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Evaluation of VCE Impact from LPG Spherical Tank

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تقييم تاثيرات انفجار سحابة بخارمن خزان كروي يحتوي غاز بترول مسال

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ABSTRACT

Vapor Cloud Explosion (VCE) occurs when there is a release of Liquified Petroleum Gas (LPG) between the upper and lower explosion concentration limits and the mixture is exposed to an ignition source. The VCE gives rise to the following effects: (1) blast wave and (2) thermal radiation. The world has witnessed many VCE incidents due to processing of LPG. This study aims to evaluate the VCE impacts which could result in from large LPG spherical tank in an oil Refinery. The objective is to evaluate the potential blast wave overpressure and thermal radiation hazards associated with such events. Two widely recognized explosion consequence models — TNT equivalency and the TNO Multi-Energy models — were employed to estimate explosion impacts at various tank fill levels up to 85% capacity. The predicted overpressure and radiation effects were analysed at multiple distances, with particular focus on the 500 m impact radius. Results indicate notable variation between model predictions, with the TNT model producing more conservative overpressure estimates than the TNO model. Findings reveal that explosion consequences could lead to structural damage to light industrial buildings and severe thermal exposure risks to workers and nearby communities. The study highlights the importance of integrating quantitative explosion modelling into refinery layout design, emergency planning, and land-use regulation to minimize industrial and societal risks.

Key words: Blast Wave, Liquefied Petroleum Gas, Over pressure, Thermal Radiation, Vapor Cloud Explosion.

الملخص

يحدث إنفجار سحابة البخار (VCE) عندما يتسرب غاز النفط المسال (LPG) ضمن حدود التركيز القابل للإنفجاروإذا تعرض هذا المزيج لمصدر اشتعال. وينتج عن هذا النوع من الإنفجارات تأثيران رئيسيان: (1) موجة الانفجار، و(2) الإشعاع الحراري. وقد شهد العالم العديد من حوادث انفجار سحابة البخارالمرتبطة بعمليات معالجة وتخزين غاز النفط المسال. تهدف هذه الدراسة الى تقييم تأثيرات انفجارسحابة البخارالناتجة عن الخزانات الكروية لغاز النفط المسال في مصفاة نفطية. وقد تم اختيارخزان كروي كبير الحجم من بين ستة خزانات غاز

بالمصفاة لإجراء الدراسة. ولقد تم الإعتماد على الحسابات الرياضية لتقييم المخاطر. تم تقدير تأثير موجة الإنفجار بالاعتماد على نموذج التكافؤ لمادة ترينيتروتولوين (TNT) ونموذج الطاقة المتعددة (TNO). كما تم حساب تأثيرات موجة الإنفجار رياضيا عند مسافة 500 متر من الخزان 6 – LPG عند مستويات مختلفة من سعة الخزان حتى 85% . وقد وجد ان أقصى ضغط زايد لموجة الإنفجار يصل الى 27400 باسكال, وهو ضغط كاف لإلحاق أضرار بالطبقة الخارجية للمباني الصناعية. كما تم تقييم تأثير الإشعاع الحراري الناتج عن الإنفجار لمسافة تصل إلى 500 متر من الخزان، حيث تبين أن حياة العاملين داخل المصفاة وكذلك الأفراد القاطنين بالقرب من المصفاة تكون معرضة للخطر في حال وجودهم خارج المباني أثناء الحادث.

الكلمات المفتاحية: الغاز النفطي المسال، انفجار سحابة البخار، موجة الإنفجار، الضغط الزايد، الإشعاع الحراري.

1. Introduction

Liquefied Petroleum Gas also referred to as LP Gas, GPL, or simply propane and butane, is a highly flammable mixture of hydrocarbon gases widely utilized as a fuel in domestic heating systems, industrial processes, and transportation applications. Approximately 60% of global LPG supply is derived from natural gas processing and crude oil extraction, while the remaining 40% is produced as a by-product of petroleum refining operations [1].

Due to its physicochemical properties and storage under pressurized liquefied conditions, LPG must be contained in engineered pressure vessels, typically in cylindrical or spherical configurations. Tank classification systems and design considerations have been extensively discussed in prior studies [2]. Among available storage options, spherical tanks are generally preferred for large-volume LPG storage because of their superior stress distribution and structural resistance to internal pressure [3].

Despite these engineering advantages, LPG storage presents significant safety challenges. One of the most severe accident scenarios is the VCE, which occurs when a substantial quantity of LPG is released, forms a flammable vapor cloud within its lower and upper flammability limits, and encounters an ignition source. The resulting explosion overpressure is strongly influenced by the degree of congestion and confinement within the surrounding environment [4].

The world has witnessed many incidents due to the operation and storage of LPG. The Flixborough (Nypro UK) Explosion in 1974 resulted in 30 tons of cyclohexane leakage from a vertical crack of one of the onsite reactors, causing the death of 28 workers and injured 36 more [5]. Another major LPG accident was the PEMEX LPG Terminal tragedy in Mexico City in 1984, which claimed over 500 lives and some 4,000 people injured. The explosions were so catastrophic that they caused severe damage to the immediate surroundings with window/glass thrown away up to 4km from the source [6]. There is also nearly similar incident such as BP Texas City Refinery Explosion in 2005 resulted in fifteen fatalities and 180 injuries [7]. Another LPG accident happened in Shandong, China. July 16, 2015, an LPG spherical tank of a chemical engineering company was leaking. There was a huge mushroom cloud in the worksite. Buildings and walls collapsed in the explosion and the fire engulfed nine spherical tanks. All the residents within the 5km range were evacuated [8]. These incidents were usually caused by VCE.

