İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

INDUSTRIAL EXPLOSIONS MODELLING; SPECIAL CASE AN LPG EXPLOSION

M.Sc. Thesis by
Levent TERZİOĞLU, B.Sc.

Department : Chemical Engineering
Programme: Chemical Engineering

JUNE 2007

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

INDUSTRIAL EXPLOSIONS MODELLING; SPECIAL CASE AN LPG EXPLOSION

M.Sc. Thesis by
Levent TERZİOĞLU, B.Sc.
(506031016)

Date of submission: 07 May 2007
Date of defence examination: 07 June 2007

Supervisor (Chairman): Dr. Hikmet İSKENDER
Members of the Examining Committee: Prof.Dr. Dursun Ali ŞAŞMAZ
Assoc. Prof. Dr. Levent TRABZON

JUNE 2007

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ENDÜSTRİYEL PATLAMALARIN MODELLENMESİ; ÖZEL DURUM LPG PATLAMASI

YÜKSEK LİSANS TEZİ

Kim. Müh. Levent TERZİOĞLU
(506031016)

Tezin Enstitüye Verildiği Tarih : 7 Mayıs 2007
Tezin Savunulduğu Tarih : 7 Haziran 2007

Tez Danışmanı : **Dr. Hikmet İSKENDER**

Diğer Jüri Üyeleri: **Prof.Dr. Dursun Ali ŞAŞMAZ**

Doç. Dr. Levent TRABZON

HAZİRAN 2007

ACKNOWLEDGEMENT

I would like to thank my advisor, Dr Hikmet İSKENDER for his guidance and encouragement. His exceptional insight and knowledge inspired me to attain new heights in my pursuit of knowledge.

Next I would like to thank the plant manager of the Hadımköy LPG filling station, Mustafa Ertürk, and the vice general manager of İpragaz, İrfan Tunca.

Thanks also to my family for instilling in me the understanding of the value of a good education and for the willingness and drive necessary to attin it. None of this would have been possible without them.

May 2007 Levent Terzioğlu

TABLE OF CONTENTS **Page Number**

LIST OF ABBREVIATIONS

LPG	:	Liquefied Petroleum Gas
CFD	:	Computational Fluid Dynamics
BLEVE	:	Boiling Liquid Expanding Vapour Explosion
BPO	:	Benzoylperoxide
MIT	:	Minimum Ignition Temperature
VCE	:	Vapor cloud explosions
TEEL	:	Temporary Emergency Exposure Limits
CASD	:	Computer Aided Scenario Design
MERGE	:	Modelling and Experimental Research into Gas Explosions

LIST OF TABLES

Page Number

LIST OF FIGURES

Page Number

LIST OF SYMBOLS

P_0 : Initial absolute pressure
V_0 : Chamber volume
k : Correlation factor
r(t) : Fireball radius
r_o : Chamber radius
S_b : Flame speed
ρ_u / ρ_b : Density ratio of unburned to burned gases
S_u : Burning velocity
$K_{st.}$: Size normalized maximum rate of pressure
b_z : Height of the cloud
$w_{e,t}$: Entrainment velocities at the upper surface and edge of the cloud.
C : Constant
g' : Effective gravity
c : Mean concentration
c_0 : Initial concentration of chemical compound
v_0 : Released volume
$b_z(x)$: Height
b(x) : Half width
ρ : Densities of the plume gas
ρ_a :Densities of ambient air.
$w_{e,e}$: Entrainment velocity at the edge of he plume.
Q : Total released mass
q : Release rate
u_a : Ambient velocity at which plume/puff is advected by wind
σ_x : Dispersion parameters in along end
σ_y : Dispersion parameters in cross-wind
σ_z : Dispersion parameters in vertical direction.
h : Height of plume centre-line
b : Radius between the jet-centre line and the boundary surface of the jet
w_e : Entrainment velocity
u_o : Exit velocity from source
b_o : Radius of real axial jet source
ρ_o : Material density
s : Axial coordinate of the jet or plume
u : Flow velocity in the jet
y : Radial coordinate
α_e : TNT equivalency based on energy
α_m : TNT equivalency based on mass
E_{mf} : Combustion energy of fuel per unit mass
E_{mTNT} : TNT blast energy per unit mass
Q_f : Mass of fuel involved
Q_{TNT} : Equivalent mass of TNT

r : Distance to explosion center
E : Total energy
p_a : Ambient pressure
t_p : Positive phase duration
p_{dyn} : Peak dynamic pressure

ENDÜSTRİYEL PATLAMALARIN MODELLENMESİ;

ÖZEL DURUM LPG PATLAMASI

ÖZET

Bu çalışmada endüstride en sık karşılaşılan iki patlama türü yer almaktadır. Bunlar gaz ve toz patlamalarıdır. Toz patlamaları ile ilgili, tarihte meydana gelen toz patlamaları, toz patlama beşgeni, toz patlamalarını tetikleyen etkenler, birincil ve ikincil toz patlamaları, toz patlama mekanizması ve toz patlama şiddetini etkileyen faktörler özetlenmiştir. Sonraki bölümde gaz patlamaları açıklandı. Gaz patlamaları meydana gelidği yere göre üç grup altında; sınırlı gaz patlamaları, kısmi sınırlı gaz patlamaları ve kışatılmamış gaz patlamaları olarak sınıflandırılır. Sınırlı gaz patlamaları, kısmi sınırlı gaz patlamaları ve kışatılmamış gaz patlamalarından sonra BLEVE olayı açıklandı. Üç buhar bulutu yayılım modeli olan; yoğun gaz yayılımı, pasif gaz yayılımı ve jet modelleri hakkında bilgiler veridi. Ayrıca mevcut gaz patlama modelleri incelenerek, bunların zayıf ve güçlü noktaları özetlendi. İncelenen gaz patlama modelleri sırası ile amprik modeller, fenomen modeller, CFD modelleri ve gelişmiş CFD modelleridir. Yine aynı bölümde mevcut gaz modelleme yazılımları özetlenmiştir. Uygulama bölümünde bir LPG dolum tesisinde meydana gelebilecek çeşitli kaza ve patlama senaryoları modellendi, ayrıca İTÜ Maslak kampüsünde bulunan LPG tankın kaza ve patlama senaryosu için modelleme yapıldı. Her bir senaryo için önce tank'tan bir sızıntı olduğu ve gazın alev almadığı kabul edilerek, zehirli alan, yanma alan ve patlama alanları modellendi, sonra tankta sızıntı olduğu ve alev aldığı kabul edilerek jet yanması modellendi, son olarak tank için BLEVE olayı modellendi. Modelleme için ALOHA programı kullanılmıştır. Son bölümde endüstride patlama modellemelerinin kullanılmasının sağladığı faydalar ve bundan sonraki çalışmalar için bilgiler verildi.

INDUSTRIAL EXPLOSIONS MODELLING; SPECIAL CASE AN LPG EXPLOSION

SUMMARY

In this study the two main hazards in industry are discussed; gas explosions and dust explosions. In the first part dust explosion case history, the dust explosion pentagon, what triggers dust explosions, primary and secondary dust explosions, dust explosion mechanism, and the dust explosability factors are summarized. In the next part the gas explosions are presented. Regarding the environment where gas explosions occur, gas explosions are classified as confined gas explosions, partially confined gas explosions, and unconfined gas explosions. After these three types of explosions, BLEVE is explained. Then, the three types of vapour cloud dispersion model which are dense gas dispersion, passive dispersion, and jet and plume rise models are presented. The current gas explosion models which are empirical models, phenomenological models, CFD models and advanced CFD models are summarised with their strong and weak points. Modelling software is presented. An experimental study was done at the LPG filling station and LPG storage tank at the İTÜ Maslak campus. The experimental chapter contains different simulation scenarios for failure and explosion of LPG tanks. For each scenario first it is assumed that there is a leak from a tank and there is no fire and toxic area of a vapour cloud, flammable area of a vapour cloud and blast area of a vapour cloud explosion is simulated. Next, it is assumed that there is a leak from a tank and it burns as a jet fire. Finally, it is assumed that BLEVE occurs, the tank explodes and the chemical burns in a fireball. Modelling was done by ALOHA program. Last chapter contains advantages of using explosion modelling in industry and recommendation for future work.

1. INTRODUCTION

Safety has always been an important consideration in industry. In recent years, environmental issues, public risk and opinion have made the analysis of plant accidents more important. In consequence more attention has been focused on the ability to model potential process accidents and determine what consequences could reasonably be expected if the potential event should occur. Most dangerous failures are explosions.

There are many types of explosions, but in industry, generally, dust and gas explosions are the most common. In the past there were many catastrophic dust and gas explosions. The primary focus of this work is on the modelling of industrial explosions, especially gas explosions.

In the second chapter dust explosion and case history, the dust explosion pentagon, what triggers dust explosions, dust explosion mechanism, primary and secondary dust explosion and dust explosion factors are summarized.

In the third chapter, first confined, partially confined, unconfined gas explosions and BLEVE are summarized. Existing vapour cloud models are examined. Empirical, phenomenological, CFD and advanced CFD gas explosion models are summarized for their weaknesses and strengths. Then, modelling software is summarized.

In the experimental chapter, a simulation and risk determination from the LPG filling station and storage tank at İTÜ was done using the ALOHA program.

2. DUST EXPLOSIONS

NFPA define "dust" as a finely divided solid, 420μm or less in diameter, according to the BS 2955:1958; materials with a particle size of less than 1000μm are defined as "powder"; while particles having diameter of less than 76 μm are defined as "dust" [1-3].

There are nearly six order difference between NFPA 68 and BS 2955; it is preferable to follow the Palmer view that does not exclude particle diameters coarser than 1000 μm [2-4]. In this thesis the term "dust" is used for all particulate material, regardless of particle size.

While in process industry more than %70 of dust is combustible, it is clear that a big part of industrial plants have dust processing equipment which has potential risks [5].

Dust explosion is the rapid combustion of a flammable cloud consisting of dust particles and air.

2.1 Dust Explosion Case History

Although dust explosions have been found in literature since 1785 [6,7], regular recording started at the beginning of the 20th century. A dust explosion occurred in a corn processing plant in Iowa in the USA and killed 43 people. This explosion occurred in 1919. Another dust explosion occurred in a similar plant in Illinois in the USA in 1924 and 42 people were killed [5].

A dust explosion at a big export grain silo plant at Christi in the USA in 1981 killed 9 personnel and injured 30 people. The material loss was estimated at about $30 million [8].

March 15, 1987 in China at the Harbin Linen Textile Plant the ignition of an electrostatic spark in one oh the dust collecting units caused a dust explosion. After that 7 other dust collecting units were affected and 13,000m2 of factory area was destroyed, 58 personnel died and 177 personnel were injured [9,10].

The illegal storage of large quantise of dry BPO (benzoylperoxide) caused another catastrophic explosion. In August, 1990, in Japan dry BPO exploded at a BPO manufacturing plant of the Dai-ichi Kasei Kogyo Company. In June, 1992, by the ignition of a powder mixture of potassium chlorate and aluminium during a mixing operation, a dust explosion was caused at the Daido Kako Enka Firework manufacturing factory in Moriya in Japan where 3 personnel died and 58 were injured [11].

One of the most expensive industrial accidents in the history of the US was an explosion in a powerhouse of the Ford Motor Company in Michigan on February 1st in 1999 where 6 workers died, 14 were injured and the cost was over $1 billion. The primary explosion was caused due to a natural gas build-up in a boiler that was being isolated. It has been suggested that the result of a secondary dust explosion caused the main damage which was a powerhouse building and connected facilities [12].

There are many dust explosion records for developed countries, but for developing countries there is not much information. In third world countries chemical industry accidents are mainly focused on toxic release, for example, in Bhopal in 1984 [13,14]. For process industry accidents, vapour cloud explosions, BLEVE, pool fires, flash fires and fireballs are the most heard of events [15-16]. In contrast; the dust explosion is less known in third world countries. For example, India is a country which has advanced technology. But, in India, dust explosions are almost non-existent [17]. In many cases, accidents are reported as explosions; the type of explosion is not recorded.

2.2 Dust Explosion Pentagon

When three factors, fuel, oxidant, and ignition come together, fire is caused and it is called the fire triangle. If any of the elements is removed, the possibility for fire is eliminated [18].

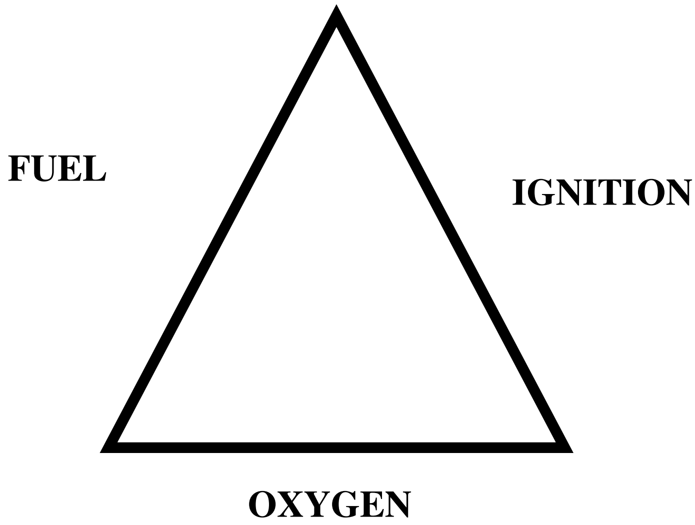

Figure 1.1 : Classic Fire Triangle [18]

A dust explosion requires two additional elements, mixing and confinement, and these five factors form the "dust explosion pentagon"; if mixing or confinement is removed from the environment a fire can continue, but an explosion will be prevented [18].

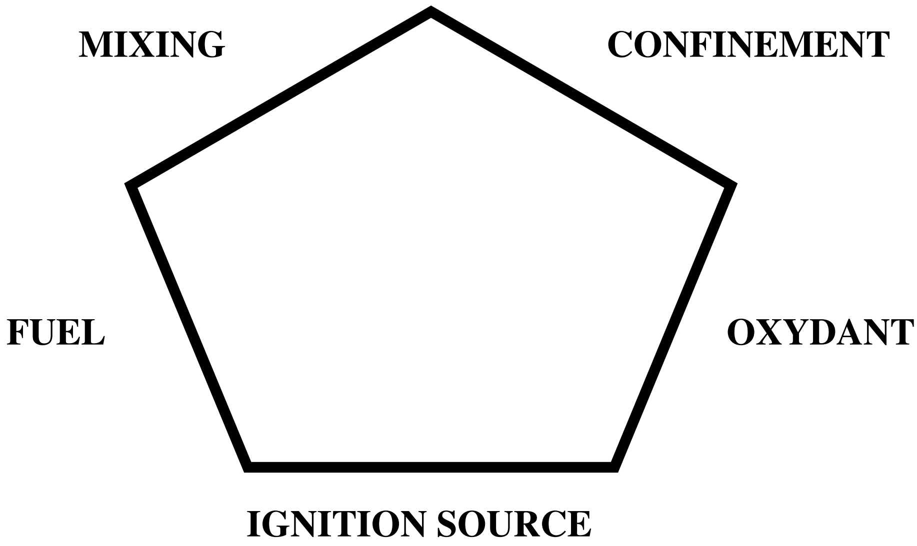

Figure 1.2 : The Dust Explosion Pentagon [18]

2.3 What Triggers Dust Explosions

There are many causes which trigger dust explosions. Some of these causes are listed below.

2.3.1 Flames and direct heat

Flames and direct heat are very dangerous for all kind of explosions. If there is a risk, direct heat should be replaced by indirect heating. For example, heating can be done by circulating hot water or steam through pipes, or a hot water bath can be used [18].

2.3.2 Hot work

There are some operations that generate excessive heat, for example, welding and cutting. If there is such an operation, extra safety measures should apply. If equipment used for this operation is not cleaned, there is a high risk of explosion [18].

2.3.2 Incandescent material

Incandescent materials are also dangerous and can trigger a dust explosion inside equipment. For example, direct firing systems are potential sources of incandescent particles [18].

2.3.4 Hot surfaces

Equipment with a hot surface also triggers dust explosions. For example, steam pipes, electric lamps and distressed bearings. If the surface temperature of the equipment is between 100 and 200 ^{o}C this may cause ignition of the dust layer [18].

2.3.5 Sparks

Electrostatic sparks

The electrostatic discharge from any equipment can cause a spark which can ignite a dust cloud.

Electrical sparks

In the normal operation of switches and relays in malfunctioning electrical equipment it is possible to form a spark.

Friction sparks and hot spots; Generally frictional sparks occur during the rubbing of one solid with another or during grinding.

Impact sparks; Impact sparks can be created by hand tools [18].

2.3.6 Self-heating

Many reactions contribute to self-heating which is another risk for dust explosions. During process and storage temperature of dust should be controlled. The tendency of dust to self-heating should be analyzed.

2.3.7 Static electricity

Static electricity is another cause for triggering a dust explosion. According to Matsuda, 25.7% of the dust explosions recorded in Japan between 1952 and 1990 were triggered by static electricity [19].

The ignition of a dust cloud by static electricity is effected by particle size distribution and the duration and rate of the application of ignition energy [20].

2.3.8 Lightning

Lightening can trigger a dust explosion.

2.3.8 Shock waves

Shock waves can trigger a dust explosion

Table 2.1 : Major dust explosion triggers [18]

Ignition source	Proportion found responsible (%)		
	Primary Explosion	Elevator incidents	Feed mills
Welding and cutting	10	24.3	12
Fire	7.8	NRA	12
Friction	8.5	NRA	4
Electrical	4.3	6.0	4
Lightening	2.8	1.5	NRA
Static electricity	4.5	1.5	NRA
Unknown	60	25.7	34

NRA: no record available

2.4 Primary and Secondary Dust Explosions

Primary dust explosions take place when a dust suspension in a container, room, mill, mixer, dryer, cyclone, hopper or piece of equipment is ignited and explodes.
The explosion at the Hayes Lemmerz is a good example of a primary dust explosion [21].

It is important to reduce the possibility of a primary explosion to prevent other explosions, which will continue if there are the proper conditions.

Secondary explosions occur when accumulated dust on any surface is ignited by a primary explosion. Often secondary dust explosions are more violent than primary explosions. A weak primary dust explosion may cause a very violent secondary dust explosion [21].

Sometimes secondary dust explosions are ignited by different explosions, not primary dust explosions. For example the dust explosion at CTA Acoustics, West Pharmaceutical Services, and Ford River Rouge were secondary dust explosions which were not ignited by dust explosions [21].

To minimize the risks for secondary dust explosions, dust accumulation should be minimized, only an approved vacuum cleaner should be used, proper cleaning procedures should be used, the proper design of areas in which there is dust and dust collectors should be used [21].

2.5 Dust Explosion Mechanism

By a combination of 5 factors, dust cloud, ignition source, oxidant, confinement and the mixing of air and a dust cloud, dust explosions occur. The rate and range of flame expansion depends on many factors some of them are an ambient condition, the nature of the dust, dust particle size and shape, by-products. The dust explosion is a complicated phenomenon which includes simultaneous momentum, energy and mass transport in a reactive multi-phase system [22].

2.5.1 Dust explosability factors

There are many factors which affect dust explosability. According to such factors the violence of explosions increases or decreases. Some of the factors are described below.

Particle size

Dust with finer particles has a larger surface area in relation to their weight and rapidly react with oxygen when mixed in air and ignite; also, these are more explosive.

The explosability of dust depends on surface area but it does not vary linearly. Also the actual speed of combustion and concentration are very important.

Dust concentration

For a dust explosion to occur dust concentration should be at certain limits. Generally, the limits are:
50-100 g/m^3: lowest concentration
2-3 kg/m^3: maximum concentration

Oxidant concentration

Another part of the pentagon is an oxidant. Generally, an oxidant is the oxygen in the air. If the concentration of oxygen in the air is greater than %21 it tends to increase the burning velocity of the fuel; otherwise, if concentration is less than %21, the burning velocity is reduced [18].

Ignition temperature

The lowest temperature at which ignition occurs is called the minimum ignition temperature (MIT). MIT increases with the presence of moisture or other inreactants in the dust cloud, and decreases with decreasing particle size [18].

Turbulence of the dust cloud

There are two types of turbulence. First is generated by dust production operations; for example, mixers, bag filters air and jet mills. The second type is generated during the combustion process after the dust cloud ignites. If the dust cloud has high degree of turbulence, a flame will ignite very quickly and this will result in a violent explosion. The turbulence affects the rate of pressure rise much more than the peak pressure [18].

Maximum rate of pressure rise

Regarding the classical combustion theory for ideal gases case, the absolute pressure is a function of time P(t); in a constant volume a spherical explosion is related with the fractional volume, V(t), possessed by a fireball during the time of propagation, t, as in the following equation [18].

$$\frac{P(t)-P_0}{P_{max}-P_0}=k\frac{V(t)}{V_0} \quad \textbf{(2.1)}$$

P_0 – initial absolute pressure

V_0 – chamber volume

k – Correlation factor related to the difference in compressibility between burned and unburned gases.

The spherical equation is:

$$\frac{V(t)}{V_0}=\left[\frac{r(t)}{r_0}\right]^3=\left[\frac{S_b t}{r_0}\right]^3 \quad \textbf{(2.2)}$$

r(t) – fireball radius

r_o – chamber radius

S_b – flame speed

$$S_b=\frac{dr(t)}{dt}=\left(\frac{\rho_u}{\rho_b}\right)S_u \quad \textbf{(2.3)}$$

ρ_u / ρ_b – density ratio of unburned to burned gases

S_u – burning velocity

Size normalized maximum rate of pressure is $K_{st.}$

$$K_{St}=\left[\frac{dP(t)}{dt}\right]_{max}V_0^{1/3}=4.84\left(\frac{P_{max}}{P_0}-1\right)P_{max}S_u \quad \textbf{(2.4)}$$

Bartknecht and Wiemann found that P_{max} increases linearly with an increase in initial pressure over the 1 – 4 bar range and K_{st} increases linearly with initial pressure [18].

Admixed inert dust concentration

Flammability curves can be created for fuel /inert dust mixtures. The flammability curve for dust is similar to gas curves and is characterized by a lower flammable limit, an upper flammable limit and a minimum inerting concentration.

Presence of flammable gases

If there is a flammable gas in dust explosabilitiy is increased. Also, if there is a gas in the dust the minimum ignition energy will be lower compared to pure dust.

3. GAS EXPLOSIONS

Industrial gas explosions are not common, but are very dangerous. These kind of explosions have a big impact on human life, industrial plants, residential areas and the environment.

A gas explosion is defined as a process wherein the combustion of a premixed cloud i.e. fuel-air or fuel- oxidizer, is causing a rapid increase of pressure [23].

On June 1st, 1974 in the Nypro plant at Flixborough one of the most dangerous explosions of the chemical industry occurred. In the explosion, 28 people were killed, 36 were injured and the plant was totally destroyed. The explosion caused serious effects outside the plant, 53 people injured, 1821 houses and 167 shops damaged. The cost of damage was over $100 mil. The reason of explosion was the release of nearly 50 tons of cyclohexane. A flammable cloud occurred and after 1 minute or so this cloud ignited and a violent explosion occurred with a blast equal to nearly 16 tons of TNT [23].

Chemical plants contain a high hazard potential. As is seen in Table 3.1 and Table 3.1 major accidents are explosions, fires and the dispersion of toxic chemicals. Vapour cloud explosions (VCE) are the most common, most destructive and dangerous. Also economic loss is high for explosions [24].

Table 3.1: Types of loss for large chemical accidents [24]

Type	Percentage
Vapour cloud explosion	%42
Fires	%35
Explosion, other	%22
Wind	%1

Table 3.2: Three types of chemical plant accidents [24]

Type	Probability of occurrence	Potential for fatalities	Potential for economic loss
Fire	High	Low	Intermediate
Explosion	High	Intermediate	High
Toxic Release	Low	High	Low

Deflagration is described as a combustion wave propagating at a subsonic velocity relative to the unburnt gas immediately ahead of the flame. Flame speed varies between 1 m/s and 500 – 1000 m/s and the explosion pressure can be a few mbar or several bar. Detonation is described as a combustion wave propagating at a supersonic velocity relative to the unburnt gas immediately ahead of the flame. For fuel –air mixtures at ambient pressure flame speed can be as large as 2000 m/s and maximum pressure can be as large as 20 bar [23].

Regarding the environment where gas explosions occur there are classifications. In some sources, gas explosions are grouped in two classes: confined or unconfined.

From another source, gas explosions are separated into three classes regarding the environment. The first class is a confined gas explosion which takes place in pipes, vessels, tunnels or channels. The second class is a partly confined gas explosion which takes place in buildings, compartments and offshore modules. The third class is an unconfined gas explosion. These kinds of explosions occur in process industry and other unconfined areas [23].

Table 3.3 Type of accidents [25]

Year	Fire	Explosion	Spill	Toxic gas Release	Misc.	Total
1960-1969	8	8	0	0	1[a]	17
1970-1979	26	5	5	0		36
1980-1989	31	16	3	2	1[a]	53
1990-1999	59	22	2	1	1[b]	85
2000-2003	21	10	8	10	2[c]	51
Subtotal	145	61	18	13	5	242

[a] Tank body distortion
[b] Personal fall
[c] 1 personnel fell and 1 personnel electrified o death.

Table 3.4: Type of tank contents [25]

Year	*Crude Oil*	*Oil Products*[a]	*Gasoline / Naphta*	*Petro-chemicals*	*LPG*[b]	*Waste oil water*	*Ammonia*	*Hydroclori cacid*	*Caustic soda*	*Molten Sulfur*	*Total*
1960-1969	6	3	0	3	3	2	0				17
1970-1979	8	7	13	3	3	2	0				36
1980-1989	17	14	17	4	1	0	0				53
1990-1999	23	19	21	11	5	4	0	1		1	85
2000-2003	12	16	6	6	1	1	3	2	3	1	51
Subtotal	66	59	55	27	15	9	3	3	3	2	242

[a] Fuel oil, diesel, kerosene, lubricants.
[b] Propane and butane included.

Generally storage tanks in industry contain flammable and hazardous materials. In Table 3.3 there is data about the type of accident in 242 tank accidents occurring in the last 40 years. As indicated, fire is the most frequent type of loss; then explosion. Fire and explosion together constitute %85 of total accidents. From Table 3.4 can be seen that storage tanks which contain LPG are in 5th place after crude oil, oil products, gasoline and petrochemicals. There are many types of causes for accidents. The most frequent is lightning, the second is maintenance error, and the others are operational errors, equipment failures, sabotage, cracks and ruptures, leaks and line ruptures, static electricity, open flames, natural disaster and runaway reactions [25].

3.1 Confined Gas Explosions

Explosions which occur in pipes, process equipment, culverts, sewage systems closed rooms and an underground installations are called confined gas explosions and also internal explosions. In this explosion the combustion process does not need to be fast to cause big problems [23].

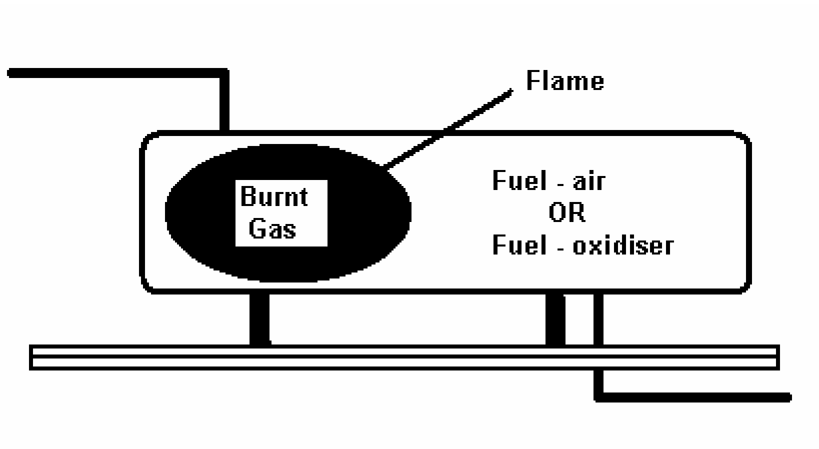

Figure 3.1: Confined Explosion within a Tank [23]

Gas explosions in vessels, pipes, channels and tunnels

In a confined explosion a gas cloud's size is the main parameter determining pressure build-up. For example, inside equipment if a big cloud is formed and then ignited the result there will be a severe explosion. In result of internal explosion will be a loss and the subsequent effect can be strong blast waves from high pressure reservoirs, fires, or toxic releases [23].

Closed Vessels

Generally, during a gas explosion, a closed vessel, to relieve pressure has a small opening like connected pipes, rupture disks or relief valves. Because the openings are small relief process is very slow and the pressure is relieved slowly and the vessel may behave as a fully closed system regarding a pressure build up. In these systems a pressure build up depends on fuel type and concentration, the initial pressure, the filling ratio, the burning rate, venting and the oxidizer [23].

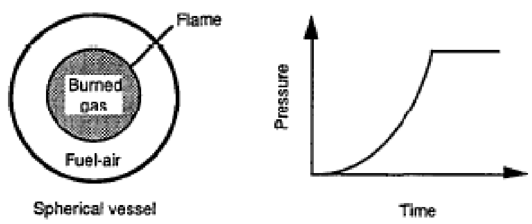

Figure 3.2 : Explosion in a Closed Vessel [23]

For a slow deflagration homogeneous gas mixture, the pressure in the vessel will gradually increase as the flame consumes the gas mixture. In Figure 3.2 the maximum pressure is easily reached when the combustion is completed [23].

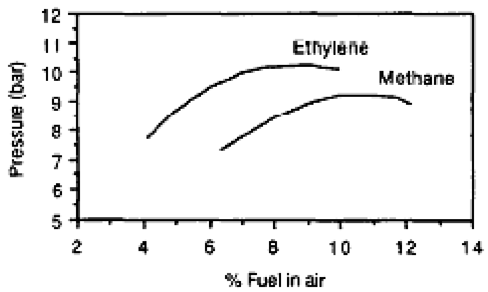

Figure 3.3 : Explosion Pressure Predicted By Stanjan for a Constant Volume Of Ethylene And Methane-Air At 1 Bar And 25 °C [23]

Figure 3.3 shows the pressure for constant volume combustion as the function of a fuel ratio of homogeneous methane and ethylene air mixtures. The highest pressure is found for slightly rich mixtures. For ethylene %6.54 and for methane %9.5 [23].

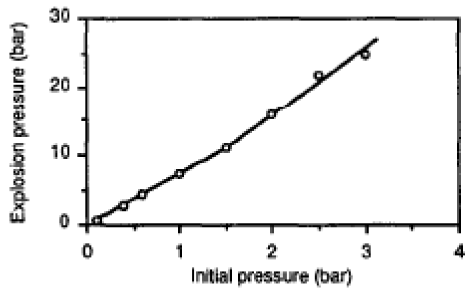

Figure 3.4 : Explosion Pressure vs. Initial Pressure For Stoichiometric Propane-Air In A 7 Vessel [23]

At a constant volume, initial pressure affects the explosion. When the initial pressure is increased, the energy content, the heat of combustion per unit volume will increase. There is a study by Bartkneck for the measurement of explosion pressure for the slow deflagration of a 7 litre spherical propane vessel. The results are shown in Figure 3.4 and as it noted that there is a nearly linear relation between initial pressure and explosion pressure [23].

Pipes

Pipes, including channels and tunnels, also have a simple geometry when confined explosions occur. In pipes, pressure generated by flame can propagate away from the combustion front.

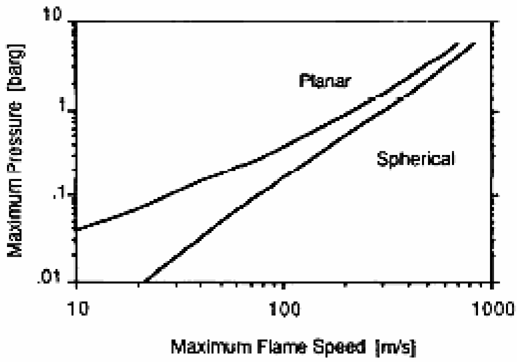

Figure 3.5 : Maximum Overpressure vs Flame Velocity For Planar And Spherical Flames [23]

In long pipes or open ended pipes a high flame speed is required to generate high explosion pressure. Figure 3.5 describe relation between flame speed and explosion pressure. In pipes, the planar case is applicable and turbulence is the main mechanism causing the flame to accelerate.

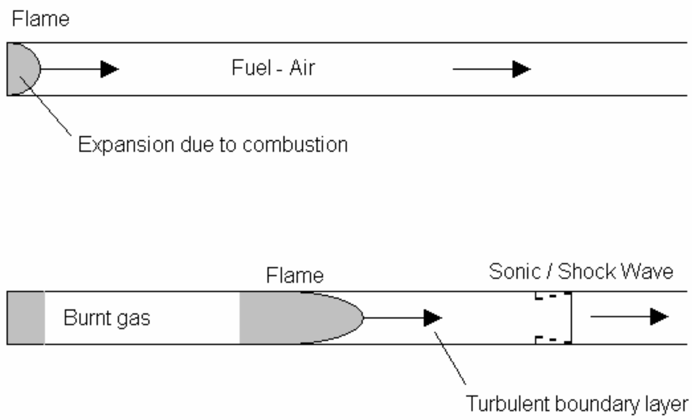

Figure 3.6 : Flame Acceleration In A Pipe, Channel Or Tunnel [23]

In Figure 3.6 shows the flame acceleration in a pipe, channel or tunnel. When the gas burnt expands and pushes the unburnt gas ahead of the flame. The flow ahead of the flame causes a turbulent boundary layer to grow and the turbulence enhances the burning rate [23].

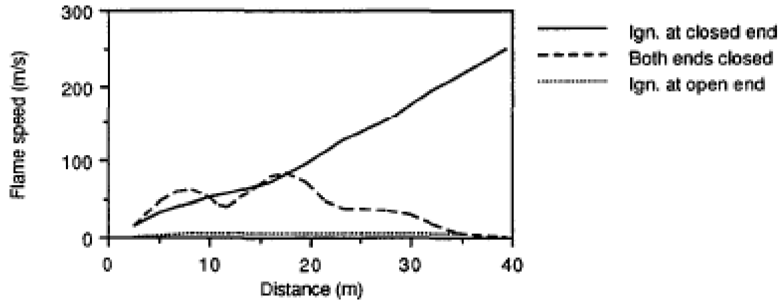

Figure 3.7 : Flame Speed in a 1.4 m Diameter Pipe With Methane-Air [23]

Bartknecht, in his study measuring flame velocities, used a 40 m long and 1.4m diameter pipe with methane –air at 1 atm while the end of the pipe was cooled and open. The results of this study are seen in Figure 3.7. The highest flame speed is observed in the case of one end being open and the gas is ignited at the other closed end. In this case, gas ahead of the flame was pushed through the pipe and a loy of turbulence was generated [23].

3.2 Partly Confined Gas Explosions

This kind of explosion occurs inside partially open buildings where fuel is accidentally released. Compressor rooms and offshore modules are good examples for partially confined gas explosions.

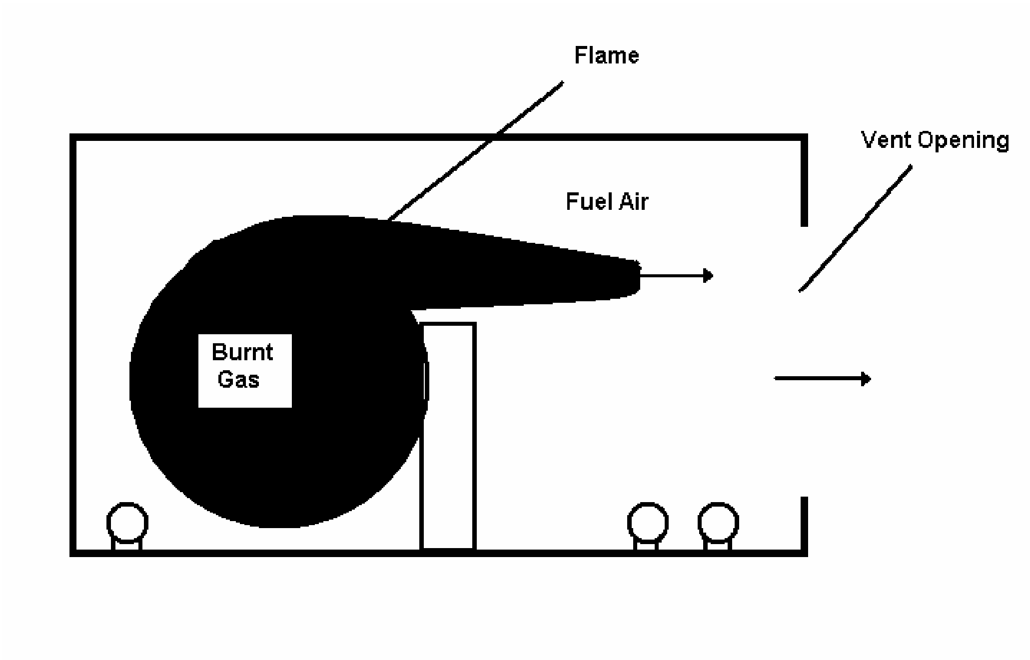

Figure 3.8: Gas Explosion in a Partially Confined Area with Process Equipment [23]

In these kinds of explosions pressure is relieved only through explosion vent areas; for example, light relief walls that open quickly at low pressure. The size and location of explosion vent areas are very significant in the resulting explosion pressure see Figure 3.8 [23].

The effects of the explosion depend on many parameters; some important parameters are fuel type, gas cloud size and concentration, ignition and geometrical layout, confinement and obstructing objects. In buildings, offshore modules and partially confined areas there exists process equipment and there are degrees of confinement and obstacles. Generally walls, roofs, floors and decks will confine the gas cloud. In partially confined gas explosions flame speed is very high. The main reason for that is the turbulent mixing caused by the generation of turbulent flow fields ahead of the flame.

A cloud is ignited in the centre of a compartment and when the flame consumes the fuel –air cloud, the gas expands at 8-9 times the initial volume. Due to this expansion, unburnt gas moves ahead of the flame and flow is generated in the compartment. Inside of the compartments there is process equipment and piping and these will obstruct the flow and generate turbulence ahead of the flame. The ignition point and vent openings are very important parameters for how flow field or turbulent flame acceleration develops during a gas explosion [23].

The shape of the compartment influences flame acceleration and pressure build-up. Generally, there are three principles to use for optimizing compartment shape. First, a flame should propagate from an ignition point in a spherical mode as long as possible. Second the ignition point should be close to main vent areas, thus hot combustion products can be vented out at the beginning of an explosion. Finally, avoid an extended flame travel distance and the turbulence in the unburnt gas ahead of the flame [23].

Types of vent area

The type of vent area is also important in gas explosions. Some of the significant factors for effective venting are the size of the vent area, how the vent areas are distributed, the direction of explosion relief, and for the explosive relief panel, how quickly it is activated.

The vent area should be as large as possible and directed into an open area with less obstruction. For example, if one compartment is venting into another or a congested area, gas clouds may be pushed into this area and will cause a violent explosion [23].

Ignition

Another important factor for partially confined explosions is location and strength of the ignition source. If the ignition is near a vent opening, the flow velocity and turbulence will be low, because combustion products will be vented.

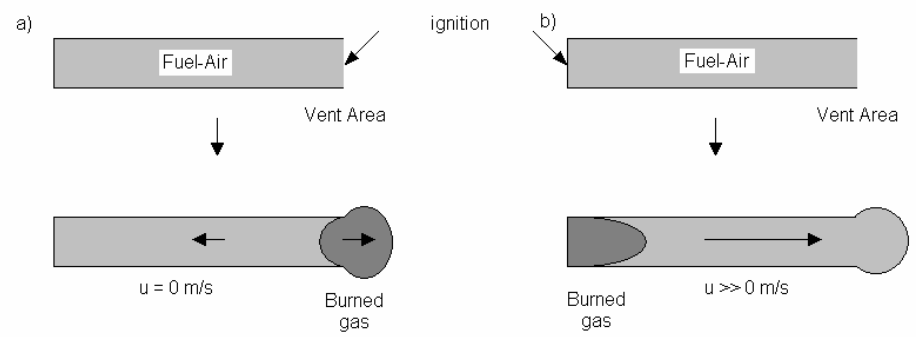

Figure 3.9 : Differently Ignition Points in a Compartaments [23]

In Figure 3.9 using the same geometry, there are two different types of ignition locations. In case a) the ignition is in open side of the compartment and the flow velocity ahead of the flame will be low. In case b) the ignition is in the closed side of the compartment and a high flow velocity will be generated ahead of the flame which will cause a violent explosion [23].

Gas cloud

When an accidental release occurs in a partially confined area, a gas cloud may fill only a part of the volume at ignition time. This filling ratio is significant to the power of the explosion. In some situations, %30- %50 filling can cause the same explosion pressure as in %100 filled compartments. The main reason for this is that during explosions, gas that burns will expand and push the unburnt gas ahead of the flame [23].

3.3 Unconfined Gas Explosions

Unconfined gas explosions are explosions which occur in open areas such as process plants.

