sato (1977) carried out a series of tests on fireballs of n-pentane and obtained formula to calculate fireball duration: $t_d=\begin{cases}1.10M^{0.097}, M \le 6.1\ kg\\1.07M^{0.181}, M \ge 6.1\ kg\end{cases}$ where, M is the initial mass of the fuel. t_d = fireball duration, seconds Fireball diameter can be calculated using the formula, $D= 5.25M^{0.314}$ Where, D = diameter of fireball (m) M= initial fuel mass(kg) The surface emissive power (SEP) of the fireball can be estimated by the formula $q_s =2.35P^{0.39}$ Where, q_s= surface emissive power, kW/m^2 P= vessel burst pressure Also it was suggested to have an average surface emissive power to be at or below 310	The proposed formulae for calculating SEP is applicable for burst vapour pressure up to 2MPa only.	*Limitations:*Since this is static model, it over predicts the extent of potentially damaging or injurious in the radiant heat hazard zones *Strengths:*This model assumes that mass of fuel involved in fireball is equal to mass released if the adiabatic flash fraction exceeds 1/3 else three times the amount flashed is used in the fireball calculation. This produces conservative result.

	kW/m^2 According to Hasegawa and Sato mass involved equals mass released if adiabatic flash exceeds 1/3. Otherwise three times the amount flashed is used in the fireball calculation (www.questconsult.com).		
Roberts (1981, 1982)	Based on a series of experiments conducted using hydrocarbons, Roberts (1981, 1982) proposed a model for estimation of fraction of the total available heat energy that is radiated by a fireball(www.questconsult.com). The fraction of the total available heat energy that is radiated by the fireball is given by $F= 0.27P^{0.32}$ where, F = fraction of heat radiated P = vapour pressure at the moment of release (MPa). He also estimated surface emissive power (SEP) of fireball to be 450 kW/m^2. The value derived for the SEP is consistent for flame temperatures in the range of 1000 – 1400 ^oC. The duration of fireball can be estimated using the formula $t_d = \begin{cases} 0.45M^{1/3}, M \leq 30{,}000\ kg \\ 2.60M^{0.167}, M \geq 30.000\ kg \end{cases}$ where, M is the initial mass of the fuel. t_d = fireball duration, seconds The mass of fuel involved in the fireball is an integral part of the equations for fireball diameter and duration. Roberts proposed that Mass of fuel involved in fireball is equal to mass released if the adiabatic flash fraction reaches 35% and zero if adiabatic flash equals zero.	This model is applicable for a fireball from a vessel which has experienced sudden loss of containment leading to BLEVE. The proposed model is applicable for burst vapour pressures up to 6 MPa only.	*Limitations:*Since this is static model, it over predicts the extent of potentially damaging or injurious in the radiant heat hazard zones. Target absorptivity and atmospheric transmissivity effects are not considered in his model.
Lihou and Maund(1982)	Lihou and Maund(1982) carried out series of experiments on hydrocarbons such as butane, rocket fuel, propylene, methane and propane, proposed model to calculate fireball diameter and duration time for fireball. Fireball diameter can be calculated from formula $D =5.72\ M^{0.303}$ Where, D = diameter of fireball (m) M= initial fuel mass(kg) Duration time for fireball is given by $t_d= 0.45\ M^{0.333}$ Where, $t_{d=}$ fireball duration, seconds M is the initial mass of the fuel According to their model, transmissivity equation is suggested as T=exp(-0.0007x)	Transmissivity equation should be used only for low relative humidity in which dust particles (haze) are the main cause of attenuation.	**Limitations:** The assumption of the fireball being located at some height greatly reduces the predicted separation distances. In light of the uncertainties involved regarding the lift-off, the ground-level fireball model is preferred.