VCEs have the greatest potential to cause property damage, business interruption and liability losses in refineries, petrochemical and gas plants. In this study the refinery stores the LPG in six LPG spherical tanks. It has been noted that the number of community housing increasing near the fence of the refinery. Some houses are located about 400m far from LPG facilities. The objective of this study is to assess the consequences of the VCE impacts from the 1000 m^3 LPG spherical tank on the workers, assets and the community.

2. Hazards from LPG

LPG is a vital energy resource widely utilized in residential, commercial, and industrial sectors. Despite its economic and operational advantages, LPG presents substantial safety hazards, primarily due to its high flammability and potential for accidental release. Gas leakage incidents may escalate rapidly into fires or explosions, posing serious threats to life, infrastructure, and the environment.

Because LPG can be liquefied under relatively low pressure, it is commonly stored and transported in pressurized tanks in liquid form and subsequently vaporized prior to end use. One of the key characteristics contributing to its hazard potential is its high expansion ratio; a single cubic meter of liquid LPG can vaporize to approximately 245 – 275 m^3 of flammable vapor. In addition, LPG possesses a heating value approximately 2.5 to 3 times greater than that of natural gas, indicating a high energy release potential within a confined storage volume. Consequently, even a limited release can generate a large flammable vapor cloud with significant destructive capacity.

Accidents involving LPG storage tanks can therefore result in severe human casualties, extensive structural damage, and major economic losses. The sequence of events following an LPG release typically begins with loss of containment, leading to vapor cloud formation and atmospheric dispersion. Upon encountering an ignition source, the vapor cloud may ignite, producing a flash fire. The flame front can subsequently propagate back toward the leak source, resulting in a sustained jet fire.

Prolonged jet fire exposure may thermally weaken the pressurized vessel, potentially triggering a Boiling Liquid Expanding Vapor Explosion (BLEVE). Alternatively, if ignition of the dispersed vapor cloud is delayed and flame acceleration occurs, a VCE may develop, generating destructive blast overpressure.

The severity and spatial extent of accident consequences depend strongly on leak size and ignition timing. Small leaks typically produce localized fires, with BLEVE representing the most severe escalation scenario. In contrast, catastrophic ruptures or large release openings may generate extensive vapor clouds capable of producing far-reaching flash fires or VCE events following delayed ignition.

Understanding these escalation pathways is essential for quantitative risk assessment, emergency planning, and the design of effective mitigation and protection systems in LPG storage facilities

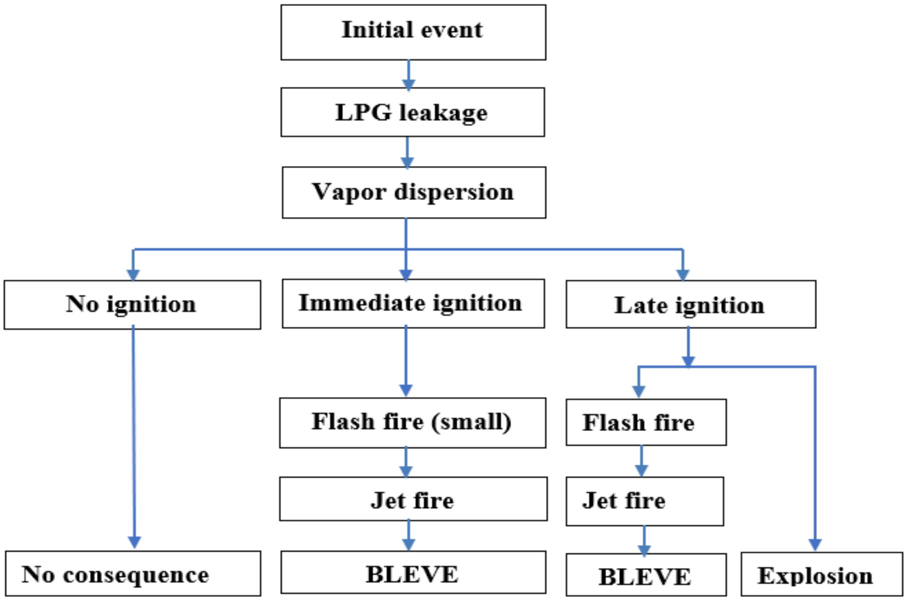


Figure 1: Event sequences of LPG leak [8].

3. Vapor Cloud Explosion

An explosion is defined as the rapid expansion of gases that generates a fast-moving pressure or shock wave [9]. The explosion of a fuel–air mixture is commonly referred to as VCE. This phenomenon occurs when a substantial quantity of flammable gas or vaporizing liquid is suddenly released into the atmosphere, forming a vapor cloud that disperses and mixes with the surrounding air. If ignition takes place before the cloud is diluted below its Lower Flammability Limit **(**LFL**)**, the result may be either a VCE or a flash fire.

For an incident to be classified specifically as a VCE, several key conditions must be satisfied:

1. Formation of a vapor cloud
2. Presence of flammable material
3. Concentration within flammable limits
4. Generation of a blast effect
5. Presence of turbulence and/or congestion

The flame front (the interface between burned and unburned gases) can propagate in VCEs through two primary combustion modes: deflagration and detonation.