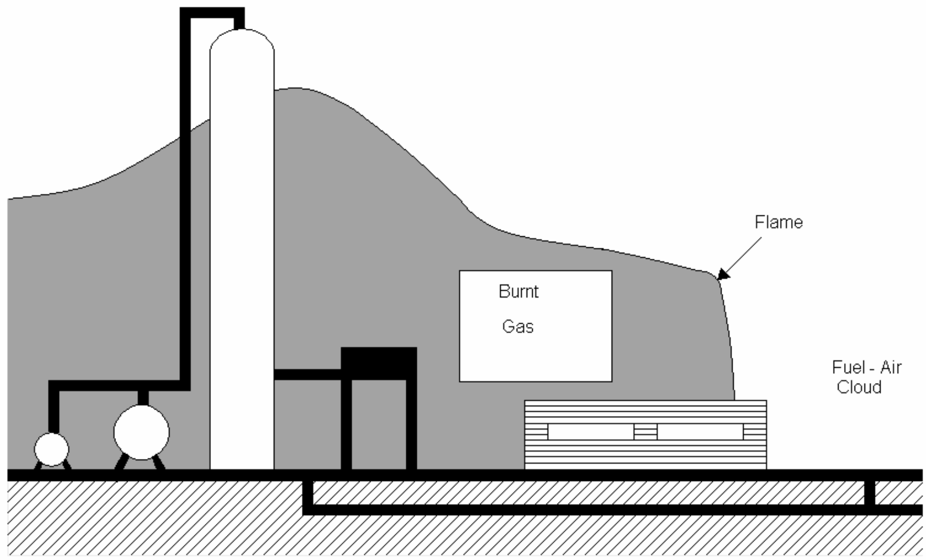

Figure 3.10 : Gas Explosion In A Process Area [23]

The density of fuel is an important parameter for the formation of a combustible cloud. If the density is lighter than the air, such as hydrogen, due to buoyancy the cloud will rise. In an open area gas will rise and be dispersed quickly. If the gas density is heavier than air it is called dense gas and dense gas will drift along the ground and will not disperse as quickly as lighter gas. A dense gas release has a higher risk for formation into a flammable cloud than does light gas [23].

Many large scale experiments show that a truly unconfined gas cloud ignited by a weak ignition source can cause a small overpressure while burning. In these cases there is no mechanism to accelerate the flame. Combustion is slow and the burned gas expands before any significant pressure can occur. In a truly unconfined deflagrating cloud the main hazard is the thermal effect. But, if the same cloud detonates due to the transition to detonation in a confined neighbouring area, it will cause a violent explosion with a strong blast wave. Generally, an open process area may be very congested. During an explosion pipes, process equipment, tanks and other obstacles will contribute to turbulence generation. The experimental results show that a spherical gas explosion in a much obstructed area needs only a few meters of flame travel before the explosion pressure reaches levels that cause violent damage [23].

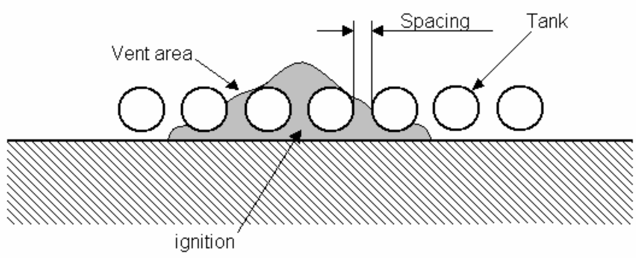

Figure 3.11 : Side View Of A Row Of Tanks [23]

Tanks and process equipment should not be located too close to each other. In Figure 3.11 there is a row of tanks. If an explosion occurs, the flame will propagate under the tanks and will accelerate the flame [23].

There is no essential difference between a vapour cloud explosion and a partly confined or an unconfined gas explosion.

3.4 BLEVEs

BLEVE is an acronym for a Boiling Liquid Expanding Vapour Explosion. After the Flixborough accident in 1974 much attention was focused on vapour cloud explosions until Kletz point out that BLEVEs should not be neglected being as dangerous as VCE and causing as much as damage as VCEs can. Really, one of the biggest accidents in the chemical process industry occurred in the LPG plant in Mexico City in 1984 where over 650 people died. The Centre of Chemical Process Safety defined BLEVE as “a sudden release of a large mass of pressurized superheated liquid to the atmosphere” [26].

Generally, there are 5 steps which are involved in a BLEVE. The first step is a vessel containing pressurized liquid gas (PLG) receives a heat load or fails due to a missile hit, fatigue, or corrosion; the second step is the vessel fails; in the third step there is an instantaneous depressurization and explosion, and in the fourth step the vessel is shattered. In the final step there is a fireball or toxic dispersion [26].

On January 4th 1966 at Feyzin in France leakage from a propane storage tank caused a big accident. Propane leaking from 1200 m^3 spherical tank formed a vapour cloud which spread for 150 m and was ignited 25 minutes after the leakage started by an automobile stopped on a nearby road. After the fire started, 19 minutes later the sphere went through BLEVE. Ten of 12 firemen within 50 m were killed. Another man which was 140 m away was badly burned. In total 15 -18 men were killed and about 80 injured [26].

On November 19th 1984 at The Pemex LPG terminal in San Juan Ixhuatepec Mexico City, 4 LPG spheres, each containing 1500 m^3 of LPG, and several cylindrical tanks suffered from BLEVE. Fragments of tanks and pipes, some of which weighed 40 tons were blown into the air and found 1200 meters away. The Pemex terminal was destroyed. In the accident 650 deaths and more than 6400 people injured. Damage was estimated at nearly 31 million dollars [26].

Table 3.5 Frequency of causative events [26]

Fire	%36
Mechanical Damage	%22
Overfilling	%20
Runaway reactions	%12
Overheating	%6
Vapour space contamination	%2
Mechanical failure	%2

In BLEVE the diameter of the fireball and its thermal radiation level is very important. There is much software which predicts thermal radiation levels and fireball diameters. For example, to illustrate an off-site emergency plan for a BLEVE scenario in a LPG bottling plant the diameter of the fireball in a BLEVE event is calculated by CHARM (Complex Hazardous Air Release Model) software [27].

For the estimation of the peak overpressure caused by BLEVE or a similar explosion a new method is proposed. In this method superheating energy is used which is the difference between the specific enthalpy of the liquid at the temperature before explosion and the specific enthalpy of the liquid at its saturation temperature at atmospheric pressure. According to this analysis, energy which is converted to overpressure will range between 3.5 and 14 % of superheating energy [28].

3.5 Vapour Cloud Dispersion Models

3.5.1 Dense gas dispersion

Dense gas dispersion occurs when a material has a greater molecular weight than air or when it is colder than air and has a greater density. Examples of gases with a molecular weight greater than air are; LPG, cyclohexane, freon and chlorine [29].

When a chemical compound is released as a cold gas, or cooled due to the evaporation process we may see LNG, ammonia or hydrogen fluoride.

Dispersion behavior can be determined by failure type. There are mainly three types. The first type is instantaneous release, where the volume of gas is released in a very short time. Ruptured vessels or rapidly emptying pressurized tanks are examples of an instantaneous source. The second type is the time-varying release. In this type, volume flows a long period in an irregular way. A liquid pool which is both spreading and vaporizing is a good example. The third type is continuous release. In a continuous release there is a constant volume flow rate taking a long time to reach steady-state. Steady-state liquid pools and small ruptures in pipes and vessels are examples of continuous release [29].

In the dispersion process of a dense gas cloud 4 phases are observed: the initial phase, the gravity spreading phase, an intermediate phase and the passive dispersion phase [29].

The gravity spreading phase best fits the effects of a typical dense gas:
Turbulence within the cloud is minimized due to the stable stratification of the dense gas layer. The density gradient suppresses mixing by the atmospheric turbulence at the top of the cloud. Gravity spreading in the horizontal direction is minimized by the density gradient [29].

Dense gas dispersion models can mainly be divided into three categories.
phenomenological models, intermediate models and advanced models that solve Navier-Stokes equations. Only the models which solve three dimensional Navier-Stokes equations describe the internal flow in the cloud [29].

3.5.1.1 Simple dense gas dispersion models

Simple dense gas dispersion models describe over all behavior of a cloud. The models for instantaneous release are called box models; models for continuous release are called grounded plume models. There is a basic assumption for both models, namely that as dispersion moves over flat terrain or water, the substrate properties are uniform over the terrain; similarities velocity and concentration profiles are imposed in all direction of cloud, local concentration fluctuations are not modelled, and spreading of the cloud is described by gravity intrusion models [29].

3.5.1.2 Box models

Box models have been developed for the description of the instantaneous release of dense gases. Some studies and computer models are: Study of Cox and Carpenter, and computer models CONSEQ, SAFETI and PHAST, Study of Eidsvik and computer model CHARM , Study of Fryer and Kaiser and computer model DENZ, study of Kaiser and Walker and computer models SAFER and TRACE [29].

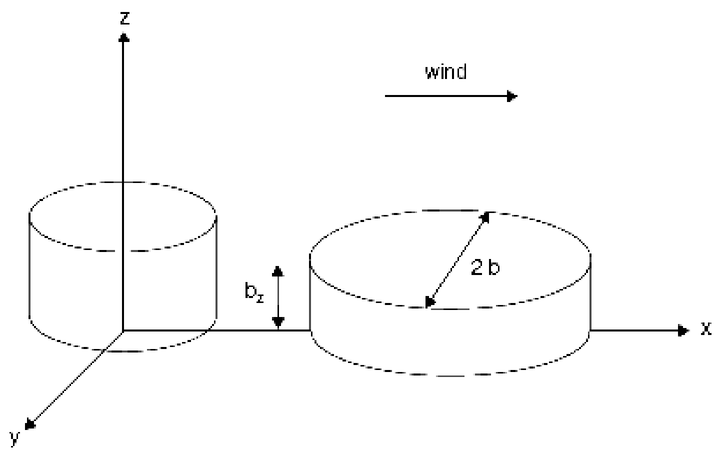

Figure 3.12 : The Box Model Of A Gas Cloud [29].

All box models assume that a dense cloud has the shape of a flat circular cylinder with a uniform radius and height and a uniform gas concentration in the cloud volume see Figure 3.12.

Mean concentration of the cloud is determined by solving the ODE for time dependent volume, radius and position of the cloud [29].

The equation for V (t) is:

$$dV / dt = \pi r^2 w_{e,t} + 2\pi . r . b_z w_{e,e} \qquad (m^3 s^{-1}) \qquad \textbf{(3.1)}$$

b_z : Height of the cloud

$w_{e,t}$: Entrainment velocities at the upper surface and edge of the cloud.

The equation for r(t) is:

$$dr / dt = C\sqrt{(g' b_z)} \qquad (ms^{-1}) \qquad \textbf{(3.2)}$$

C : constant

g' : effective gravity

This equation is also called a gravity front equation. It describes gravity slumping in the initial dispersion phase.

The mean concentration in the cloud is calculated as a function of down-wind distance x as in equation:

$$c(x) / c_o = v_0 / v_{(x)} \qquad \textbf{(3.3)}$$

c: mean concentration

c_0: Initial concentration of chemical compound

v_0 : released volume

This equation is valid for cases in which there is no heat exchange between the cloud and its environment or there is no internally generated heat or chemical conversion. In most of the present box models these internal heats are included [29].

3.5.1.3 Grounded plume models

Grounded plume models have been developed for describing the continuous release of a dense gas. If the time variable is replaced with down-wind distance, the source plumes from a continuous source can be developed in a similar way to box models. For example see the study of Jagger. Developed computer models are CRUNCH, PHAST, and DRIFT [29].

In a grounded plume model it is assumed that the plume has rectangular cross – section.

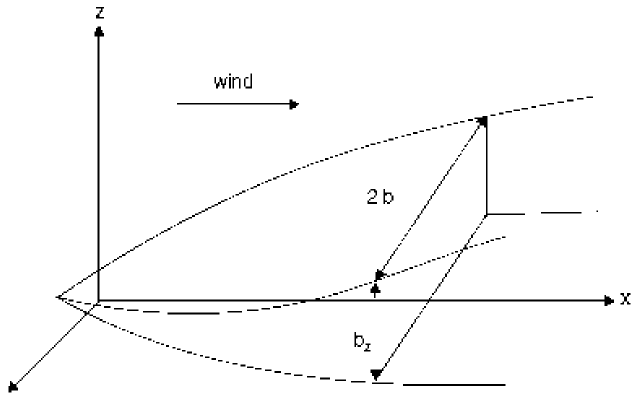

Figure 3.13 : The Grounded Plume Model Of A Continuous Dense Gas Plume [29]

$b_z(x)$: height

$b(x)$: half width

Concentration (c) of gas and the advection velocity (u) are uniform over the entire area of the cross-section (A(x)).

The equation for the increase of total mass is:

$$d(\rho.u.A)/d_x = 2\rho_a b\, w_{e,t} + 2\rho_a b_z\, w_{e,e} \qquad (kg\, m^{-1} s^{-1}) \qquad \textbf{(3.4)}$$

ρ **a**nd ρ_a are, respectively, the densities of the plume gas and of the ambient air. $w_{e,t}$ and $w_{e,e}$ are entrainment velocities at the upper surface and at the edge of he plume.

There are similarities between the box model and the plume model, and if it is assumed that there are the same closure relations for entrainment, a plume model equivalent can be built for each box model. The equation for b(x) is:

$$u.db/dx = C\sqrt{(g' b_z)} \qquad (ms^{-1}) \qquad \textbf{(3.5)}$$

C : constant

g' : Effective gravity

In the steady state plume model gravitational slumping and mixing in longitudinal direction is neglected.

There is another technique whereby steady release divides total release into many puffs and each is considered as a separate release. This technique is used in computer model CHARM [29].

3.5.1.4 Generalised plume models

Generalized plume models give many spatial variations to the dense gas concentration other than assuming only a rectangular or Gaussian profile. In these models, the process can be modelled more realisticly. A good example for this is the Colenbrander model where similar concentration profiles present plumes as a horizontally homogeneous centre section with Gaussian concentration profile edges [29].

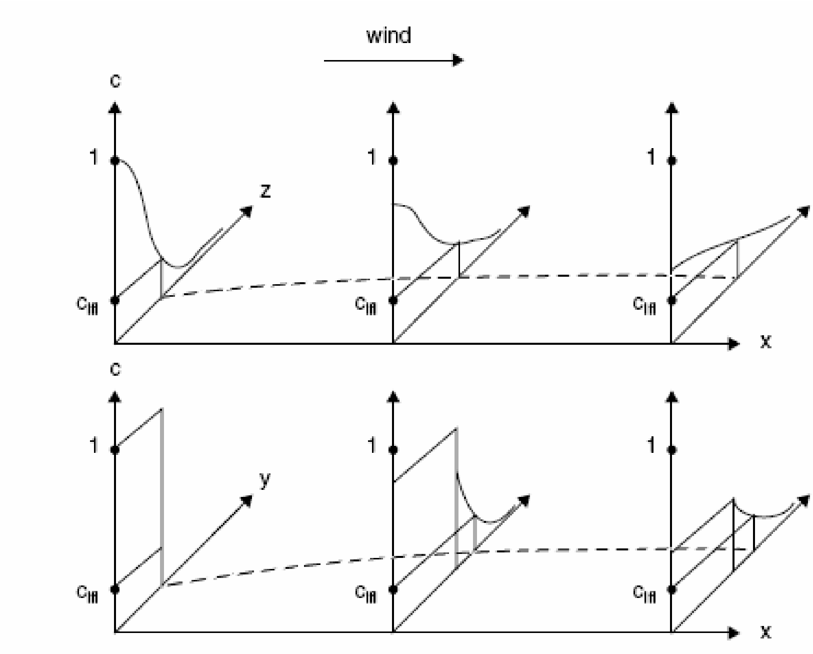

Figure 3.14 : The Down-Wind Development Of The Concentration Profiles In Vertical And Lateral Direction, In A Generalized Plume Model [29].

In formula:

$$\begin{aligned}
&c(x,y,z) = c_c(x)\,F_Y(y)\,F_z(z), && (kg\,m^{-3})\\
&F_y(y) = && for|y| \le b,\\
&F_y(y) = \exp(-(|y| - b(x))^2/\sigma_y(x)^2) && for|y| > b,\\
&F_z(z) = \exp(-z/\sigma_Z(x))^2)
\end{aligned} \qquad \textbf{(3.6)}$$

The model is formulated by eddy-diffusivities and it is solved in the vertical and lateral direction. The Colenbrander model has been implemented in computer models HEGADAS and DEGADIS [29].

If the volume flow rate varies with time, this will affect the concentration level in the plume. Colenbrander proposed a concept for these kinds of releases [29].
The actual concentration is determined from a Gaussian integration with respect to the down-wind distance of all observed concentrations. The Gaussian integration involves longitudinal diffusion by means of a down-wind dispersion coefficient which is often used as.

$$\sigma_x(x) = 0.13x \qquad \textbf{(3.7)}$$

The equation is:

$$c_c(x,t) = \int c_c(u_a t)/(\sqrt{(2\pi)}.\sigma_x(u_a t))\exp(-0.5(x-u_a t)^2/\sigma_x(u_a t)^2)du_a t \qquad \textbf{(3.8)}$$

3.5.1.5 The conservation equations for a dense gas release

Navier-Stokes equations for instantaneous velocity and density describe the full release of a dense gas. These equations express the conservation of total mass, the concentration of components and enthalpy, and a 3 vector equation of motion. Navier-Stokes equations are partial differential equations [29].

The shallow layer theory is a 3- dimensional approach and is based on a set of conservation equations. The advantage of this theory is the simple structure of dense gas clouds in cross-wind planes. Zeman has developed the formalism for the dispersion of a dense gas release in the presence of wind in a 1-dimensional shallow layer model. A computer model based on formalism is the SLAB model [29].

3.5.1.6 The shallow layer plume model

The physical quantity fields in a plume are dependent only on down wind distance, x, and these are averaged in a cross-wind direction. In shallow plume layer models, conservation equations are equivalent to the equations for a 1-dimensional integral model with an additional term. Shallow layer equations can be used for lofted plumes in the region [29].

3.5.1.7. The shallow layer cloud model

Zeman's shallow layer model treats puff as a grounded cloud with a half length, half-width and a height. In this model, physical quantity fields in the cloud are averaged over the cloud volume. The shallow layer cloud model can be used for releases above ground level [29].

3.5.2 Passive dispersion

Passive dispersion is solely caused by atmospheric turbulence. From the stability of the atmosphere and the height above the surface atmospheric turbulence is determined.

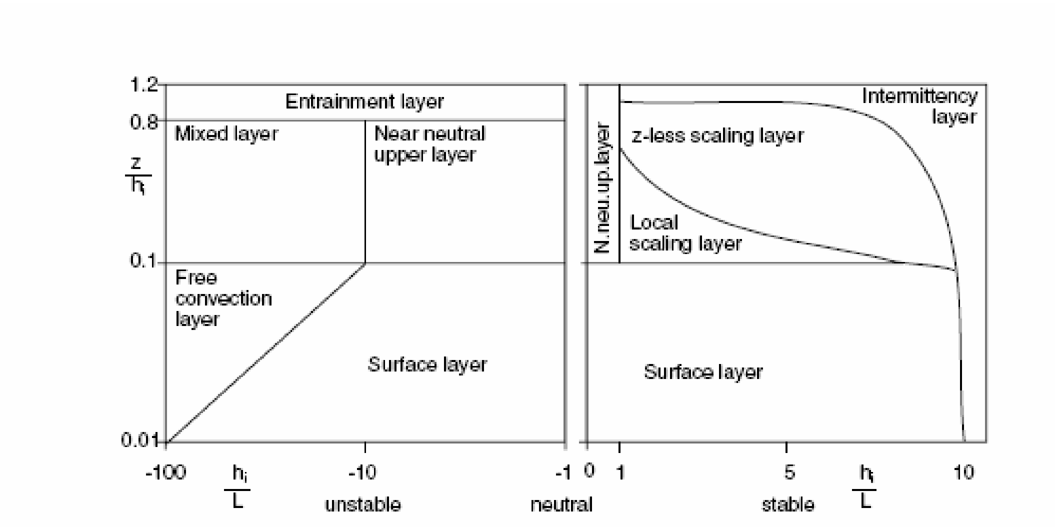

Figure 3.15: The Scaling Region of the Atmospheric Boundary Layer [29].

In figure 3.15 scaling region are defined by Gryning.

Gaussian plume models have been used for all regions on Figure 3.5

For continuous releases the basic equation of the Gaussian plume model is:

$$c(x,y,z)=\frac{q}{2\pi.u_a\sigma_y\sigma_z}\cdot\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\cdot\exp\left(-\frac{(h-z)^2}{2\sigma_y^2}\right) \qquad (kgm^{-3}) \qquad \textbf{(3.9)}$$

For instantaneous release equations is written as:

$$c(x,y,z,t)=\frac{Q}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\cdot\exp\left(-\frac{(x-u_a.t)^2}{2\sigma_x^2}\right)\cdot\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\cdot\exp\left(-\frac{(h-z)^2}{2\sigma_z^2}\right)$$

$$(k.g.m^{-3}) \qquad \textbf{(3.10)}$$

$c(x, y, z)$:concentration at x, y, z position

Q : total released mass

q : release rate

u_{a} : ambient velocity at which plume/puff is advected by wind

σ_x , σ_y, σ_z – dispersion parameters in along end, cross-wind and vertical direction.

h – Height of plume centre-line

The choice of the plume for averaging transport velocity and dispersion parameters is very important.

Generally, transport velocity is taken as wind speed at plume fifth, with a minimum of h surface releases. There are many approaches for dispersion parameters, fundamentals are discussed in Pasquill and Smith. The Gaussian plume model can not be applied to passive dispersion in the surface layer, due to the vertical variations of wind speed and the turbulence intensity in the surface layer [29].

3.5.3 Jet and plume rise (modelling of turbulent jet and plumes)

A pure jet is defined as the source of momentum and energy in the atmospheric environment. There are positively and negatively buoyant jet releases. When the inertial force and buoyancy force are in the same direction it is called a positive buoyant release; when the two force act in opposite directions, it is called negative buoyant release. Some examples for buoyant jet releases are exhaust, safety valves, punctures in pipes and vent stacks. All positively buoyant jets become a plume. The pure plume can emerge from a source without initial momentum. For example, cooling towers, chimneys, burners, and pool fires.

The below assumptions are made to simplify jet analysis:

- The release of the chemical material consists of a turbulent outflow of gases.
- The source is axially symmetric with uniform outflow.
- Buoyancy can be neglected or is parallel to the inertial forces.

Analysis is valid only if there is no large density difference between the jet and the surrounding atmosphere. This is called a Boussinesq approximation. Compressibility effects are neglected. The atmospheric environment consists stable air in ambient conditions. There is no wall or any obstacle [29].

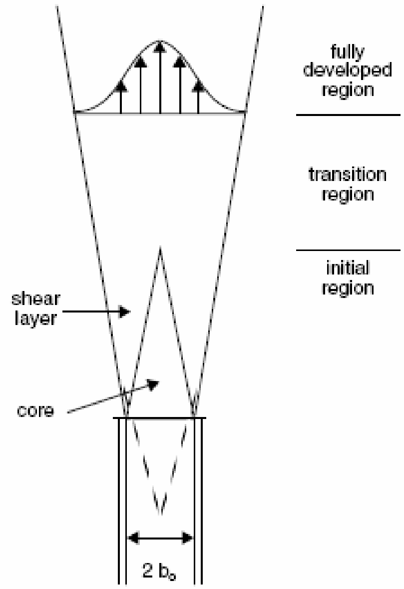

Figure 3.16 : The Development Of A Turbulent Jet In Still Air [24]

A turbulent jet or plume consist of 3 regions, the first region is the initial region which consists of the main flow and a surrounding shear layer; the second region is a transition region, and the third, a fully developed jet in Figure 3.16.

3.5.3.1 Non-buoyant jets

Mass flow q(s) in the jet increase with axial distance

$$dq / ds = 2\pi.b.\rho_a.w_e \qquad (k.g.m^{-1}) \qquad \textbf{(3.11)}$$

b – Radius between the jet-centre line and the boundary surface of the jet

ρ_a – Ambient density

w_e – Entrainment velocity

3.5.3.2 Buoyant jets

In buoyant jets there is a buoyancy flux factor F_0, of the chemical material and ambient air appear as a third parameter different from non-buoyant jets. There is no dynamic similarity for buoyant jets, so it is not possible to derive simple relations for flow quantity as in non-buoyant jets [29].

3.5.3.3 Pure plume

A plume is a buoyant jet whose initial momentum is a nearly zero. It is assumed that plume weighs less per unit volume than air and the molecular diffusion is negligible compared with turbulent transport.

Flow quantity can be estimated by a dimensional analysis which begins with the definition of the Froude number [29].

$$F_r = \frac{\rho_0}{|\rho_a - \rho_0|} \cdot \frac{u_0^2}{2b_0 g} \tag{3.12}$$

u_o – exit velocity from source

b_o – radius of real axial jet source

ρ_o – material density

ρ_a – ambient density

3.5.3.4 Jets and plume in a cross wind

The release of a gas is generally deflected by the ambient wind and it is called a jet in a cross-wind. The release of a chemical in the jet can be calculated with models which incorporate the full set of conservation equations for all related elements. There are two modifications of assumption for jet and plume rise [29].

Atmosphere is not quiescent and the Boussinesq approximation is not used. In this type the wind imposes a pressure field on the jet. And after some distance, the jet movement is approximately horizontal, with mean velocity approaches the wind's velocity as seen in Figure 3.17.

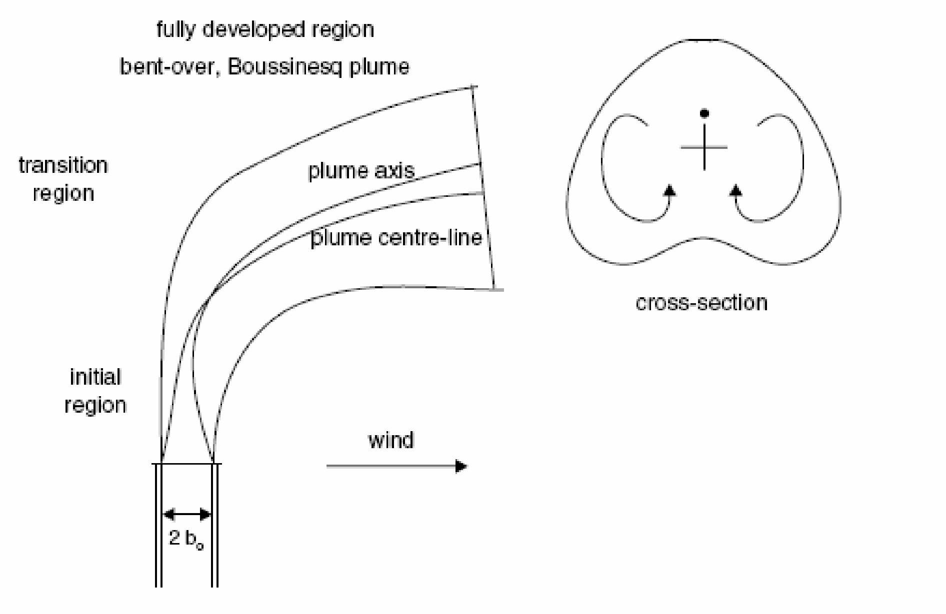

Figure 3.17 : The Plume Trajectory In A Cross-Flow [29]

One-dimensional integral trajectory models:

Integral models are based on a simple profile shape for velocity, temperature and density distribution in the jet cross-section. Mass, momentum, energy and chemical compound conservation equations can be integrated over the jet cross-section to get ordinary differential equations of some velocity and density characteristics. Further assumptions about the entrainment of air into the jet should be adapted to the slody system of equations.

The integral equations are of the form [29]:

$$\frac{d}{ds}\left[\int_{0}^{\sqrt{2b}} \rho.u.\phi.2\pi y.dy\right] = 2\pi b.\rho_a \phi_a w_e(s) + f(s) \qquad (\phi.k.gm^{-1}s^{-1}) \quad \textbf{(3.13)}$$

s : axial coordinate of the jet or plume

y : radial coordinate

ρ : density

u : flow velocity in the jet

b : width parameter of jet

ρ_a – density of ambient air

According to the differences in the assumption of integral trajectory models there are differences implemented in the four dense gas dispersion models: DEGADIS, HGYSYSTEM, PHAST and SLAB. The four implemented plume models are;

Ooms model, HFPLUME model, TECJET model, Model of Hoot, Meroney and Peterka [29].

3.6 Gas Explosion Modeling

The effects of a gas explosion depend on many factors, for example maximum pressure, duration of shock wave interaction with buildings and equipment. Also these factors depend on many variables such as fuel type, stociometry of the fuel, ignition source type, confinement and venting, initial turbulence level in the plant, blockage ratios, size, shape, number and location of obstacles and scale of the experiment [30].

The reactivity of a fuel has a big effect on the generation of overpressure. For example methane is the least reactive gas, while acetylene and hydrogen cause very high pressure. Another important issue is the stociometry of a gas cloud. A rich mixture produces a higher overpressure than a lean mixture. Ignition sources play an important role in generated overpressure. Jet type ignition sources cause higher over-pressure than point sources [30].

Venting is one of the ways to reduce over-pressure. Over pressure of explosions in a turbulent environment is greater than in a stagnant environment. The blockage ratio describes plant congestion. Generally, explosions in a plant with a high blockage ratio generate higher over-pressure according to a lower blockage ratio. Size, location and shape play an important role in over-pressure [30].

The scale of an experiment is important. Large scale experiments make higher over-pressure than small scale experiments. This is why it is difficult to predict the effects of an explosion in a real plant in a small scale experiment. A good model should include: all variable effects of gas explosions containing the appropriate physics and can be suitable for different kinds of gases under different types of conditions.

If a model is implemented is computer code, the model should be numerically accurate, user friendly, the run time should be short and the model should be applied accurately to different geometries.

There are many requirements: in some of them there is an inconsistency. Many complex models, for example, run slowly. Also, there are some computer hardware limitations, such as processor speed and memory. Many of the CFD codes don't allow for flame front tracking [30].

Although all models have some limitations, generally, the results of the simulations are compatible with experiments. The selection of the model depends on its accuracy level, detail level and running time.

There are many different methods to model gas explosions. Some of them are simple with short calculations, some of them are complex. Gas explosion models are divided into 4 classes [30].

3.6.1 Empirical models

These models are obtained from experimental data.

3.6.1.1 TNT equivalency method

The TNT method is simple and widely used. It assumes that a gas explosion can be related to a equivalent TNT explosion. The available combustion energy in a vapour cloud is converted into an equivalent charge weight of TNT according to:

$$Q_{TNT} = a_e x \frac{Q_f x.E_{mf}}{E_{mTNT}} = a_m x Q_f \qquad \text{(kg)} \qquad \mathbf{(3.14)}$$

α_e	=	TNT equivalency based on energy	[-]
α_m	=	TNT equivalency based on mass	[-]
E_{mf}	=	Combustion energy of fuel per unit mass	[J-kg^{-1}]
E_{mTNT}	=	TNT blast energy per unit mass	[J-kg^{-1}]
Q_f	=	Mass of fuel involved	[kg]
Q_{TNT}	=	Equivalent mass of TNT	[kg]

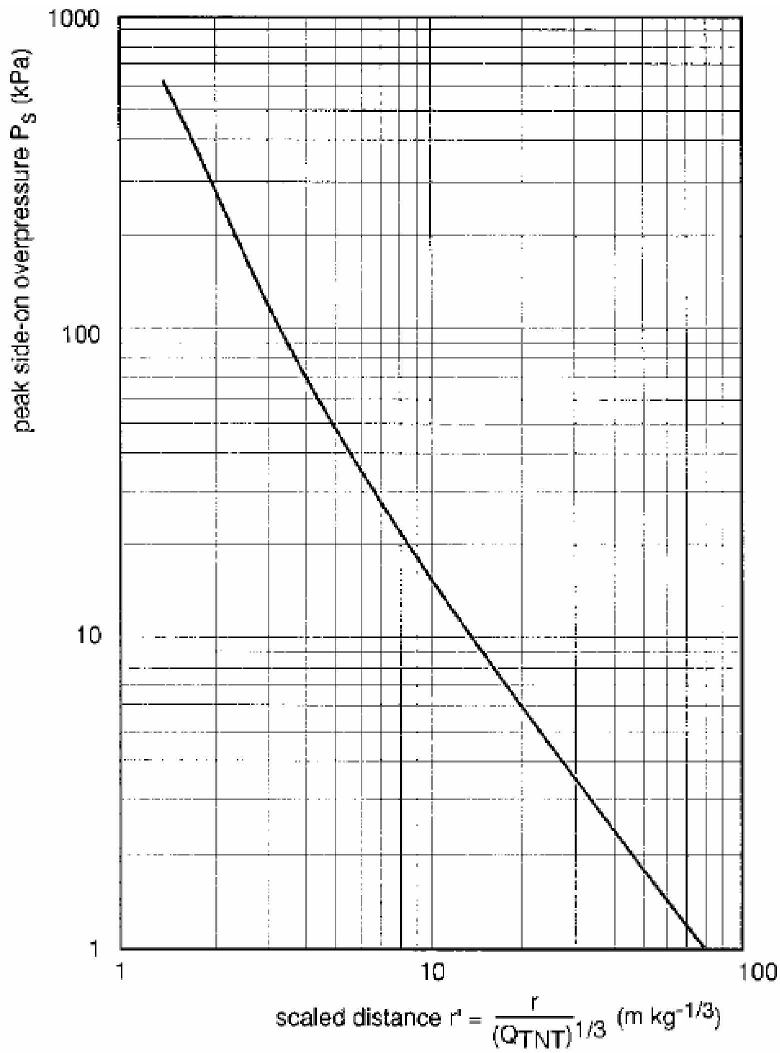

Figure 3.18 : Peakside-on Overpressure Due To A Surface TNT Explosion According to Marshall [29].

Value of E_{mTNT} is used in a range of 4.19 - 4.65 MJ/kg. In the literature, TNT equivalency also indicates as the equivalency factor, yield factor, efficiency factor or efficiency [29].

If the TNT-charge weight is known from the graph blast, characteristics in terms of the peak side overpressure can be read. TNT equivalency factors have to be use with a particular method to find the amount of fuel involved and in relation to specific TNT blast charts. All TNT-equivalence factors are based on energy. Brasie and Simpson and Brasie recommended TNT equivalency of %2 for near-field and %5 for far-field effects. Eichler and Nspsdensky recommended %20 for the 6.9 kPa overpressure level only.

The Health Safety Executive recommended a value of %3 for gases with average reactivity such as methane, % 6 for above average gases such as propane oxide and % 10 for very reactive gases such as ethane oxide. The maximum overpressure in the cloud is taken as 100 kPa and the duration of the blast should be between 100 and 300ms. Exxon recommended TNT- equivalencies of %3 for a vapour cloud covering open terrain and %10 for a vapour cloud in a partially confined or obstructed area. Industrial Risk Insurers IRI uses a TNT-equivalence factor of %2. Factory Mutual Research factors are assigned to three classes: low-reactive %5, average-reactive %10, and high-reactive %15. CPR-14E uses a TNT equivalency factor of %10. The British Gas method is intended for a non-detonating cloud of natural gas. Their method is based on the mass of the material which can be contained in stochiometric proportions in any severely congested region within a limited area. A TNT equivalency factor of %20 is used for the total congested mass. Direction des etudes et Recherches, France refers to a statistical analysis of 120 damage points of 23 accidents which show a wide distribution of TNT equivalencies (%0.02 – %15.9) In %97 of all cases the TNT equivalency is lower or equal to %10 while the mean value observed was %4 covering %60 of the cases. French Authority Safety Rule recommends % 10 for safety factors and the French Chemical Industry recommends the % 4 equivalency; both are based on the full amount of released fuel [29].

The weakness points of this model are:

- A Non-specific ratio is necessary
- The weak gas explosion representation is not good
- It is very difficult to define an accurate charge centre
- If the physical behaviour of a gas explosion differs from a solid explosion, this model can not be used for modelling a gas explosion.
- Information applies only to the positive phase duration [30].

3.6.1.2 TNO method

This method is developed by the Netherlands Organization for Applied Scientific Research, known as TNO. This model is similar to the Multi-Energy method; the main difference is that the TNO method assumes that the whole vapour cloud contributes to the over-pressure; Multi-energy deals with only the portion which happens to be in a confined and/or congested area. The TNO model was used in the handbook of methods for the calculation of the physical effects of the escape of dangerous materials CPR14E. In the revised version of the CPR14E handbook the TNO model was replaced with the Multi-Energy method [30].

3.6.1.3 Multi-energy concept

The multi-energy concept assumes that only a confined or obstructed part of the gas cloud will contribute to the blast. Unconfined vapour clouds can give rise to a small over-pressure if ignited. The over-pressure increases with the increase of confinement. The method is based on numerical simulations of a blast wave from a centrally ignited spherical cloud with constant velocity flames [29].

The blast parameters are read from blast charts, see Figure 3.19

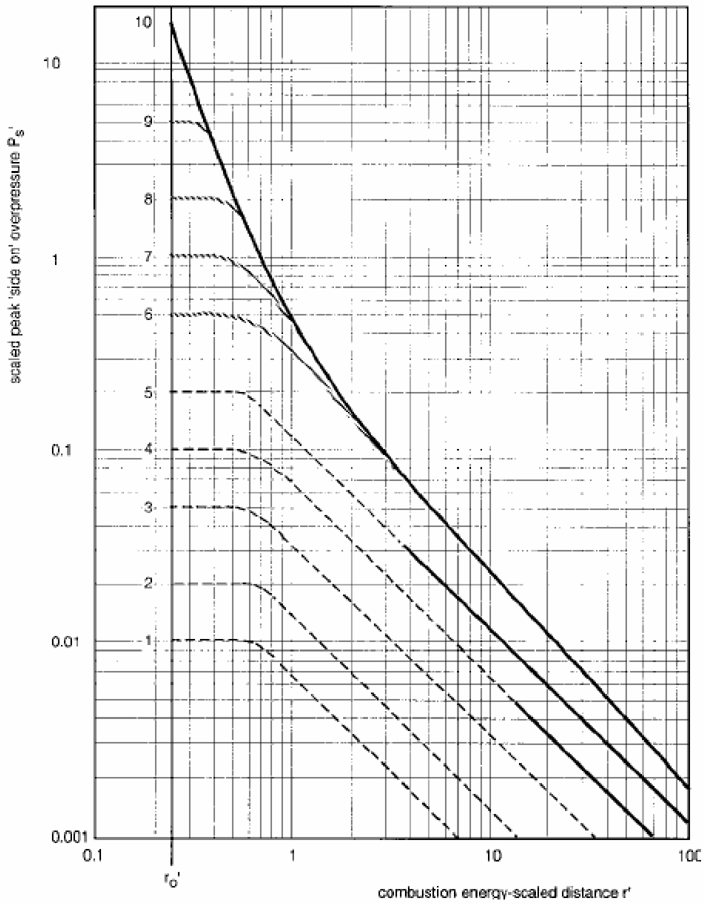

Figure 3.19 : Multi-Energy Method Blast Chart: Peak Side-On Overpressure [29]

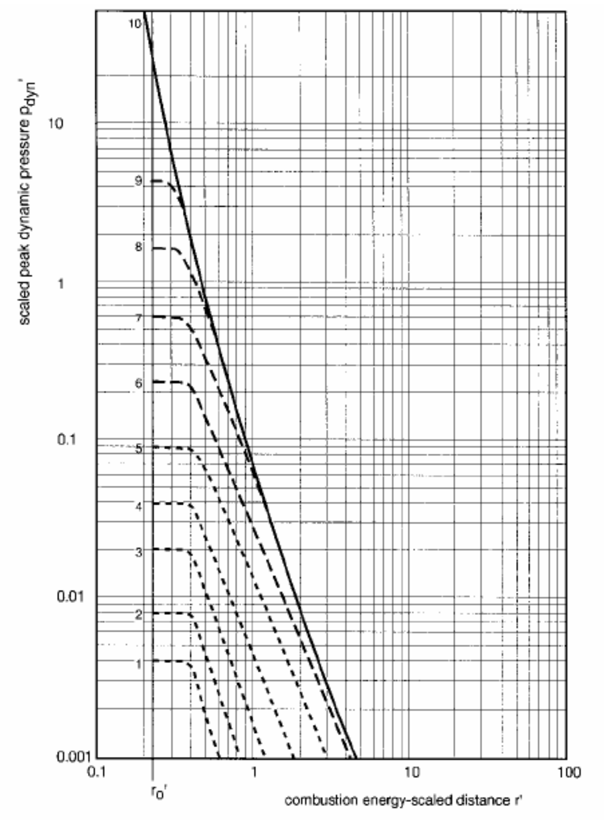

Figure 3.20 : Multi-Energy Method Blast Chart Peak Dynamic Pressure [29].