	where, x is the distance to the source in metre, constant - 0.0007 is in m^{-1} T is transmissivity (unit less) As liftoff is considered in this model, they gave a relationship to calculate height Z(m)of the fireball as Z= 10t Where, constant = 10 is in m/s t= duration time of combustion in (s)		
Moorhouse and Pritchard(1982)	Moorhouse and Pritchard (1982) proposed a model to estimate diameter and duration time for fireball based on experiment on flammable liquid. Fireball diameter can be calculated using the formula, $D = 5.33M^{0.327}$ Where, D = diameter of fireball (m) M= initial fuel mass(kg) Duration time for fireball can be calculated by the formula $t_d=0.923\ M^{0.303}$ Where, $t_{d=}$ fireball duration, seconds M is the initial mass of the fuel. The surface emissive power (SEP) of the fireball can be estimated by the formula $q_s = 2.35P^{0.39}$ Where, q_s= surface emissive power, kW/m^2 P= vessel burst pressure They suggested an average surface emissive power to be $150KW/m^2$ and a maximum value of $300\ KW/m^2$ for industrial fireballs of pure vapour. Moorhouse and Pritchard presented the following relationship to approximate transmissivity of radiation from hydrocarbon flames through the atmosphere by T = 0.998X where, X= distance to the source(m) and the constant 0.998 in m^{-1}	The equation used for calculating transmissivity is valid for only distances up to 300m. The proposed formula for calculating SEP is applicable for burst vapour pressure up to 2MPa only.	**Strengths:** Assumption of all the available fuel participating in the fireball reaction leads to conservative result.
Hymes (1983)	Hymes (1983) provided point source model to calculate the radiation received bya receptor at some distance from the fireball center. He developed an equation for incident radiation by combining Roberts's (1982) correlation of the duration of the combustion phase of a fireball and generalised formula of point source model and it is given by $Q = \frac{2.2\tau R H_C M^{0.67}}{4\pi L^2}$ Where, M = mass of fuel in the fireball (kg)	Point source model cannot be applied for target positions close to emitting surfaces, i.e., it can be used for targets greater than 5 pool diameters from the centre of the flame.	**Strengths:** It is simplest practical model for fireball. It is more accurate for far field predictions. Atmospheric absorption is considered. **Limitations:** Accuracy of the result from this model is insufficient in the near field of pool fires. In the near field the point source model will

	τ= atmospheric transmissivity H_c = net heat of combustion per unit mass (J/kg) R = radiative fraction of heat of combustion L = distance from fireball center to receptor (m) Q= radiation received by the receptor (W/m^2)		overestimate the incident heat flux, which is a great disadvantage when predicting safe distances for process equipment and human beings.
TNO(1983)	TNO (1983) developed solid flame model which assumes that the fire can be represented by a solid body of a simple geometrical shape, and thermal radiation is emitted from its surface. According to this model incident radiation is given by $q = FE\tau$ Where, q = incident radiation (W/m^2) F = view factor (no unit) E = emissive power of fire per unit surface area (W/m^2) τ= atmospheric attenuation factor (transmissivity)	This model is applied to near field measurements.	**Strengths:** Solid flame models are mathematically simple and can be easily computer programmed with short run times. Atmospheric absorption is considered. Geometries of the fire and target, as well as their relative positions are taken in to account. **Limitations**: During estimating radiation flux the flame geometry is idealized and does not considered to fluctuate with time.
Martinsen and Marx(1991)	Martinsen and Marx (1991) based on experiment carried out on flammable liquid attempted to model the time-varying behaviour of fireballs in order to predict the thermal radiation consequences of actual fireballs. He obtained fireball diameter from the formula $D = 8.66M^{0.25}t^{0.333}$ Where, D is the diameter of the fireball (m) M is the mass of fuel (kg) t = duration of fireball (s) Duration time for fireball can be calculated by the formula $t= 0.9M^{0.25}$ As lift off is considered in this model, height of the fireball is calculated by $H= 4.33M^{0.25}t^{0333}$	The proposed diameter and height of the fireball formula can be used only when $0 \leq t \leq t_d/3$ Where, t=time elapsed after BLEVE (s) t_d= duration of fireball	**Strengths:** The model sets the path length equal to the distance between the target and the nearest point of the fireball surface. (This is a conservative assumption since thermal radiation from all other points on the surface of the fireball would need to travel a greater path length) This model provides better predictions of hazard zones by treating fireballs as dynamic events. Atmospheric absorption is considered.

Table 2: Models commonly used to forecast the nature and impact of pool fires (Lees, 2005; archive.org; www.iitk.ac.in; www.pstrust.org).