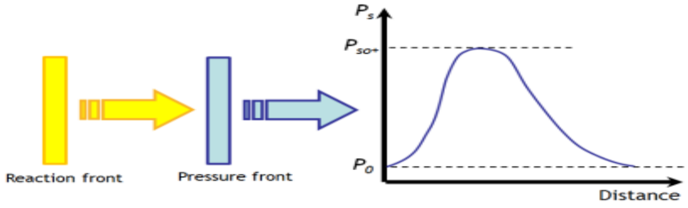
In deflagration, flame propagation occurs via heat and mass transfer to the unreacted mixture. This mechanism is relatively slow, with flame speeds always lower than the speed of sound in the unburned medium.

In contrast, detonation propagates through shock-induced compressive heating. This mechanism is extremely rapid due to the intense mechanical energy transmitted through the shock wave, with propagation velocities exceeding the speed of sound.

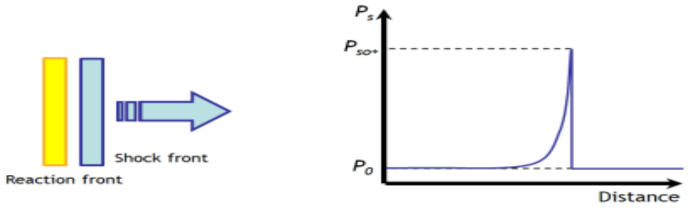
The resulting overpressure–time characteristics differ significantly between the two modes. For an equivalent explosion energy:

- Deflagrations typically exhibit a gradual rise to peak overpressure, sustained pressure duration, and a slow decay forming what is commonly termed a *pressure wave*.
- Detonations display an almost instantaneous rise to peak overpressure followed by a rapid decay, producing a highly idealized *shock front*.

These contrasting pressure profiles are commonly illustrated in comparative overpressure diagrams (e.g., Figures 2-a and 2-b).



(a) Deflagration



(b) Detonation

Figure 2: Pressure-distance shape following an explosion [10].

3.1. Mechanism of VCE

When a flammable chemical is released into the atmosphere, it forms a vapor cloud that disperses as it migrates downwind. If the cloud encounters an ignition source, regions where the vapor concentration lies within the flammable range will ignite and burn. Under certain conditions, combustion may accelerate to the extent that it generates a destructive explosive force, producing a blast wave [11].

In VCE events, the blast wave intensity is governed primarily by:

- The rate of fuel consumption
- The total mass of fuel involved

Fuel consumption rate is strongly influenced by flame speed, which can be significantly enhanced when the flame propagates through congested environments (e.g., process equipment, piping) or when expanding combustion gases experience partial confinement.

Generally, flame acceleration must exceed approximately 0.2 times the speed of sound in air (≈ 70 m/s) to generate a damaging blast wave. When vapor clouds burn at lower flame speeds, the event is typically classified as a flash fire rather than an explosion.

Although flash fires can cause severe thermal radiation and direct flame injuries, they rarely produce significant overpressure damage effects. The sequential stages leading to a VCE event are typically illustrated in process diagrams such as Figure 3.

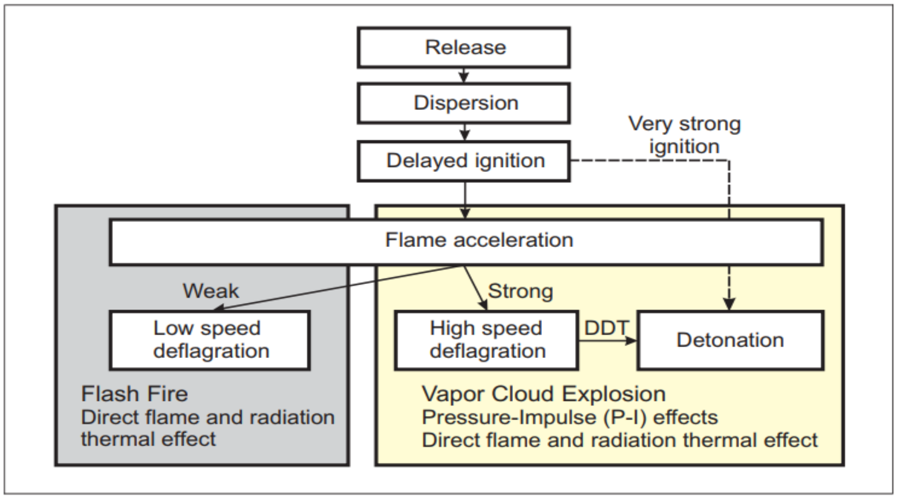


Figure 3: VCE mechanism [12].

3.2. VCE Blast wave Overpressure

Explosions represent some of the most catastrophic events encountered in the process industries as well as in transportation and storage operations. Such incidents commonly involve the ignition of flammable vapor–air mixtures or dust–air mixtures, triggered by ignition sources such as open flames, mechanical friction, electrical sparks, or hot surfaces. Typical fuels include hydrocarbon gases such as LPG notably propane and butane as well as combustible particulates such as sugar or coal dust.

In many scenarios, only a minimal ignition energy is required to initiate combustion, which can rapidly escalate into an explosive event. The resulting explosion generates a powerful blast wave accompanied by high overpressure levels capable of causing severe injury to people and extensive structural damage at considerable distances from the source.

overpressure is defined as the transient pressure increase produced by a blast wave above the normal atmospheric pressure [13]. These pressure effects arise from the rapid release of large quantities of energy within a very short time frame during the explosion.