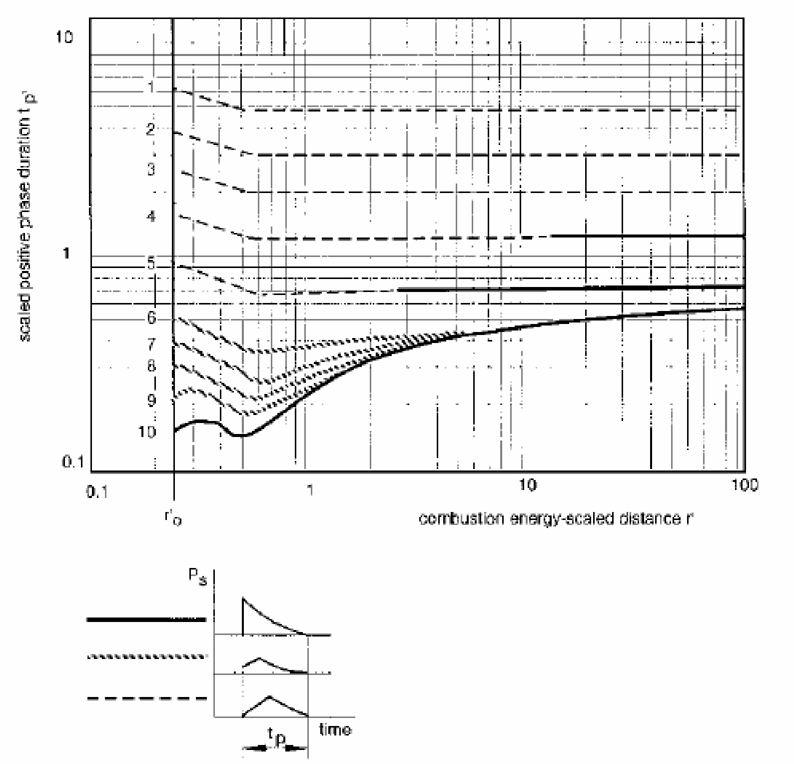

Figure 3.21 : Multi-Energy Method Blast Chart: Positive Phase Duration And Blast-Wave Shape [29]

Equation for scaled distance r' is:

$$r' = r/(E/p_a)^{1/3} \qquad \textbf{(3.15)}$$

r - Distance to explosion centre

E – Total energy

p_a – ambient pressure

Assuming an explosion strength (of class 1 to 10) and by reading the chart from side to side, over pressure P'_s, scaled peak dynamic pressure p_{dyn}, and the scaled positive phase duration can be determined.

Peak over-pressure is P_s

$P_s = P'_s \times p_a$

Positive phase duration is t_p

Calculate the positive phase duration t_p from:

$$t_p = t'_p x(E/p_a)^{1/3}/a_a \qquad \text{(s)} \qquad \textbf{(3.16)}$$

Calculate the peak dynamic pressure p_{dyn} from:

$$P_{dyn} = P'_{dyn} \times P_a \qquad \text{(Pa)} \qquad \textbf{(3.17)}$$

Determine the shape of the blast-wave from Figure 3.21.

Calculate the positive impulse i_s by integrating the overpressure variation during the positive phase resulting in multiplying the side-on overpressure with the positive phase duration and with a factor of 1/2 [29]:

$$i_s = 1/2 \times P_s \times t_P \qquad \text{(Pa.s)} \qquad \textbf{(3.18)}$$

Strength points of this model are;

- Quick calculation
- Conservative approximation can be made [30].

Weakness points of this model are;

- Difficult to set a sensible value for charge strength, total combustion energy and charge size
- Not well suited for a weak explosion
- It is not clear how to apply it to several congested regions and multiple blast waves.
- Difficult to represent complex geometries [30].

3.6.1.4 Baker-strehlow method

This method was developed by Baker, Tang Schiere and Silva for the estimation of blast pressures from vapour cloud explosions. Later this model was extended by Baker, Doolitle, Fitsgerald and Tang. In this model there are number of steps, assessing flame speed, fuel reactivity, confinement. In theBaker-Strehlow Method blast pressure and impulse are read from graphs [30].
In the revision results were obtained from experience by Baker et all.

Strength points of this model are;

- Quick calculation
- Easy to use
- Includes some geometric detail regarding confinement
- Deal with Multi ignition points [30].

Weakness point of this model is;

- Could be over conservative [30].

3.6.1.5 Congestion assessment method

This model was developed at the Shell Thronton Research Centre by Cates and Samuels. Later, this model was extended by Puttock. In this model, Cates and Samuels designed a decision tree procedure for estimating source pressure by taking into consideration the layout of plant, confinement, congestion and type of fuel. This method was designed to get a conservative pressure measurement [30].

The Congestion Assessment Method consists of three steps;
By the assessment of the congested region reference pressure is assigned P_{ref}. This pressure is calculated by a maximum over-pressure deflagration of a VCE of propane. Fuel factor is used to take account of fuel type. This factor is multiplied by the reference pressure to calculate the maximum source pressure. And, it is possible to calculate pressure at different distances from the ignition point. Cates and Samuels assume [30].

Puttock extended the model after the result of the MERGE (Modelling and Experimental Research into Gas Explosions) project was published.

The congestion assessment model is the most advanced empirical model in the report of the HSL. But it is not known how the model will react for new scenarios for which the model has not been calibrated.

In this program the user must assess the level of congestion and confinement. If the geometry is minimal and simple it is easy, but, generally, many plants are very complex in design. Although there are guidelines on how to assess confinement and the congestion of the plant, it is possible that two different people can find different assessment results. As a result the predicted explosions over-pressure will differ [30].

Strong points of this model are;

- Easy to use
- Short run
- Calibrated against many experiments
- Can deal with non-symmetrical congestion and a long, narrow plant
- Approaches the sensible maximum over-pressure as the severity index approaches infinity [30].

Weak points of this model are;

- Allows only a relatively rough representation by geometry
- There is no specific assessment of the level of congestion and confinement. [30].

3.6.1.6 Sedgwick loss assessment method

The Sedgwick Loss Assessment Method is based on Puttock's Assessment Method. There is some refinement according to the CAM. The Sedgwick Energy Ltd. Explosion model was tested by Thyer and, due to less detail in the promotional leaflets of Sedwick, it is not easy to asses similarities with the Congestion Assessment Method. The package has a graphic interface which allows for setting up a simulation of simple plants [30].

The relation of overpressure to distance from the explosion centre is predicted by the multi-energy model, congestion assessment model, TNO model and TNT model. In two cases, the Flixborough accident and the La Mede Refinery accident, predictions were calculated and compared. As a result, among the four models, TNO was the worst in two cases and the TNT model overestimated the explosion overpressure.

The multi-energy and congestion assessment models were more consistent with the observed data [31].

3.6.2 Phenomenological models

Phenomenological models represent only the essential physics of an explosion. These models are simplified physical models. The biggest simplification is made with reference to modelled geometry. Mainly instead of modelling the actual events geometry, it represents an idealized system. This approach can be used with certain types of geometry. But this is not applicable to complex situations. When the complexity of the models type is considered phenomenological it exists between the empirical and CFD models. Run time of phenomenological models is short. These models are suited to run different scenarios and then to have some of these scenarios analyzed in more detail with the CFD model [30].

3.6.2.1 Shell code for over-pressure prediction in gas explosions (SCOPE)

The SCOPE model was developed at Shell's Thornton Research Center. This model can be applied to much geometry. But, initially, it was designed for modelling explosions in offshore modules. In March of 1994 SCOPE 2 and in 1997 SCOPE 3 were released [30].

The SCOPE code model gas explosion applies the essential physics in a simplified form. The SCOPE model is one dimensional and is based on the idealized geometry of a vented vessel containing many obstacle grids. Flows through these grids determine the turbulence and rate of turbulent combustion downstream from the grid. For modelling flows from vents, standard compressible vent flow relations are used. The SCOPE 2 can model vent opening. A mushroom-shaped jet is formed by vented gas and the highest external pressure is generated when the flame burns in the vortex of the mushroom head [30].

Many experiments have been conducted at different scales and include a 2.5 m^3 box, a 35 m^3 box, and the 550 m^3 SOLVEX experiments. According to these experiments, good calibration was done by comparing idealized geometries similar to those modelled by SCOPE 2 [30].

Many improvements came with SCOPE 3, including the usage of mixed scale objects and a revised turbulent velocity formulation. In addition to side and main vents, SCOPE 3 allows for rear venting. The model was validated by more than 300 experiments [32]

There was an improvement in the basic combustion model which now gives a better result for variations in stochiometry and mixtures of fuel gases. Also, a pressure dependency has been implemented for the expansion ratio, the laminar burning velocity and the modelling of an unconfined but congested plant through with central ignition [30].

Strong points of this model are;

- The handling of venting and external explosions
- Less geometrical detail than the CFD models
- For the evaluation of different scenarios during the plant design phase, SCOPE is a fast tool
- Validated by many experiments, small, medium, and large scale including different gases and various degrees of congestion.
- Imposed limits to flame self-acceleration yield sensible flame speeds [30].

Weak points of this model are;

- Less geometric details than CFD
- Only deals with single enclosures
- Do not provide the same quality information for flow fields as do CFD models [30].

3.6.2.2 Confined linked chamber explosion (CLICHE)

The CLICHE code has been developed by Advantica Technologies LTD. Initially it was developed for confined explosions in buildings, then as it developed its use was extended to modelling off-shore and on-shore plants.

A numerical database which contains details of plant geometry is used for the calculation of the necessary parameters to model the drag and flame / obstacle interactions. Laminar and turbulent velocities are determined from a sub-combustion model based on local flow properties. In the CLICHE explosion model for unburnt and burnt gas volumes in each chamber conservation laws were applied while it is assumed that properties in each chamber are uniform and momentum changes occur only at the perimeter of these volumes occurs. According to the geometry and volume of burnt gas a flame shape is empirically predicted [30].

Many chamber equations form a system of coupled, ordinary differential equations which are solved numerically. It is assumed that burnt gas properties are equal to equilibrium properties which are calculated during the running of the CLICHE model and take into account the temperature and pressure relation.
Empirical correlations of the flame speed as a function of flame give the laminar burning velocity. The turbulent burning velocity is based on a Kolmogorov, Petrovsky and Piskounov analysis of the combustion model of Bray [30].

Strong points of this model are;

- Uses a sample combustion model, based on a mixture of some physics and emprical equations
- Handles external explosions
- Includes flame distortion effects due to vents.
- The ignition location can be anywhere within a cubic volume
- Short running time
- From an obstacle database can generate its own input parameters [30].

Weak points of this model are;

- The simple geometry through a series of inter linked chambers.
- Flow field results are not as accurate as in CFD models [30].

3.6.3 CFD models

Computational Fluid Dynamics (CFD) is widely used in designing vehicles, air planes, weather forecasting, and environmental modelling. CFD models are better suited to model explosions in complex geometries. CFD models solve partial differential equations related to the explosion process.
CFD model solutions offer very accurate result regarding flow field, velocities, pressure, density and concentrations [30].

The advantage of CFD models is to simulate flow behaviour where it is not practical or possible to carry out experiments. It is possible to run different cases in a short period of time. Sub-models which are used are validated by experiments. If the model is not validated, the result obtained will not be reliable. CFD models are very useful tools if they are used correctly [30].

For the simulation of vapour cloud explosions CFD models are the best. By using CFD code it is possible to make significant research into the VCE process. Phenomenological models are more accurate than correlation (empirical) models and can be used for safety evaluations in the design stage of plants. Although the correlation model has a limited usage, they are easy to use and can be used for risk analysis [31].

In the CFD models, new model development or extensions of the current models are minimal. Also, in CFD models turbulence remains an active topic in the research area. There are many improvements in the mathematical concept, but, still, there are some subjects which are not dealt with fully, for example, the transition from laminar flow to turbulence flow [30].

With the current rate of progress it seems that the simulation of turbulent combustion in a real plant with all its components and with real scale and all its complexity will take many years. However, the rapid development in computer hardware, high memory and parallel processing will bring some advantages. It may also be required to rewrite some codes to increase efficiency [30].

3.6.3.1 Exsim

The EXSIM model was developed at the Telemark Technological R&D Centre (Tel-Tek) in Norway and Shell Global Solutions in United Kingdom. EXSIM uses the PDR approach and small object are defined by volume, porosity, area porosity, and a drag coefficient.

In version 3.3 a box shaped domain is specified and to build a subsequent geometry there are eight basic objects [30].

These objects are:

- Large box, resolved by the grid.
- Cylinder aligned with one of the co-ordinate directions.
- Pipe bundle in the form of a box.
- General porous box.

- Louvered wall
- Box beam or box that is not resolved by the grid.
- Sharp edged beam.
- Grating [30].

The EXIM version 3.3 can convert data from different types of CAD formats, which helps to set up geometry quickly. Version 3.3 of Exsim has been validated by much experimental data, some of which is the experimental data from Phase 2 of the Flast and Fire Engineering for Topside Structures, DNV experiments, Shell Solvex full and 1/6-th scale tests, CMR experiments on their M24 and M25 modules, experiments carried out by Shell at their Buxton site. EXIMS can be used for congested configurations with varying degrees of confinement, including a completely unconfined geometry [30].

Strong points of this model are;

- Compares many small, medium and large scale experiments.
- Can be used to model congested but unconfined geometries.
- Can be used to model external explosions
- CAD data can be used
- Spatial resolutions of obstacle can be specified [30].

Weak points of this model are;

- Uses a standard k – e model
- Does not have a local grid refinement [30].

3.6.3.2 Flame acceleration simulator (FLACS)

The FLACS were developed at the Christian Michelsen Research Institute in Norway, now called CMR-GEXCON. It is based on a structured cartesian grid. FLACS has an advanced user interface: include Computer Aided Scenario Design (CASD) and Flowvis. Scenario definition for FLACS are generated by CASD, the results of simulations are realized by Flowvis. For defining scenarios simple geometry is used. For example, pipes are represented by long cylinders. For modelling walls and decks there are four different methods: solid unyielding surfaces, porous surfaces, blow out / explosion relief panels, or open. CMR has stated that FLACS has been validated by a wide range of experiments, but many of these results are confidential [30].

Some of the predictions of FLACS were compared with various measurements and published as parts of MERGE, EMERGE and BFETS projects. The latest developments in FLACS are not published in the open literature [30].

Strong points of this model are;

- Supported by many small, medium and large scale experiments.
- Incorporate a water deluge model
- Can use CAD data
- Can be used to model congested but unconfined geometries.
- Can be used to model external explosions
- Only for the reaction progress variable it uses a second order accuracy discretisation scheme, a van Leer Upwind scheme [30].

Weak points of this model are;

- Use a k-e model with modifications
- Instead of a reaction progress variable, uses a first order of accuracy, weighted up wind/ central differencing scheme
- Latest developments are not available in the literature
- Early versions up to 1993 were calibrated against 1 m cube grid cell size [30].

3.6.3.3 Autoreagas

AutoReaGas was developed by Century Dynamics Ltd. and TNO. This code includes features of REAGAS and BLAST which were developed by TNO and has an interactive environment based on the AUTODYN-3D code which was developed by Century Dynamics. AutoReaGas run on many computer platforms such as UNIX, Windows 95, Windows NT and later versions of Windows [30].

Strong points of this model are;

- Supported by many small, medium and large scale experiments.
- Incorporate a water deluge model
- Can use CAD data

- Possible to define many objects through a dynamic memory allocation of the object database [30].

Weak points of this model are;

- Uses the standard k –e turbulence model
- Uses a first order of accuracy discretization scheme for all variables [30].

3.6.3.4 Cebam

The CEBAM model was developed by Dr. Clutter at the University of Texas in San Antonio. CEBAM is CFD code for aero-propulsion usage, based on a gas-phase, multi-step, finite rate combustion. In the CEBAM model combustion reaction assumes a one-step, irreversible chemical reaction including fuel, air and material products. The model can solve partial differential equations either in the Euler or Navier-Stokes form. For the gas explosion code the developer recommended the Euler version [33].

Many VCE scenarios have been simulated with CEBAM and simulation results are compared with test data. Overpressure and capture effects were accurately predicted by the CFD model [34].

3.6.4 Advanced CFD models

The main difference between CFD and advanced CFD models is the representation of geometry and the accuracy of the numerical schemes which are used [30].

3.6.4.1 CFX-4

The CFX-4 code is a commercially available CFD code, developed by AEA Technology Engineering Software at Harwell. An explosion module of CFX-4 has been developed by the code suppliers and is financed by HSE [30].

Strong points of this model are;

- Provides multi-block capability for greater control over the meshing
- Provides a wide range of discretization schemes
- Many turbulence models are implemented, including Reynolds stress transport models.
- Can use CAD data
- Good results for CH_4 and H_2 deflagrations [30].

Weak points of this model are;

- Weak results for experiments with gases other than methane and hydrogen,
- Uses a thin flame model. This model is not very suitable for explosion modelling.
- Ignition model is not complete.
- Validation deficient for the explosion model and ignition model [30].

3.6.4.2 Cobra

This code was developed by Mantis Numerics Ltd. with Advantica Technologies Ltd.

Strong points of this model are;

- Cartesian mesh
- Improved grid refinement/de-refinement facility
- Can use CAD data [30].

Weak points of this model are;

- Building a complex geometry is very difficult and time-consuming.
- No model for transition from laminar to turbulent flow [30].

3.6.4.3 Newt

Newt is used for modelling very complex geometries. It is an unstructured adaptive mesh, a three dimensional, finite volume, computational fluid dynamics code. After being developed for non-combusting turbo machines, it is used today for explosion prediction at the Engineering Department of Cambridge University and is financially supported by the Offshore Safety Division of the Health & Safety Executive.

Strong points of this model are;

- Adaptive mesh algorithm
- Requires minimum effort to generate a mesh or complex geometries
- Converting output to appropriate format used by Newt, any tetrahedral mesh generated can be used [30].

Weak points of this model are;

- Uses the standard k-3 model
- Uses a crude ignition and transition model [30].

3.6.4.4 Reacflow

REACFLOW is a CFD code for simulating gas flows during chemical reactions which was developed over the last nine years at the Joint Research Centre of the European Union in Ispra, Italy. It can be also used for two or three dimensional geometry models [30].

Strong points of this model are;

- Capable of easier meshing
- Better obstacle representation and flame front resolution with adaptive meshing
- Fast and good problem solver with the help of a second-order van Leer discretisation scheme [30].

Weak points of this model are;

- Standard k-3 turbulence model
- Simple combustion models [30].

3.6.4.5 Imperial college research code

It is a 2D computer code using a combustion model, a sophisticated gradient/flame front tracking refinement and de-refinement mesh algorithm using an accurate time and spatial dicretisation (Total Variation Diminishing-TVD) schemes. Developed by Professor Lindstedt and his group, it also has a parallelized version for greater speed.

Strong points of this model are;

- Uses second-order moment closures and higher order spatial and temporal discretization techniques
- Adaptive mesh algorithm
- Simulates detailed chemical kinetics
- Exists in a parallelized version
- Obtains the PDF by a realistic method [30].

Weak points of this model are;

- Requires long run times for large-scale industrial problems
- Huge memory usage with tabulated rate data
- A research code [30].

3.7 Modelling Software

Adora

ADORA is the acronym for Atmospheric Dispersion of Reacting Agents, which was developed by the BlazeTech Corporation for calculating downwind toxic concentrations. A free demonstration is available for Windows 95/NT or Windows 3.1/3.11 [35].

BLEVE Incident Simulator (BIS)

The BLEVE is the acronym for Boiling Liquid Expanding Vapour Explosion which is an incident simulator for Windows 95/Nt. With this program, for different incident scenarios, the user can obtain various information about the estimated time to tank failure or tank empty; blast, fireball, projectiles and vapour cloud explosion hazards; required cooling water flow rates and quantities; suggested responder position and distance. It also has a graphic information module [35].

Breeze

BREEZE HAZ is especially designed by Trinity Consultants' for the Risk Management Planning and Offsite Consequence Analysis which helps to increase productivity, visualize data, analyze offsite consequence issues and prepare a risk management plan. It is useful to navigate the US EPA's requirements and integrates the EPA's most popular air dispersion model for accidental chemical releases [35].

BREEZE VEXDAM, the Vapour-cloud Explosion Damage Assessment Model which can be used to evaluate the damage caused to structure and injury on humans. Structure can constructed of many types of materials, for example, aluminium, asbestos, brick, concrete, glass, steel and wood [36].

Charm®

CHARM® is an MS Windows program developed by the URS Corporation for complex hazardous air release model software which calculates the movement and concentration of airborne plumes from released chemicals, thermal radiation from BLEVE's, pool and jet fires and over pressures from vapour explosions. It is also useful for overlaying footprints on maps for console display or print [35].

Osiris

Osiris Suite of Emergency Tools is a great tool for safety and hazmat professionals. It has a 7 modules; Osiris 4.0 for windows 95/98/NT encompasses the following hazmat emergency situations:

- Leak flow
- Evaporation
- Dispersion
- Explosion
- Fire

Osiris' Database includes more than 120 commonly used chemicals and it can be customized easily. The program has a user-friendly graphic interface which makes it a great tool for risk assessment. Osiris is generally used by firefighters during real life emergency responses [35].

Phast

PHAST Professional software is used for starting from a potential incident to initial release through formation of a cloud or pool to its final dispersion – concentration, fire radiation, toxicity and explosion overpressure endpoints can be calculated.

This program can be used in the design and operation of many industries. The program is a user friendly. Advanced users can create and manage their own scenarios for new users there are many helpful options which they can use step by step through definition, modelling and the presentation of cases. A MS Windows interface can be shown on maps, satellite photos and plant layouts can be used for design plans, management and government compliance reports, emergency preparedness and response plans, and community awareness programs [35].

PlantSafe™

PlantSafe & trade run on a windows platform such as Windows 95/97/NT.This program include hazmat/fire/ems expert knowledge bases, plume models, electronic white boards, GIS maps reports and more. PlantSafe can be used in emergency response and dispatch personnel in case of hazmat releases fires and explosions [35].

Trace®

TRACE is special software for Chemical Risk Management with which it is possible to simulate hazards associated with exposure to toxic chemicals, thermal radiation from fires and blast overpressure from explosions. Also, it can be used for the estimation of the number of impacted people and the effectiveness of a protection strategy. Trace has a graphic interface which allows the user to define different cases and the result of these simulations can be shown on a map. It is also possible to export results in many different formats, such as word, excel or power point. This program is generally used in quantitative risk analysis, plant design, emergency preparedness planning and for regulatory requirements [35].

Aloha ®

The ALOHA program has many features. This program can estimate the maximum distance of danger in event of the release of toxic materials; also, it is possible to calculate the area wherein the concentration of flammable material can explode.
This program uses the physical characteristics of released chemicals and a real time simulation of known cases to predict a hazardous gas cloud. The program menu is user friendly and supported with helpful menus. Aloha has its own library for chemicals and it's possible to extend this library manually. Results are presented in different form such a graphs, and texts [37].

Exsim

EXSIM is a CFD code for analyzing gas explosions in industry. The developer of this code is the Telemark Technological R&D Centre in Porsgrunn, Norway with support from the Shell Research Ltd. and the Commission of the European Communities (CEC). Validation is done for many scales; the main features are gas explosions, gas dispersion, smoke & pollutant dispersion, mitigation, ventilation, fires & radiation [38].

Flacs

FLACS-GASEX is a part of the FLACS simulator. In this program ventilation and dispersion capabilities are removed. In the gas explosion area, FLACS-GASEX is one of the leading programs; it has many features. Some of the features are; the possibility of importing geometry from CAD; import of dispersed gas clouds, well validated CFD-explosion simulator; efficient pre-processing and simulation times, there are many gases and mixtures of some lean fuel; stoichiometric and rich mixtures with air; the effect of a water deluge and dilution by an inert gas; the effect of an increased oxygen content in the air, non-standard temperatures and initial pressure; initial turbulence, rupture discs, relief panels and simplified wall failures; blast propagation, local pressures and average wall pressures; 2D and 3D field plots of various variables. It also generates automatic mpg-videos from the postprocessor [39].

FLACS is generally used in offshore installations, onshore plants, for explosions in factory buildings, domestic explosions, explosions inside process equipment/ exhaust systems, tunnel explosions and more than 300 platforms and processes in the world use FLACS for design and explosion risks [39].

In the North Sea, BP, Mobil, Norsk Hydro and Statoil have used FLACS in the design of new platforms and in the assessment of existing installations.
It is used also in offshore accident analysis, public inquiries of Piper Alpha and West Vanguard, and the evaluation of the vapour cloud explosion accident at the onshore process plant in Beek, Holland [40].

AutoReaGas

AutoReaGas is a software for modeling gas explosions, and their consequences.
This program includes both laminar and turbulent combustion models and flame acceleration effects can be simulated in the Gas Explosion Solver with a 3D geometry. Also, AutoReaGas has a special feature: the Blast Solver calculates the propagation of blast waves quickly and accurately. Blast solver (Euler Based) and the gas explosion solver are in communication with each other. For example, the result of the gas explosion solver may be transferred to the Blast Solver. This software is validated by many experiments in small, medium and large scale gas explosions [41].

Hams-Gps

This program is Window based. HAMS-GPS has a wide usage. For example, HSE-Management Studies includ risk assessment, accident analysis, ASCLAP-distribution, plume, puff, spill pool evaporation dispersion modelling, Safety Audits, Emergency Management Planning and Control; PROBIT computations, percent and absolute fatality; injury computations; fire and explosion (Vapour Cloud, BLEVE, Confined, Unconfined, Mechanical) modelling; explosion prevention; DOW-fire and explosion computations; EIA and developing and establishing an integrated system on EMS and OHSMS under International Standards, on personal health and fitness [42].

4. EXPERIMENTAL CHAPTER

In this study the special case of LPG explosions was chosen because, in Turkey, LPG is widely used and has a high risks. There are many reasons for LPG explosion; for example, fire, sabotage, terrorist attack, technical problem, maintains problem, and personal error. There is much software for modelling an explosion. Some of these programs don’t have an academic license, some of them have, but the program is very restricted, and some these programs have academic license but only for use in the US. In this study, the ALOHA program was used. ALOHA contains two types of dispersion model the Gaussian dispersion model and the heavy gas dispersion model, and according to the chemical material, atmospheric data and release source, it is possible to simulate many cases such as the toxic area of the vapour cloud, the flammable area of the vapour cloud, the blast area of the vapour cloud explosion, jet fire and BLEVE [43-44].
Aloha version 5.4.1 was used.

ALOHA doesn’t account for the effects of the following factors;

a) By products from fires, explosions, chemical reactions
b) Particulates
c) Chemical mixtures

ALOHA is designed to model only pure chemicals and some solutions. The property of materials in its library is not valid for mixtures of materials. It is difficult to model with mixtures because it is very hard to predict accurate the chemical properties such as vapour pressure.

d) Terrain:

The program expects the ground below the leaking tank to be flat; and the liquid to spread out in all directions

e) Hazardous fragments:

In case of an explosion there will be flying debris from the container and the surrounding area; this is not modelled with ALOHA.

In the first part of the experiments there were 8 different case simulations for an LPG filling station. In the second part there is a case simulation for an LPG storage tank at İTÜ. For each case there was a simulation of the toxic area of a vapour cloud, the flammable area of a vapour cloud, the blast area of a vapour cloud explosion, the burning of chemicals as a jet fire, and BLEVE, where the tank explodes and the chemical burns in a fireball. For some simulations results are shown on a real map for the İpragaz Hadımköy LPG filling station and for a storage tank at the İTÜ. The third part includes simulation of the blast area of the vapour cloud explosion in case -1 for 14 different over pressure values

For the gas propane was used because in industry tanks are designed according to propane's properties. There are some fixed parameters which are used for each simulation, these are: date and time by a computer clock; building type is a single storied building; the location is ABILENE, TEXAS; the building surroundings are unsheltered surroundings; ground roughness is urban or forest; cloud cover is partly cloudy; measurement height above ground is 3 meters; stability class is D; there is no inversion option; the state of the chemical is liquid and all leaks are through a short pipe/valve.

4.1 LPG Filling Station

In this section there are 8 different scenarios for the LPG filling station. In each case there is a toxic area of vapour cloud, a flammable area for the vapour cloud, a blast area of vapour cloud explosion; the burning of the chemical as a jet fire and BLEVE, the tank explodes and the chemical burns in fireball simulations.

4.1.1 Case – 1

In the first case, it is assumed that there is a leakage from a 2 inc circular opening at the bottom of the tank and the tank is %90 full. For this case, it is first assumed that there is a leak from the tank and that there is no fire area of vapour cloud; the flammable area of the vapour cloud and the blast area of the vapour cloud explosion is simulated. Then, it is assumed that there is a leak from the tank and it burns as a jet fire. Finally, it is assumed that BLEVE occurred, the tank explodes and the chemical burns in a fireball. Input values for the program are presented in Table 4.1.

Table 4.1 : Case 1 Input Data

Parameter	**Unit / Value**
Gas	Propane
Tank type	Cylindrical
Tank diameter	3.6 m
Tank length	18 m
Wind speed, direction	10.8 m/s NNE
Ambient Temperature	10.5 ^{o}C
Humidity	% 70
Temperature inside tank	8 ^{o}C
Filling ratio of tank	% 90
Leak type, dimension	Circular opening 2 inc at bottom of tank

In figure Figure 4.1 the results of a toxic area of vapour cloud are presented, the maximum distance for TEEL-1, TEEL-2 and TEEL-3 is 158 meters. Figure 4.2 includes the result for a flammable area of vapour cloud; the red zone is calculated as 36 meters, but the threat zone is not drawn because the effects of near-field patchiness make dispersion predictions less reliable than for short distances. The orange zone is up to 53 meters where the concentration is %60 of LEL and flame pockets occurs. The yellow zone is up to 176 meters where the concentration is %10 of LEL. Figure 4.3 presents results from the blast area of a vapour cloud explosion. It is assumed that the time of the vapour cloud ignition is not known; it is ignited by a flame or a spark and the level of congestion is defined as congested. The red zone in Figure 4.3 indicates a 55.2 kPa overpressure which is never exceeded; the orange zone is as large as 39 meters where the overpressure is 24.15 kPa and the yellow zone is as large as 60 meters where the overpressure is 6.9 kPa. The orange zone is in danger from the triggering any fire or explosion and the effects of a 24.15 kPa overpressure for the property are a collapse of self-framing steel buildings, the rupture of the oil storage tank, and snapping failure of the wooden utility tanks. The yellow zone presents less dangerous effects to property at 6.9 kPa overpressure, with shattering glass windows, occasional damage to window frames, partial demolition of houses, the shattering of corrugated asbestos siding, the failure of corrugated aluminium-steel panelling, and the failure of wood siding panels. In the yellow zone, the main threat to humans is skin laceration from flying glass [45].

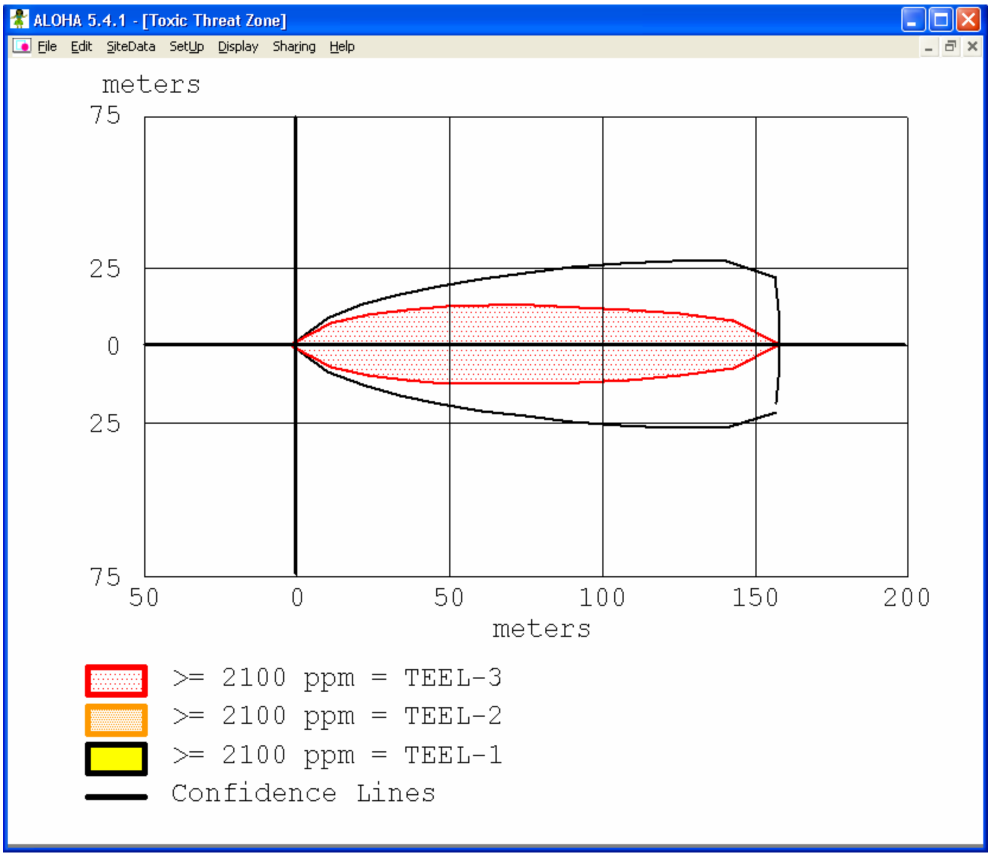

Figure 4.1 : Case – 1 Toxic Area of Vapour Cloud

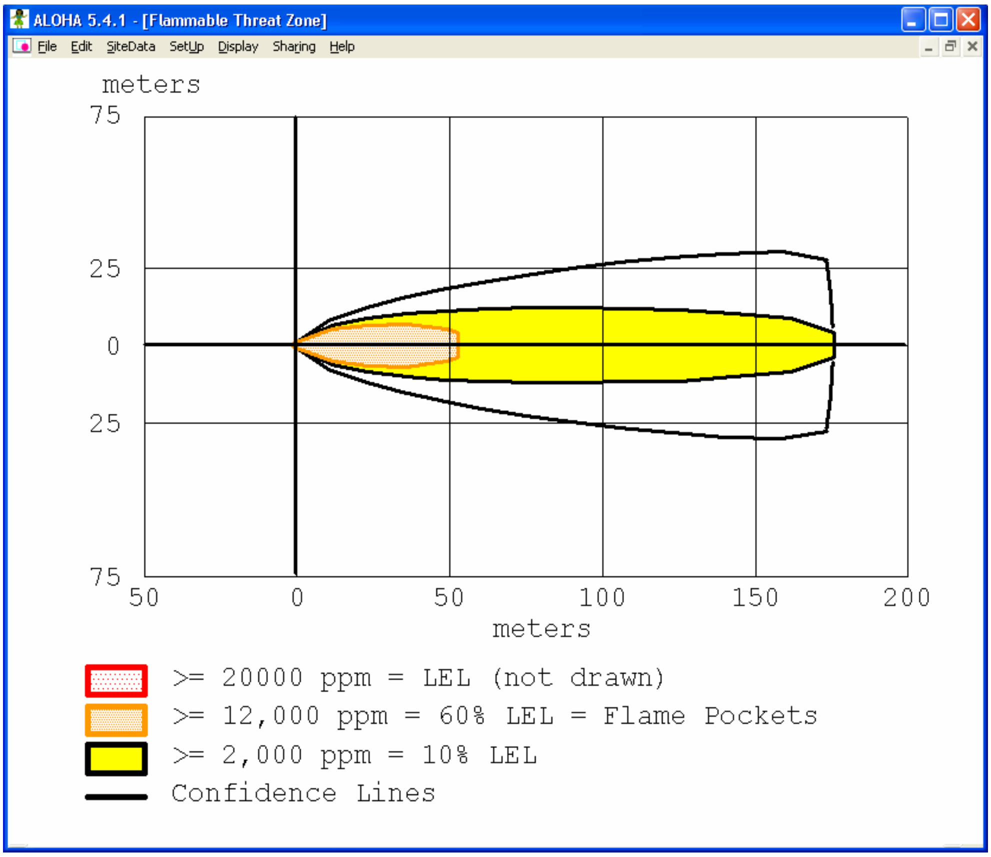

Figure 4.2 : Case – 1 Flammable Area of Vapour Cloud

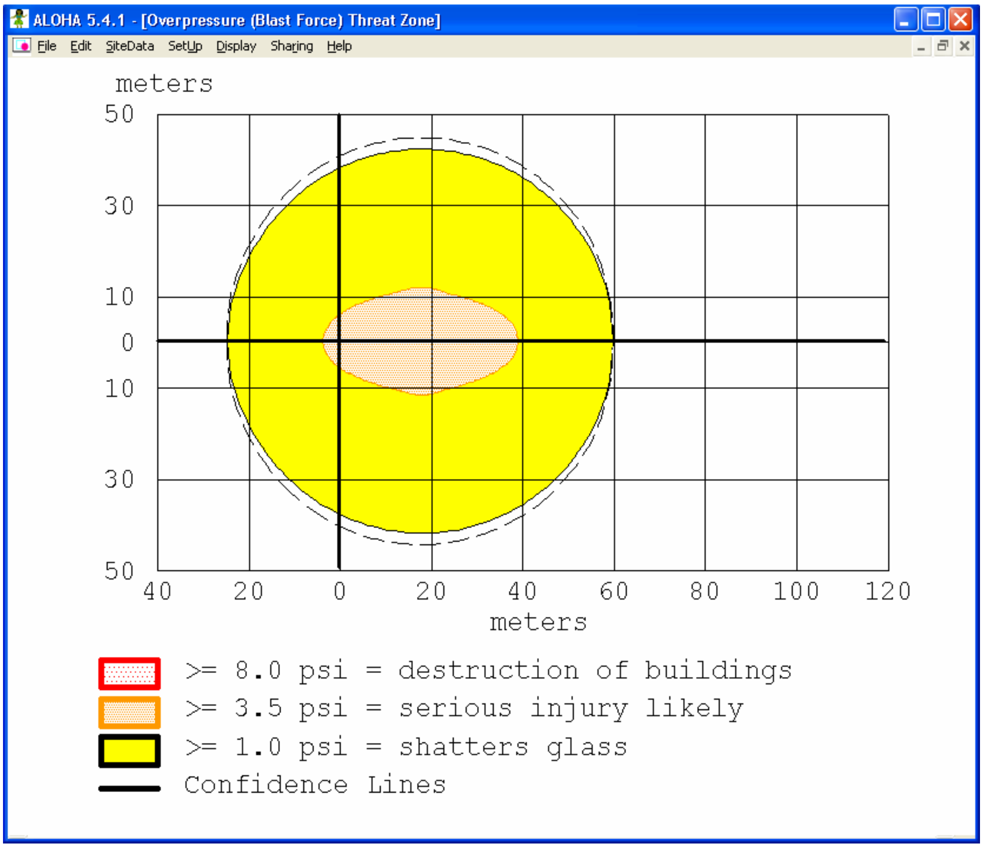

Figure 4.3 : Case – 1 Blast Area of Vapour Cloud Explosion

Figure 4.4 indicates the simulation results for the burning of a chemical as a jet fire. In this situation there is leakage from the tank and it burns as a jet fire. In figure 4.4 the red zone is as large as 33 meters wherein thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds, the orange zone is as large as 45 meters wherein thermal radiation is 5.0 kW/m^2 and 2nd degree burns occurs within 60 seconds, and finally the yellow zone is, as large as 68 meters with a thermal radiation of 2.0 kW/m^2 and pain occurs within 60 seconds.

Figure 4.5 indicates the simulation results for BLEVE, a tank explosion and the LPG burns in a fireball. The red zone is as large as 580 meters wherein thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds; the orange zone is as large as 819 meters wherein the thermal radiation is 5.0 kW/m^2 and 2nd degree burns occurs within 60 seconds; the yellow zone is as large as 1.3 km wherein the thermal radiation is 2.0 kW/m^2 and pain occurs within 60 seconds.