Model type	Description	Range of validity	Limitations/strengths
Point Source Model	Point source models do not attempt to predict flame shape and assume that the source of heat radiation is a point. In point source model the received radiation flux is given by $q = \frac{P}{4\pi r^2}$ Where, P = emissive power of the flame(kW/m^2) r = distance from source to receiver(m)	They are applicable to estimate thermal radiation for hazardous gas fire scenario. This model can be used for targets greater than 5 pool diameters from the centre of the flame.	**Strengths:** Simple and more accurate for far field predictions. **Limitations:** Accuracy of the result from this model is insufficient in the near field of pool fires. In the near field, the point source model will overestimate the incident heat flux, which is a great disadvantage when predicting safe distances for process equipment and human beings. This model doesn't include effects of winds (e.g. flame tilt and flame drag) satisfactorily. The use of point source models is limited for offshore structures. Radiation obscuration by flame soot is not considered in this model. For liquid fuel fires the point source model may be too conservative because liquid fires are more predictable as their dynamics is understood.
Solid flame model	This model considers the flame as a body which emits thermal radiation. The shape or geometry of this body may be idealized as a cylinder or a cone for all fires except fireball scenario which maybe idealized as a sphere. In solid flame model the received radiation flux is given by $q = \tau VS$ Where, τ = atmospherictransmissivity V = view factor S = surface emissive power($kW/m^{2)}$	They are applicable to estimate thermal radiation flux from liquid pool fires. This model is developed for fire hazards in relatively open spaces with good ventilation. This model is applied to near field measurements.	**Strengths:** Solid flame models are mathematically simple and can be easily computer programmed with short run times. This model provides a better prediction of flame geometry and external thermal radiation for offshore fires than is possible with point source models. Radiation obscuration by flame soot is considered. **Limitations**: During estimating radiation flux the flame geometry is idealized and does not considered to fluctuate with time They have no consideration of the interaction between fires and the surrounding obstacles.
Babrauskas (1986)	Babrauskas (1986) produced a model for pool fire representing flame geometry as cylinder for which he presents a correlation for mass burning rate as $m = m_\infty (1 - e^{(-k\beta D)})$	Mass burning rate equation can be applicable only for pool diameter greater than 0.2m with no external heating and windless atmosphere.	**Strengths:** Calculation is simple since it assumes that the emitted radiation originates from a point source of the flame without regard to the shape of the flame.

	where, m_∞ and kβ are empirical factors for different fuels and D is the diameter of pool (m) The heat radiated by the flame is expressed in terms of P where $P = mF_r\Delta h_c\left(\frac{\pi D^2}{4}\right)$ Where, Δhc is the heat of combustion (kJ/kg) m is the mass burning rate (kg/m^{2}s) F_r is the fraction of heat radiated And P is the radiative power (kW) The thermal radiation incident on the target(kW/m^2) is given by the formula $Q = \frac{m_\infty \Delta h_c F_r}{16L^2}\left[1 - e^{(-k\beta D)}\right]$ for L > 4 $Q = F(0.131F_r\Delta h_c)m_\infty\left[1-e^{(-k\beta D)}\right]$ for 0.5 < L < 4 Where, $L = \frac{\text{Distance from its centre to target(m)}}{\text{Pool diameter(m)}}$		

Table 3: Models commonly used to forecast jet fires (Lees, 2005; environment.gov.ab.ca; www.bozpinfo.cz; Cheremisinoff, 2006; Woodward 2010; www.aidic.it)

Model	Description	Range of validity	Limitations/strengths
Chamberlain (1987)	Chamberlain (1987) produced models for predicting flare flame shape and radiation field from the work done on natural gas. He idealized the flame as a frustum of a cone, and defined the fraction of the net heat content of the flame that appears as radiation from the surface of this solid body as $F_s = \frac{Q}{SEP.A}$ where, SEP= surface emissive power (kW/m^2) Fs = fraction of heat radiated from surface of flame A = surface area of frustum including end discs (m^2) Q = net heat release (kW)	This model is applicable for angled and vertical flames for consequence prediction on onshore structures. This model can be used to cover the range of pipe diameter: 0.006 to 1.07 m and wind velocity of 2.7 to 13 m/s.	**Strengths:** Chamberlain model better mimics the actual size and shape of a flare. It allows a quick and fast estimation of the heat radiation from Jet Fire and could be further developed according to actual needs. They are mathematically simple and easily understood This model yields most accurate results (irrespective of fire scenario) both in the near and far field of any fire. Effect of wind momentum is accounted **Limitations:** Because of the simplicity, they are designed to predict only those quantities of direct relevance to consequence assessment such as flame shape and heat fluxes, rather than to provide detailed description of fire itself. They have no consideration of the interaction between fires and the surrounding obstacles.
Point Source Model	Point source models do not attempt to predict flame shape and assume that the source of heat radiation is a point. In point source model the received radiation flux is given by $q = \frac{P}{4\pi r^2}$ Where, P = emissive power of the flame(kW/m^2) r = distance from source to receiver(m)	This model can be used for targets greater than 5 pool diameters from the centre of the flame. The Point source model' has been used for flames which have a large flame height to diameter ratio (i.e. jet fires and diffusive flare fires from comparatively small openings compared to the flame height) except very close to the fire. It is developed for designing vertical flare stacks producing subsonic flares.	**Strengths:** Simple and more accurate for far field predictions. **Limitations:** It is known to be insufficient within one to two flame lengths for short-term radiation levels and hence use of point source models within offshore structures is limited. This model over-predicts the heat flux for near-field conditions. This model doesn't include effects of winds (e.g. Flame tilt and flame drag) satisfactorily.
Craven (1972)	Craven had developed a model of jet flame for the purpose of designing of emergency relief vents. In his model the shape of the flame is considered as inverted cone with the apex at the orifice and the flame length can be calculated by	Craven points out that the model can be applied only to the highly turbulent flame occurring during the main discharge. Thus not intended to be used for flames on flare stacks, which are not highly turbulent and are	**Strengths:** Value of flame temperature assumed in this model depicts the temperature that is likely to occur in practice.