When a gas explosion occurs, a reaction front propagates radially outward from the ignition point. This combustion front is preceded by a shock wave (pressure front). Once the combustible material is fully consumed, the reaction front ceases; however, the pressure wave continues to travel outward through the surrounding medium.

A blast wave comprises two principal components:

- The initial pressure (shock) wave
- The subsequent high-velocity blast wind

It is primarily this combined blast wave that accounts for the majority of structural damage and human injury.

The pressure–time history at a fixed location some distance from the explosion source typically follows a characteristic profile (e.g., Figure 4):

- The explosion initiates at time t_0.
- A finite travel time exists before the shock front reaches the observation point.
- Upon arrival, peak overpressure is recorded almost instantaneously, followed by an intense transient wind.
- Pressure then decays rapidly back to ambient conditions.

The interval between the arrival of the shock front and the return to ambient pressure is termed the shock duration. This phase represents the period of maximum destructive potential, particularly for free-standing structures; therefore, accurate estimation of shock duration is critical in damage assessment and structural design.

An additional measurement consideration relates to sensor orientation. When a pressure transducer is positioned perpendicular to the direction of blast wave propagation, the recorded value is referred to as the side-on overpressure, which differs from reflected overpressure measured on surfaces facing the blast.

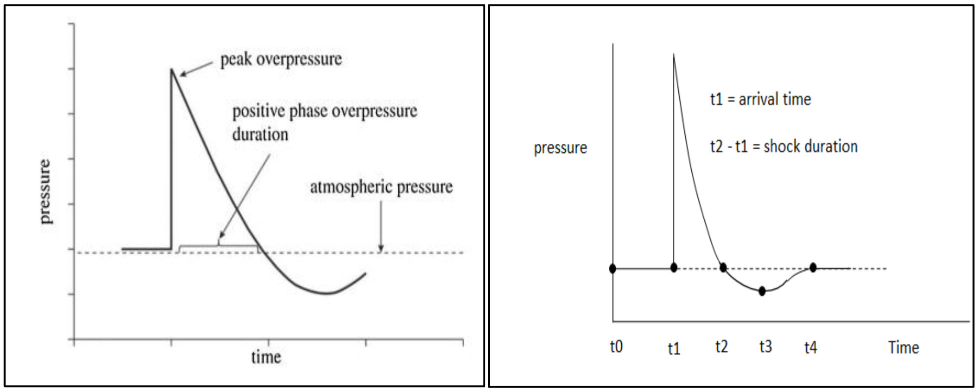


Figure 4: Blast wave pressure at a fixed location [14].

Figure 5 shows the blast wave development phases.

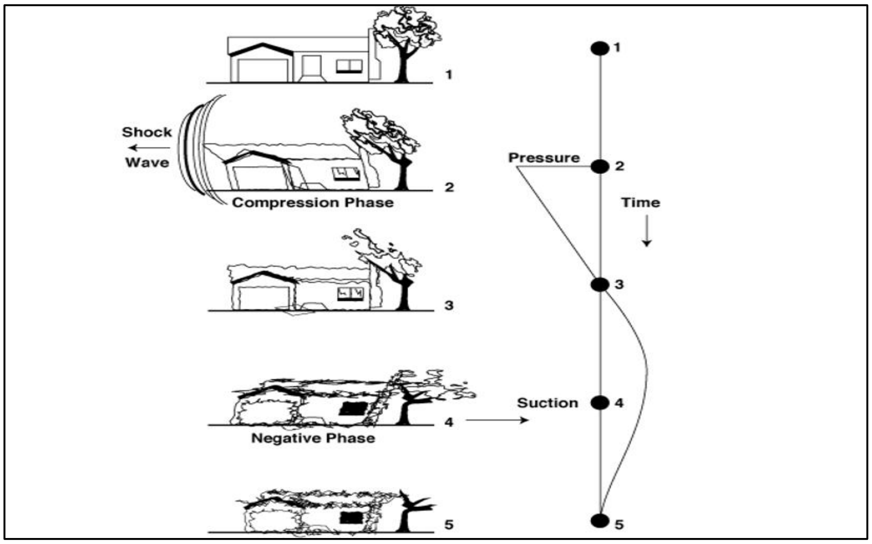


Figure 5: Illustration of a left going pressure wave 1. ambient pressure 2. positive phase 4. negative phase 5. return to ambient pressure [15].

3.3. Hazards of VCE

The destructive consequences of VCE incidents are dominated by two primary hazard mechanisms:

- Blast wave overpressure
- Thermal effects and subsequent fires

Explosion impacts often extend beyond immediate structural damage. Critical infrastructure including emergency response systems may be severely disrupted. In particular, firefighting capabilities can be compromised, allowing secondary fires, which frequently follow the initial explosion, to escalate uncontrollably [16].