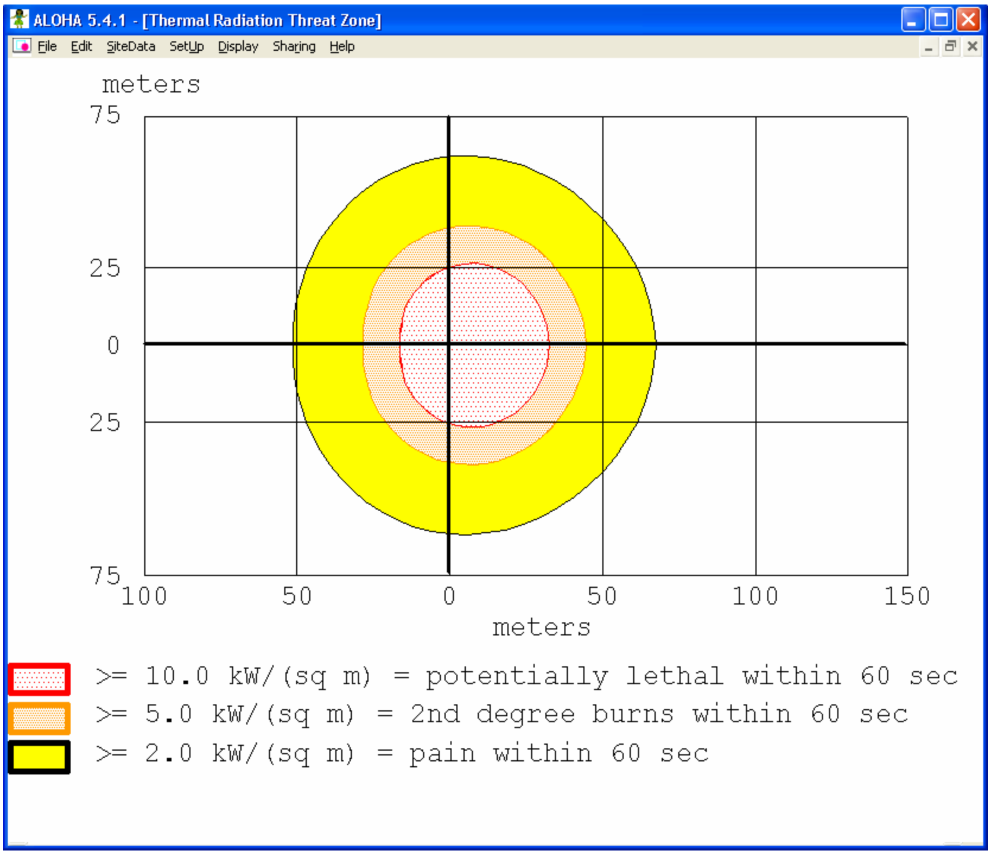

Figure 4.4 : Case -1 Chemical is Burning as a Jet Fire

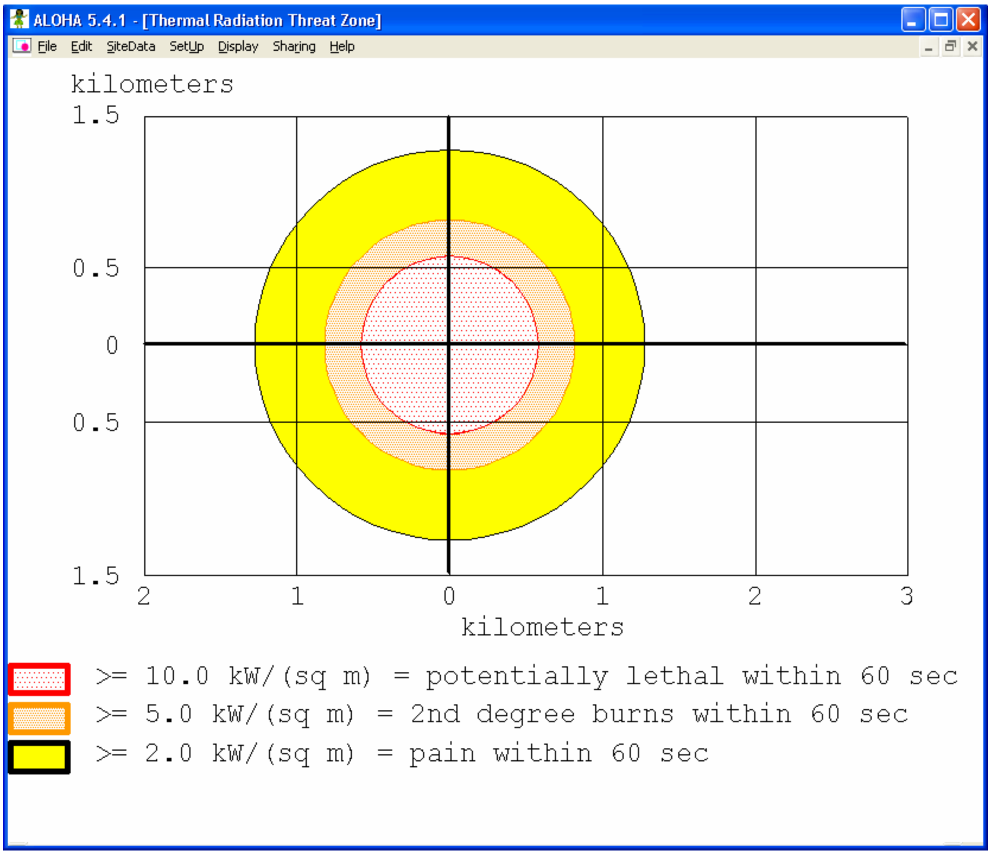

Figure 4.5 : Case -1 BLEVE, tank explodes and chemical burns in a fireball

4.1.2 Case – 2

In the second case it is assumed that there is a leakage from a 2 inc circular opening at the bottom of a tank and that the tank is %30 full. In this case it is first assumed that there is a leak from the tank and that there is no fire and that the area of the vapour cloud, the flammable area of the vapour cloud and the blast area of the vapour cloud explosion is simulated. It is then assumed that there is a leak from the tank and it burns as a jet fire. Finally, it is assumed that BLEVE occurs, the tank explodes and there are chemical burns in a fireball. The input values for the program are presented in Table 4.2.

Table 4.2 : Case 2 Input Data

Parameter	**Unit / Value**
Gas	Propane
Tank type	Cylindrical
Tank diameter	3.6 m
Tank length	18 m
Wind speed, direction	10.8 m/s NNE
Ambient Temperature	10.5 ^{o}C
Humidity	% 70
Temperature inside tank	8 ^{o}C
Filling ratio of tank	% 30
Leak type, dimension	Circular opening 2 inc at bottom of tank

Figure 4.6 presents results from a toxic area of vapour cloud where the maximum size of TEEL-1, TEEL-2 and TEEL-3 is as large as 158 meters. Figure 4.7 shows the effects in the flammable area of a vapour cloud; the red zone is calculated up to 36 meters, but the threat zone is not drawn because the effects of near-field patchiness make dispersion predictions less reliable for short distances. The orange zone is as large as 53 meters wherein the concentration is %60 of LEL and flame pockets occur. The yellow zone is as large as 175 meters wherein the concentration is %10 of LEL. Figure 4.8 indicates the effects found in the blast area of a vapour cloud explosion. It is assumed that the time of the vapour cloud ignition is not known; it was ignited by a flame or spark and the level of congestion is defined as “congested”.

The red zone in Figure 4.8 indicates 55.2 kPa which is never exceeded; the orange zone is as large as 30 meters where the overpressure is 24.15 kPa. The yellow zone is as large as 60 meters with an overpressure of 6.9 kPa. The orange zone is hazardous for its potential to trigger a fire or explosion and the effects of it’s 24.15

kPa overpressure for property are the collapse of self-framing steel buildings, the rupture of the oil storage tank, and snapping failure of the wooden utility tanks. The yellow zone has at, 6.9 kPa overpressure, less dangerous effects on property with the shattering of glass windows, occasional damage to window frames, the partial demolition of houses, the shattering of corrugated asbestos siding, the failure of corrugated aluminium-steel panelling, and the failure of wood siding panels. In the yellow zone the danger to humans is skin laceration from flying glass [45].

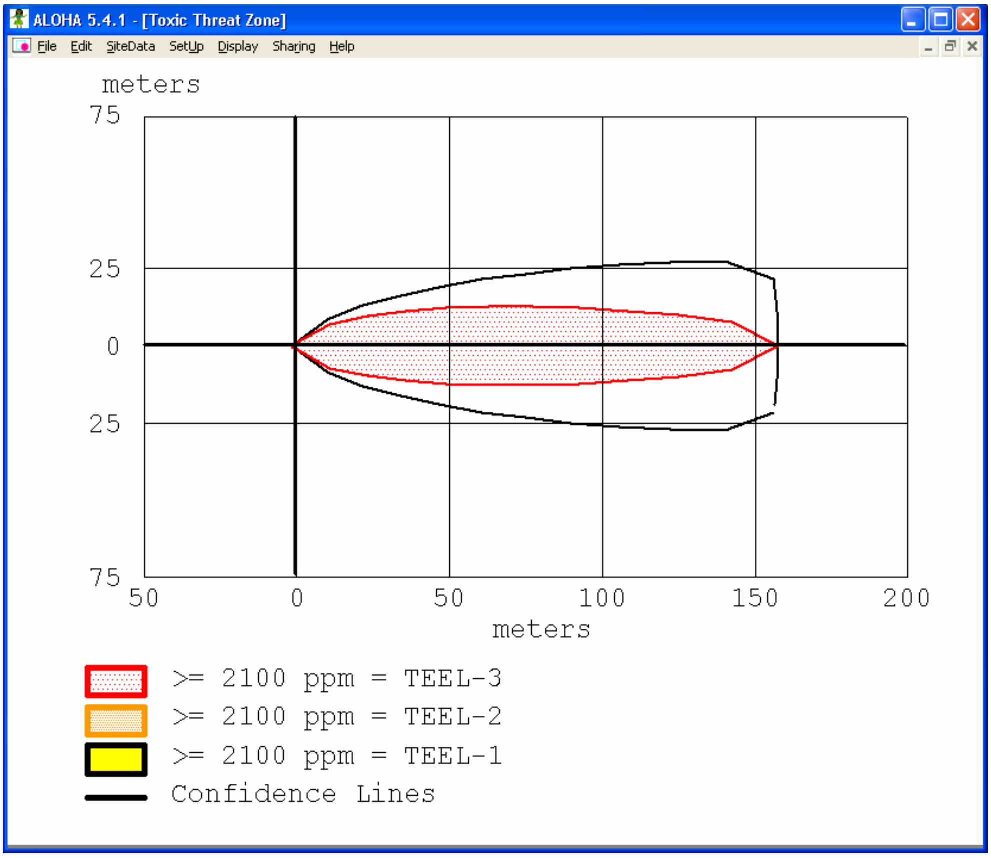

Figure 4.6 : Case -2 Toxic Area of Vapour Cloud

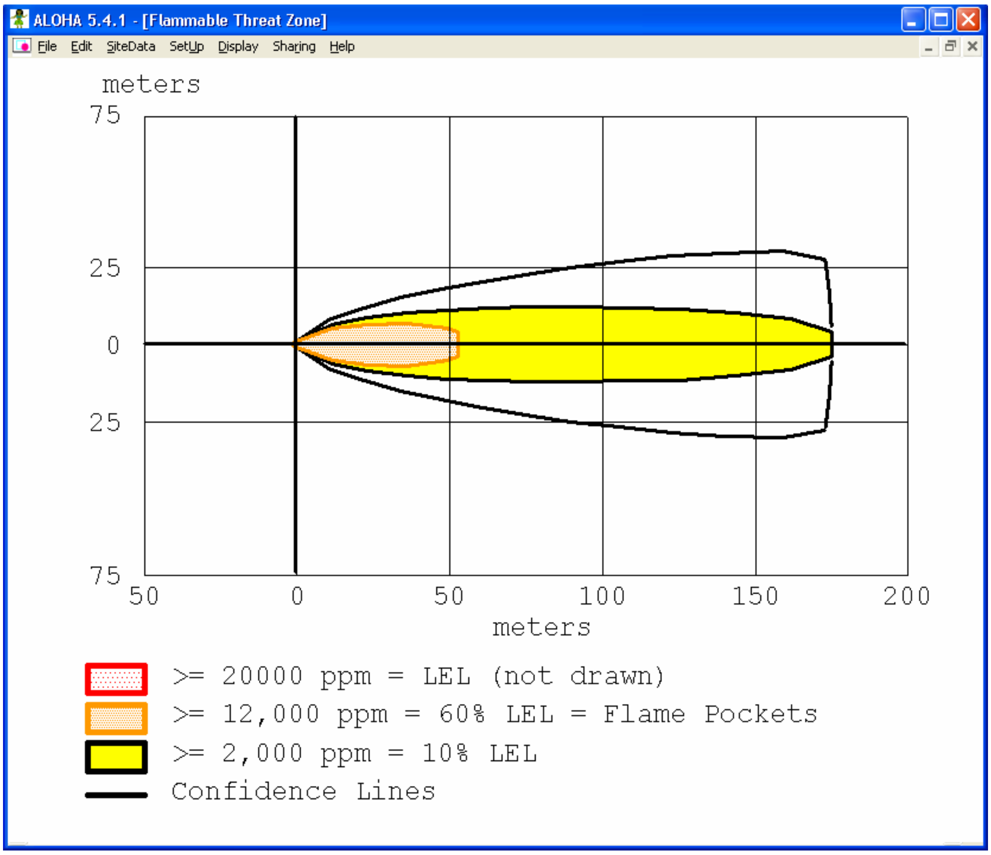

Figure 4.7 : Case – 2 Flammable Area of Vapour Cloud

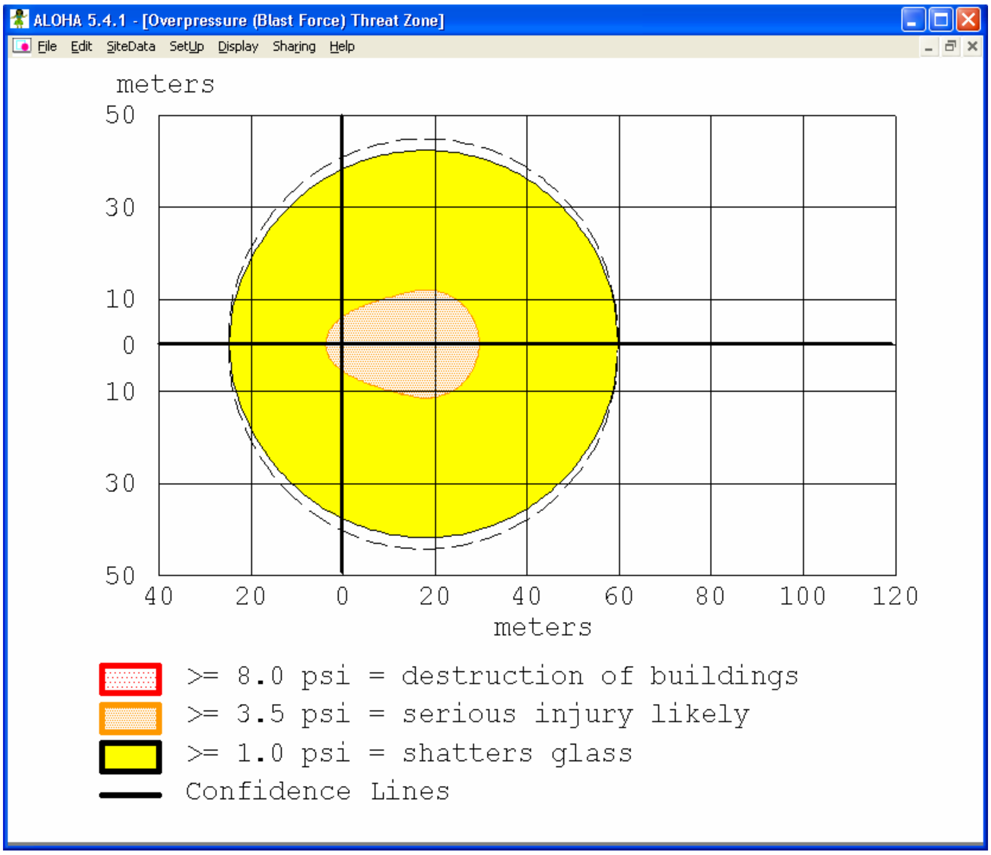

Figure 4.8 : Case – 2 Blast Area of Vapour Cloud Explosion

Figure 4.9 indicates simulation results from burning propane as a jet fire. In this situation there is leakage from a tank and it burns as a jet fire. In figure 4.9 the red zone is as large as 33 meters with thermal radiation of 10.0 kW/m^2; it is potentially lethal in 60 seconds; the orange zone is as large as 45 meters wherein thermal radiation is 5.0 kW/m^2 and 2nd degree burns occurs within 60 seconds; the yellow zone is as large as 67 meters with a thermal radiation of 2.0 kW/m^2 and pain occurs within 60 seconds.

Figure 4.10 indicates simulation results for BLEVE, a tank explosion and the propane burns in a fireball. The red zone is as large as 416 meters wherein thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds. The orange zone is as large as 587 meters wherein thermal radiation is 5.0 kW/m^2 and 2nd degree burns occurs within 60 seconds. The yellow zone is as large as 916 meters wherein thermal radiation is 2.0 kW/m^2 and pain occurs within 60 seconds.

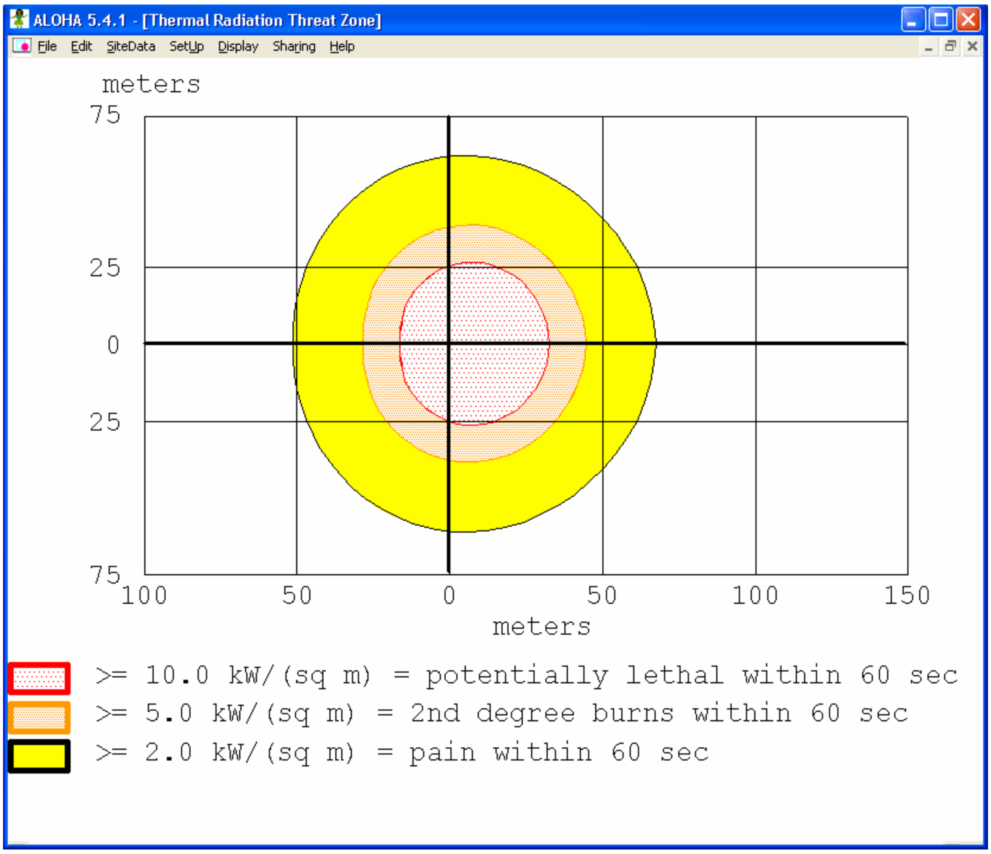

Figure 4.9 : Case – 2 Chemical is Burning as a Jet Fire

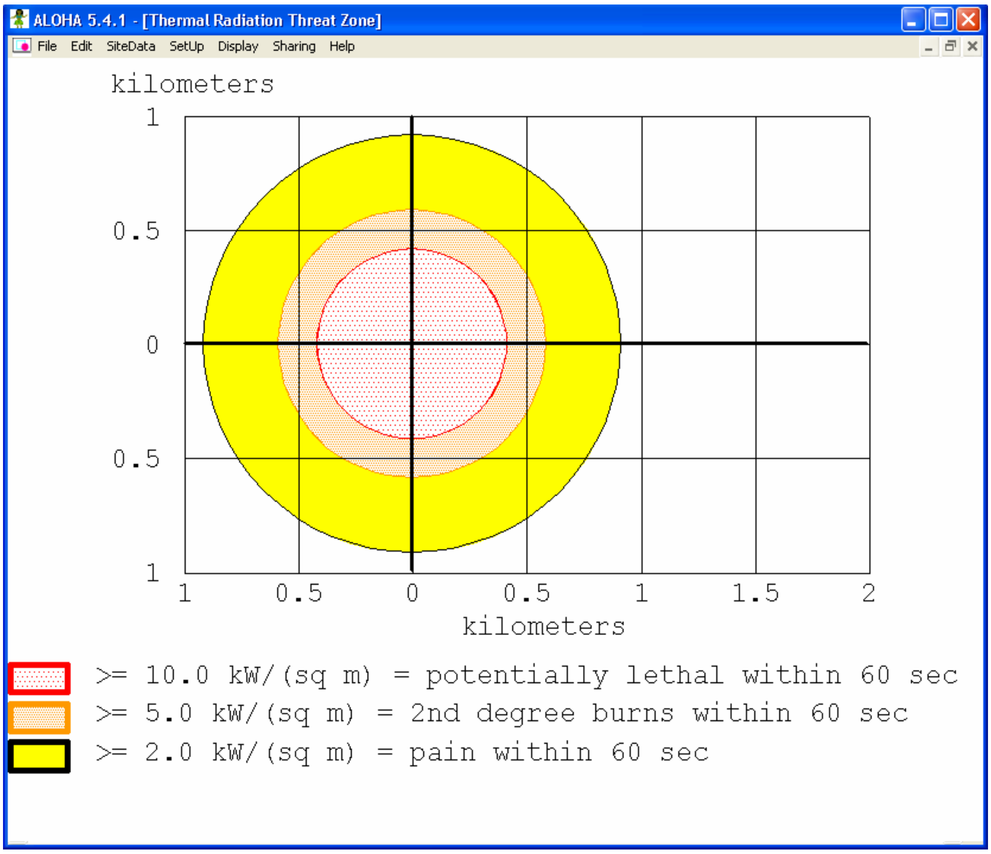

Figure 4.10 : Case -2 BLEVE, tank explodes and chemical burns in a fireball

4.1.3 Case – 3

In the third case it is assumed that there is a leak from a 2 inc circular opening at the bottom of a tank and the tank is %70 full. In this case it is first assumed that there is a leak from the tank and that there is no fire and the area of the vapour cloud, the flammable area of the vapour cloud and the blast area of the vapour cloud explosion is simulated. It is then assumed that there is a leak from the tank and it burns as a jet fire. Finally, it is assumed that BLEVE occurs, the tank explodes and the propane burns as a fireball. Input values for the program are presented in Table 4.3.

Table 4.3 : Case 3 input data

Parameter	Unit / Value
Gas	Propane
Tank type	Cylindrical
Tank diameter	3.6 m
Tank length	18 m
Wind speed, direction	10.8 m/s NNE
Ambient Temperature	10.5 ^{o}C
Humidity	% 70
Temperature inside tank	8 ^{o}C
Filling ratio of tank	% 65
Leak type, dimension	Circular opening 2 inc at bottom of tank

In Figure 4.11 the findings from the toxic area of a vapour cloud are presented; the maximum distance for TEEL-1, TEEL-2 and TEEL-3 is up to 160 meters. Figure 4.12 includes the effects from the flammable area of a vapour cloud; the red zone is calculated as 36 meters, but the threat zone is not drawn because the effects of near-field patchiness make dispersion predictions less reliable than for short distances. The orange zone is as large as 53 meters wherein the concentration is %60 of LEL and flame pockets occurs. The yellow zone is as large as 176 meters wherein concentration is %10 of LEL.

Figure 4.13 presents the results from the blast area of a vapour cloud explosion. It is assumed that the time of vapour cloud ignition is not known, that it is ignited by a flame or spark and that the level of congestion is defined as “congested”. The red zone in Figure 4.13 indicates a 55.2 kPa overpressure which is never exceeded; the orange zone is as large as 39 meters wherein the overpressure is 24.15 kPa and the yellow zone is as large as 60 meters wherein the overpressure is 6.9 kPa. The orange zone is dangerous because it has a potential to trigger a fire or explosion and the effects of a 24.15 kPa overpressure on property are the collapse of self-framing steel buildings, the rupture of oil storage tanks, and snapping failure of wooden utility tanks. The yellow zone has the less dangerous effects of a 6.9 kPa overpressure wherein glass windows shatter; there is occasional damage to window frames, the partial demolition of houses, the shattering of corrugated asbestos siding, the failure of corrugated aluminium-steel panelling, and the failure of wood siding panels. In the yellow zone hazardous effects for humans is skin laceration from flying glass [45].

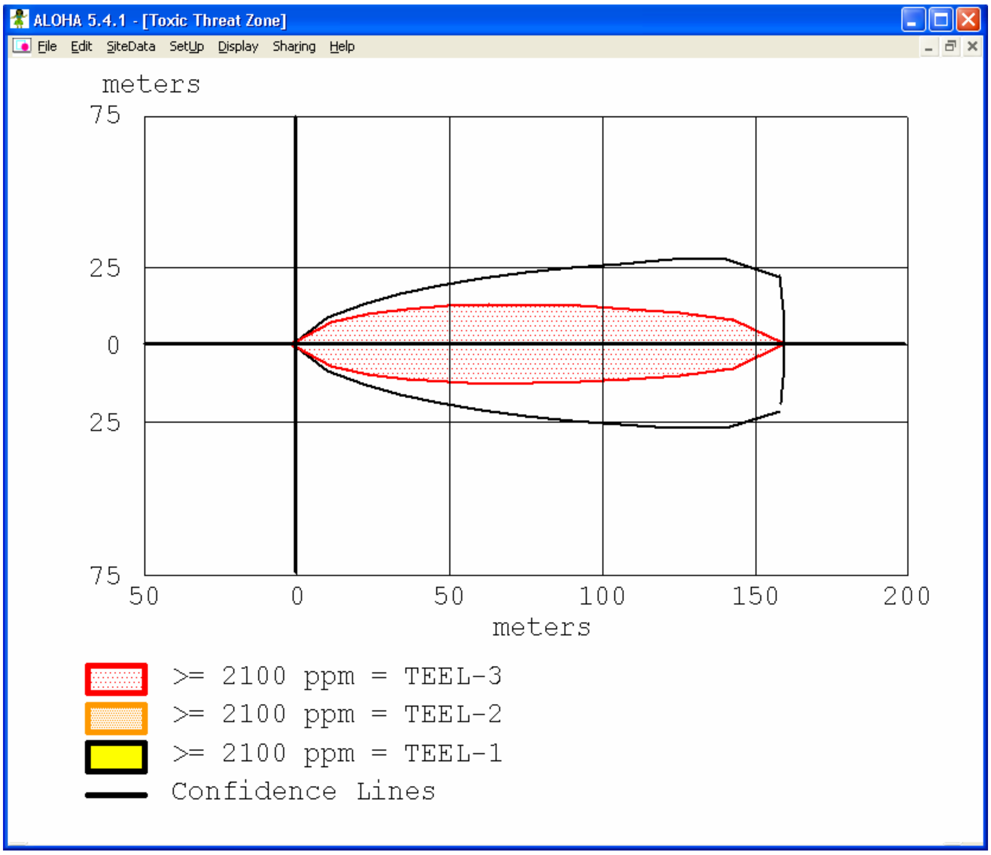

Figure 4.11 : Case -3 Toxic Area of Vapour Cloud

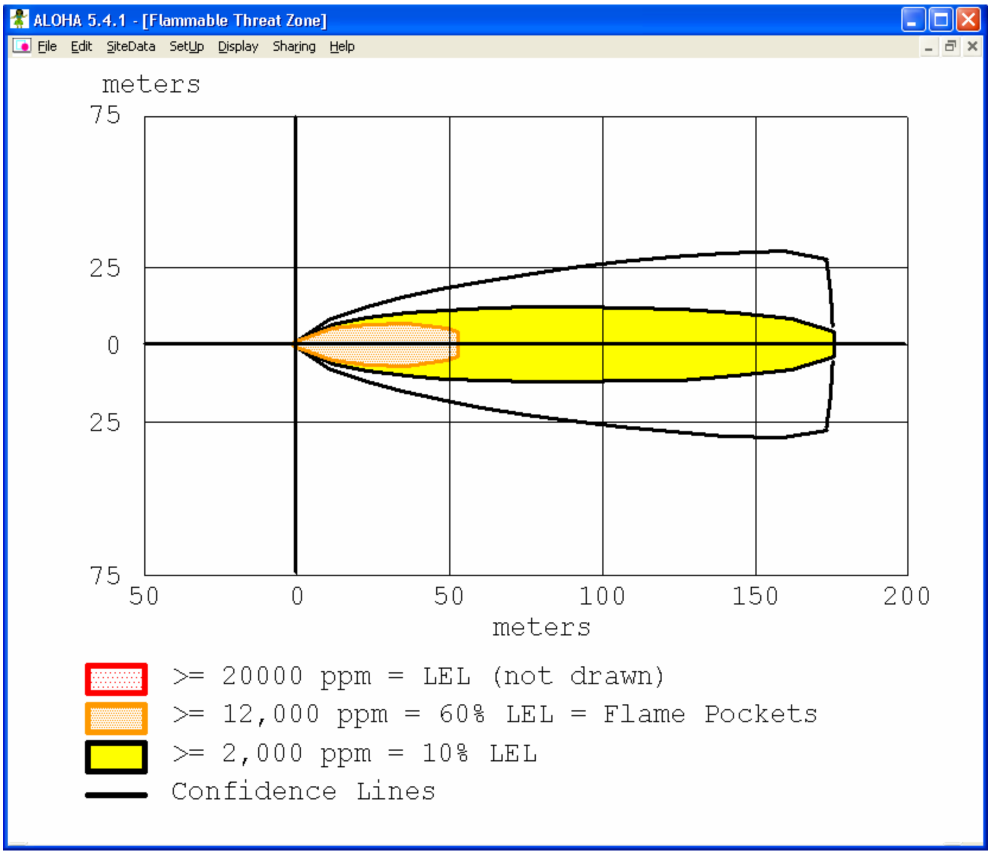

Figure 4.12 : Case – 3 Flammable Area of Vapour Cloud

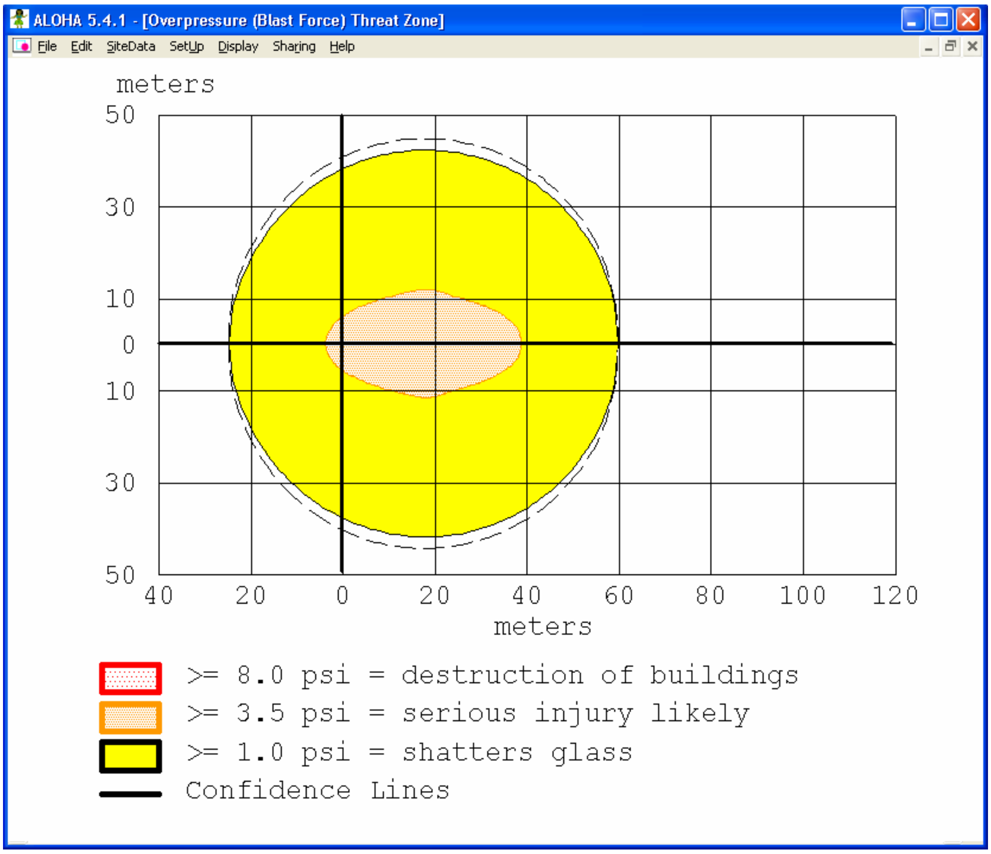

Figure 4.13 : Case – 3 Blast Area of Vapour Cloud Explosion

Figure 4.14 indicates simulation results from the burning of propane as a jet fire. In this situation there is leakage from a tank and it burns as a jet fire. In figure 4.14 the red zone is 33 meters wherein thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds; the orange zone is as large as 45 meters wherein thermal radiation is 5.0 kW/m^2 and 2^{nd} degree burns occurs within 60 seconds, and the yellow zone is as large as 68 meters wherein thermal radiation is 2.0 kW/m^2 and pain occurs within 60 seconds.

Figure 4.15 indicates the simulation results for BLEVE, a tank explosion and propane burning as a fireball. The red zone is as large as 525 meters wherein thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds; the orange zone is as large as 741 meters wherein thermal radiation is 5.0 kW/m^2 and 2^{nd} degree burns occurs within 60 seconds; the yellow zone is as large as 1.2 km wherein thermal radiation is 2.0 kW/m^2 and pain occurs within 60 seconds.

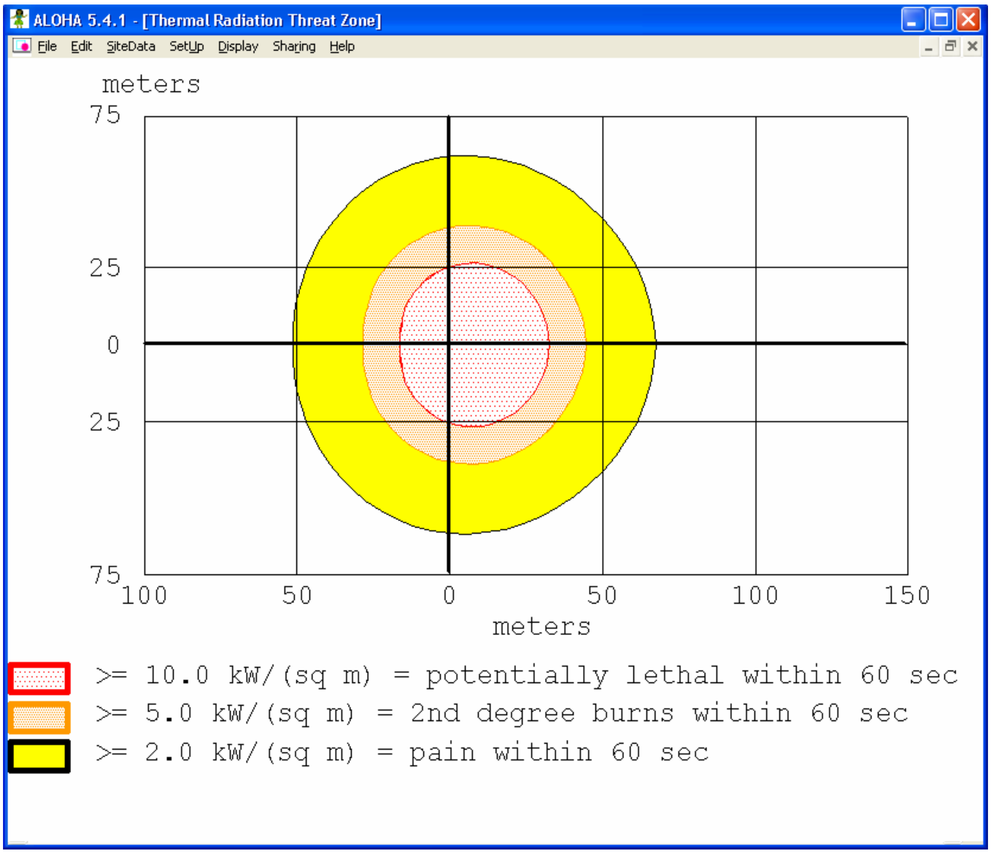

Figure 4.14 : Case – 3 Chemical is Burning as a Jet Fire

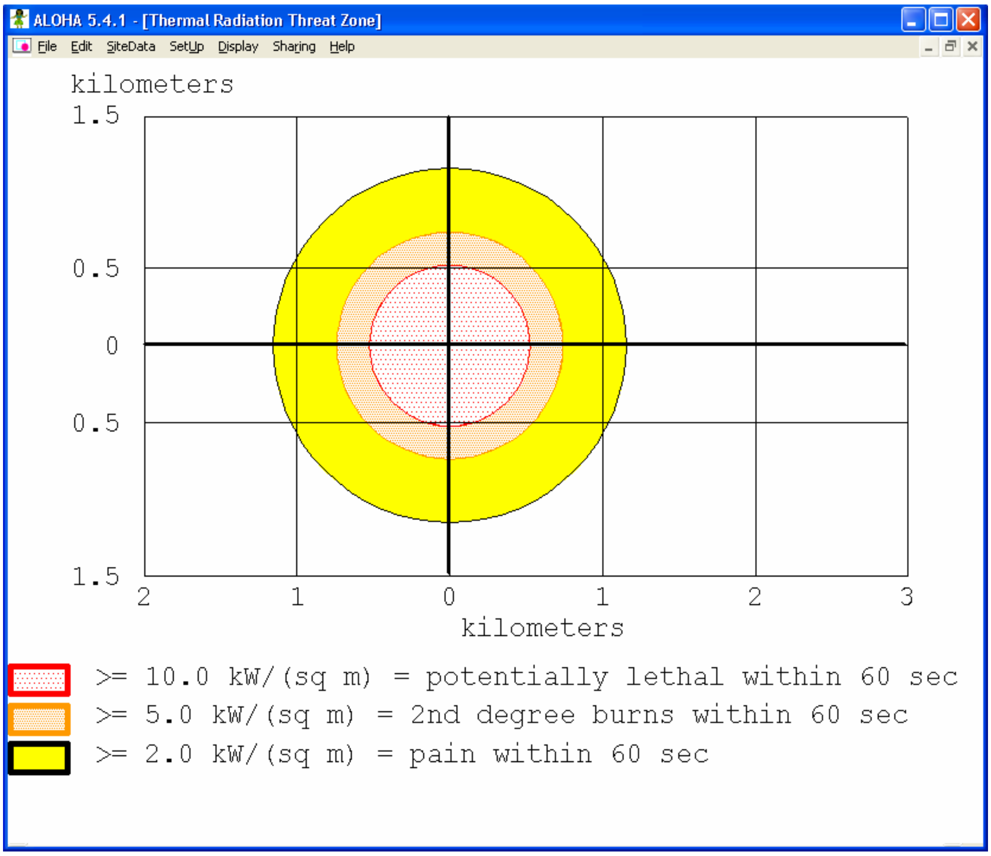

Figure 4.15 : Case -3 BLEVE, tank explodes and chemical burns in a fireball

4.1.4 Case – 4

In the fourth case it is assumed that there is a leak from a 2 inc circular opening at the bottom of a tank and that the tank is %90 full, but atmospheric conditions are different. For this case it is first assumed that there is a leak from the tank and there is no fire and the area of the vapour cloud, the flammable area of the vapour cloud and the blast area of the vapour cloud explosion are simulated. It is further assumed that there is a leak from the tank and it burns as a jet fire. Finally, it is assumed that BLEVE occurs, the tank explodes and the chemical burns as a fireball. The input values for the program are presented in Table 4.4.

Table 4.4 : Case 4 Input Data

Parameter	**Unit / Value**
Gas	Propane
Tank type	Cylindrical
Tank diameter	3.6 m
Tank length	18 m
Wind speed, direction	2 m/s NNE
Ambient Temperature	28 ^{o}C
Humidity	% 70
Temperature inside tank	26 ^{o}C
Filling ratio of tank	% 90
Leak type, dimension	Circular opening 2 inc at bottom of tank

Figure 4.16 presents the effects of toxic area of a vapour cloud; the maximum distance for TEEL-1, TEEL-2 and TEEL-3 is as large as 291 meters. Figure 4.17 shows the results of a flammable area of a vapour cloud; the red zone is as large as 85 meters wherein concentration is equal to the LEL value. The orange zone is as large as 111 meters wherein concentration is %60 of LEL and flame pockets occurs. The yellow zone is as large as 299 meters wherein concentration is %10 of LEL. Figure 4.18 indicates results from the blast area of a vapour cloud explosion. It is assumed that the time of the vapour cloud ignition is not known, that it is ignited by a flame or spark and the level of congestion is defined as “congested”.