	$\frac{L}{D} = 5.3 \frac{W}{D}$ Where, W = diameter at the top of the flame(m) D = diameter of the pipe (m) L = flame length (m) The radiant heat flux is calculated by $E = \epsilon \sigma T^4$ where E is the radiant heat flux (W/cm^2) T is the absolute temperature of the flame (K) E is the emissivity of the flame which is assumed to be unity σis the Stefan Boltzmann constant.	therefore cooler.	**Limitations:** This method is not intended to use for hazard assessment rather than for designing purpose.
Murray (1982)	McMurray presented a model called the integrated mixed source model (IMS model), which is based on regression analysis and predicted radiation over the whole of the radiation field. This model consists of two set of equations for predicting radiative flux in which one assumes that the flame is completely transparent to radiation. And other equation assumes that flame is completely opaque so that the radiation emanates from the surface of the flame envelope. However neither of the models provided a good description of the radiation field.	This model is applied on both far and near field predictions.	**Limitations:** It does not allow for variation in heat release along the length of the flame. This model over-predicts the heat flux for near-field conditions.
De Faveri et al. (1985)	De Faveri et al performed wind tunnel experiments on small 'flares' in a wind and obtained correlations for various features of the flare such as the downwind position of the flame tip and the axis of the flame. The correlation for heat flux is given as $Q = (4.24)(10^{-8})(d_j R)^{1.06} f T^4$ $\int_0^{x_1} \frac{(Ax^{0.36} + h - z)}{x^{0.6}\{(Ax^{0.36}+h-z)^2+(x^{-}-x)^2\}^{\frac{2}{3}}} dx$ Where, Q = Thermal radiation ($Kcal/s.m^2$) f = Fraction of radiant heat release T = temperature (K) x = downstream distance (m) h = height of flare stack (m) z = cross-stream distance (m) d = diameter of flare stack	This model is applied for far field predictions.	**Strengths:** Effect of wind is accounted. **Limitations:** This model is relatively complex. This model over-predicts the heat flux for near-field conditions.
Clay et al (1988)	Clay et al proposed a jet flame model for hazard assessment for which the flame length is given as $F = \frac{(H_c m)^{0.444}}{161.66}$ Where,	This model is applied for far field predictions.	**Strengths:** This model is simple and produces conservative result.

	F is the flame length (m), H_c is the heat of combustion(J/kg) and m is the mass flow (kg/s). The flame is modelled as a point source radiator with heat radiated from a point located 4/5 of the flame length from the origin. For the thermal radiation the relation used is $q = \frac{fm\tau H_c * 10^{-3}}{4\pi x^2}$ with $\tau = 1 - 0.0565 \ln x$ Where, f is the fraction of heat radiated q is the thermal radiation received by the target (kW/m^2) x is the distance between the source and the target (m) τ is the atmospheric transmissivity.		
Carter (1991)	Carter has given a model for the thermal radiation incident on a target from a jet flame from a gas pipeline. The flame is treated as a multiple source radiator and its dimensions are based on its state 30 s after release. For each source in the flame the relation for the thermal radiation is $Q = \frac{F_r(-\Delta H_C)\, m\tau}{4\pi X^2}$ Where, F_r is the fraction of heat radiated $\Delta H_c$is the heat of combustion (kJ/kg) M is the mass flow (kg/s) Q is the heat incident on the target (kW/m^2) x is the distance from the source to the target (m) τ is the atmospheric transmissivity.	This model is applied for far field predictions.	**Strengths:** This model is simple and produces conservative result.
Johnson et al (1994)	A.D. Johnson, Brightwell and Carsley (1994) have described a model for a jet flame of natural gas issuing horizontally, which is an extension of the flare model of Chamberlain (1987). As in the original model, the flame is represented as the frustum of a cone and the thermal radiation can be calculated from the formula $Q = (F_{sd}S_{sd} + F_{en}S_{en})\tau$ Where, F is the view factor Q is the thermal radiation incident on the target (kW/m^2) τ is the atmospheric transmissivity. S is the surface emissive power (Subscripts en and sd denote the end and the side of the flame respectively)	This model is applicable to horizontal jet flames.	**Strengths:** Effect of the wind is accounted in this model. . This model produces conservative result.