4. VCE Explosion Modelling Approaches

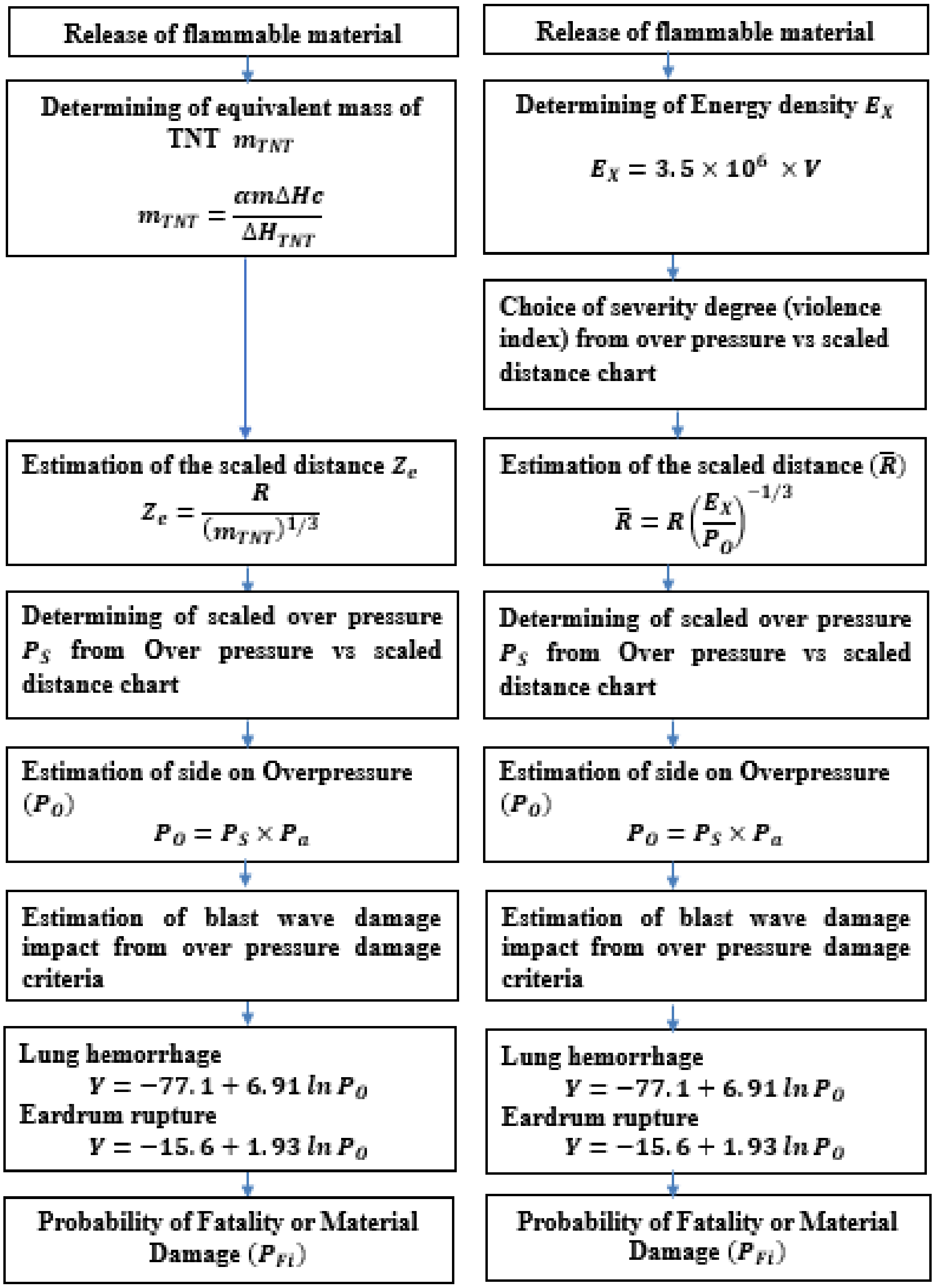
Blast prediction models for VCE have been grouped into three types according to their features and complexity [17]. They are numerical models, phenomenological models and correlation models.

The numerical models use a Computational Fluid Dynamics (CFD) approach. This type of model is designed to generate numerical solutions to the partial differential equations governing the explosion processes. The most well-known numerical VCE model is the Flame Acceleration Simulator (FLACS) and its PC version, FLACS.

Phenomenological models are also called physical models. These models are simplified models, which attempt to model the essential physical process of VCE based on idealized geometry and empirical correlation. Representatives of this type of models are the SCOPE and CLICHE models.

Correlation models are also known as empirical models or scaling law models. They were developed based on experimental results. This type of models includes the TNT equivalency model, TNO model, multi-energy model (ME model) and congestion assessment model (CAM model). The TNT equivalence model is easy to use and has a wide range of applications. The TNO model can estimate the blast parameters, such as peak pressure and the duration of the positive pressure phase, of VCE.

The TNT equivalency and TNO models have been adopted for this study. Comparative summaries of these modelling methodologies are typically illustrated in schematic frameworks (e.g., Figure 6). Once the scaled distances are estimated the side on peak overpressures can be determined from the charts shown in Figure 7 and Figure 8.



(a) TNT Equivalency Model (b) TNO Multi Energy Model

Figure 6: The VCE explosion models.

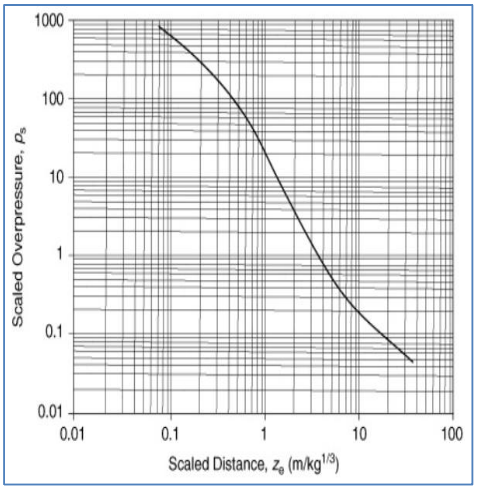


Figure 7: Scaled distance and explosion scaled overpressure [18].