The red zone in Figure 4.18 indicates 55.2 kPa which is never exceeded; the orange zone is as large as 93 meters wherein the overpressure is 24.15 kPa. The yellow zone is as large as 155 meters wherein overpressure is 6.9 kPa. The orange zone is susceptible to the triggering of a fire or explosion and the effects of a 24.15 kPa overpressure for property are the collapse of self-framing steel buildings, the rupture of oil storage tanks, and snapping failure of wooden utility tanks. The yellow zone has less dangerous effects of a 6.9 kPa overpressure with the shattering of glass windows, occasional damage to window frames, partial demolition of houses, the shattering of corrugated asbestos siding, the failure of corrugated aluminium-steel panelling, and the failure of wood siding panels. In the yellow zone effects on humans is skin laceration from flying glass [45].

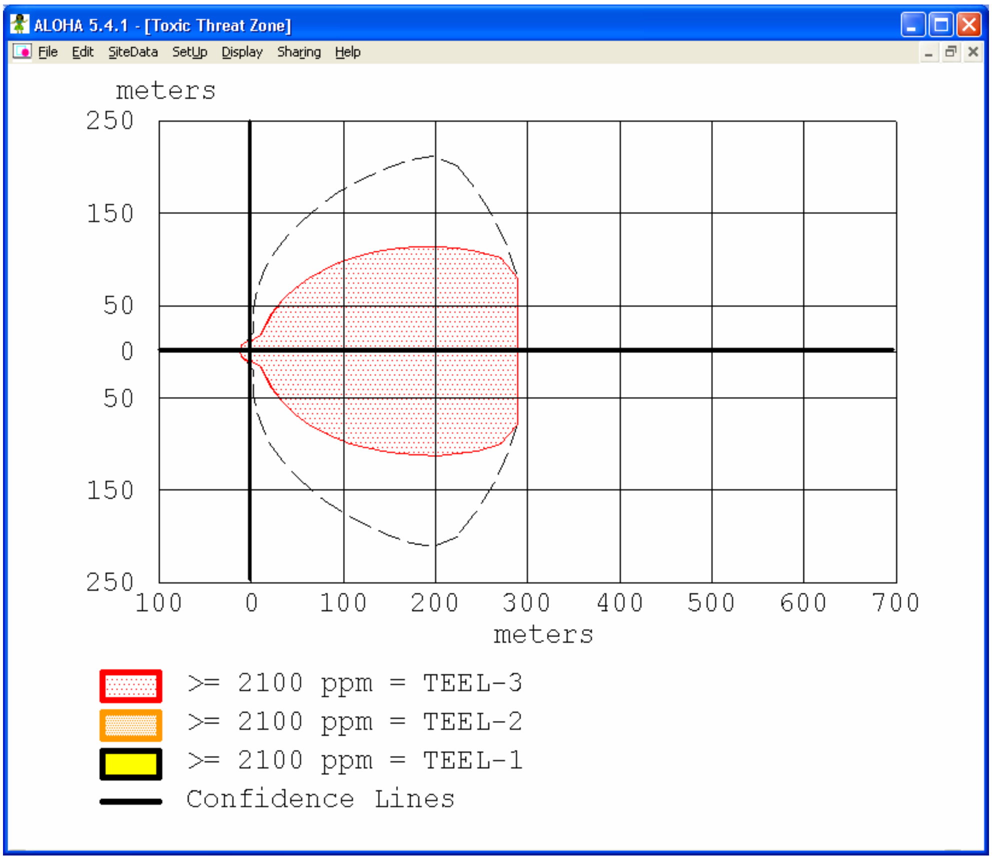

Figure 4.16 : Case -4 Toxic Area of Vapour Cloud

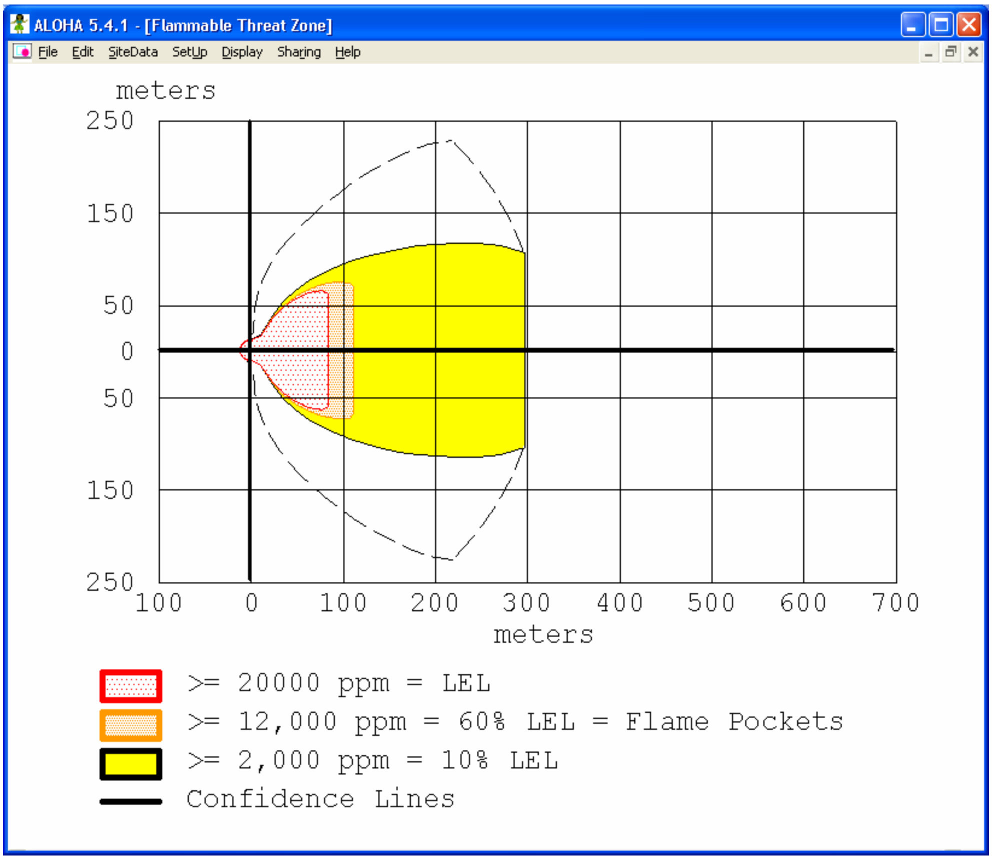

Figure 4.17 : Case – 4 Flammable Area of Vapour Cloud

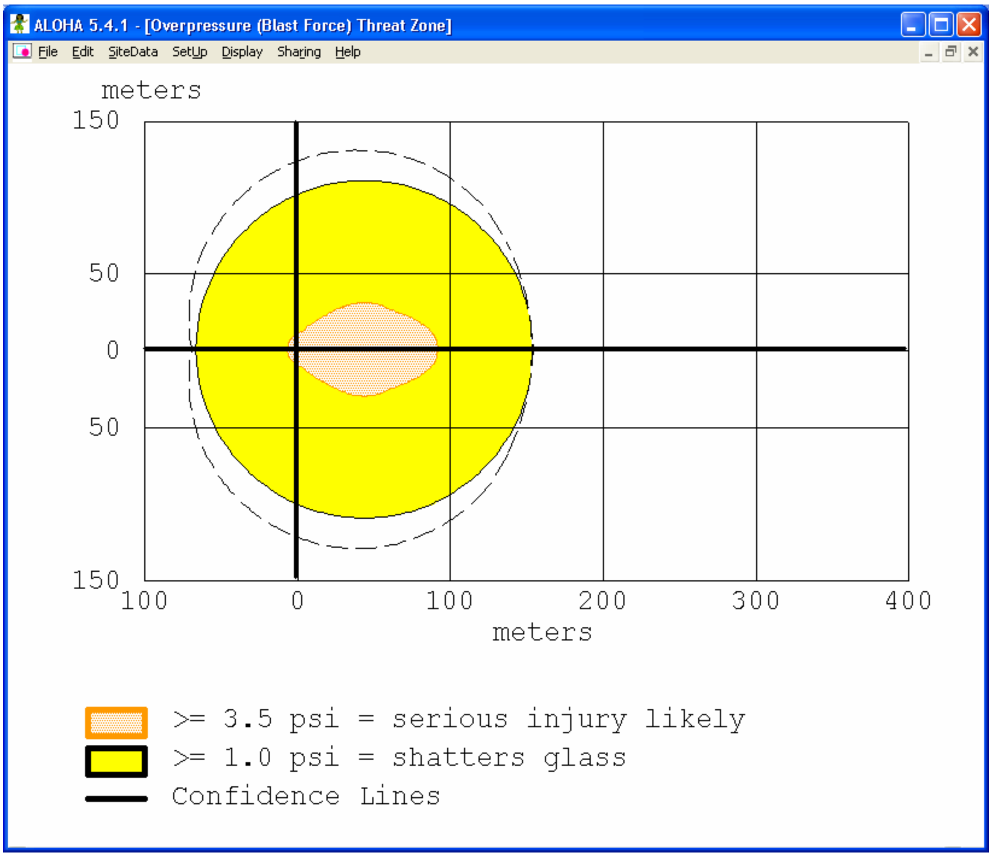

Figure 4.18 : Case – 4 Blast Area of Vapour Cloud Explosion

Figure 4.19 indicates simulation results from burning propane as a jet fire. In this situation there is leakage from a tank and it burns as a jet fire. In figure 4.19, the red zone is as large as 31 meters wherein thermal radiation is 10.0 kW/m2 and potentially lethal in 60 seconds; the orange zone is as large as 45 meters wherein thermal radiation is 5.0 kW/m2 and 2nd degree burns occurs within 60 seconds; the yellow zone is as large as 70 meters wherein thermal radiation is 2.0 kW/m^2 and pain occurs within 60 seconds.

Figure 4.20 indicates simulation results for BLEVE, a tank explosion and propane burning in a fireball. The red zone is as large as 540 meters wherein the thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds. The orange zone is as large as 762 meters wherein thermal radiation is 5.0 kW/m^2 and 2nd degree burns occurs within 60 seconds. The yellow zone is as large as 1.2 km meters wherein thermal radiation is a 2.0 kW/m^2 and pain occurs within 60 seconds.

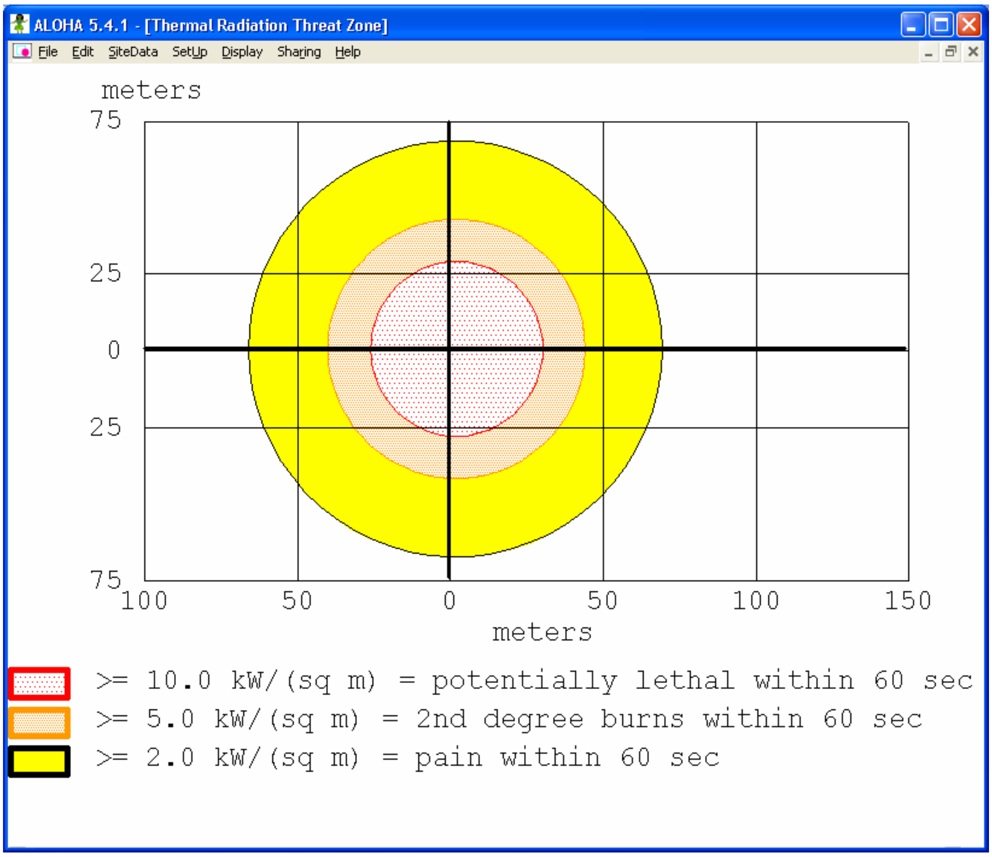

Figure 4.19 : Case – 4 Chemical is Burning as a Jet Fire

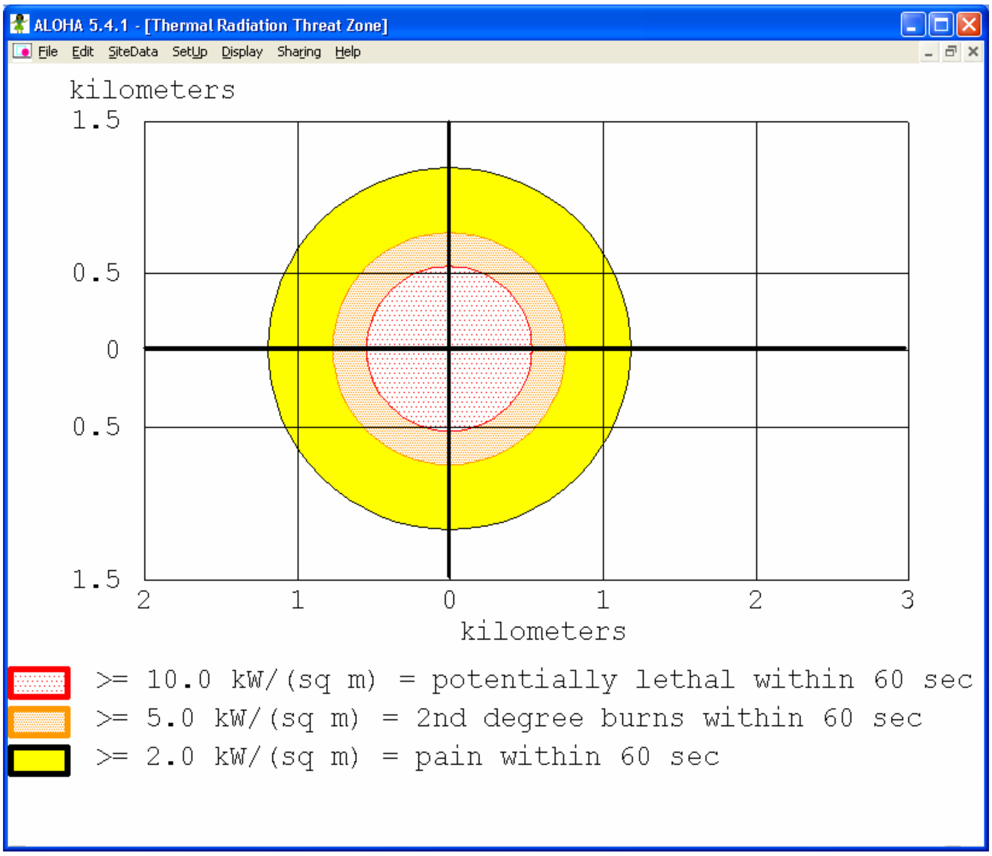

Figure 4.20 : Case - 4 BLEVE, tank explodes and chemical burns in a fireball

4.1.5 Case – 5

In the fifth case, it is assumed that there is a leak from a 4 inc circular opening at the bottom of a tank and the tank is %90 full. In this case first it is assumed that there is a leak from a tank and there is no fire and the area of the vapour cloud, the flammable area of the vapour cloud and the blast area of the vapour cloud explosion is simulated. Then, it is assumed that there is a leak from a tank and it burns as a jet fire. Finally, it is assumed that BLEVE occurs, the tank explodes and the chemical burns in a fireball. Input values for the program are presented in Table 4.5.

Table 4.5 : Case 5 input data

Parameter	**Unit / Value**
Gas	Propane
Tank type	Cylindrical
Tank diameter	3.6 m
Tank length	18 m
Wind speed, direction	10.8 m/s NNE
Ambient Temperature	10.5 ^{o}C
Humidity	% 70
Temperature inside tank	8 ^{o}C
Filling ratio of tank	% 90
Leak type, dimension	Circular opening 4 inc at bottom of tank

Figure 4.21 shows the effects of toxic area of a vapour cloud, the maximum distance for TEEL-1, TEEL-2 and TEEL-3 of up to 325 meters. Figure 4.22 shows the effects of the flammable area of a vapour cloud; the red zone is as large as 73 meters wherein concentration is equal to the LEL value. The orange zone is as large as 102 meters wherein concentration is %60 of LEL and flame pockets occur. The yellow zone is as large as 343 meters wherein concentration is %10 of LEL. Figure 4.23 indicates results from the blast area of the vapour cloud explosion. It is assumed that the time of the vapour cloud ignition is not known, that it is ignited by a flame or spark and the level of congestion is defined as “congested”.

The red zone in Figure 4.23 indicates 55.2 kPa is which is never exceeded; the orange zone is as large as 70 meters wherein overpressure is 24.15 kPa. The yellow zone is as large as 113 meters wherein overpressure is 6.9 kPa. The orange zone is susceptible to the triggering of a fire or explosion and the effects of a 24.15 kPa overpressure for property are the collapse of self-framing steel buildings, rupture of oil storage tanks, and the snapping failure of wooden utility tanks. The yellow zone has the less dangerous effects of a 6.9 kPa overpressure wherein glass windows shatter, there is occasional damage to window frames, partial demolition of houses, the shattering of corrugated asbestos siding, failure of corrugated aluminium-steel panelling, and the failure of wood siding panels. In the yellow zone, effects on humans include skin laceration from flying glass [45].

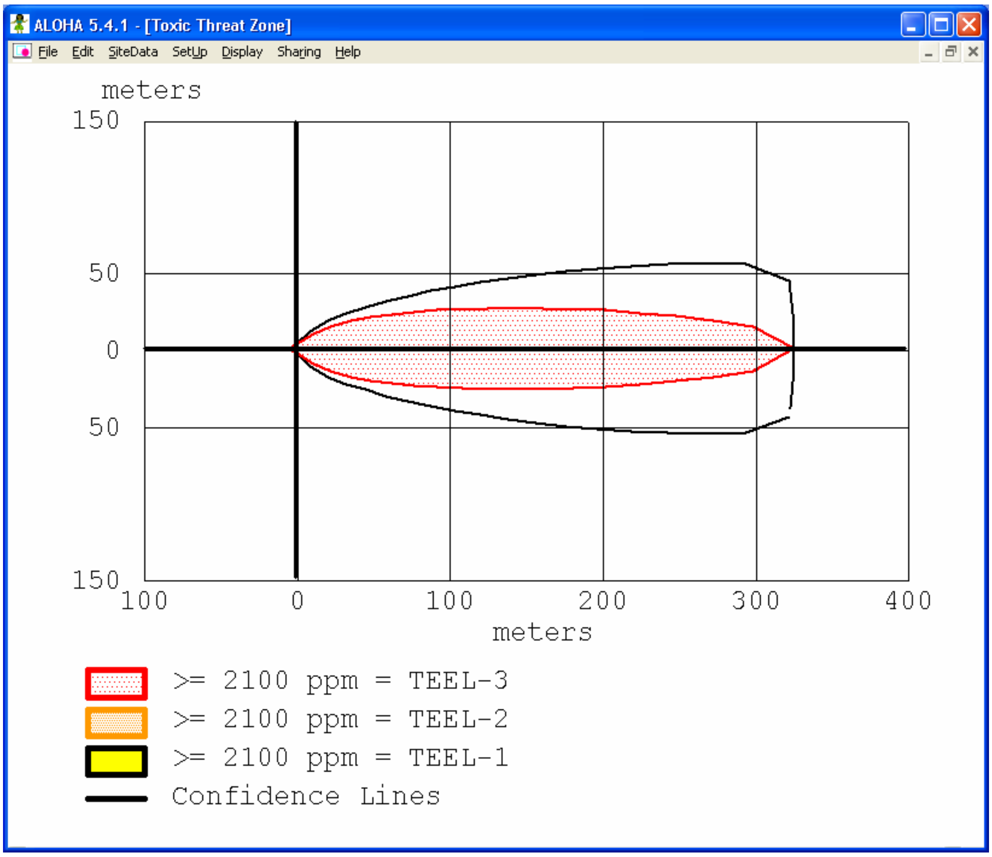

Figure 4.21 : Case -5 Toxic Area of Vapour Cloud

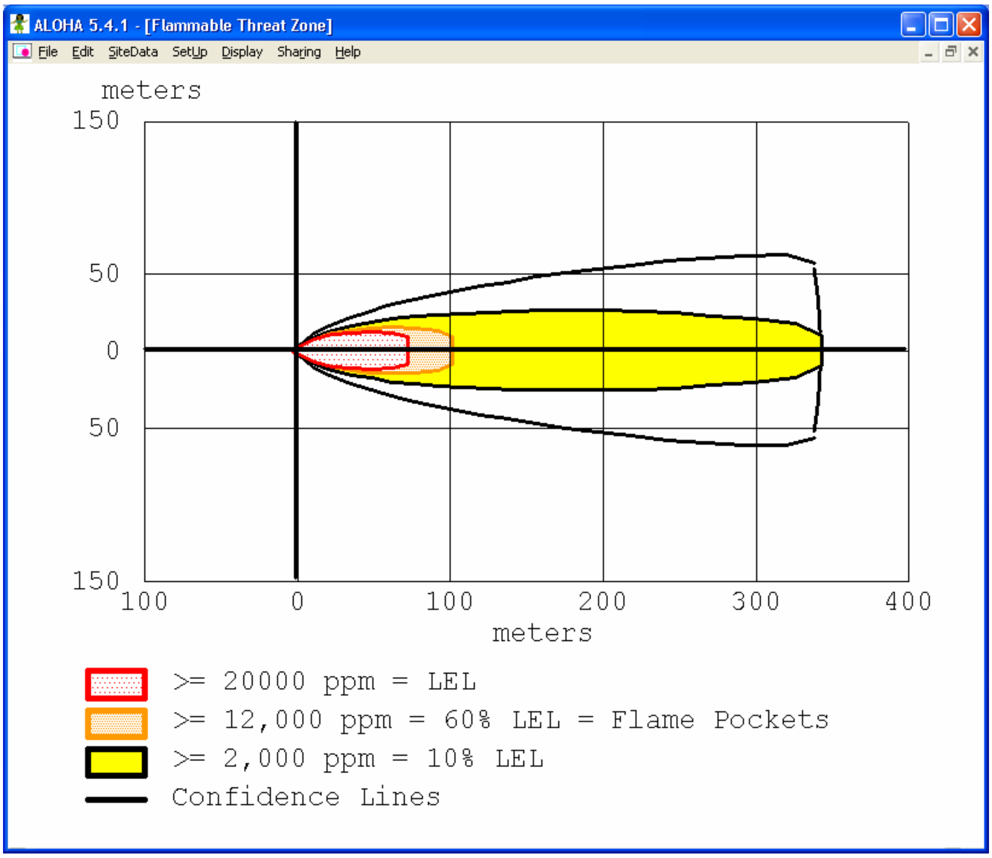

Figure 4.22 : Case – 5 Flammable Area of Vapour Cloud

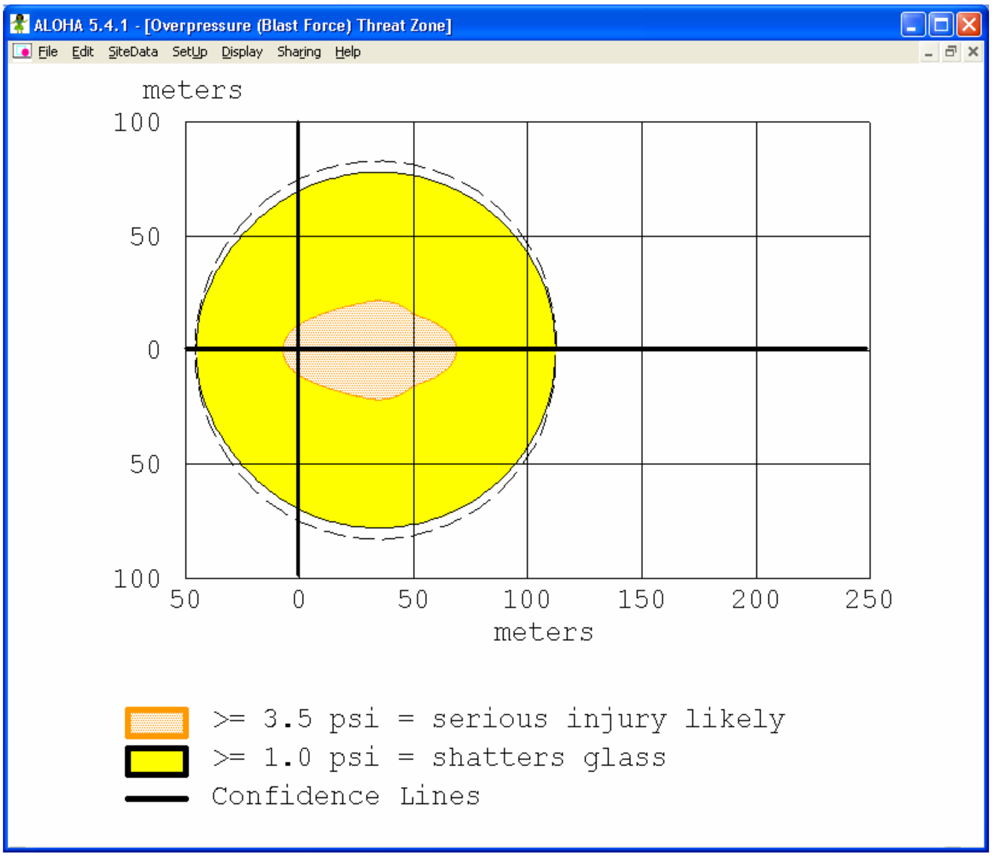

Figure 4.23 : Case – 5 Blast Area of Vapour Cloud Explosion

Figure 4.24 indicates simulation results from the burning of propane as a jet fire. In this situation there is leakage from a tank and it burns as a jet fire. In figure 4.24 the red zone is as large as 62 meters wherein thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds; the orange zone is as large as 85 m wherein thermal radiation is 5.0 kW/m^2 and 2^{nd} degree burns occurs within 60 seconds, and the yellow zone is as large as 131 meters with thermal radiation of 2.0 kW/m^2 and pain occurs within 60 seconds.

Figure 4.25 indicates the simulation results for BLEVE, a tank explosion and propane burning in a fireball. The red zone is as large as 580 meters wherein thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds; the orange zone is as large as 819 wherein thermal radiation is 5.0 kW/m^2 and 2^{nd} degree burns occurs within 60 seconds, and the yellow zone is as large as 1.3 km with thermal radiation of 2.0 kW/m^2 and pain occurs within 60 seconds.

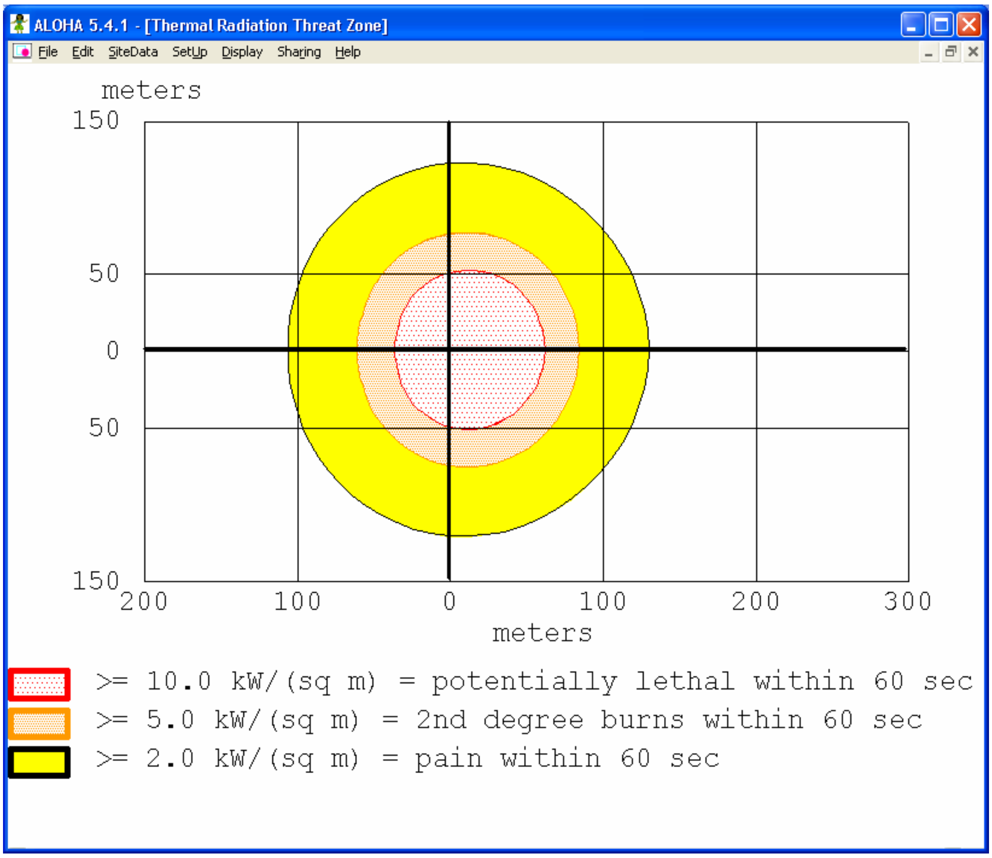

Figure 4.24 : Case – 5 Chemical is Burning as a Jet Fire

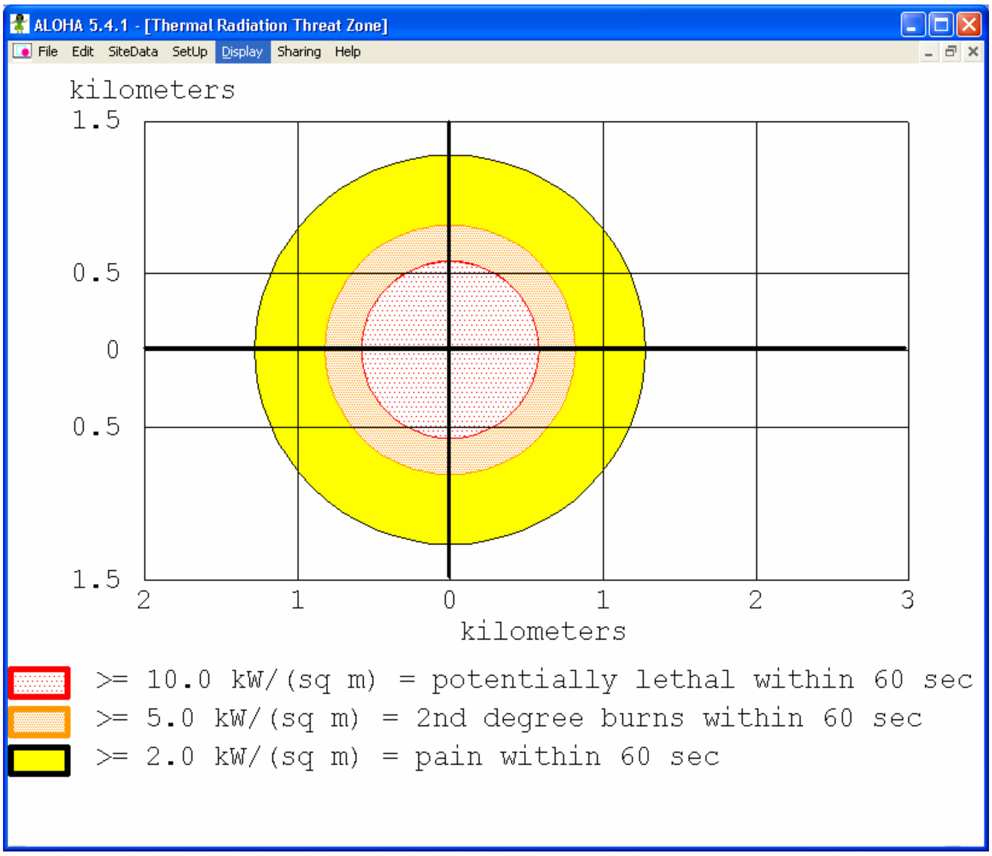

Figure 4.25 : Case -5 BLEVE, tank explodes and chemical burns in a fireball

4.1.6 Case – 6

The sixth case assumes that there is a leak from a 2 inc circular opening at the top of a tank and that the tank is %90 full. For this case it is first assumed that there is a leak from the tank, that there is no fire, the flammable area of the vapour cloud and the blast area of the vapour cloud explosion is simulated. It is then assumed that there is a leak from the tank and it burns as a jet fire. Finally, it is assumed that BLEVE occurs, the tank explodes and the chemical burns in a fireball. Input values for the program are presented in Table 4.6.

Table 4.6 : Case 6 input data

Parameter	**Unit / Value**
Gas	Propane
Tank type	Cylindrical
Tank diameter	3.6 m
Tank length	18 m
Wind speed, direction	10.8 m/s NNE
Ambient Temperature	10.5 ^{o}C
Humidity	% 70
Temperature inside tank	8 ^{o}C
Filling ratio of tank	% 90
Leak type, dimension	Circular opening 2 inc at top of tank (%85 of tank)

Figure 4.26 shows the effects of a toxic area of a vapour cloud where the maximum distance for TEEL-1, TEEL-2 and TEEL-3 is up to 160 meters. Figure 4.27 shows the effects of the flammable area of vapour cloud; the red zone is calculated as 36 meters, but, the threat zone is not drawn because the effects of near-field patchiness make dispersion predictions less reliable for short distances. The orange zone is as large as 53 meters wherein concentration is %60 of LEL and flame pockets occur. The yellow zone is as large as 173 meters wherein concentration is %10 of LEL. Figure 4.28 shows the effects from the blast area of a vapour cloud explosion. It is assumed that the time of the vapour cloud ignition is not known, that it is ignited by a flame or spark and the level of congestion is defined as "congested".

The red zone in Figure 4.28 indicates 55.2 kPa which is never exceeded; the orange zone is as large as 39 meters wherein overpressure is 24.15 kPa. The yellow zone is as large as 60 meters wherein overpressure is 6.9 kPa. The orange zone is susceptible to the triggering of a fire or explosion and the effects of a 24.15 kPa overpressure on property is the collapse of self-framing steel buildings; rupture of oil storage tanks, and the snapping failure of wooden utility tanks. The yellow zone has the less dangerous effects of a 6.9 kPa overpressure. There is shattering of glass windows, the occasional damage to window frames, the partial demolition of houses, the shattering of corrugated asbestos siding, failure of corrugated aluminium-steel panelling, and the failure of wood siding panels. In the yellow zone the effects on humans are skin laceration from flying glass [45].

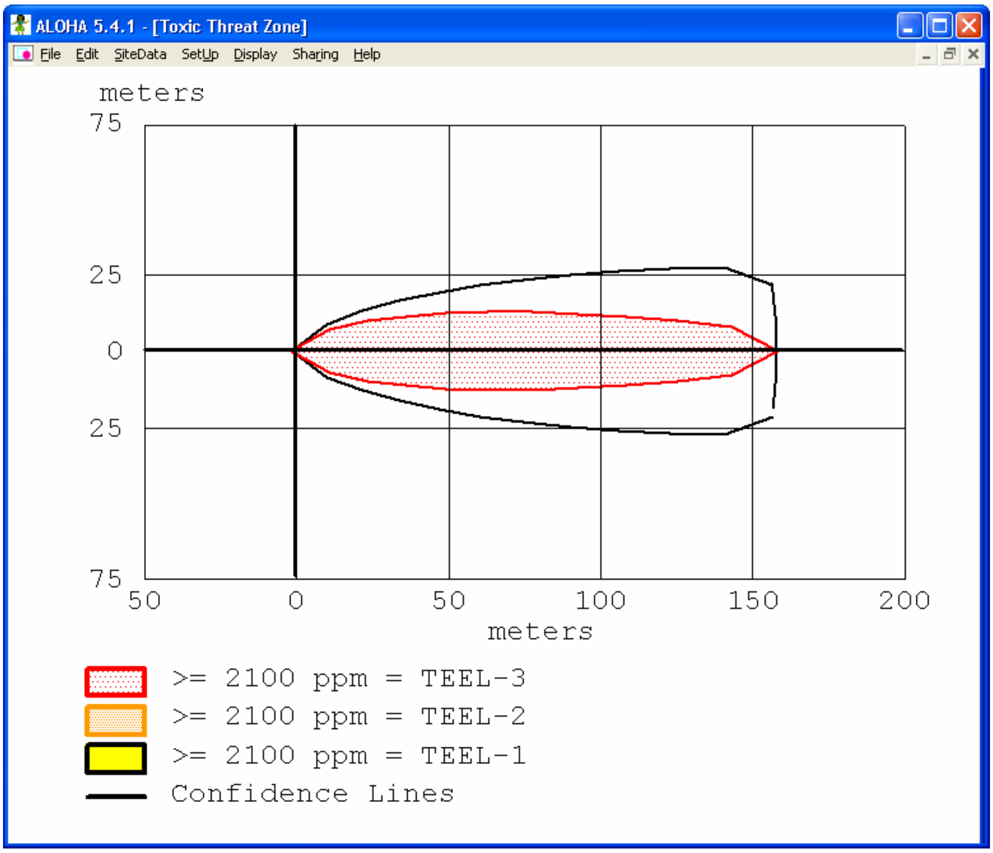

Figure 4.26 : Case -6 Toxic Area of Vapour Cloud

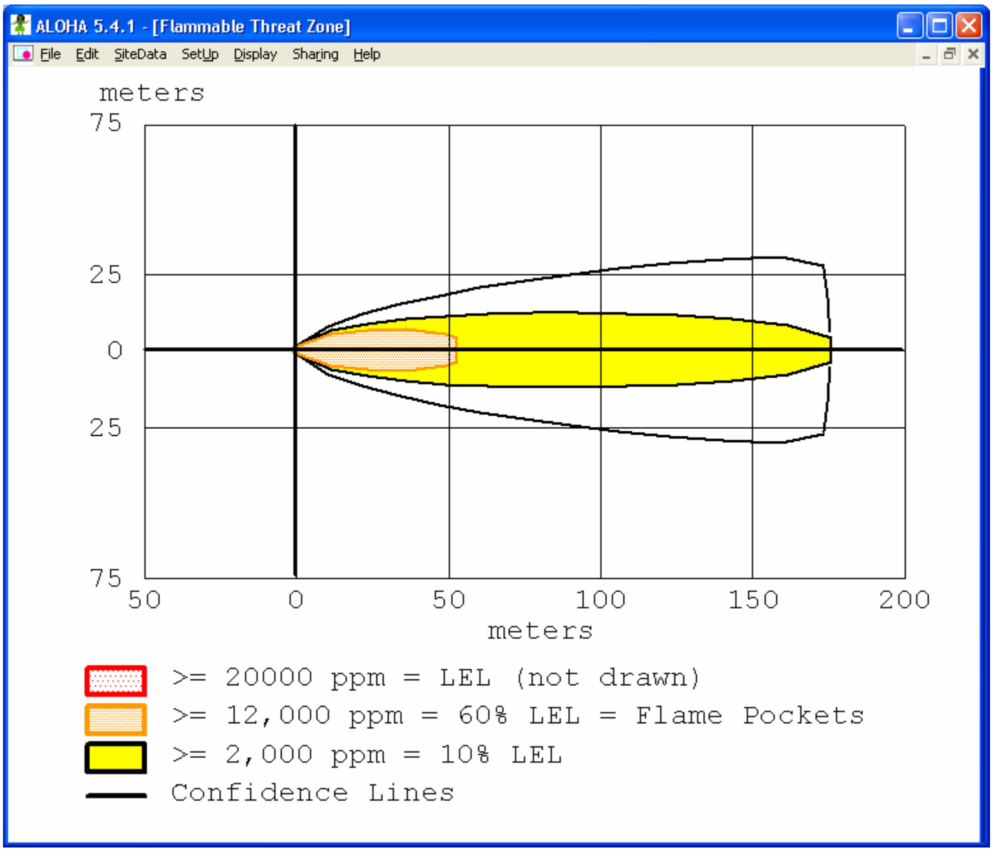

Figure 4.27 : Case – 6 Flammable Area of Vapour Cloud

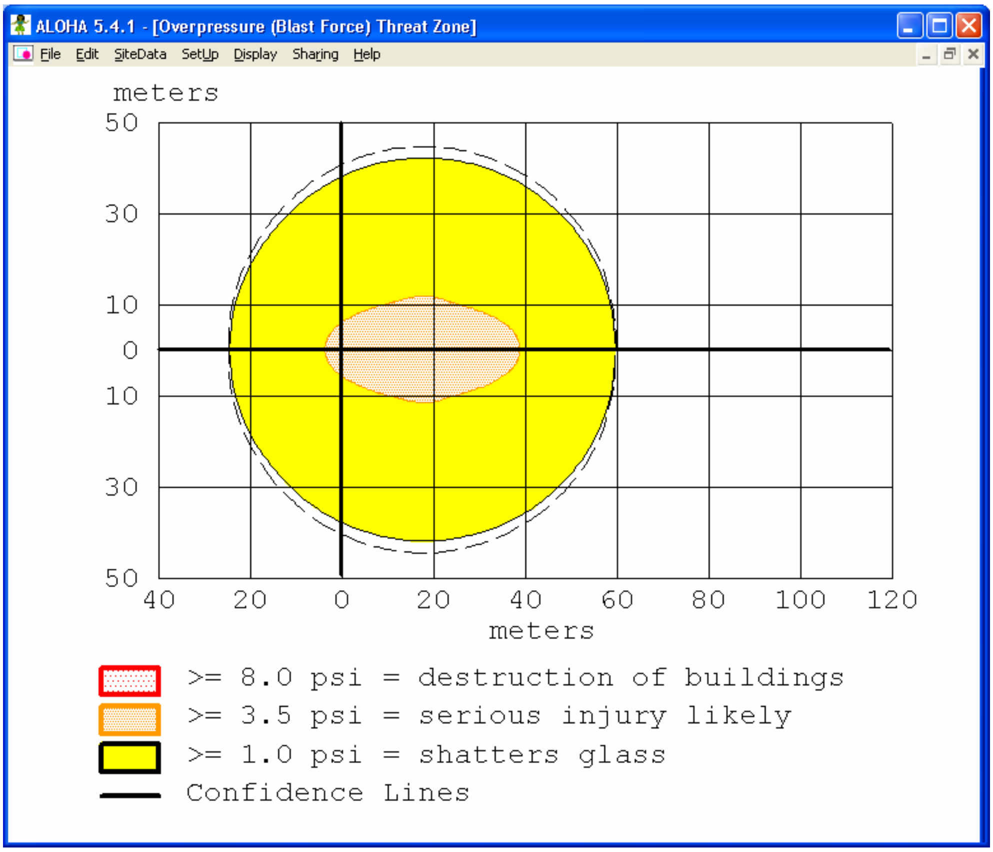

Figure 4.28 : Case – 6 Blast Area of Vapour Cloud Explosion

Figure 4.29 indicates the simulation results from the burning of propane as a jet fire. In this situation there is leakage from a tank and it burns as a jet fire. In figure 4.29 the red zone is as large as 33 meters wherein thermal radiation is 10.0 kW/m2 and potentially lethal in 60 seconds; the orange zone is as large as 45 meters wherein thermal radiation is 5.0 kW/m2 and 2nd degree burns occurs within 60 seconds; the yellow zone is as large as 67 meters wherein thermal radiation is 2.0 kW/m2 and pain occurs within 60 seconds.