Table 4: Models commonly used to forecast flash fires (Lees, 2005; www.aidic.it; Woodward, 2010)

Model	Description	Range of validity	Limitations/strengths
Raj & Emmons (1975)	Raj and Emmons (1975) modelled a flash fire assuming the geometry of the fuel vapor cloud is two dimensional, the combustion is controlled by natural convection and the flame propagation velocity with respect to the unburned gases is constant. The model consists of determination of the Flash fire dynamics, then calculation of heat radiation.	The factor W which represents inverse of the volumetric expansion due to combustion in the plume in calculating flash fire dynamics depends on clouds composition. $W = \frac{\emptyset - \emptyset_{st}}{\alpha(1-\emptyset_{st})}$ for $\emptyset > \emptyset_{st}$ and if the mixture in the cloud is stoichiometric or lean, W = 0 where, $\emptyset_{st}$= stoichiometric mixture composition (fuel volume ratio) $\emptyset$= fuel-air mixture composition (fuel volume ratio)	**Strengths:** This model takes into account the speed of the flame propagating through the cloud. The atmospheric attenuation factor takes into account the influence of absorption and scattering by water vapor, carbon dioxide, dust, and aerosol particles. **Limitations:** The model takes burning speed is proportional to wind speed which implies that, under calm atmospheric conditions, burning velocities become improbably small and flash-fireduration proportionately long. This makes the approach improper.
Einsenberg et al. (1975)	Einsenberg et al. (1975) developed a model based on the assumption of Gaussian atmospheric dispersion to estimate the fuel concentration within the cloud and the cloud size. The model estimates the volume and area of radiation, assuming that the combustion process is no tintense and that the burning is controlled by buoyancy.	This model can be applied to neutral, light and heavy gas.	**Strengths:** Calculation process is simple. This model calculates effective duration of flash fire. **Limitations:** The thermal radiation model used in this model based on the Stefan-Boltzmann equation; this is a problem as temperature is difficult to estimate due to its large variation.

Table 5: Models commonly used to forecast dispersion of toxic gases (Lees, 2015; www.eng-consult.com; www.trinityconsultants.com; www.epa.state.oh.us; www.breeze-software.com; www.ofcm.gov; docslide.us; www2.dnv.com; pubweb.epa.gov; www.dnv.co.za; Witlox, 1994; www.hgsystem.com; ehsfreeware.org; is.nea.fr; www.pstrust.org; www.science.gov; Fullwood, 2000).

Author/source	Description	Range of validity	Limitations/strengths
Kunkel, (1980)	AFTOX is a Gaussian puff/plume dispersion model developed by Bruce Kunkel(1980) is intended for estimating concentrations downwind from accidental chemical releases, where the dispersing plume has the same density as air.	AFTOX is restricted to neutrally buoyant releases which can be gas and liquid(evaporating to neutrally buoyant gas). AFTOX can model the downwind concentration from several source types, including point, area, and liquid spill sources. For each source type, the release can be continuous, finite, or instantaneous in duration.	**Strengths:** AFTOX calculates 90% confidence interval (CI) for toxic corridor and concentrations at a point. It can directly calculate the evaporation rate from liquid spills. **Limitations:** It does not treat dense gases, which are frequently encountered in accidental release scenarios. This model doesn't consider chemical reaction, effects of complex terrain and wet and dry deposition.
Zeman, (1982)	Zeman (1982) developed a model SLAB to simulate the atmospheric transport and dispersion of dense gas releases from area sources.	The model can be applied to continuous, finite and instantaneous releases for dense gas or liquid spills that evaporate to dense gas This model applies for following types of releases Ground level evaporating pool Elevated horizontal jet Elevated vertical jet.	**Strength:** Easy and fast dispersion estimates **Limitations:** This model assumes flat atmospheric flow field with no obstructions by buildings, trees considered. This model can't be used for strong buoyant plume. Doesn't take into account sloping terrain. Source release rate can't be calculated. Prediction of turbulent mixing between scattering gas and air particles demands the use of specific turbulent model.
USEPA (1984)	INPUFF is a Gaussian puff model, developed by the U.S. EPA is intended for simulating the atmospheric dispersion of neutrally buoyant or buoyant chemical releases.	INPUFF is restricted to neutrally buoyant gas releases which can be used to simulate dispersion from both semi instantaneous and continuous point sources. This model is also applied to stationary and mobile sources	**Strengths:** INPUFF code includes the capabilities of handling time-dependent release rates and multiple release locations up to 100 receptors. **Limitations:** No consideration for pollutant removal or chemical reaction. No consideration for building wake and cavity effects. No consideration of effects of complex terrain.