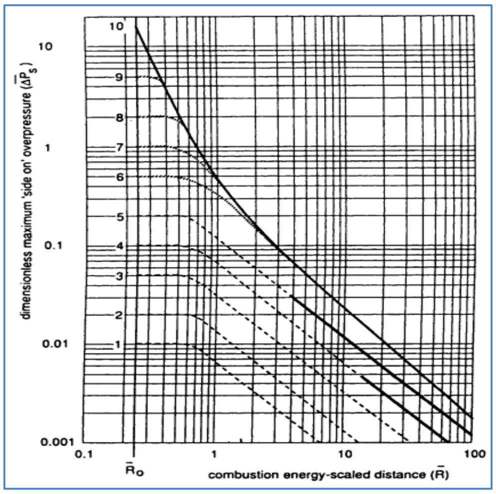


Figure 8: Side on overpressure as a function of the scaling distance [19].

5. Blast wave overpressure damage criteria

The blast wave overpressure damage criteria have been summarized in Table 1 and Table 2. Table 1 summarizes the damage estimates at low level of side on overpressure and Table 2 summarizes the consequences of over pressure on human and structure.

Table 1: Damage estimates based on overpressure [9].

Over pressure (kPa)	Damage
0.14	Annoying noise (137 dB if of low frequency, 10 – 15 Hz)
0.21	Occasional breaking of large glass windows already under strain
0.28	Loud noise (143 DB), sonic boom, glass failure
0.69	Breakage of small windows under strain
1.03	Typical pressure for glass breakage
2.07	"Safe distance" (probability 0.95 of no serious damage below this value); projectile limit; some damage to house ceilings; 10% window glass broken

Table 2: Consequences of overpressure on human and structures [20].

Over pressure (kPa)	Effect on structures	Effect on human body
6.9	Window glass shatters	Light injuries from fragments occur
13.8	Moderate damage to houses	People injured by flying glass and debris
20.7	Residential structures collapse	Serious injuries are common, fatalities may occur
34.5	Most buildings collapse	Injuries are universal, fatalities are widespread
69.0	Reinforced concrete buildings are severely damaged or demolished	Most people are killed
137.9	Reinforced concrete buildings are severely damaged or demolished	Fatalities approach 100%

6. Thermal radiation models

Prugh [21] summarized the relationships selected by the Centre for Chemical Process Safety for fire ball thermal radiation models as follows:

Fireball diameter $D = 6.48\ m^{0.325}$ meters (1)

Fireball duration $t = 0.825\ m^{0.26}$ seconds (2)

Fireball elevation $H = 0.75\ D$ meters (3)

View factors $F_{21} = \frac{D^2}{4X^2}$ (4)

Atmospheric transmissivity $\tau = 2.02(P_w X)^{-0.09}$ (5)

Fireball surface power density $E = \frac{F_{rad}\ m\ H_c}{\pi (D)^2 t}$ kW/m^2 (6)

Received power flux $Q_R = E\ \tau\ F_{21}$ kW/m^2 (7)

7. Thermal Radiation Criteria:

Thermal radiation from fires and explosions causes a wide range of damage on people and structures. Table 3 summarizes Thermal radiation criteria.

Table 3: Thermal radiation criteria [22].

Radiation (kW/m^2)	**Impact**
1.2	received from sun in summer at noon
1.6	Minimum necessary to be felt as pain
4.7	Pain in 15-20 seconds, 2nd degree burns after 30 s.
12.6	30% chance of fatality for continuous exposure. Minimum level to melt plastic tubing
23.0	100% chance of fatality for continuous exposure. 10% chance for instantaneous exposure.
35.0	25% chance of fatality for instantaneous exposure. Damage to process equipment.
60.0	~100% chance of fatality for instantaneous exposure

8. Case Study Description

The present case study examines an LPG storage installation located within a petroleum refinery, comprising six spherical storage tanks dedicated to liquefied petroleum gas containment. These vessels are designated sequentially as LPG-1 through LPG-6 and are primarily utilized for the storage and operational management of LPG products.

The storage configuration includes two capacity categories:

- Four small spherical tanks (LPG-1, LPG-2, LPG-3, and LPG-4), each with a storage capacity of 500 m³.
- Two large spherical tanks (LPG-5 and LPG-6), each possessing a storage capacity of 1000 m³.

This mixed-capacity arrangement allows operational flexibility in product storage, transfer, and inventory balancing within the refinery's LPG handling system.

The physical layout of the six spherical tanks, together with the separation distances maintained between adjacent vessels, is illustrated in Figure 9. Adequate spacing has been implemented in accordance with recognized industrial safety and fire-protection design practices to reduce the potential for domino effects, escalation, or thermal radiation impact in the event of fire or explosion scenarios.