Figure 4.30 indicates the simulation results for BLEVE, tank explosion and propane burning in a fireball. The red zone is as large as 580 meters wherein thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds. The orange zone is as large as 819 meters wherein thermal radiation is 5.0 kW/m^2 and 2nd degree burns occurs within 60 seconds. The yellow zone is as large as 1.3 km wherein thermal radiation is a 2.0 kW/m^2 and pain occurs within 60 seconds.

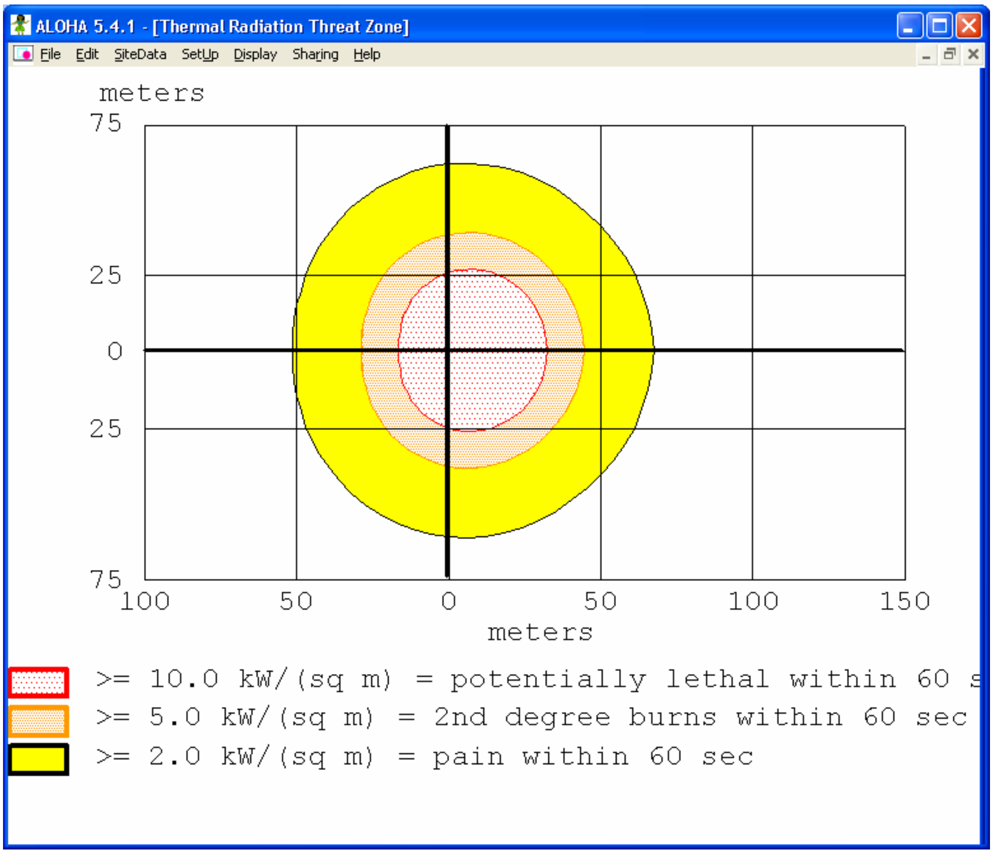

Figure 4.29 : Case – 6 Chemical is Burning as a Jet Fire

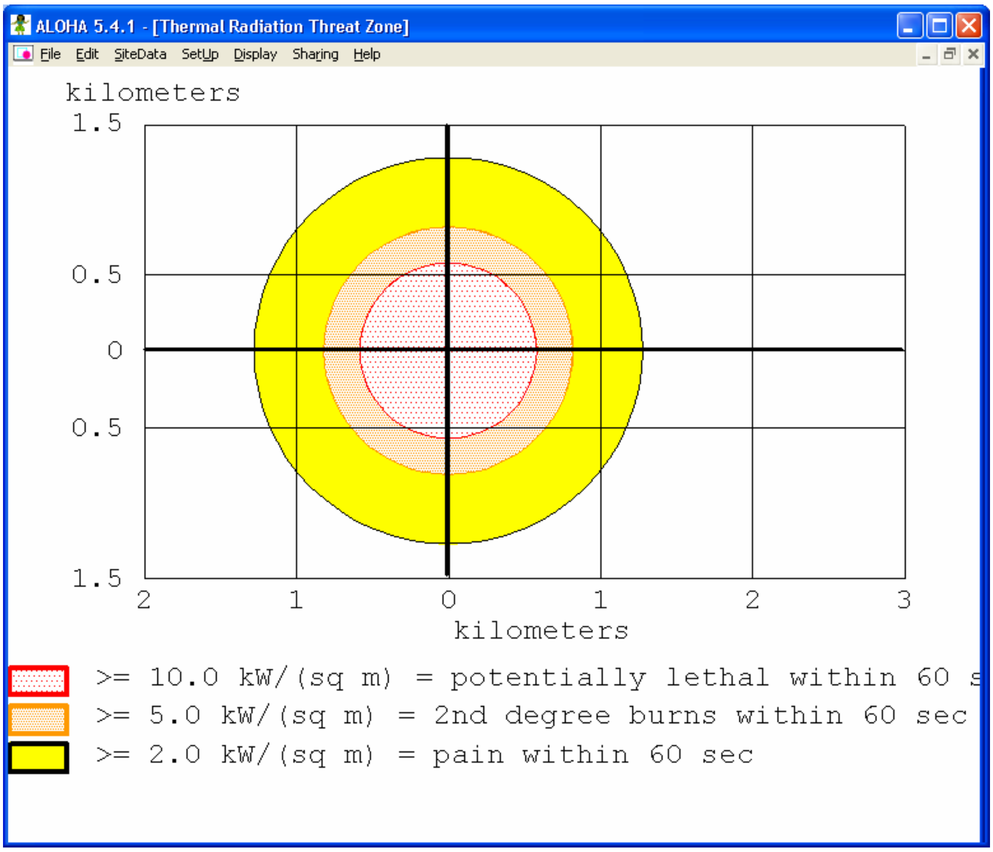

Figure 4.30 : Case -6 BLEVE, tank explodes and chemical burns in a fireball

4.1.2 Case – 7

In the seventh case it is assumed that there is a leak from a 4 inc circular opening at the top of a tank and that the tank is %90 full. For this case, it is first assumed that there is a leak from the tank and there is no fire and the area of the vapour cloud, the flammable area of the vapour cloud and the blast area of the vapour cloud explosion is simulated. Then, it is assumed that there is a leak from tank and it burns as a jet fire. Finally, it is assumed that BLEVE occurs, the tank explodes and the chemical burns in a fireball. Input values for the program are presented in Table 4.7.

Table 4.7 : Case 7 Input Data

Parameter	Unit / Value
Gas	Propane
Tank type	Cylindrical
Tank diameter	3.6 m
Tank length	18 m
Wind speed, direction	10.8 m/s NNE
Ambient Temperature	10.5 ^{o}C
Humidity	% 70
Temperature inside tank	8 ^{o}C
Filling ratio of tank	% 90
Leak type, dimension	Circular opening 4 inc at top of tank (%85 of tank)

In figure Figure 4.31 the effects of the toxic area of a vapour cloud are presented; the maximum distance for TEEL-1, TEEL-2 and TEEL-3 is as large as 324 meters. Figure 4.32 includes the effects of the flammable area of a vapour cloud; the red zone is calculated as 72 meters wherein concentration is equal to LEL. The orange zone is as large as 102 meters wherein concentration is %60 of LEL and flame pockets occur. The yellow zone is as large as 342 meters wherein concentration is %10 of LEL.

Figure 4.33 presents results from the blast area of a vapour cloud explosion. It is assumed that the time of the vapour cloud ignition is not known, that it is ignited by a flame or spark and that the level of congestion is defined as “congested”. The red zone in Figure 4.33 indicates a 55.2 kPa overpressure which is never exceeded; the orange zone is as large as 57 meters wherein the overpressure is 24.15 kPa and the yellow zone is as large as 113 meters wherein overpressure is 6.9 kPa. The orange zone is liable to the triggering of a fire or explosion and the effects of 24.15 Kpa overpressure for property are the collapse of self-framing steel buildings, the rupture of oil storage tanks, and the snapping failure of wooden utility tanks. The yellow zone has the less dangerous effects of a 6.9 kPa overpressure with shattering glass windows, occasional damage to window frames, the partial demolition of houses, shattering corrugated asbestos siding, the failure of corrugated aluminium-steel panelling, and the failure of wood siding panels. In the yellow zone the danger to humans is skin laceration from flying glass [45].

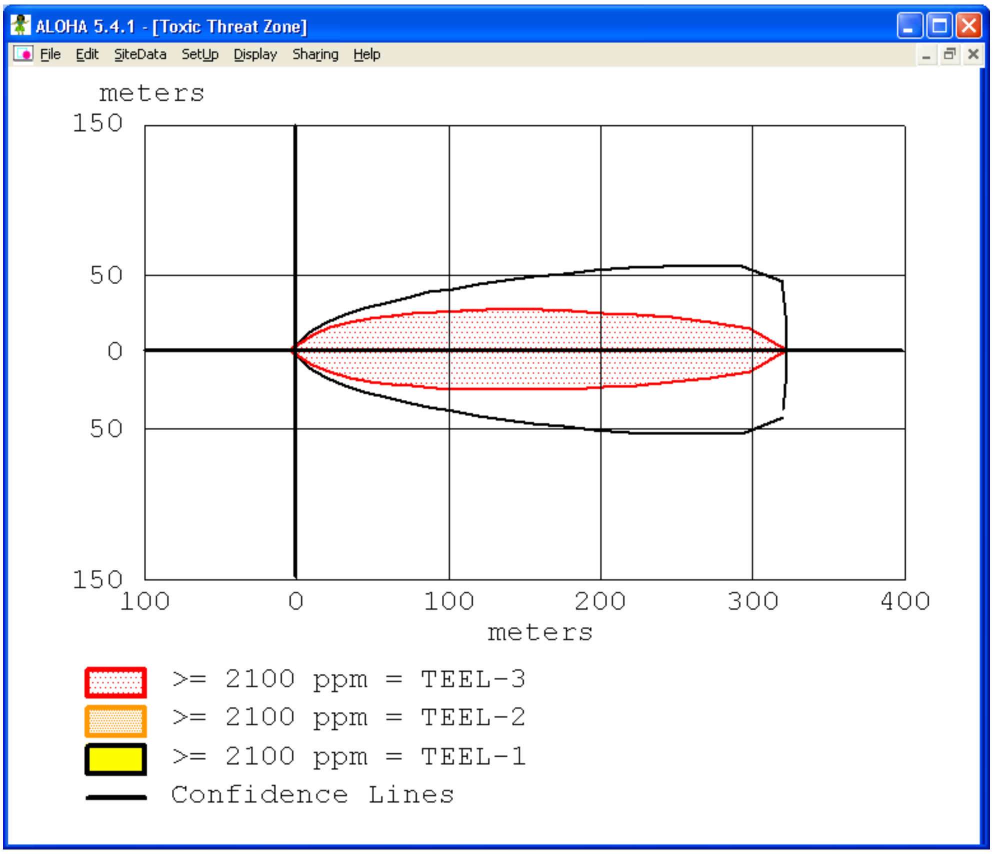

Figure 4.31 : Case -7 Toxic Area of Vapour Cloud

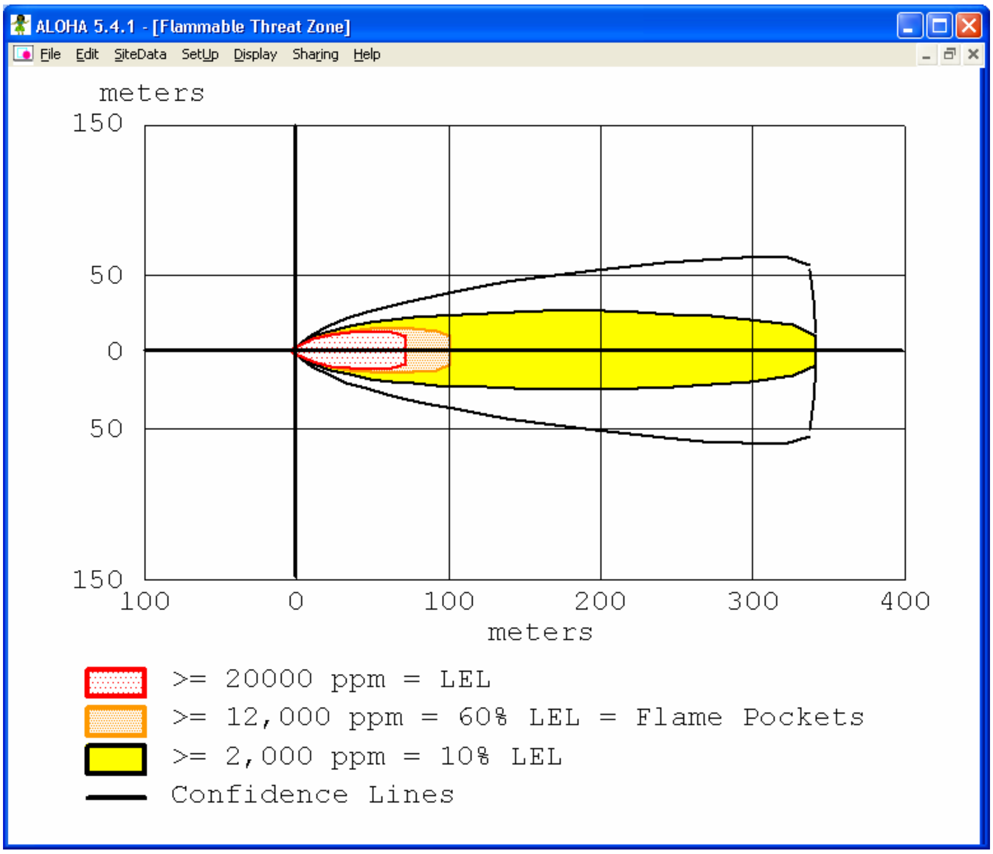

Figure 4.32 : Case – 7 Flammable Area of Vapour Cloud

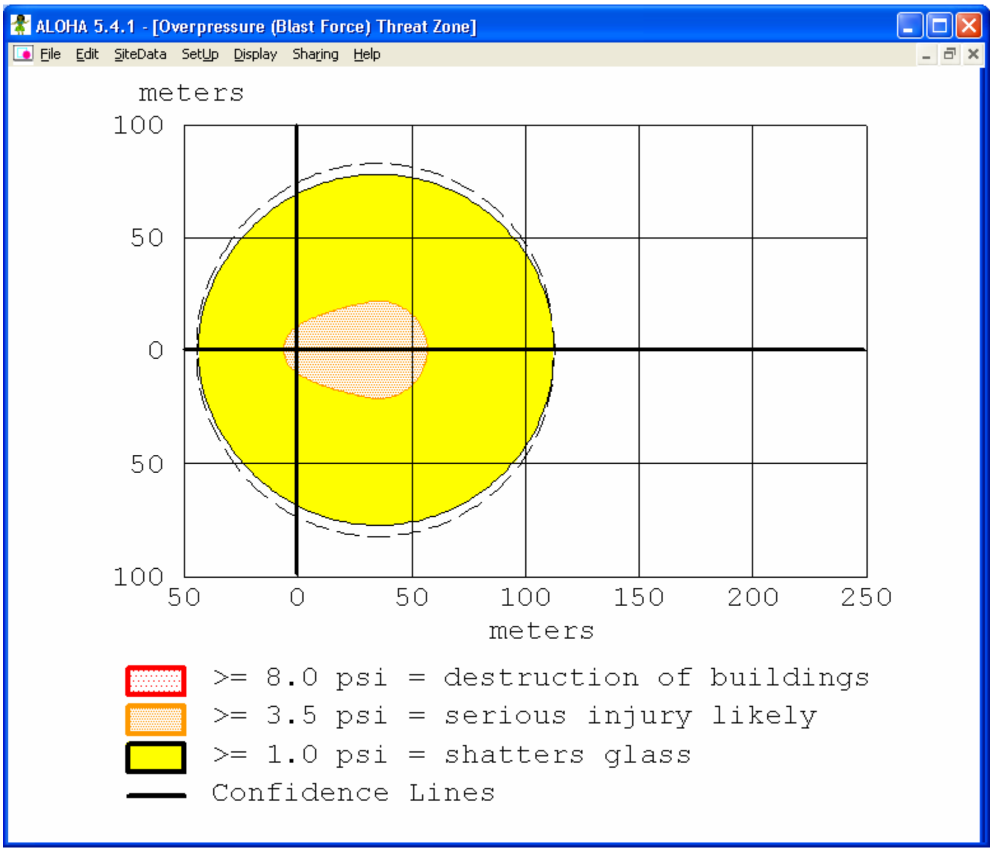

Figure 4.33 : Case – 7 Blast Area of Vapour Cloud Explosion

Figure 4.34 indicates simulated results of burning propane as a jet fire. In this example there is leakage from a tank and it burns as a jet fire. In Figure 4.34 the red zone is as large as 62 meters wherein thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds; the orange zone is as large as 85 meters wherein thermal radiation is 5.0 kW/m^2 and 2nd degree burns occurs within 60 seconds, and, finally the yellow zone is as large as 130 meters wherein thermal radiation is 2.0 kW/m^2 and pain occurs within 60 seconds.

Figure 4.35 indicates the simulation results for BLEVE, a tank explosion and propane burning as a fireball. The red zone is as large as 580 meters wherein thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds; the orange zone is as large as 819 wherein thermal radiation is 5.0 kW/m^2 and 2nd degree burns occurs within 60 seconds; the yellow zone is as large as 1.3 km with thermal radiation of 2.0 kW/m^2 and pain within 60 seconds.

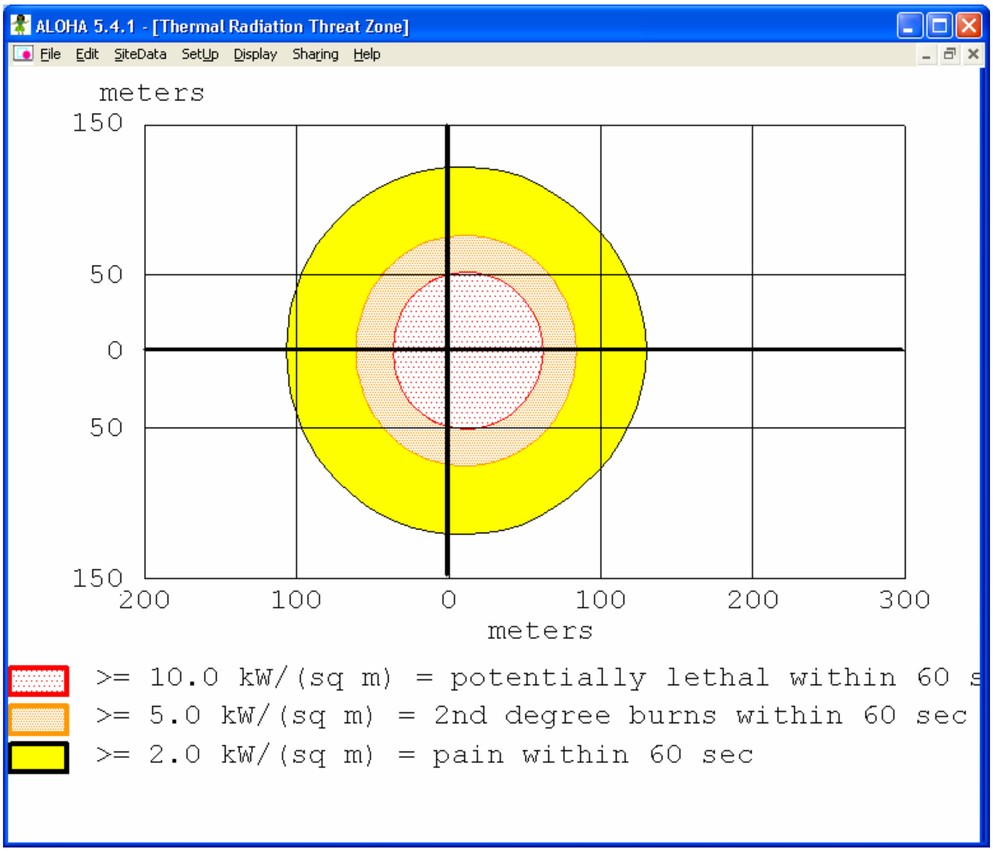

Figure 4.34 : Case – 7 Chemical is Burning as a Jet Fire

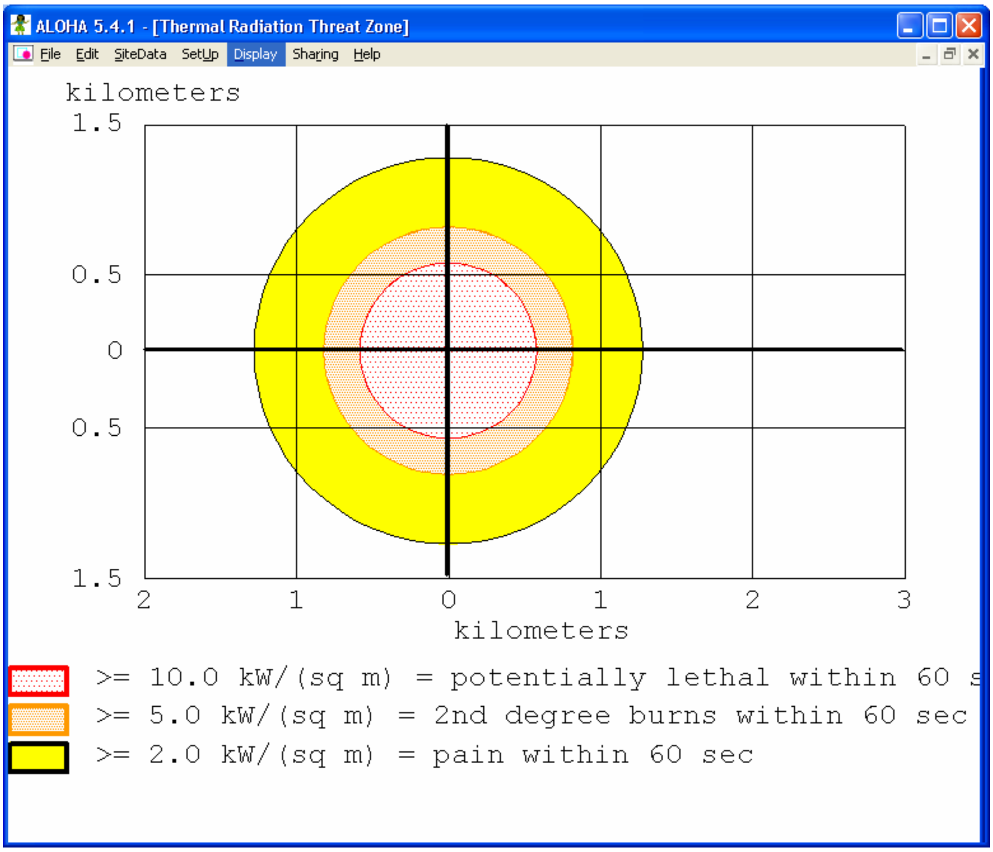

Figure 4.35 : Case -7 BLEVE, tank explodes and chemical burns in a fireball

4.1.8 Case – 8

In the last case, it is assumed that there is a leak from a 2 inc circular opening at the top of a tank, the tank is %90 full, but the atmospheric conditions are different. For this case, it is first assumed that there is a leak from the tank and that there is no fire and the area of the vapour cloud, the flammable area of the vapour cloud and the blast area of the vapour cloud explosion is simulated. It is then assumed that there is a leak from the tank and it burns as a jet fire. Finally, it is assumed that BLEVE occurs, tank explodes and the chemical burns as a fireball. Input values for the program are presented in Table 4.8.

Table 4.8 : Case 8 input data

Parameter	**Unit / Value**
Gas	Propane
Tank type	Cylindrical
Tank diameter	3.6 m
Tank length	18 m
Wind speed, direction	2 m/s NNE
Ambient Temperature	28 ^{o}C
Humidity	% 70
Temperature inside tank	26 ^{o}C
Filling ratio of tank	% 90
Leak type, dimension	Circular opening 2 inc at top of tank (%85 of tank)

Figure 4.36 shows the effects of the toxic area of a vapour cloud, where the maximum distance for TEEL-1, TEEL-2 and TEEL-3 is up to 291 meters. Figure 4.37 includes the effects of the flammable area of the vapour cloud; the red zone is calculated as 85 meters wherein concentration is equal to the LEL value. The orange zone is as large as 111 meters wherein concentration is %60 of LEL and flame pockets occur. The yellow zone is as large as 299 meters wherein concentration is %10 of LEL. Figure 4.38 indicates the results from the blast area of a vapour cloud explosion. It is assumed that the time of ignition is not known, that it is ignited by a flame or spark and the level of congestion is defined as “congested”.

The red zone in Figure 4.38 indicates a 55.2 kPa which is never exceeded; the orange zone is as large as 91 meters wherein the overpressure is 24.15 kPa. The yellow zone is as large as 155 meters wherein overpressure is 6.9 kPa. The orange zone is susceptible to the triggering of fires or explosion and the effects of a 24.15 kPa overpressure to property is the collapse of self-framing steel buildings, the rupture of oil storage tank; and the snapping failure of wooden utility tanks. The yellow zone has the less dangerous effects of a 6.9 kPa overpressure with the shattering of glass windows, occasional damage to window frames, the partial demolition of houses, the shattering of corrugated asbestos siding, the failure of corrugated aluminium-steel panelling, and the failure of wood siding panels. In the yellow zone the effects on humans are skin laceration from flying glass [45].

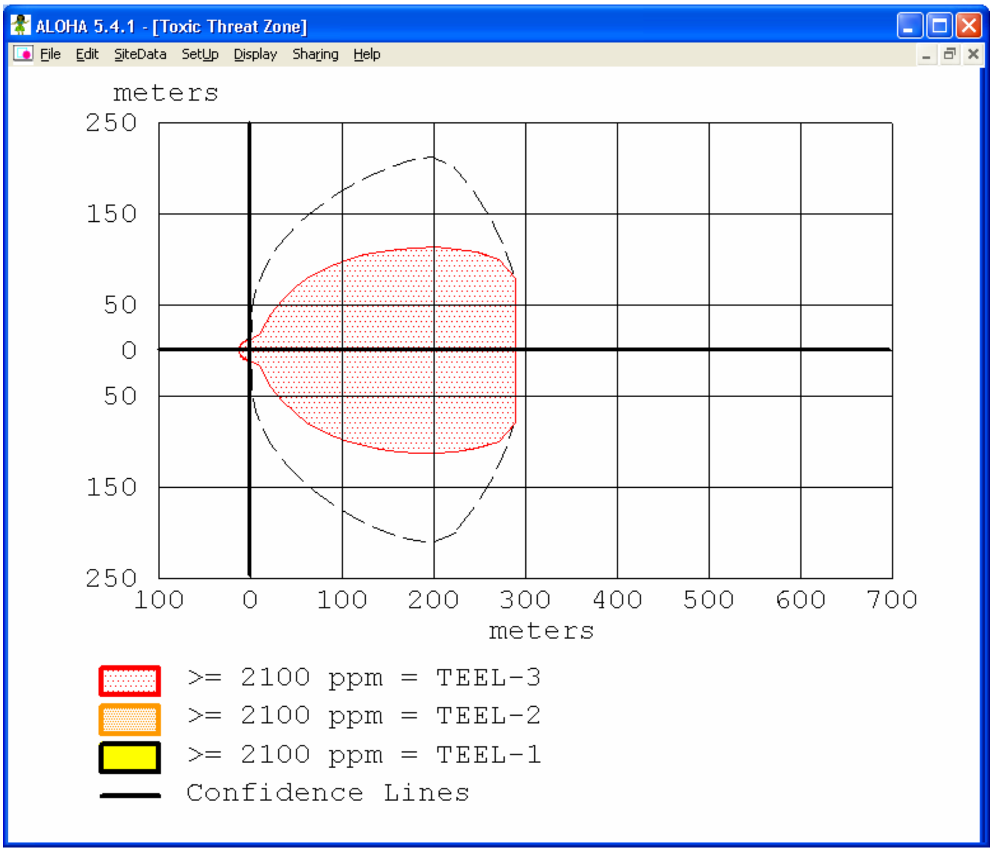

Figure 4.36 : Case -8 Toxic Area of Vapour Cloud

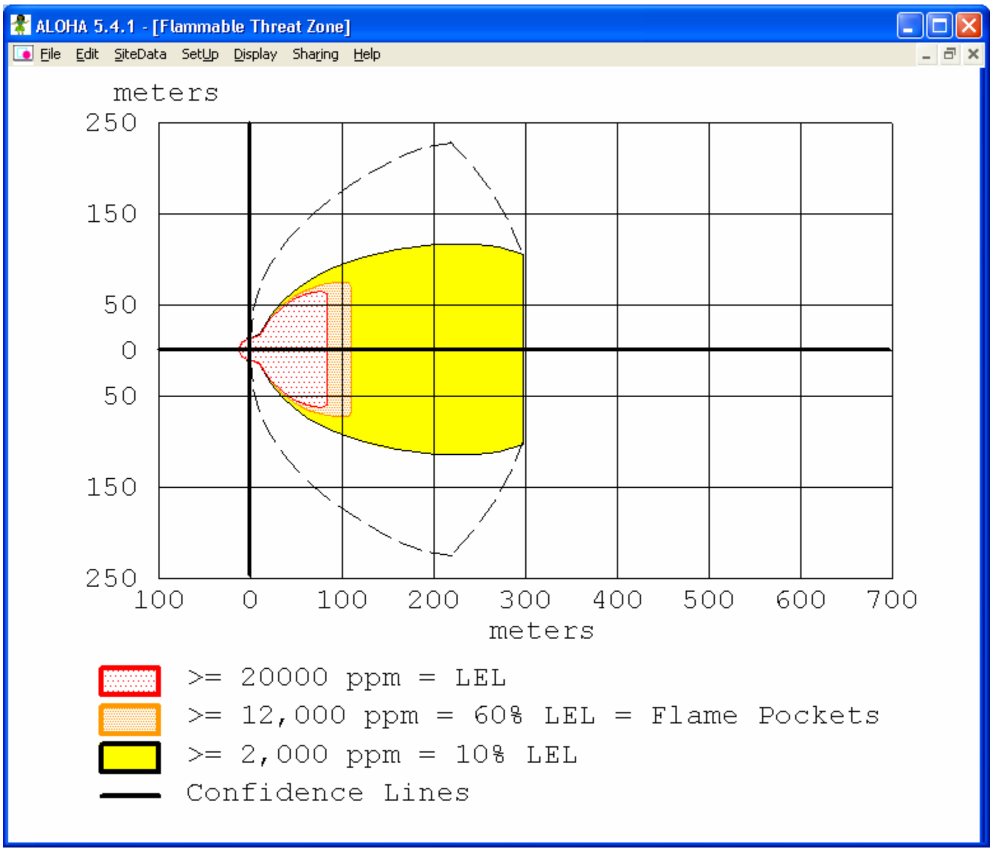

Figure 4.37 : Case – 8 Flammable Area of Vapour Cloud

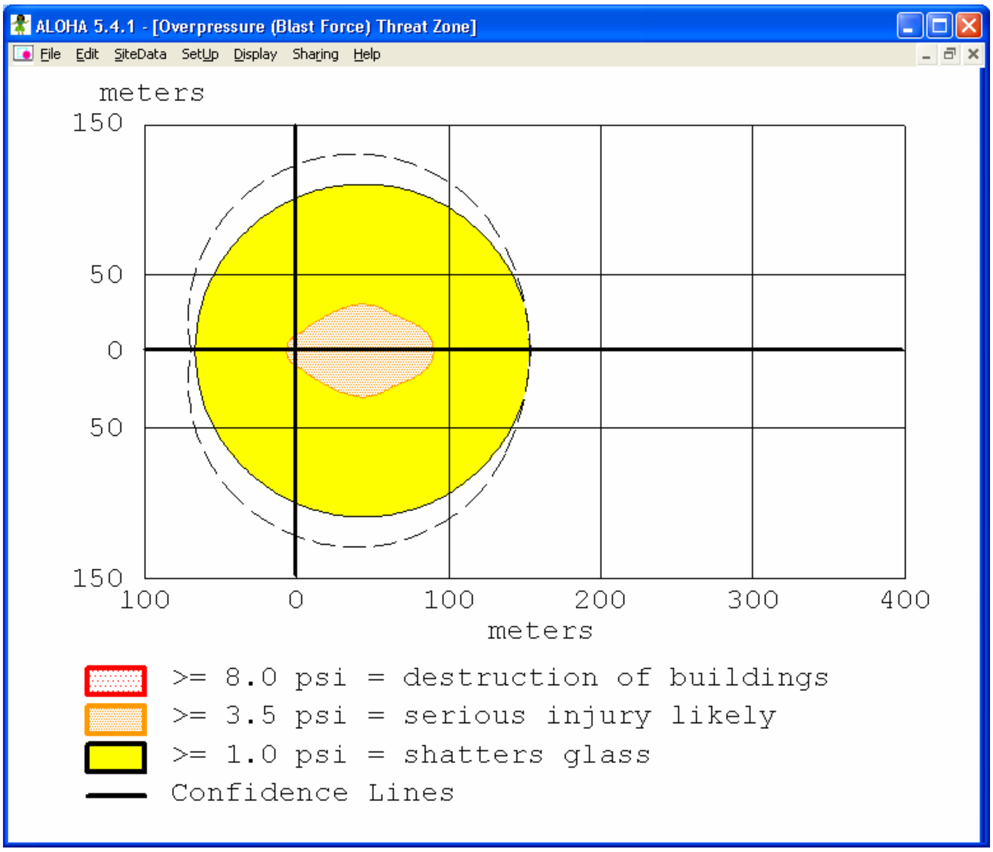

Figure 4.38 : Case – 8 Blast Area of Vapour Cloud Explosion

Figure 4.39 indicates the simulation results from burning propane as a jet fire. In this situation there is a leak from a tank and it burns as a jet fire. In figure 4.39 the red zone is as large as 31 meters wherein thermal radiation is 10.0 kW/m2 and potentially lethal in 60 seconds; the orange zone is as large as 45 m wherein thermal radiation is 5.0 kW/m2 and 2nd degree burns occurs within 60 seconds; the yellow zone is as large as 70 meters with a thermal radiation of 2.0 kW/m2 and pain occurs within 60 seconds.

Figure 4.40 indicates simulation results for BLEVE, tank explosion and propane burning in a fireball. The red zone is as large as 540 meters wherein thermal radiation is 10.0 kW/m2 and potentially lethal in 60 seconds. The orange zone is as large as 762 meters wherein the thermal radiation is 5.0 kW/m^2 and 2nd degree burns occurs within 60 seconds. The yellow zone is as large as 1.2 km with thermal radiation of 2.0 kW/m^2 and pain within 60 seconds.

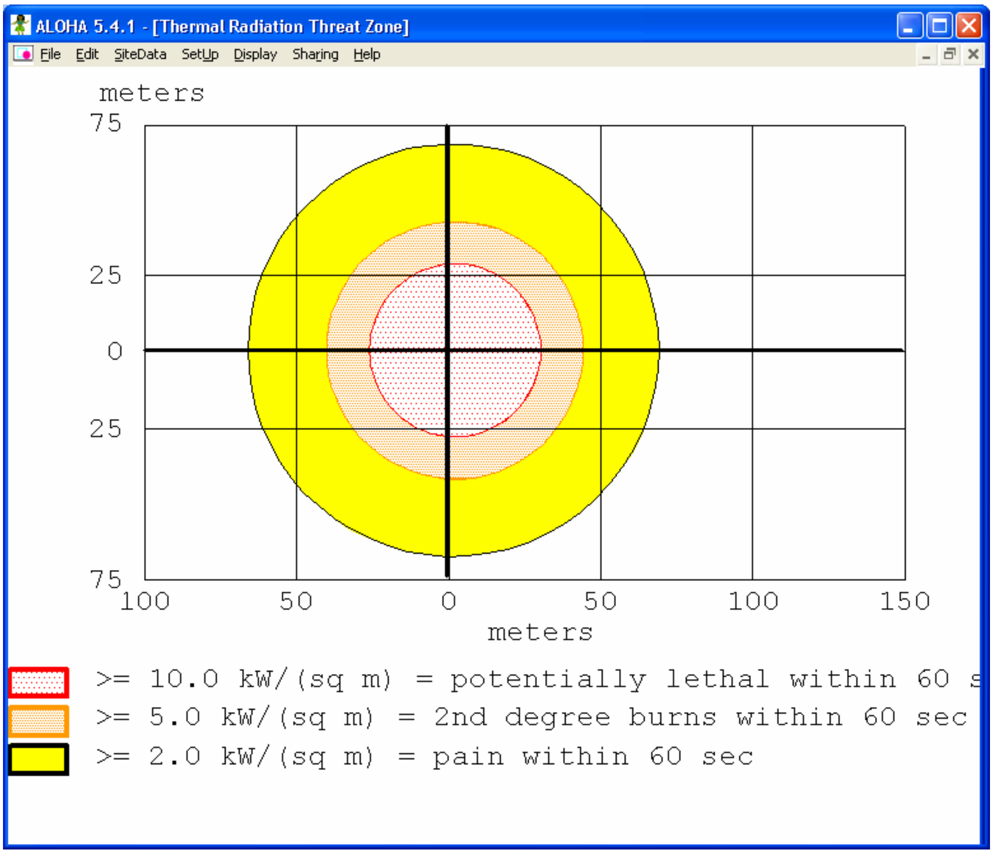

Figure 4.39 : Case – 8 Chemical is Burning as a Jet Fire

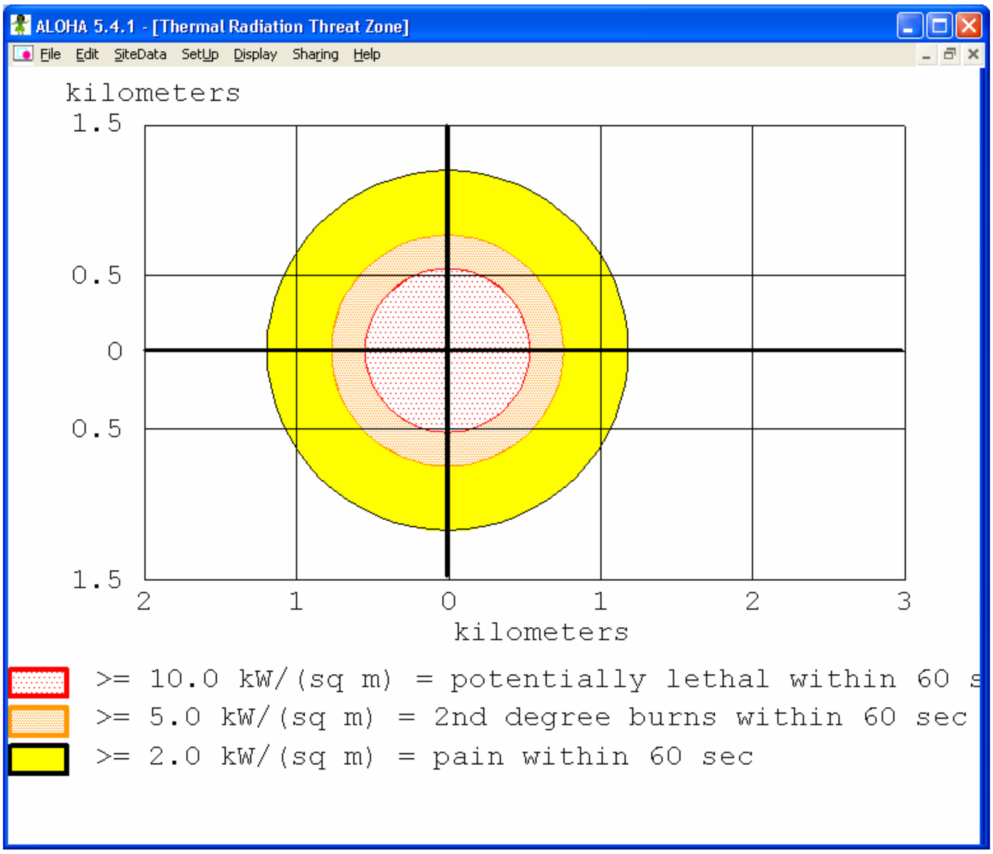

Figure 4.40 : Case -8 BLEVE, tank explodes and chemical burns in a fireball

4.1.9 Risk determination of case -1

For case -1 the simulation of the toxic area of the vapour cloud, the flammable area of a vapour cloud, the blast area of a vapour cloud explosion and the burning of a LPG as a jet fire are shown on a real plant. In figure 4.41 there is a map of the LPG filling station.