Havens and Spicer, (1986)	Havens and Spicer(1986) developed a model DEGADIS(Dense gas dispersion model) for estimating concentrations downwind from an accidental chemical release, where the dispersing toxic or flammable plume is initially heavier than air.	DEGADIS presently provides only for vertical releases. This model can be used only for dense gas releases or liquid spills that evaporate to dense gas. This model can be applied to both continuous and instantaneous release in the presence of non variant wind conditions.	**Strengths:** They are able to address atmospheric dispersion of contaminant releases in the following fluid flow regimes 1.Buoyancy-dominated 2. Stably-stratified 3. Passive dispersion. 4. Jet This model can account for a large spectrum of surface roughness elements. Ground reflection is considered in this model. **Limitations:** Unable to address complex meteorological flow phenomena (e.g., mountain-valley flows, sea breezes). Does not account for aerodynamic effects of nearby buildings. Does not account for positive thermal buoyancy (i.e., plume rise). Does not account for dry or wet deposition effects. Can only address pure chemical releases. Wind variation in time and space, complex terrain and distance limit are not considered in this model.
Cook andWoodward,(1995)	Woodward and cook(1995) developed a model called Unified Dispersion model (UDM) for modelling jet, heavy and passive two-phase dispersion including possible droplet rainout, pool spreading and re-evaporation.	UDM can be used to model the dispersion following a ground-level or elevated two-phase unpressurised or pressurised release. UDM allows for continuous, instantaneous, constant finite-duration, and general time-varying releases.	**Strengths:** The UDM model appears to be currently the only model allowing for automated calculations of pool formation following rainout, with vapour from the pool added back to the cloud. It is the single model for the entire dispersion regime from the point of release to the far-field dispersion. Vertical variation in wind speed, temperature and pressure are considered.
Eulerian grid model	Dispersion model named Eulerian Grid Model is designed to model high resolution concentration fields.	Eulerian grid models are suited for modelling concentrations and exposures associated with complex sources, distributed over an area (e.g. road traffic).	**Strengths:** It has ability to better and more fully characterize physical processes in the atmosphere and predict the species concentrations throughout the entire model domain. Mixing and chemical interactions between different air parcels well described/accounted in this model

			Limitations: Difficult to relate the emissions from a source to concentrations at a given receptor site. The model has limited spatial resolution. Actual trajectories only indirectly calculated. Because they consider only ambient concentrations, dispersion model do not provide direct estimates of human exposure.
Colenbrander, (1980)	HEGADAS is heavy gas dispersion model from area sources developed by Colenbrander in 1980. It is a further improvement of a mathematical model developed by TeRiele (1977) for the prediction of gas concentrations in ground-level plumes emitted by area sources in steady-state situations. HEGADAS has two versions. The first, HEGADAS-S, is the steady-state model for a continuous release and the other version, HEGADAS-T, is the quasi-steady-state model for a transient release.	HEGADAS can be used both for steady-state calculations and for transient (time-dependent) calculations. HEGADAS is intended for heavy gas dispersion simulations. It should not be used for buoyant clouds or clouds that become buoyant. It should also not be used for clouds which have considerable momentum of their own.	**Strengths:** HEGADAS uses the concept of 'breakpoints'. Using a breakpoint, HEGADAS calculations can be interrupted or initiated at a specified downwind location. Can model gravity spreading and along-wind dispersion . Includes the effects of heat and water vapour transfer from the substrate. HEGADAS takes into account both free and forced heat convection **Limitations:** The HEGADAS-T model is quite complex to use and interpret. Run times will be long upto several minutes. Liquid aerosol rainout is not accounted in this model.
USAF, (1980)	Air Force Dispersion Assessment Model (ADAM) is a modified box and Gaussian dispersion model which incorporates thermodynamics, chemistry, heat transfer, aerosol loading, and dense gas effects.	ADAM is designed to model following types of release : • Continuous and instantaneous release • Area and point sources • Pressurized and unpressurized release • Liquid/vapour/two phase outflow. This model is limited to eight chemicals (Chlorine, Fluorine, Nitrogen tetroxide, Hydrogen sulfide, Hydrogen fluoride, Sulfur dioxide, Phosgene, and Ammonia) and cannot be used for other chemicals without modifying the source code.	**Strengths:** ADAM treats a wide variety of source emission conditions and accounts for the effects of dense gases, chemical reactions, and latent heat exchanges. The formulas have been designed to reduce to AFTOX for neutrally dense (i.e., passive) clouds. **Limitations:** ADAM does not treat the vertical component of the jet trajectory. It can be applied to only eight chemicals.
Jagger, (1983)	The CRUNCH model for a dispersion of a dense gas, described by	CRUNCH can be used to model the dispersion	**Strengths:**