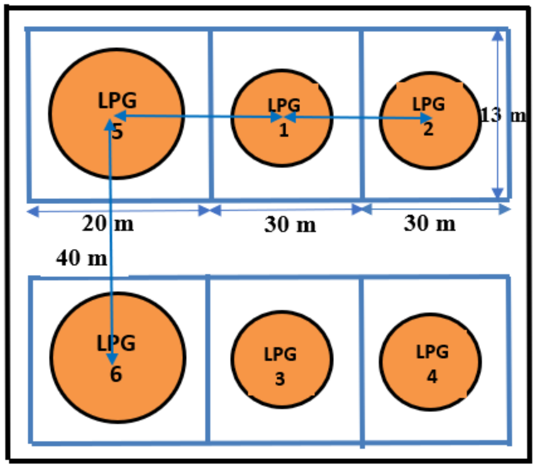


Figure 9: The lay out of the LPG spherical tanks

The LPG spherical storage tanks are equipped with an integrated piping and process handling network designed to ensure safe storage, operational flexibility, and product quality control. This network comprises multiple dedicated lines, including inlet, suction, transfer, return, balance, circulation, drain, and discharge lines, each serving specific operational and safety functions.

The inlet line is responsible for charging the spherical tanks with LPG products received from upstream processing units. The suction line facilitates withdrawal operations and is designed to support simultaneous process functions where required by operational demand.

A transfer line interconnects the spherical tanks, enabling the movement of LPG from one vessel to another. This arrangement is particularly critical during maintenance activities, inventory redistribution, or emergency response scenarios requiring rapid product relocation.

The return line provides a controlled pathway for redirecting LPG back to storage in cases where laboratory analysis indicates that the product does not conform to required specifications. Complementing this function, the balance line is installed to prevent overfilling by transferring excess product to available empty tanks, thereby maintaining safe fill levels and operational continuity.

To ensure product homogeneity, a circulation line is employed. This system withdraws LPG from the bottom of the vessel and reintroduces it at the top, promoting uniform mixing of components. The circulation process typically operates for approximately four hours, after which LPG samples are collected and sent to the laboratory for compositional and quality analysis. Certification is subsequently issued to confirm the product's suitability for domestic applications, including cooking fuel use.

In addition to process piping, the LPG spherical tanks are fitted with comprehensive control, protection, and firefighting systems designed in accordance with industrial safety standards. These include pressure relief devices, level monitoring instrumentation, emergency shutdown systems, and fixed fire suppression arrangements.

For early leak detection, four gas detectors are strategically installed at ground level around the perimeter of the containment dike. Their placement at angular positions ensures effective monitoring coverage and rapid detection of any released flammable vapor.

A detailed schematic representation of the LPG spherical storage tank and associated systems is presented in Figure 10**.**

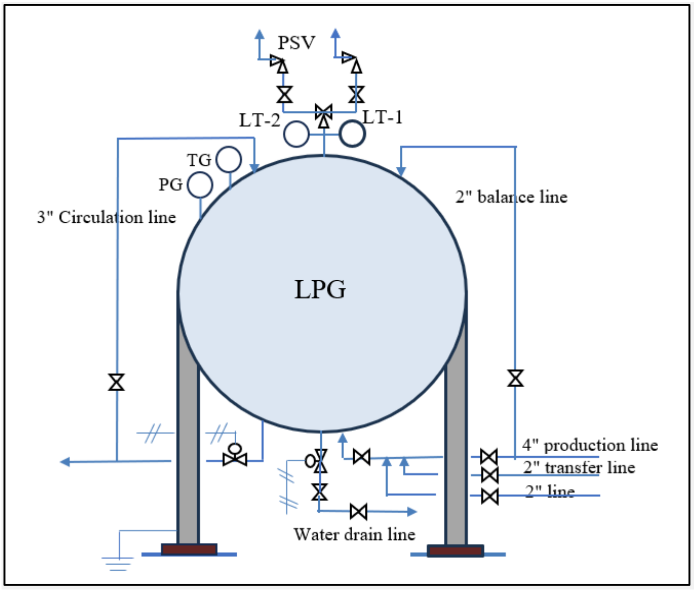


Figure 10: LPG spherical tank

The Characteristics of LPG spherical tank has been summarized in Table 4.

Table 4: Characteristics of LPG spherical tank

Characteristics	**Values**
Substance	LPG
Design pressure (kg/m^2)	10
Test pressure (kg/m^2)	15
Operating pressure (kg/m^2)	5.8
Design temperature (C)	80
Operating temperature (C)	35
Volume m^3	1000
Density (kg/m^3)	530

9. Estimation of Blast Wave Effects from LPG–6

The blast wave consequences associated with a potential VCE originating from tank LPG–6 were quantitatively estimated using established consequence modelling approaches. Mathematical simulations were performed employing both the TNT equivalency and the TNO models, which are widely recognized methodologies for evaluating explosion overpressure and associated damage radii in hydrocarbon storage scenarios.

The consequences of VCE blast waves were evaluated at varying tank inventory conditions to assess the influence of fill level on explosion severity. The analysis was conducted at a fixed radial distance of 500 m from the explosion source, representing a credible off-site impact zone for consequence assessment and land-use planning.

The calculated overpressure values corresponding to the different fill levels, as predicted by the TNT model, are presented in Table 5. Likewise, the overpressure outcomes derived from the TNO model for the same inventory conditions are summarized in Table 6.

Table 5: The results of TNT model at different degree levels.