Figure 4.42 shows simulation results for the toxic area of the vapour cloud. In the figure it is indicated that the toxic area of the vapour cloud is covering the LPG pump area and maximum perimeter is outside of the plant area. So there is a risk to the neighbouring area. There is no significant risk for workers because management and social facility building, and the filling house are outside of the affected area.

Figure 4.43 indicates the flammable area of the vapour cloud. If there is leakage the flammable area of the vapour cloud is covers the LPG pump area and a zone of outside the plant. It is advantageous that the LPG pump station is exproof because in this area the concentration of gas is %60 of the LEL value. Because the flammable area is outside of the plant zone there is a risk to neighbouring plants and property.

There is no significant risk for workers because management and social facility building and filling house are outside of the affected area.

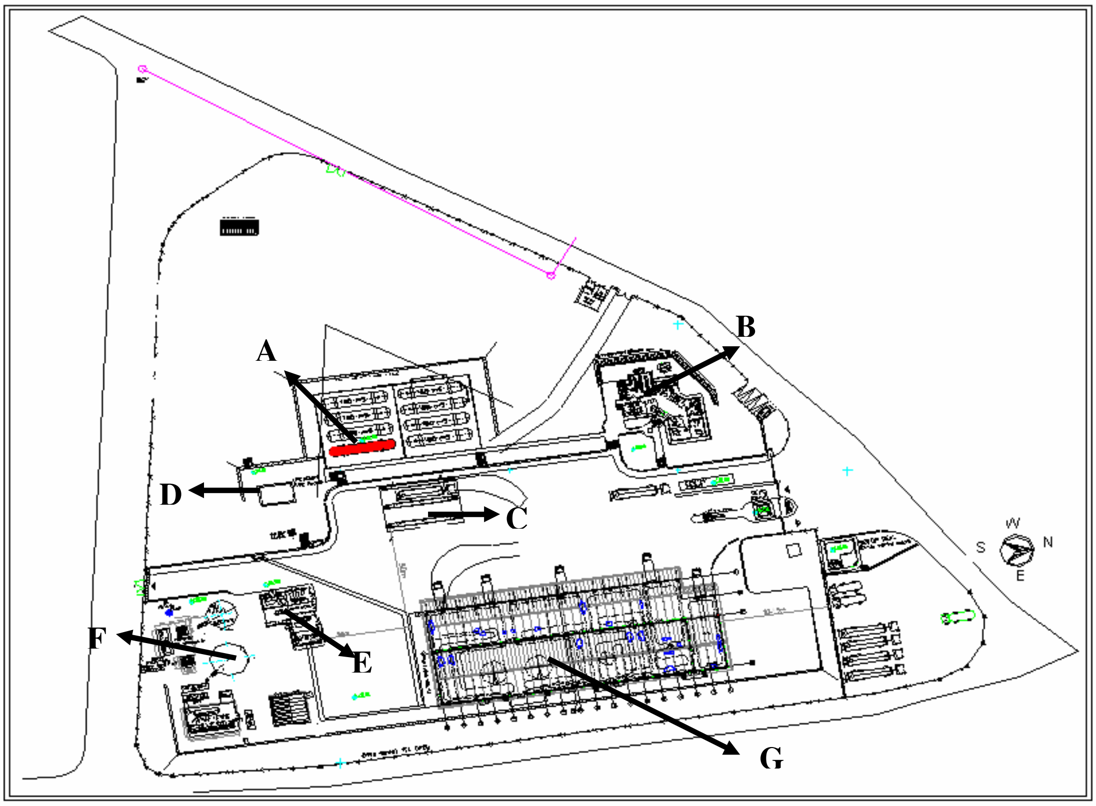

Figure 4.41 : Map of LPG Filling Station

A: Propane Storage Tank

B: Management and Social Facility Building

C: Truck Tanker

D: LPG Pump

E: Power Buıldıng

F: Water Tanks

G: Filling House

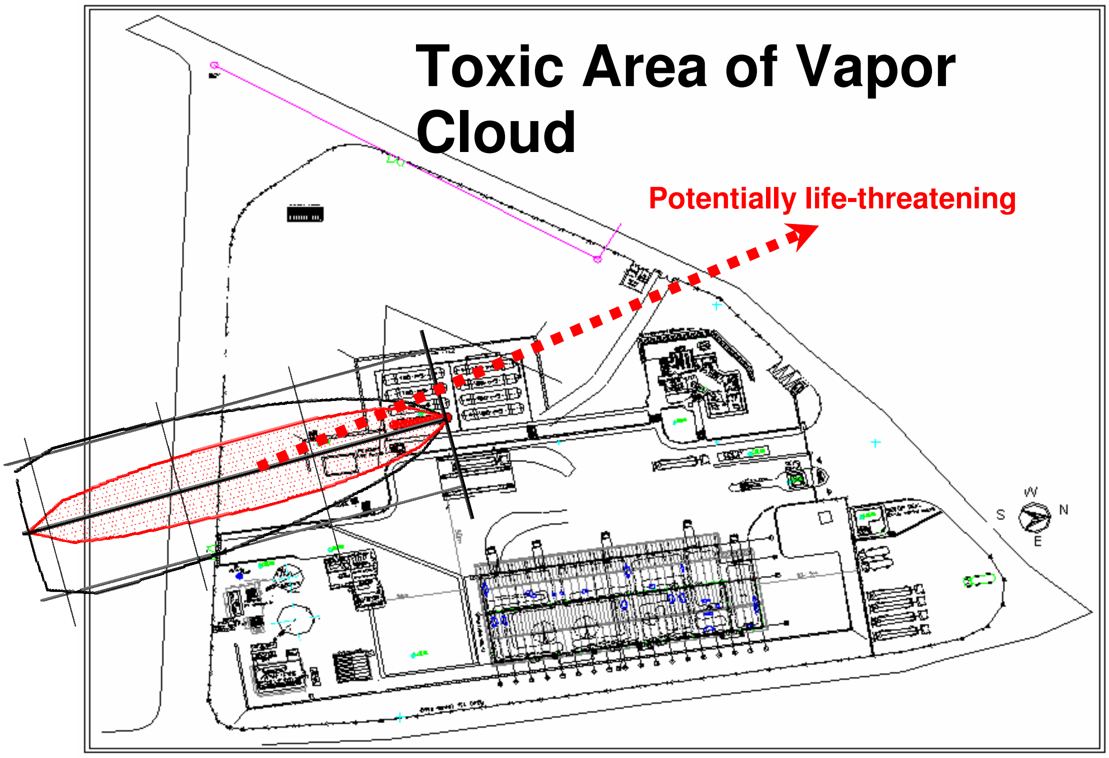

Figure 4.42 : Toxic Area Of Vapour Cloud

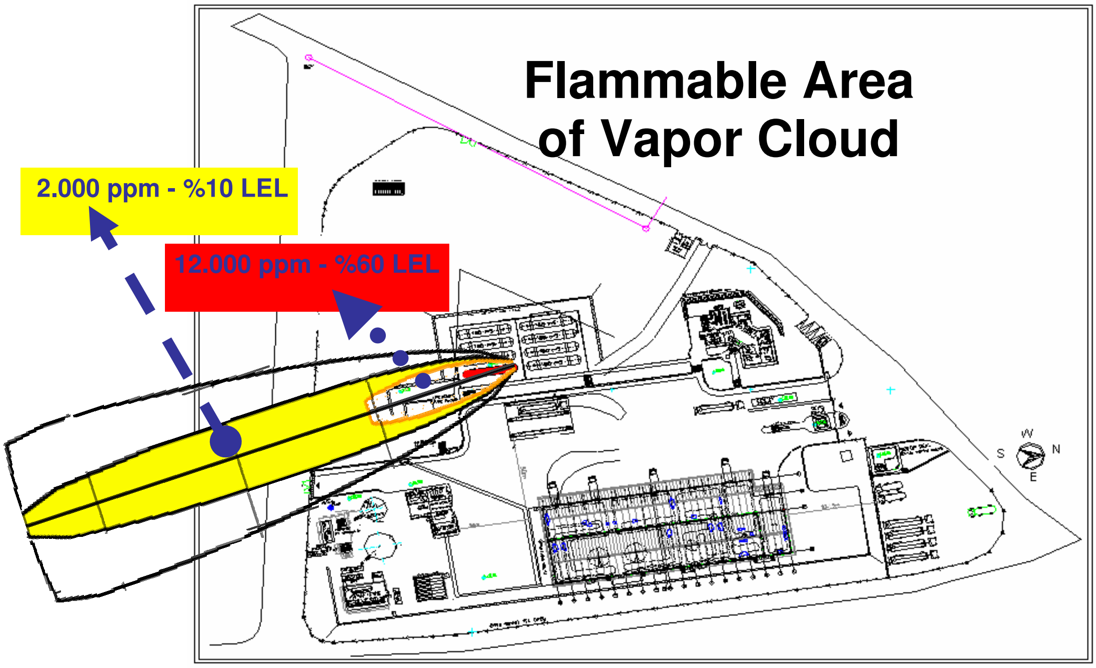

Figure 4.43 : Flammable area of vapour cloud

Figure 4.44 indicates the blast area of the vapour cloud explosion. In the event of a vapour cloud explosion, blast effects for 6.9 kPa and 24.15 kPa are simulated on the map. The orange zone is dangerous for its susceptibility to fire or explosion; the effects of a 24.15 kPa overpressure to property are a collapse of self-framing steel buildings, the rupture of oil storage tanks, and a snapping failure of wooden utility tanks. The yellow zone has the less dangerous effects of a 6.9 kPa overpressure to property with the shattering of glass windows, occasional damage to window frames, the partial demolition of houses, shattering of corrugated asbestos siding, the failure of corrugated aluminium-steel panelling, and a failure of wood siding panels. In the yellow zone the effect on humans is skin laceration from flying glass [31]. The red zone includes LPG pump and the neighbouring LPG storage tanks. The yellow zone is wide and includes a truck tanker, a power building and a small part of the filling house. There is no significant risk to workers because management, the social facility building and the filling house are outside the affected area.

Figure 4.45 indicates thermal radiation zone. The burning of a chemical as a jet fire is simulated on the map in three different zones: the first zone is very dangerous because thermal radiation is 10 KW/(sq m) and causes a death in 60 seconds. This zone includes the truck tanker and also a neighbouring storage tank. This can lead to an explosion of other storage tanks and the killing of workers in the truck tanker. The second zone is also dangerous as in this area the thermal radiation is 5 KW/(sq m) and resulting 2^{nd} degree burns in 60 seconds. The third zone is less dangerous as in this area thermal radiation is 2 KW/(sq m) and results in pain in 60 seconds. There is no significant risk to workers because management and the social facility building and the filling house are outside the affected area.

For case- 1 the BLEVE scenario is not shown on the map because for a % 90 full tank it is nearly impossible for BLEVE to occur. To simulate a BLEVE scenario, there should first be a calculated volume and the conditions in which BLEVE can occur.

As is indicated from the simulation results management and social facility building, and the filling house locations are in correct location. There is no significant risk for these places. But if there was a factory in south side of the plant it is necessary to do a risk assessment for that plant.

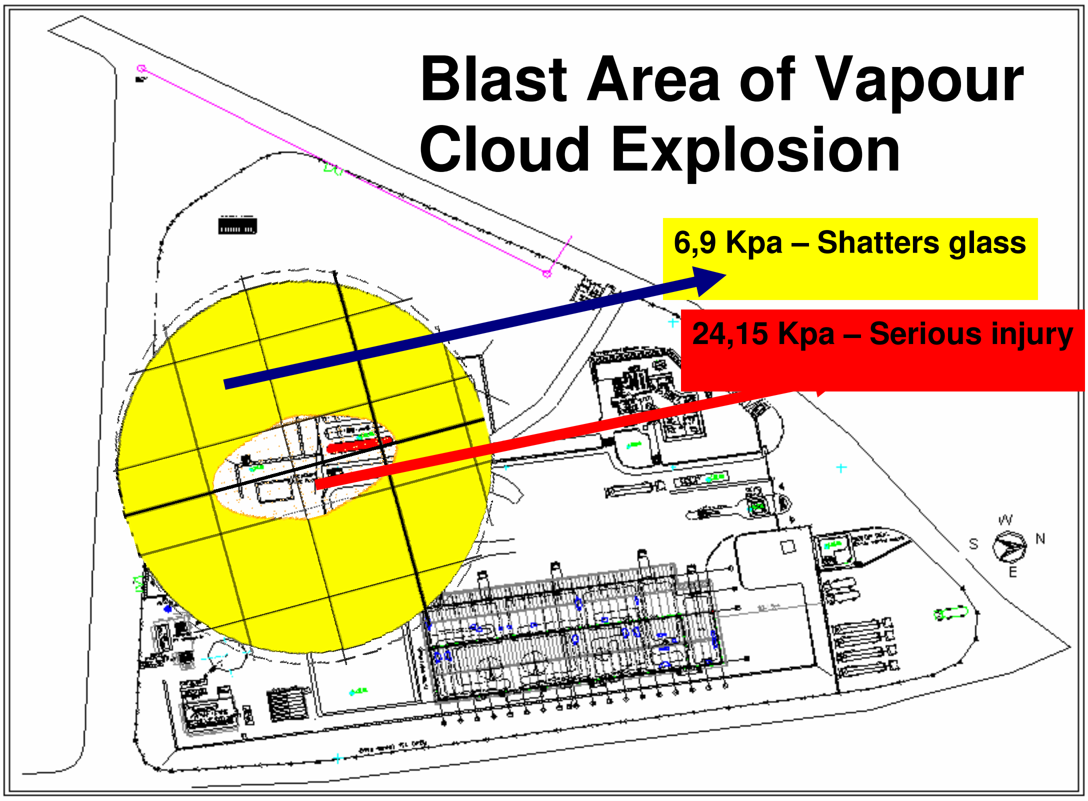

Figure 4.44 : Blast Area of Vapour Cloud Explosion

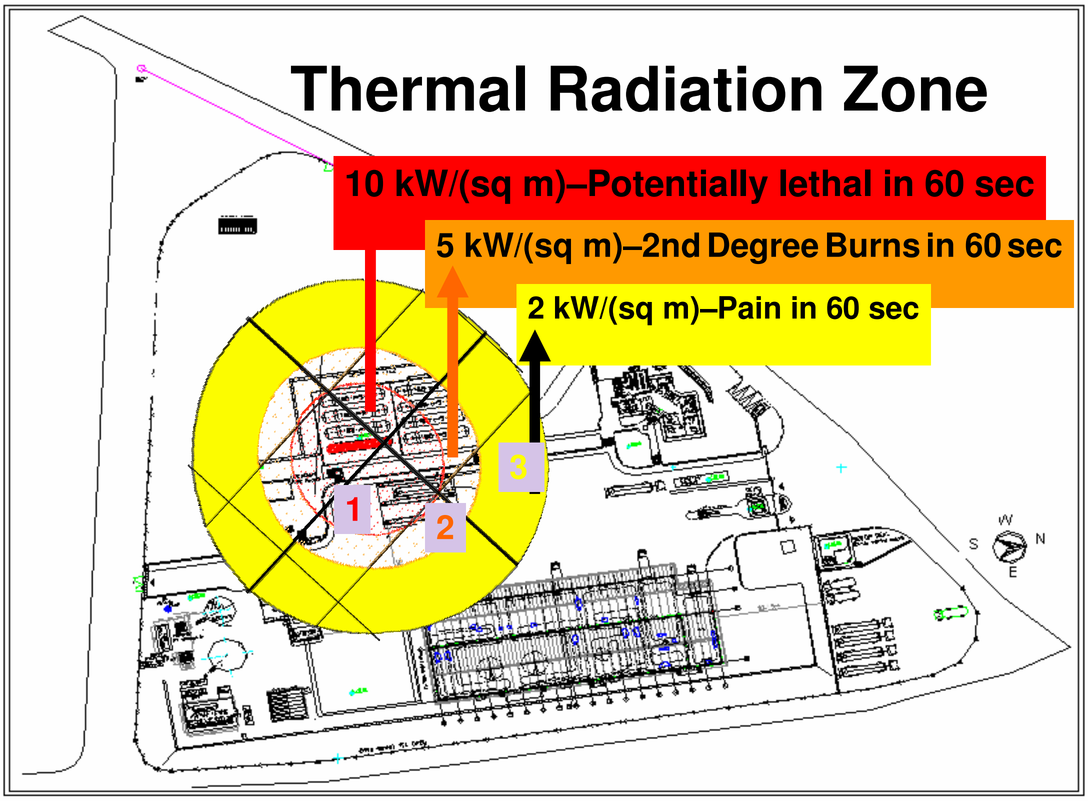

Figure 4.45 : Thermal Radiation Zone

Table 4.9 : Property Damage Criteria [45]

Overpressure (kPa)	Injury	Source
0,207	Occasional breaking of large glass windows already under strain	a
0,276	Loud noise (143 dB). Sonic boom glass failure	a
0,69	Breakage of small windows, under strain	a
1,035	Typical pressure for glass failure	a
2,07	Safe distance" (probability 0.95 no serious damage beyond this value) Missile limit Some damage to house ceilings 10% window glass broken	a
2,76	Minor structural damage	a, c
3,45 - 6,9	Shattering of glass windows, occasional damage to window frames. One source reported glass failure at 1 kPa (0.147 psi)	a, c, d, e
4,83	Minor damage to house structures	a
6,9	Partial demolition of houses, made uninhabitable	a
6,9 - 13,8	Shattering of corrugated asbestos siding Failure of corrugated aluminum–steel paneling Failure of wood siding panels (standard housing construction)	a, b, d, e
8,97	Steel frame of clad building slightly distorted	a
13,8	Partial collapse of walls and roofs of houses	a
13,8 - 20,7	Shattering of nonreinforced concrete or cinder block wall panels [10.3 kPa (1.5 psi) according to another source]	a, b, c, d
15,87	Lower limit of serious structural damage	a
17,25	50% destruction of brickwork of house	a
20,7	Steel frame building distorted and pulled away from foundations	a
20,7 - 28,29	Collapse of self-framing steel panel buildings Rupture of oil storage tanks Snapping failure — wooden utility tanks	a, b, c
27,6	Cladding of light industrial buildings ruptured	a
33,12	Failure of reinforced concrete structures	e
34,5	Snapping failure — wooden utility poles	a, b

Table 4.9 : Property Damage Criteria [45]

Overpressure (kPa)	Injury	Source
34,5 - 48,3	Nearly complete destruction of houses	a
48,3	Loaded train wagons overturned	a
48,3 - 55,2	Shearing/flexure failure of brick wall panels [20.3 cm to 30.5 cm (8 in. to 12 in.) thick, not reinforced] Sides of steel frame buildings blown in Overturning of loaded rail cars	a, b, c, d d b,c
62,1	Loaded train boxcars completely demolished	a
69	Probable total destruction of buildings	a
207	Steel towers blown down	b, c
607,2	Crater damage	e

aF. Lees, Loss Prevention in the Process Industries, 1996.
bBrasie and Simpson, 1968.
cU.S. Department of Transportation, 1988.
dU.S. Air Force, 1983.
eMcRae, 1984.

4.2 LPG Storage tank at İTÜ

In the Maslak Campus next to the central canteen there is a LPG storage tank. In this area if there is a leak from the tank the toxic area of the vapour cloud, the flammable area of the vapour cloud, the blast area of the vapour cloud explosion, the burning of a LPG as a jet fire and a BLEVE scenario are simulated. The first four simulations are shown on the İTÜ map, the map is copied from a google earth program.

Table 4.10 : Input Data for LPG Storage Tank at İTÜ

Parameter	Unit / Value
Gas	Propane
Tank type	Cylindrical
Tank diameter	1.17 m
Tank length	4.64 m
Wind speed, direction	4 m/s NNE
Ambient Temperature	10.5 ^{o}C
Humidity	% 70
Temperature inside tank	8 ^{o}C
Filling ratio of tank	% 90
Leak type, dimension	Circular opening 2 inc at bottom of tank

This case assumes there is a leakage from a 2 inc circular opening at the bottom of the tank and the tank is %90 full. For this scenario it is first assumed that there is a leak from the tank and there is no fire and area of vapour cloud, flammable area of vapour cloud and blast area of vapour cloud explosion is simulated. Then, it is assumed that there is a leak from the tank and it burns as a jet fire. Finally, it is assumed that BLEVE occurs, the tank explodes and the chemical burns as a fireball. The input values for program are presented in Table 4.10.

Figure 4.46 shows the toxic area of the vapour cloud, with a maximum distance for TEEL-1, TEEL-2 and TEEL-3 of up to 187 meters.

Figure 4.47 shows the flammable area of the vapour cloud; the red zone is calculated as 47 meters but the threat zone is not drawn because the effects of near-field patchiness make dispersion predictions less reliable for short distances. The orange zone is as large as 63 meters where concentration is %60 of LEL and flame pockets occurs. The yellow zone is as large as 193 meters where concentration is %10 of LEL.

Figure 4.48 indicates results from the blast area of a vapour cloud explosion. It is assumed that the time of the vapour cloud ignition is not known, that it is ignited by a flame or spark, and the level of congestion is defined as "congested". The red zone in Figure 4.48 indicates a 55.2 kPa which is never exceeded; the orange zone is as large as 43 meters with an overpressure of 24.15 kPa. The yellow zone is as large as 89 meters wherein the overpressure is 6.9 kPa. The orange zone is susceptible to the triggering of a fire or explosion and the effects of a 24.15 kPa overpressure for property are the collapse of self-framing steel buildings, the rupture of oil storage tanks, and the snapping failure of wooden utility tanks. The yellow zone has the dangerous effects of a 6.9 kPa overpressure for property with the shattering of glass windows, occasional damage to window frames, the partial demolition of houses, the shattering of corrugated asbestos siding, the failure of corrugated aluminium-steel panelling, and the failure of wood siding panels. In the yellow zone, the effects on humans is skin laceration from flying glass [45].

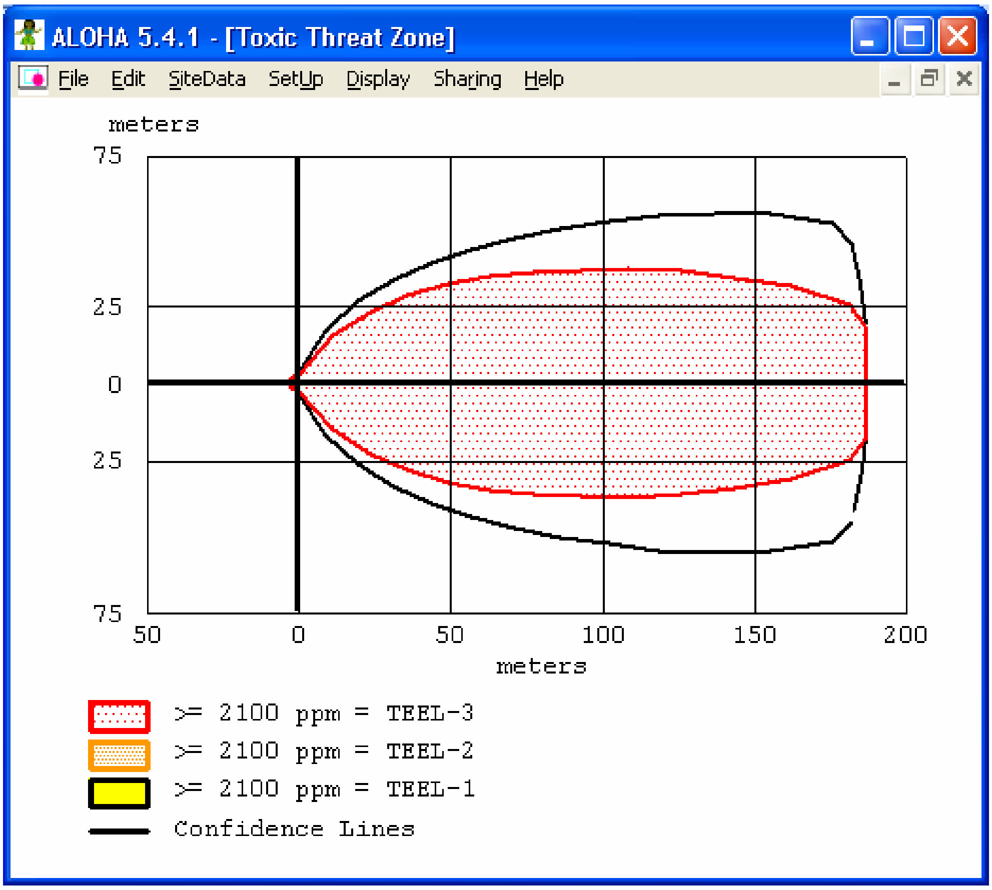

Figure 4.46 : Toxic Area of Vapour Cloud

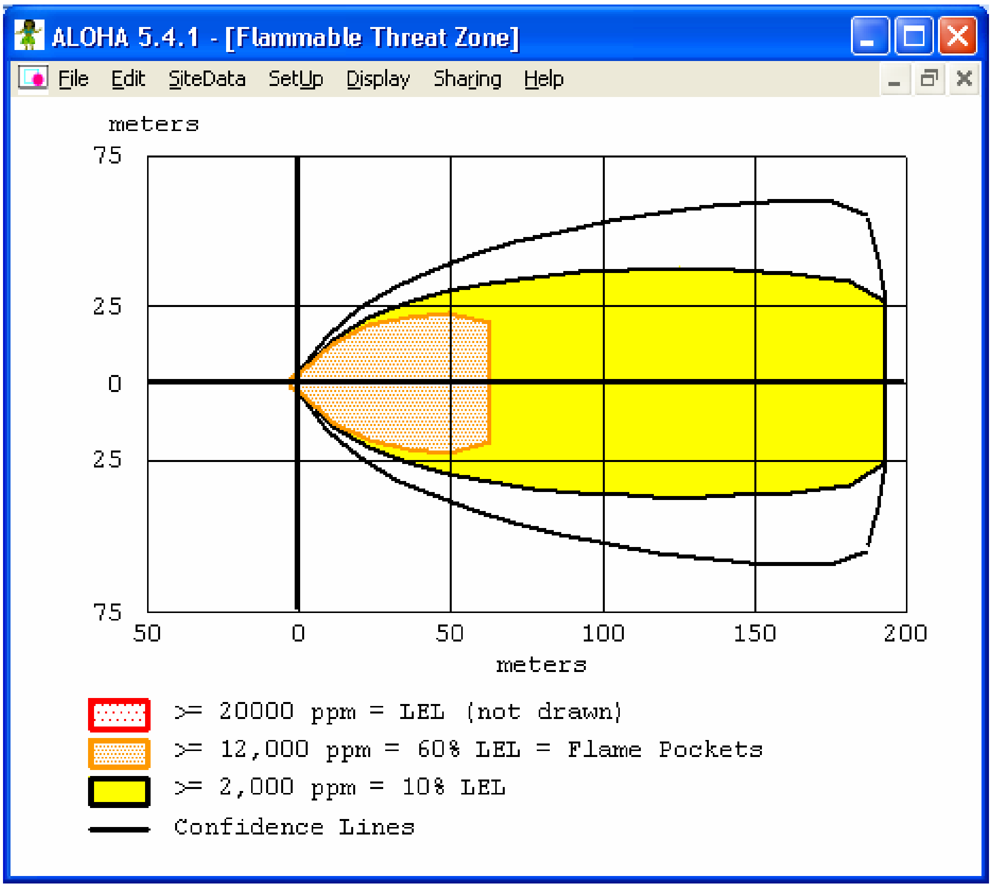

Figure 4.47 : Flammable Area of Vapour Cloud

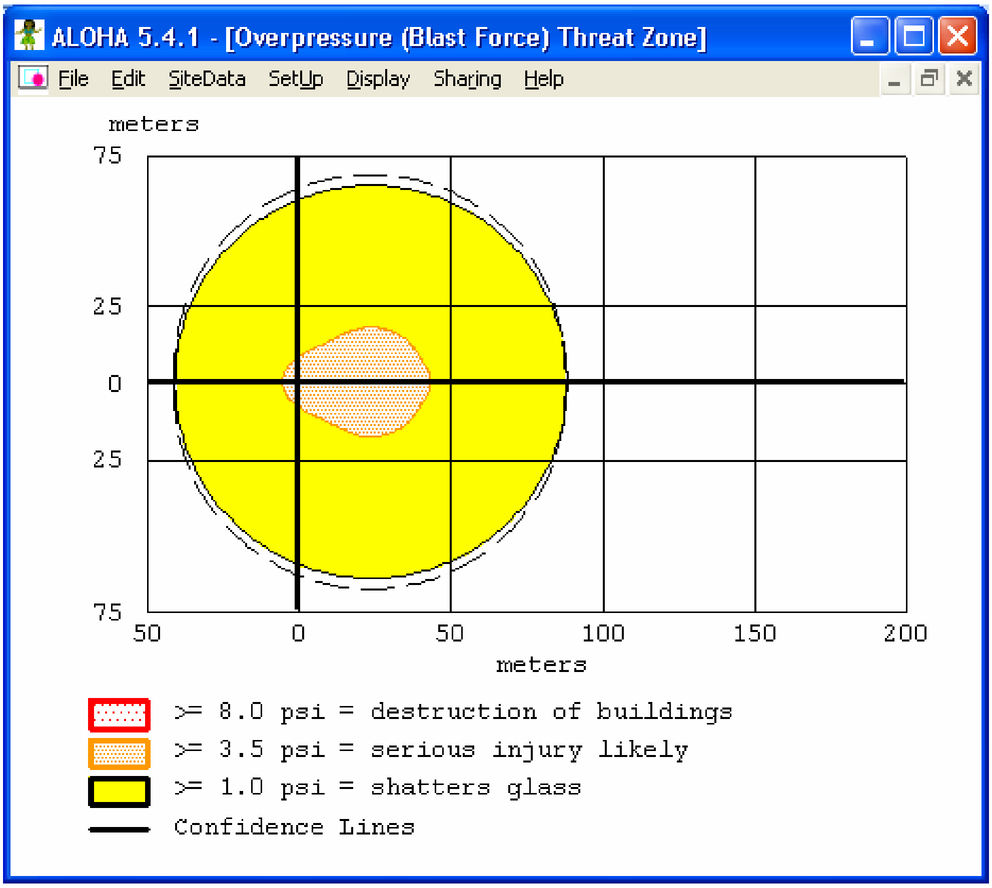

Figure 4.48 : Blast Area of Vapour Cloud Explosion

Figure 4.49 indicates the simulation results from burning propane as a jet fire. In this situation there is leakage from a tank and it burns as a jet fire. In figure 4.49 the red zone as large as 29 meters wherein thermal radiation is 10.0 kW/m2 and potentially lethal in 60 seconds; the orange zone is as large as 41 meters wherein thermal radiation is 5.0 kW/m^2 and 2nd degree burns occur within 60 seconds; the yellow zone is as large as 64 meters wherein thermal radiation is 2.0 kW/m2 and pain occurs within 60 seconds.

Figure 4.50 indicates simulation results for BLEVE, tank explosion and propane burning as a fireball. The red zone is as large as 184 meters wherein thermal radiation is 10.0 kW/m^2 and potentially lethal in 60 seconds. The orange zone is as large as 260 meters with thermal radiation of 5.0 kW/m^2 and 2nd degree burns occurs within 60 seconds. The yellow zone is as large as 406 meters wherein thermal radiation is a 2.0 kW/m^2 and pain occurs within 60 seconds.

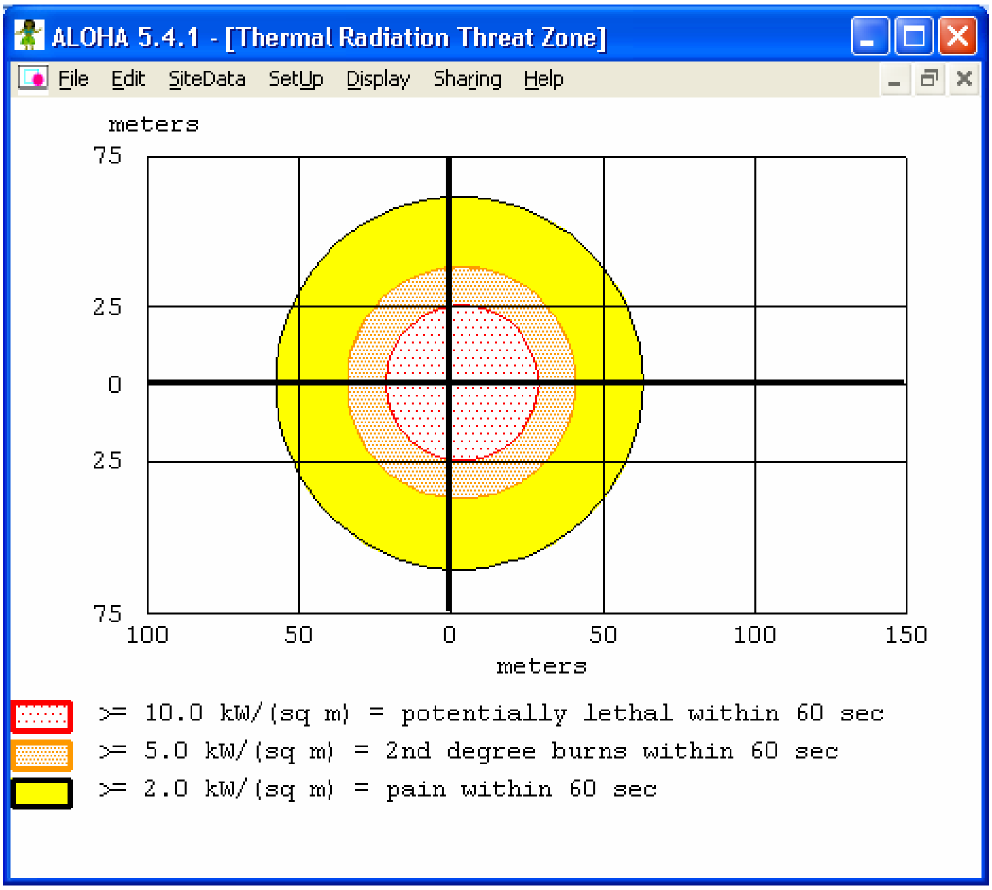

Figure 4.49 : Chemical is Burning as a Jet Fire

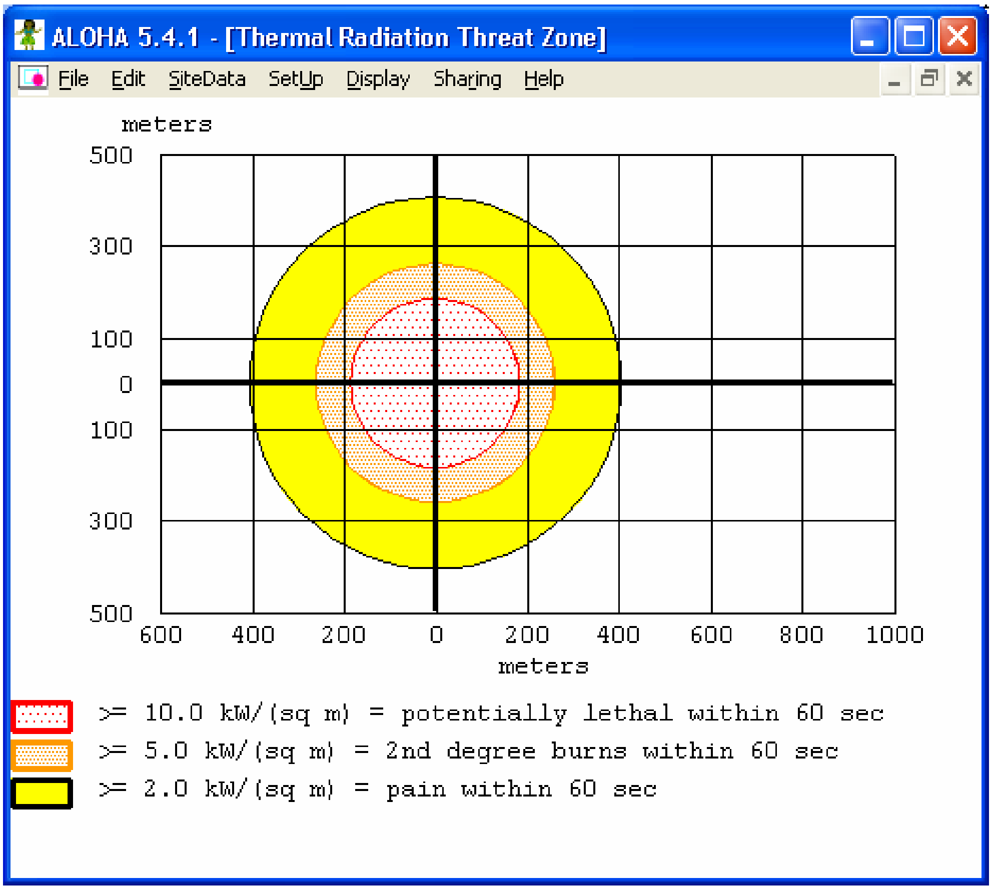

Figure 4.50 : BLEVE, tank explodes and chemical burns in a fireball

4.2.1 Risk determination of LPG storage tank

Figure 4.52 indicates that the toxic area of the vapour cloud is covering the gym and the road between the gym and canteen. Figure 4.53 indicates that in case of a leak the flammable area of vapour cloud will cover the intermediate road and some part of the canteen where the car and truck are stopped. This area is very dangerous because if either the car or truck is ignited, there could be a big explosion. So, there is a risk for personnel and students in this area.