	Jagger (1983) is based on three simultaneous differential equations for the half-width of the cloud, the mass of air in the cloud and the temperature of the cloud.	from instantaneous, continuous types of release. This model is applicable for dense and neutral gas cloud but not buoyant cloud. This is model is not applicable for jet releases.	Surface roughness is considered in this model. **Limitations:** Acceleration of the plume to the wind velocity is not considered Wind shear effects on cloud structure are not included for a puff release producing a cloud of finite extent, but for a plume, extending to large downwind distances, can be argued to have only a minor influence at the advancing front. Dry or jet deposits are not considered in this model. This model tends to under predict the dispersion results.
Chan, et al., Ermak, (1984)	Chan, Rodean and Ermak (1984) developed FEM3 which is a three-dimensional computer model that was designed for simulating the atmospheric dispersion of heavy gas releases. This computational approach is based on a solution of the fully three-dimensional, time-dependent conservation equations of mass, momentum, energy, and chemical species.	Models both isothermal and non-isothermal dense gas releases as well as neutrally buoyant vapour emissions. The model can be applied to multiple simultaneous sources of instantaneous, continuous, and finite-duration releases. It can simulate dispersion of hazardous liquids with boiling points that are approximately equal to or less than normal ambient temperature	**Strengths:** Models the effects of obstructions to flow and complex terrain on the vapour concentration field. **Limitations:** Physical processes such as rainout, aerosol drop-size distribution, and chemical reactions are not included in the model. Although the code can treat complex terrain (ground elevation profile), it is difficult to model the presence of inhomogeneous vegetation coverage. The code tends to overestimate the rate of droplet evaporation in the near field and underestimate the dense gas effects in the far field.
Puttock, (1987)	HEGABOX model was developed by Puttock to describe the transient dispersion behaviour of instantaneous 'box' releases of heavy gases. HEGABOX either uses the full hydrogen fluoride (HF) chemistry and thermodynamics or the standard HGSYSTEM multi-compound, two-phase aerosol thermodynamics model.	The model can be applied to dense gas releases at low wind speeds and sudden releases of large quantities of dense gas. HEGABOX can only simulate the initial cloud which is stagnant and dense.	**Strength:** This model accounts the effect of gravity spreading and slumping along the wind direction for instantaneous release at low wind. It can link to HEGADAS-T for modelling far-field time-dependent heavy gas dispersion **Limitations:** Liquid aerosol rainout is not modelled.

Table 6: Models commonly used to Vapour Cloud Explosion (Lees, 2005; nparc.cisti-icist.nrc-cnrc.gc.ca; Zhang, 2016; chempedia.info; www.hse.gov.uk; www.ogp.org.uk.

Model	Description	Range of validity	Limitations/strengths
TNT equivalent model	TNT equivalent model is based on the assumption that gas explosions in some way resemble those of high charge explosives, such as TNT and it has been used extensively to predict peak pressures from explosions.	TNT equivalent method is applied for the analysis of detonations from solid charges and gas charges.	**Strengths:** Easy to use and has wide range of applications because it does not require the vapour cloud size and space conditions as input parameter. **Limitations:** Shape of blast wave of TNT explosion is different from that of VCE. TNT explosion is of shorter duration and produces higher overpressure than VCE for same energy. Impact of blast wave of TNT explosion on structures is quite different compared to that of VCE. Therefore use of TNT equivalence model is not recommended for predicting the result of VCE, especially in the vicinity of explosion. TNT equivalency method is considered to be too conservative due to its application for detonation.
Van denBerg(1985)	The TNO multi-energy model developed by Van Den Berg (1985) is based on the supposition that the energy of an explosion is governed largely by the level of confinement and congestion (i.e. location specific factors) within which the vapour cloud is located. This method is based on class number to estimate positive overpressure and positive impulse.	This model is applied for gas explosions.	**Strengths:** Conservative approximation can be made. **Limitations:** Setting a sensible value for the charge strength is difficult. Not ideally suited to weak explosions, i.e. partly confined clouds. Difficult to accurately represent complicated geometries. Not clear how to deal with several congested regions. Not clear how to deal with multiple blast waves.
Baker, *et al.*,(1994)	Baker, Tang, Scheier, Silva(1994) developed Baker Strehlow Model(BST) for evaluating blast effects from a vapour cloud explosion involves defining the energy of the explosion, calculating the scaled distance, then graphically reading the dimensionless peak pressure and dimensionless specific impulse. The BST method is based on the Mach number of the flame (flame velocity/sound velocity) and the reactivity of the fuel.	This method is applied to gas fuels alone where it can range from low reactive materials like CH_4,CO to high reactive materials like H_2, acetylene, ethylene oxide, propylene oxide.	**Strengths:** Materials of different reactivity can be adequately represented. Selection of flame expansion and obstacle density is simpler. Takes in to account representative geometrical details with regard to confinement. Can handle multi ignition points.

			Limitations: Can be over conservative.
Wiekema, (1980)	This model is also called as TNO shock wave model which uses gas dynamics induced by a spherical expanding piston as a model for estimating peak overpressure and the duration time of the explosion. This approach considers two major characteristics of a blast. First, itsscale, as determined by the amount of combustion energy involved and other its initial strength, as determined by combustion rate in the explosion process.	This model is applicable for both deflagration and detonation.	**Strengths:** It accounts for the effects of fuel reactivity on the blast characteristics by distinguishing fuel reactivity. **Limitations:** This model tries to accounts for the effect of obstacles in the congested region on the blast characteristics such as flame acceleration by relating the boundary of the reactivity region to the obstacle density, even though this approach is not adequate**.**
Cates and Samuels, (1991)	Cates and Samuels (1991) devised a decision tree procedure as guidance for estimating the source strength of an explosion taking into account the layout of the plant (i.e., degree of confinement and congestion and the type of fuel involved) and it is calculated for decay of blast wave. This model is called as Congestion Assessment Method (CAM).	Handles both asymmetrical and symmetrical congested areas.	**Strengths:** Can deal with non-symmetrical congestion. This model takes more realistic approach in predicting overpressure in congested plant gas explosions. **Limitations:** Allows only a relatively crude representation of the geometry.
Baker, (1994)	This method is called Sedgwick Assessment Loss method (SALM) and it is refinement of Puttock's CAM model in estimating pressure experienced at various distances from source of explosion.	Handles both asymmetrical and symmetrical areas.	**Strengths:** It is easy to use and produces results fast. This model allows the user to set up a simple computer representation of the plant, using a graphical interface. **Limitations:** Complex geometries are not well represented.

Table 7: Models commonly used to forecast Fire ball (Lees, 2005)

Model	Description	Range of validity	Limitations/strengths
Marshall, (1987)	Marshall (1987) proposed a model for fireball based on set of experiments for which he had given correlations for estimating heat radiation, diameter and duration time of the fireball. For the massof fuel in the fireball $M = 2\phi M_s$ for winter $M = 3\phi Ms$ for summer Where, M is the mass of fuel entering the fireball (te), M_s isthe mass of fuel in the vessel (te) and $\phi$is the theoreticaladiabatic flash fraction (TAFF). The radius and duration time of the fireball are $R_{FB}= 27.5\ M^{1/3}$ $D_{FB} = 3.8\ M^{1/3}$ Where D_{FB} is the duration time of the fireball (s) and R_{FB} isits radius (m). According to his model, transmissivity can be calculated by $\tau = X - 0.12 \log_{10} R_T$ where, X is the parameter whose value depends on relative humidity and R_T is the distancefromthe centre of the fireball to the target (m). The thermal radiation received by the target is then $I_{TA}=\tau I_T$ Where, τ is atmospheric transmissivity. $I_T$is thermal radiation intensity (W/m^3)	Transmissivity equation is applicable only for relative humidity of 20,50 and 100	**Strengths:** It is simple and easy to use. **Limitations:** This model over predicts the thermal radiation value.