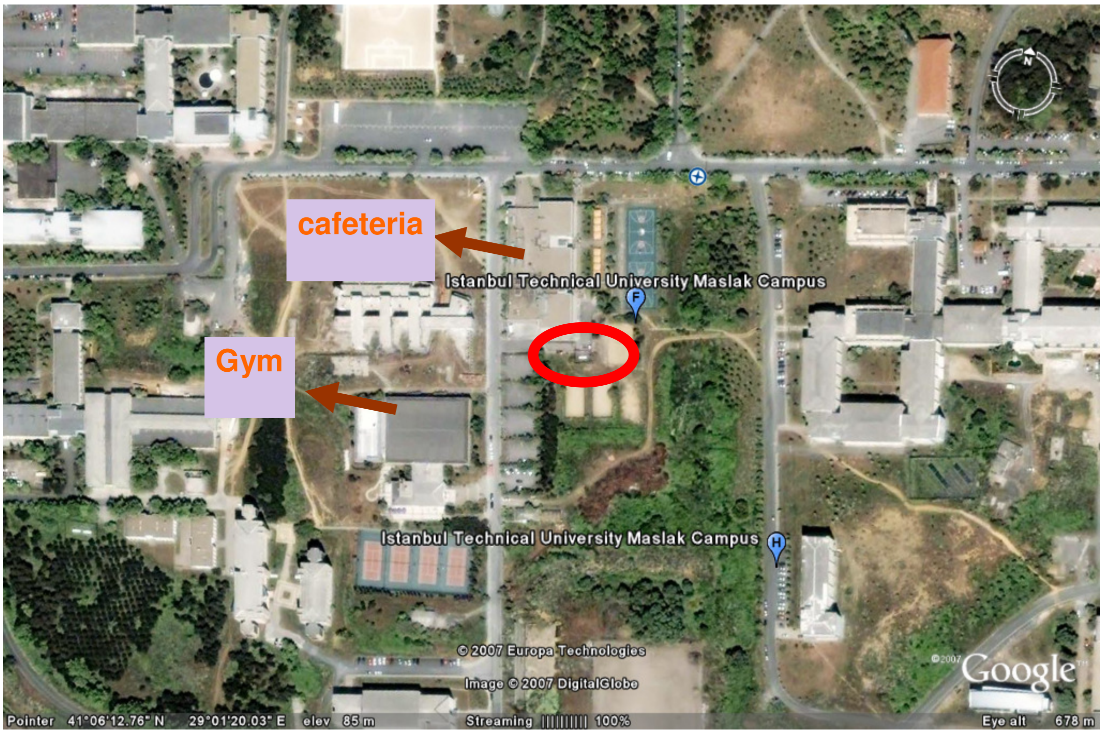

Figure 4.51 : Map of İTÜ Maslak campus

Figure 4.52 : Toxic Area of Vapour Cloud

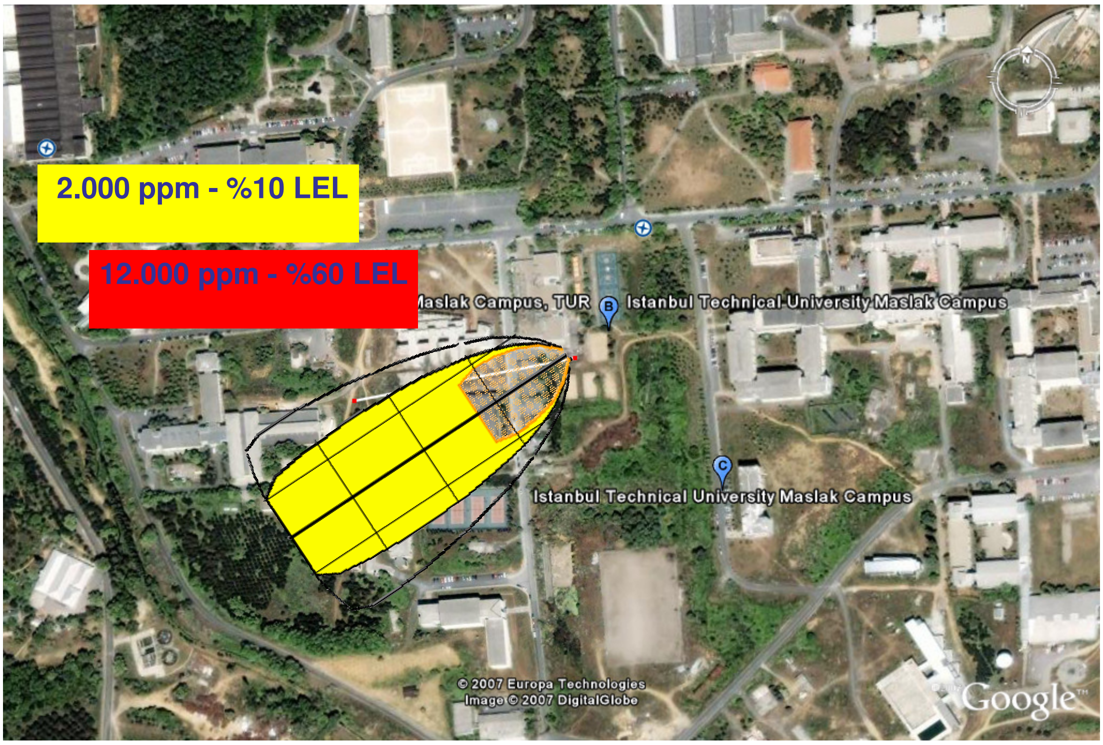

Figure 4.53 : Flammable Area of Vapour Cloud

Figure 4.54 indicates the blast area of the vapour cloud explosion. In the instance of a vapour cloud explosion, blast effects for 6.9 kPa and 24.15 kPa are simulated on the map. The orange zone is dangerous for triggering a fire or explosion and the effects of a 24.15 Kpa overpressure for property are the collapse of self-framing steel buildings, the rupture of oil storage tanks and the snapping failure of wooden utility tanks.

The yellow zone has the less dangerous effects of a 6.9 kPa overpressure which leads to the shattering of glass windows, the occasional damage to window frames, the partial demolition of houses, shattering of corrugated asbestos siding, the failure of corrugated aluminium-steel panelling and the failure of wood siding panels. In the yellow zone the effects on humans are skin lacerations from flying glass [31]. The red zone includes the intermediate road and a small part of the canteen. The yellow zone is wide and includes intermediate road, and some parts of the gym and canteen. There is a risk for personnel and students near this are.

Figure 4.55 indicates the burning of propane as a jet fire. The burning of propane as a jet fire is simulated on the map for three different zones. The first zone is very dangerous because the thermal radiation is 10 KW/(sq m) and can result in death in 60 seconds. This zone includes some part of the canteen, the parking area, and part of volleyball and mini football area. If there is a truck or car this can lead another explosion. The second zone is also dangerous in this area as thermal radiation is 5 KW/(sq m) and can result in 2nd degree burns in 60 seconds. The third zone is less dangerous as thermal radiation is 2 KW/(sq m) and results in pain in 60 seconds.

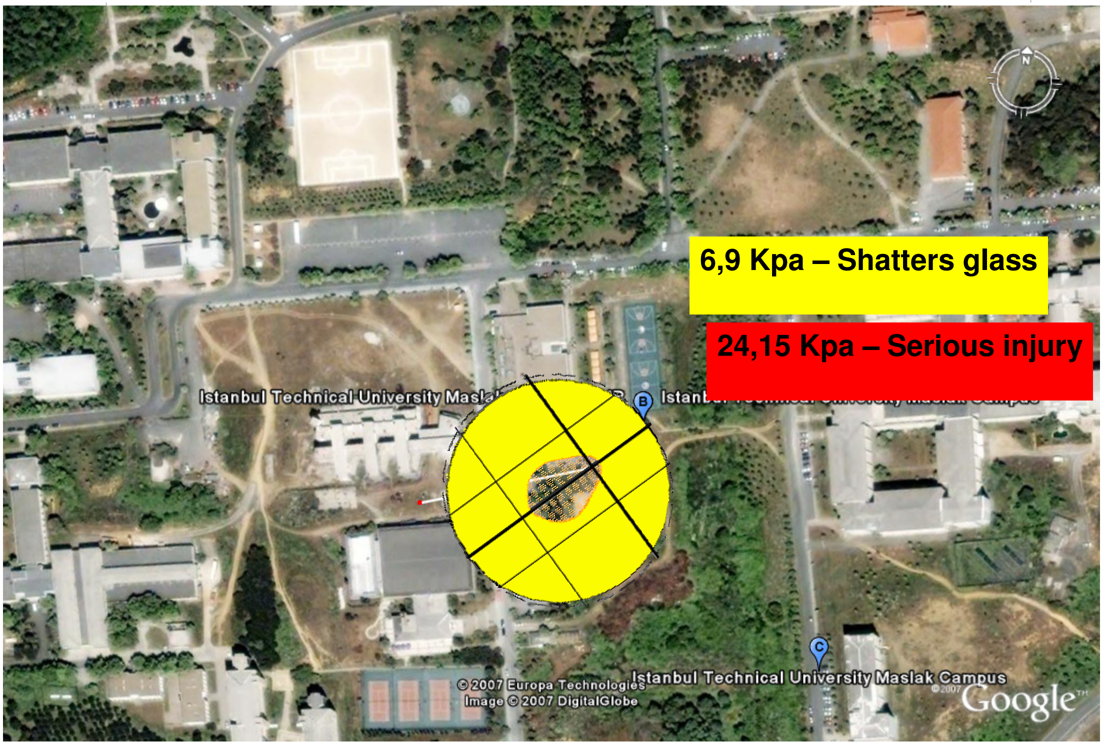

Figure 4.54 : Blast Area of Vapour Cloud Explosion

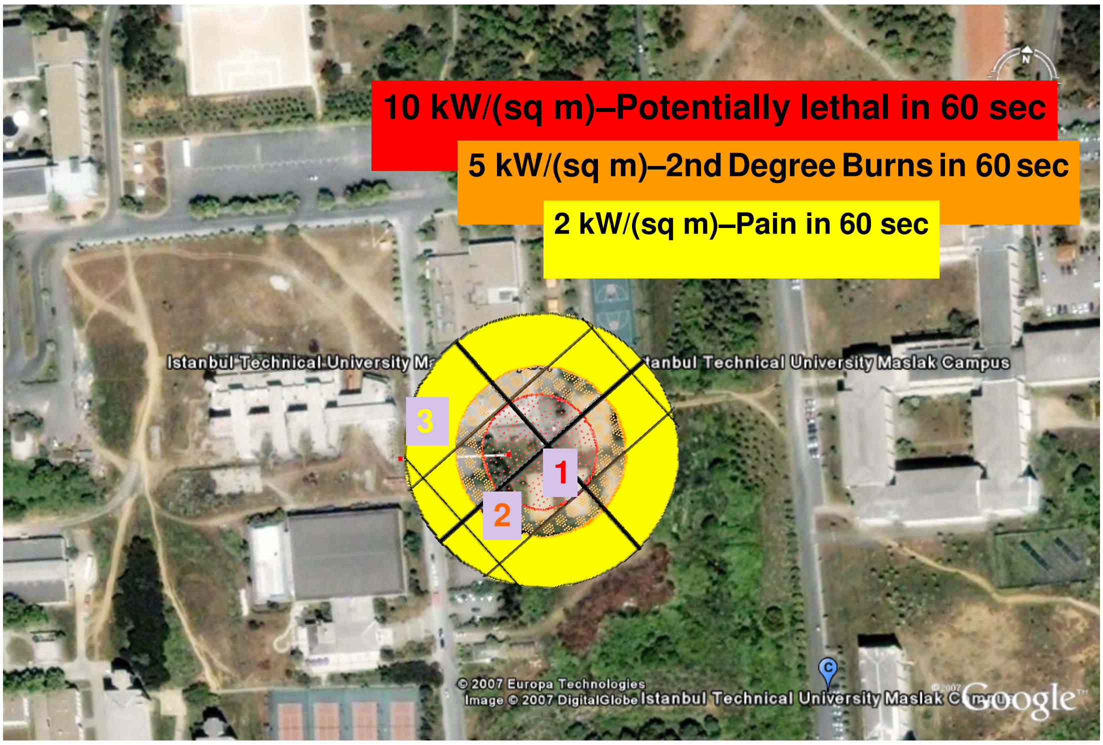

Figure 4.55 : Chemical is Burning as a Jet Fire

Table 4.11 : Human Injury Criteria (Includes Injury from Flying Glass and Direct Overpressure Effects) [45]

Overpressure (kPa)	Injury	Comments	Source
4,14	Threshold for injury from flying glass*	Based on studies using sheep and dogs	a
6,9 - 13,8	Threshold for skin laceration from flying glass	Based on U.S. Army data	b
5,4	Threshold for multiple skin penetrations from flying glass (bare skin)*	Based on studies using sheep and dogs	a
13,8 - 20,7	Threshold for serious wounds from flying glass	Based on U.S. Army data	b
16,56	Threshold for eardrum rupture	Conflicting data on eardrum rupture	b
19,32	10% probability of eardrum rupture	Conflicting data on eardrum rupture	b
20,7	Overpressure will hurl a person to the ground	One source suggested an overpressure of 1.0 psi for this effect	c
23,46	1% eardrum rupture	Not a serious lesion	d
27,6 - 34,5	Serious wounds from flying glass near 50% probability	Based on U.S. Army data	b
40,02	Threshold for body-wall penetration from flying glass (bare skin)*	Based on studies using sheep and dogs	a
43,47	50% probability of eardrum rupture	Conflicting data on eardrum rupture	b
48,3 - 55,2	Serious wounds from flying glass near 100% probability	Based on U.S. Army data	b
69	Threshold lung hemorrhage	Not a serious lesion [applies to a blast of long duration (over 50 m/sec)]; 20–30 psi required for 3 m/sec duration waves	d
100,05	Fatality threshold for direct blast effects	Fatality primarily from lung hemorrhage	b
110,4	50% eardrum rupture	Some of the ear injuries would be severe	d
120,75	10% probability of fatality from direct blast effects	Conflicting data on mortality	b

Table 4.11 : Human Injury Criteria (Includes Injury from Flying Glass and Direct Overpressure Effects) [45]			
Overpressure (kPa)	**Injury**	**Comments**	**Source**
141,45	50% probability of fatality from direct blast effects	Conflicting data on mortality	b
175,95	90% probability of fatality from direct blast effects	Conflicting data on mortality	b
186,3	1% mortality	A high incidence of severe lung injuries [applies to a blast of long duration (over 50 m/sec)]; 60–70 psi required for 3 m/sec duration waves	d
200,1	99% probability of fatality from direct blast effects	Conflicting data on mortality	b

For SI units, 6.9 kPa = 1 psi.
*Interpretation of tables of data presented in reference.
aFletcher, Richmond, and Yelverron, 1980.
bF. Lees, Loss Prevention in the Process Industries, 1996.
cBrasie and Simpson, 1968.
dU.S. Department of Transportation, 1988.

4.3 Over Pressure and Effects for Case -1

In this section of case-1 the blast area of a vapour cloud explosion was simulated for 14 different over pressure values. The program plotted the graph and also gave the results in a text format, where the maximum distance for simulated overpressure is written. In all cases, it is assumed that the time of the vapour cloud ignition was not known, it was ignited by a flame or spark and the level of congestion is defined as "congested".

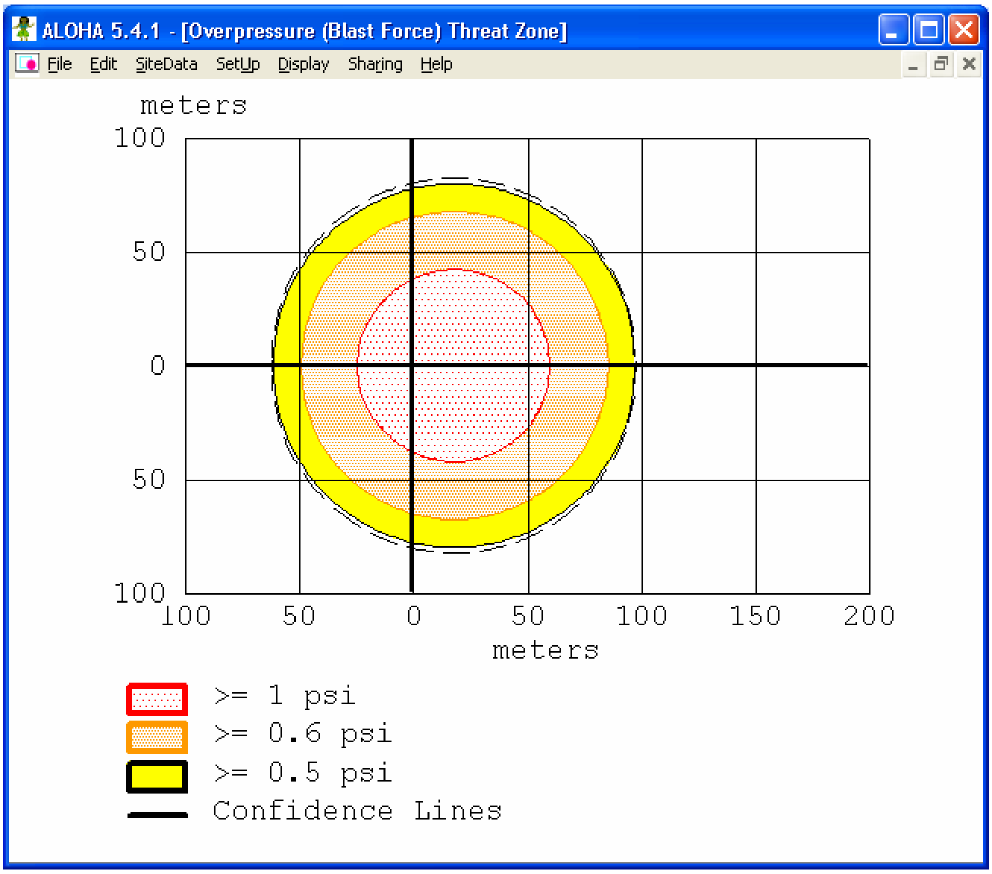

Figure 4.56: Blast Area of Vapour Cloud Explosion

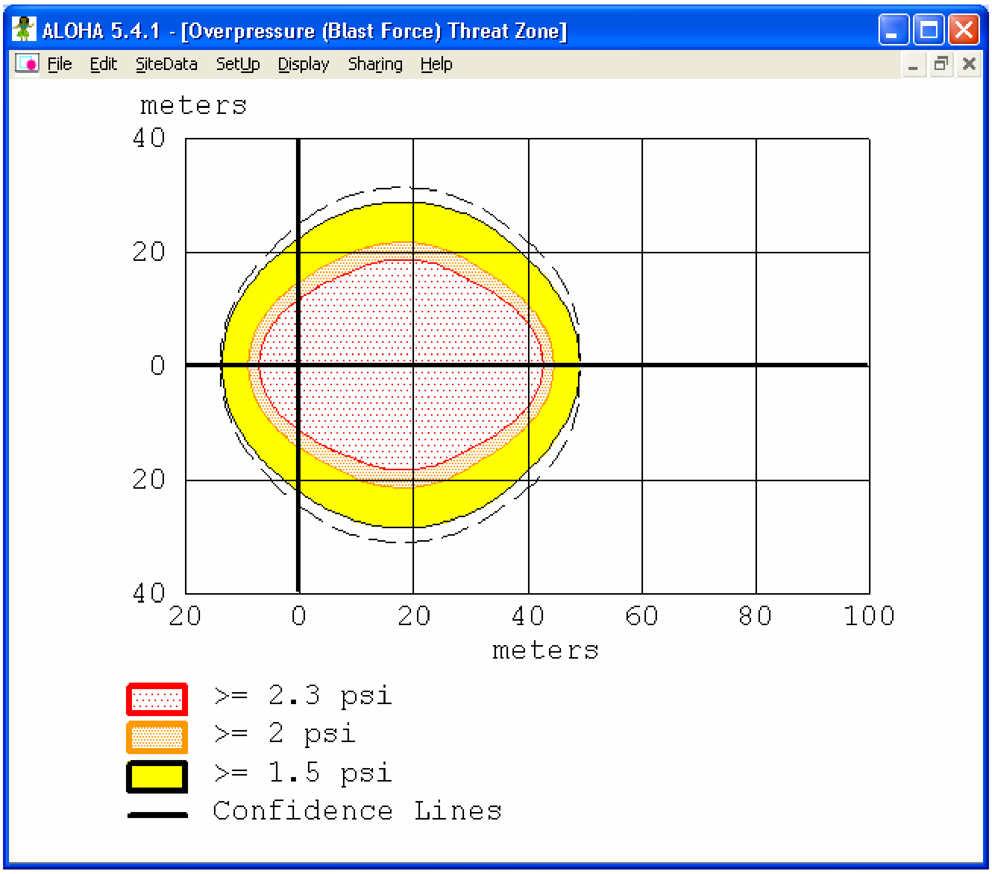

Figure 4.57 : Blast Area of Vapour Cloud Explosion

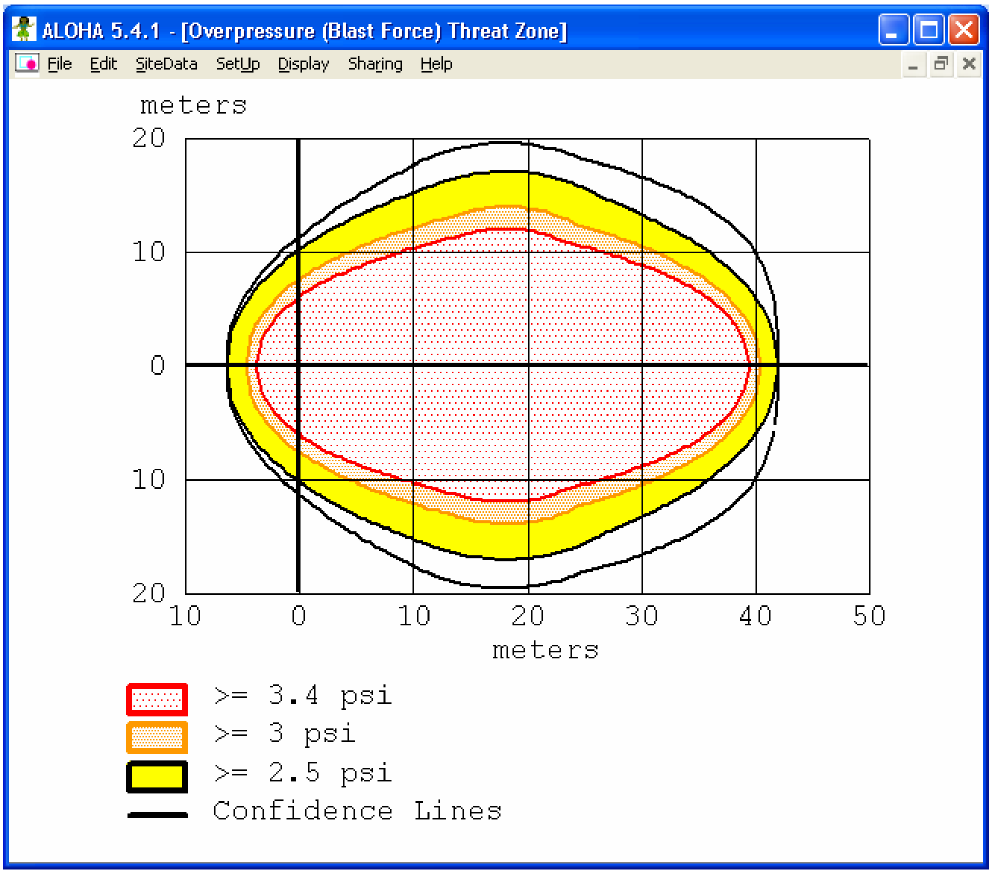

Figure 4.58 : Blast Area of Vapour Cloud Explosion

Figure 4.56 indicates a red zone is as large as 60 meters wherein the overpressure is 6.9 kPa; the orange zone is as large as 86 meters wherein overpressure is 4.14 kPa; the yellow zone is as large as 98 meters with an overpressure of 3.45 kPa.

Figure 4.57 indicates that the red zone is as large as 43 meters with an overpressure of 15.87 kPa; the orange zone is as large as 45 meters with an overpressure of 13.8kPa and the yellow zone is as large as 49 meters with an overpressure of 10.35 kPa.

Figure 4.58 indicates a red zone is as large as 39 meters wherein the overpressure is 23.46 kPa; the orange zone is as large as 40 meters wherein the overpressure is 20.7 kPa; the yellow zone is as large as 42 meters wherein the overpressure is 17.25 kPa.

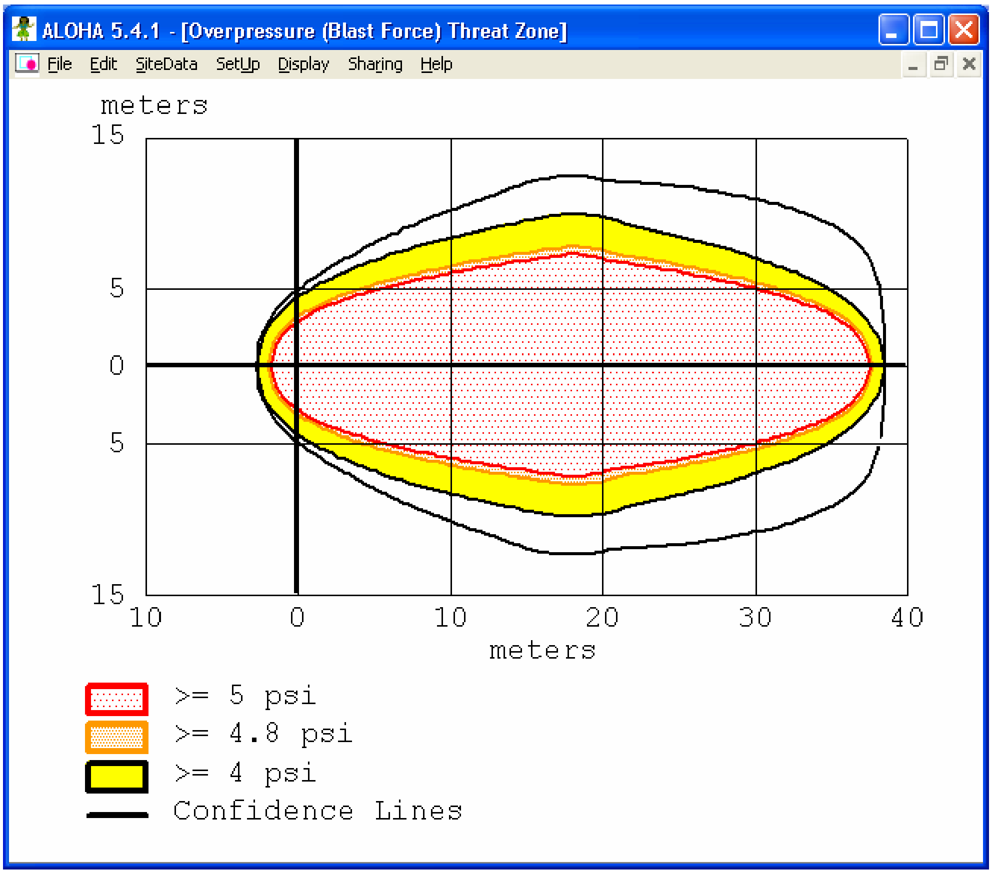

Figure 4.59 : Blast Area of Vapour Cloud Explosion

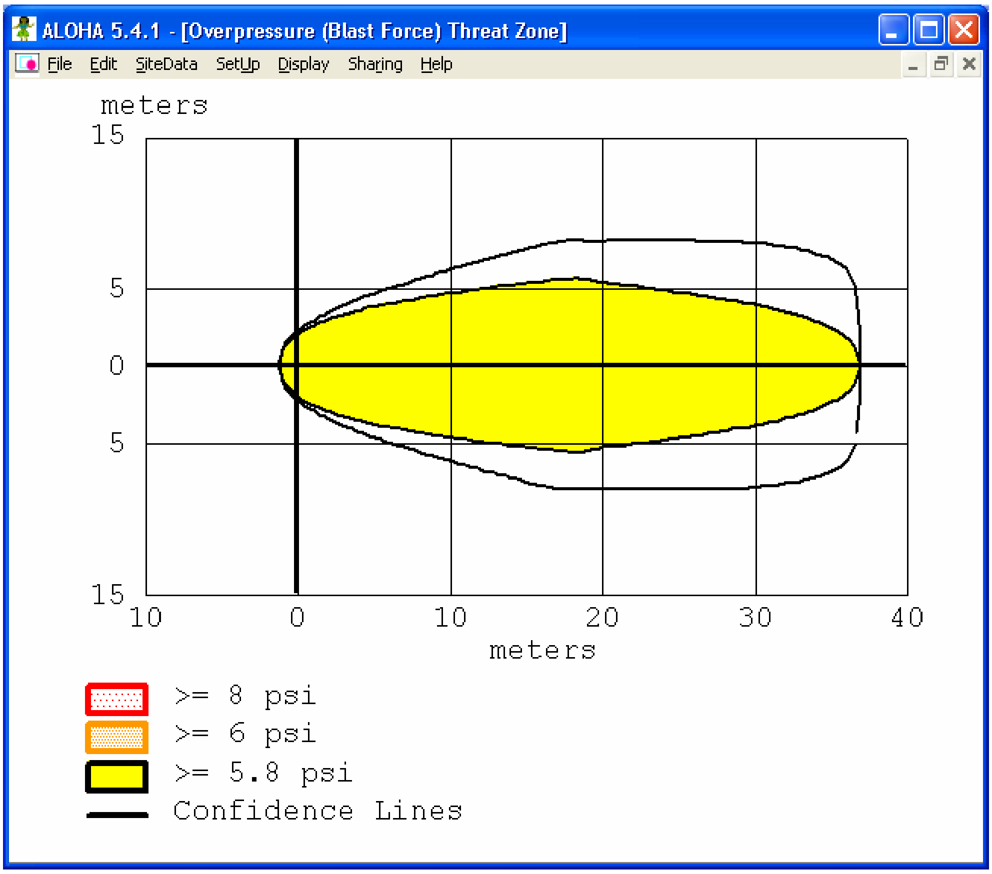

Figure 4.60 : Blast Area of Vapour Cloud Explosion

Figure 4.59 indicates that the red zone is as large as 38 meters within overpressure of 34.5 kPa; the orange zone is as large as 38 meters wherein overpressure is 33.12 kPa; the yellow zone is as large as 39 meters wherein the overpressure is 27.6 kPa.

Figure 4.59 indicates that the red zone never grows where the overpressure is 34.5 kPa; the orange zone never grows where the overpressure is 33.12 kPa; and the yellow zone is as large as 37 meters where overpressure is at 27.6 kPa.

Table 4.12 : Overpressure- maximum distance

Overpressure (Kpa)	Maximum Distance (meter)
3,45	98
4,14	86
6,9	60
10,35	49
13,8	45
15,87	43
17,25	42
20,7	40
23,46	39
27,6	39
33,12	38
34,5	38
40,02	37
41,4	--
55,2	--

5. CONCLUSION

Explosion modelling is very important for plant design. According to the materials which will be produced in the plant or the materials which will be used in the plant and their quantity, explosion modelling should be done before adding a new facility or for plant optimization. Also it is very important in new plant design; according to the simulation results, the location of facility and alternative input materials can be determined.

Another area where explosion modelling is useful is in risk management. In many kinds of risk management the results from explosion modelling can be used. Risk management should include some physical data, and for explosion modelling it is very hard to do calculations manually. With regard to this requirement an appropriate software can be used.

The simulation result of the LPG filling station showed that the location of the buildings was done logically, especially in the location of the management and social facilities buildings and the filling house.

Mitigation is very significant topic in all types of industrial accidents. In case of an explosion, damage should be minimized to the environment, buildings and humans. To minimize hazards, mitigation studies should be done for plants and buildings. With regard to explosions there should be appropriate explosion modelling and, according to these results, mitigation of damage to the environment, buildings and humans can be done. For example, using some kind of panel or removing some material from the working area can reduce the effects of an explosion.

Explosion modelling can be used in damage assessment. On the market there are many powerful tools for the estimation of damage to property and human life. These tools can be used to get accurate results for damage assessment in explosions.

Disaster planning is another area where explosion modelling can be used. It is important to have a disaster plan and to know the worst case and to take some action and make prevention plans for that situation.

After an explosion it is very hard to assess what exactly happen and why it happened. In this field explosion modelling can be used for accident investigation and for the assessment of what questions are appropriate. For example, what kind of cloud, the diameter of the cloud, concentration and so forth.

Explosion modelling is very useful to determining safe distances inside and outside of plants. By using simulation tools these areas can be determined and, in case of any disaster, these areas can be used as a refuge. So, in this way, chaos will be prevented because every one will know that if there is an accident, they should go to these safety areas.

Further, CFD code for can be used for simulation and multi scenarios can be modelled together.

During the research stage of this study much communication was done with a software supplier, all of them are of foreign origin. Many of the suppliers refused to send their software for academic research; some of them said that the software can be used for academic purposes only in their own country. So with this study, explosion models are summarized and the next step, according to the current situation and future trends is for a national code to be established.

REFERENCES:

[1] **BS2955:** 1958. Glossary of Terms Relating to Powders, No. 505, *British Standard Institute*, London.

[2] **Lees, F.P.,** 2005. Lees' Loss Prevention in the Process Industries (Partially updated by S. Mannan), vols. 1–3, *Elsevier/Butterworth-Heinemann*, Oxford.

[3] **NFPA 68,** 2002. Guide for Venting of Deflagrations, *National Fire Protection Association*

[4] **Palmer, K.N.,** 1973. Dust Explosions and Fire, *Chapman & Hall*, London.

[5] **Vijayaraghavan, G.,** 2004. Impact assessment, modelling, and control of dust explosions in chemical process industries, MTech Thesis, Department of Chemical Engineering, *Coimbatore Institute of Technology.*

[6] **Eckhoff, R.K.,** 2003. Dust Explosions in the Process Industries, 3rd ed., *Gulf Professional Publishing,* USA.

[7] **Lees, F.P.,** 1996. Loss Prevention in the Process Industries—Hazard Identification, Assessment and Control, vol. 2, *Butterworth-Heinemann*, London.

[8] **Kauffman, C.W. and Hubbard, R.F.,** 1984. An Investigation of Fourteen Grain Elevator Explosions Occurring between January 1979 and April 1981, *Occupational Safety and Health Administration*, Washington, DC.

[9] **Bowen, X.,** 1988. The explosion accident in the Harbin Linen textile plant, *EuropEx Newslett.* (6)

[10] **Hailin, Z.,**1988. Investigation of the dust explosion in Harbin linen factory, *Unpublished English manuscript.*

[11] **Failure Knowledge Database***, Japan Science and Technology Agency*, http://shippai.jst.go.jp/en/Detail?Ffn=0&id=CC1200059&.

[12] **MIOSHA News,** 1999. vol. 3, no. 3, OSHA, Michigan.

[13] **Khan, F.I. and Abbasi, S.A.,** 1998. Risk Assessment in the Chemical Process Industries: Advanced Techniques, *Discovery Publishing House*, New Delhi.

[14] **Abbasi, S.A.,** 1999. Environmental pollution and its control, *Cogent Int. Pondicherry*, xi + 439 pages.

[15] **Khan, F.I., Hussain, T. and Abbasi,** S.A., 2002. Design and evaluation of safety measures using a newly proposed methodology 'SCAP', J. Loss Prevent. *Process Ind*. 15 129–146.

[16] **Abbasi, T. and Abbasi, S.A.,** 2006. The boiling liquid expanding vapour explosion (BLEVE): mechanism, consequence assessment, management, *J. Hazard. Mater*. doi:10.1016/j.jhazmat.2006.09.056.

[17] **Vijayaraghavan, G., Abbasi, T., Ramesh, N. and Abbasi, S.A.,** Dust explosions in process industry: a case for greater awareness in India*, Indian Chem. Eng*., in press.

[18] **Abbasi, T. and Abbasi S.A.,** 2006. Dust explosions - Cases, causes, consequences and control, *Center for Pollution Control and Energy Technology,* Pondicherry University, Pondicherry *605014, India.*

[19] **Matsuda, T.,** 1993. Dust explosion incidents in Japan, in: Proceedings of the Second IUPACWorkshop on Safety in *Chemical Production*, Yokohama, p. 256.

[20] **Nifuku, M. and Katoh, H.,** 2001. Incendiary characteristics of electrostatic discharge for dust and gas explosion*, J. Loss Prevent. Process Ind*. 14 547–551.

[21] **Combustible Dust Hazard Study,** 2006. U.S. *Chemical Safety and Hazard Investigation Board*, Investigation Report No.2006-H-1, USA.

[22] **Steen, H.,** 2000. Handbuch des Explosions schutzes,*Wiley-VCH Verlag GmbH*, Weinheim.

[23] **Bjerketvedt, D., Bakke,J.R. , Wingerden, V.K** , 1997, Gas Explosion Handbook, Journal of Hazardous Materials 52 1 - 150

[24]**D.A. Crowl and J.F. Louvar**, *Chemical Process Safety. Fundamentals with Applications*, Englewood Cliffs:Prentice Hall, 1990.

[25]**Chang J.I.,Lin C.C**, 2006, A study of storage tank accidents, *Journal of Loss Prevention in the Process,* 19, 51-59

[26]**Tasneem Abbasi, S.A. Abbas**, , The Boiling liquidexpanding vapour explosion (BLEVE) Mechanism, consequence assessment, management, *Journal of Hardaous Materials*, In press, 2006

[27] **Biswajit Ruj, Imranur Rehman** , A.K. Bandyopadhya, Off-site emergency scenario, a case study from a LPG Bottling Plant, *Jounal of Loss Prevention in the Process Industry 19*, 2006, 645 – 647

[28] **Joaquim Casal , Josep M. Salla** , Using liquid superheating energy for a quick estimation of overpressure in BLEVEs and similar explosions, *Journal of Hazardous Materials*, A137 , 2006 , 1321-1327

[29] **Van Den Bosch, C.J.H. and Weterings, R.A.P.M.,** 2005. Methods for the calculation of physical effects, *VROM*.

[30] **Ledin, H.S. and Lea C.J.,** 2002. A Review of the State-of-the-Art in Gas Explosion Modelling, Health & Safety Laboratory, United Kingdom.

[31] **Jiang, J.; Liu, Z.G.;Kim, A.K**., Comparison of Blast Prediction Models for Vapor Cloud Explosion, National Research Council Canada, Ottawa K1A0R6, Canada

[32] **Puttock J.S., Yardley M.R.,Cresswell,** 2000. Prediction of vapour cloud explosions using SCOPE model, *Journal of Loss Prevention in the Process Industry* 13, 419-431

[33] **Ledin, H.S. and Lea C.J.,** 2006, Review of CEBAM Explosion Model A Review of the State-of-the-Art in Gas Explosion Modelling, Health & Safety Laboratory, United Kingdom.

[34] **Clutter J.K., Mathis J.** 2002. Computational modeling of vapor cloud explosions in off-hore rings using a flame speed based combustion model, *Journal of Lodss Prevention in the Process Industry* 15, 391-401

[35] **U.S. Environmental Protection Agency**, Chemical Emergency Preparedness and Prevention, http://yosemite.epa.gov/oswer/ceppoweb.nsf/content/ds-noep.htm, February 2007

[36] [] **BREEZE**,VEXDAM, http://www.breezesoftware.com/prod/brzSoftware.asp?P=VEXDAM, February 2007

[37] **EPA**, Downloading, Installing, and Running ALOHA, http://www.epa.gov/ceppo/cameo/aloha.htm, February 2007

[38] **EXSIM Consultants AS**, http://www.exsim-consultants.com/index.htm, February 2007

[39] **Gexcon AS**, FLACS – GASEX, http://www.gexcon.com/index.php?src=flacs/tools/flacs-gasex.html, May 2007

[40] **Gexcon AS**, 2007. Flame Acceleration Simulator, http://www.gexcon.com/index.php?src=flacs/flacs.html, May 2007

[41] **Century Dynaics Inc.**, 2007. AutoReaGas - CFD Software for Gas Explosion Safety, http://www.century-zzdynamics.com/index.htm?mf=http://www.century-dynamics.com/dc_products/autoreagas/autoreagas.htm, May 2007

[42] **Hamsagars**, 2007. HAMS-GPS Safety Software, http://www.hamsagars.com/hams_gps_home.htm, May 2007

[43] "Disaster Management Perspective of Terrorist Attacks in İstanbul on November 15 & 20 2003", İTÜ Press, 2005

[44] **Iskender H., Erdogan N.**, 2007. The Evaluation of Terrorist Attacks from an Emergency Management Perspective, 2. İstanbul Democracy and Global Security Conference, İstanbul, Turkey, June 14-16

[45] **NFPA 921,** 2004. Guide for Fire and Explosion Investigations, *National Fire Protection Association*

GLOSSARY

<u>**English**</u>		<u>**Turkish**</u>
Explosion	:	Patlama
Gas Explosion	:	Gaz patlaması
Dust Explosion	:	Toz patlaması
Confined	:	Sınırlı, kapalı, kuşatılmış
Unconfined	:	Kuşatılmamış
Blast	:	Patlamadan sonraki yıkıcı hava dalgası
Overpressure	:	Aşırı basınç, fazla basınç
Buoyant	:	Yüzen
Dispersion	:	Dağılma, yayılma
Spill	:	Dökmek, dökülmek
Mitigation	:	Zarar azaltma

CIRRICULUM VITAE

Levent Terzioğlu was born in Bulgaria in 1980. He finished Çorlu High School in 1998. He graduated from Istanbul Technical University Chemical Engineering department and after receiving B.Sc. degree in Chemical Engineering in 2003, he enrolled to the graduate school at ITU to purse a M.Sc. degree in a Chemical Engineering. From 2005 he works in Eczacıbaşı Health Products as a raw material weighing specialist.