Degree of fill (%)	m_{TNT} **(kg TNT)**	**Z** $(\mathrm{m/kg^{1/3}})$	P_S **(Unitless)**	P_O **(Pa)**	**Effects on structures**	**Effects on human body**
10	26203.16	16.834	0.11	11145.75	Window glass shatters.	Light injuries from fragments occur
20	52406.33	13.361	0.17	17225.25	Moderate damage to houses	People injured by flying glass and debris
30	78609.49	11.672	0.18	18238.5	Moderate damage to houses	People injured by flying glass and debris
40	104812.7	10.605	0.2	20265	Residential structures collapse	Serious injuries are common, fatalities may occur
50	131015.8	9.845	0.21	21278.25	Residential structures collapse	Serious injuries are common, fatalities may occur
60	157219	9.264	0.22	22291.5	Residential structures collapse	Serious injuries are common, fatalities may occur
70	183422.1	8.80	0.23	23304.75	Residential structures collapse	Serious injuries are common, fatalities may occur
80	209625.3	8.249	0.25	25331.25	Residential structures collapse	Serious injuries are common, fatalities may occur
85	222726.88	8.25	0.27	27400	Residential structures collapse	Serious injuries are common, fatalities may occur

Figure 11 shows the tank capacity degree of fill percentage and the TNT side on overpressure

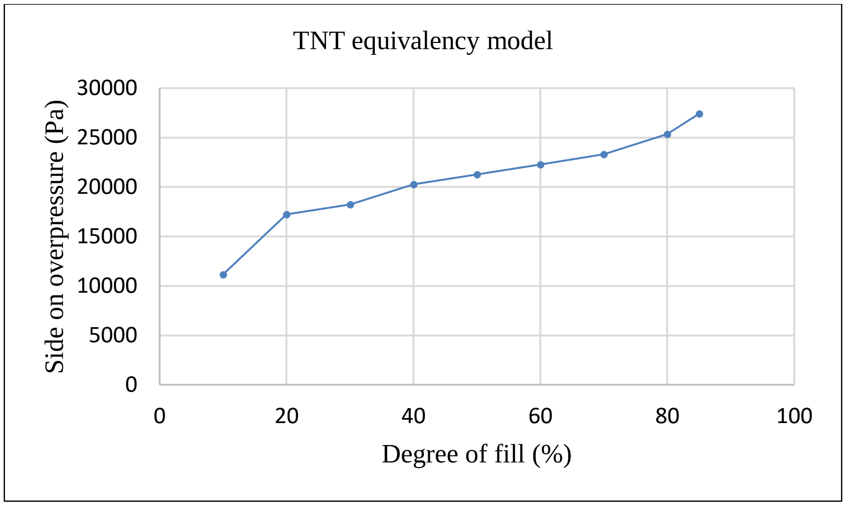


Figure 11: Degree of fill percentage and the side on overpressure

Table 6: The results of TNO model at different degree levels.

Degree of fill (%)	E (J)	$\bar{R}$ (m)	P_S **(Unitless)**	P_O **(Pa)**	**Extent of damage**
10	3E7	33.077	0.009	689.01	Breakage of small windows under strain
20	3.5E7	26.253	0.01	911.925	Breakage of small windows under strain
30	7E8	22.934	0.012	1013.25	Typical pressure for glass breakage
40	1.05E9	20.837	0.013	1215.9	Typical pressure for glass breakage
50	1.4E9	19.343	0.015	1317.225	Typical pressure for glass breakage
60	1.8E9	18.203	0.016	1519.875	"Safe distance" (probability 0.95 of no serious damage below this value); projectile limit; some damage to house ceilings; 10% window glass broken
70	2.1E9	17.291	0.016	1621.2	"Safe distance" ………………………..
80	2.5E9	16.538	0.017	1722.525	"Safe distance"…………………………
85	3E9	16.207	0.018	1725.2	"Safe distance" …………………………

Figure 12 shows the tank capacity degree of fill percentage and the TNO side on overpressure

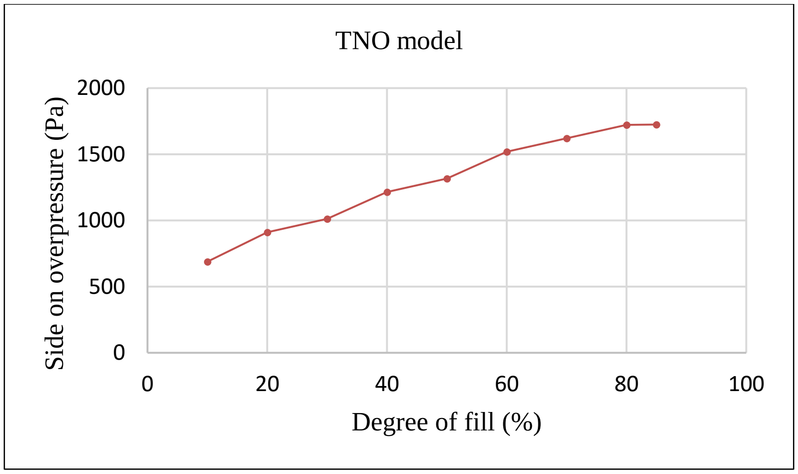


Figure 12: Degree of fill percentage and the side on over pressure

10. VCE Thermal Radiation Effects

In addition to blast overpressure, the thermal consequences associated with the VCE event were assessed for tank LPG–6 at varying fill percentages. The thermal radiation hazard was evaluated based on the fireball phenomenon typically accompanying large-scale hydrocarbon vapor cloud explosions.

The resulting fireball thermal radiation intensities, corresponding to the different tank inventory levels, are summarized in Table 7. The analysis provides critical insight into escalation risks, personnel exposure thresholds, and potential secondary fire initiation zones surrounding the storage facility.

Table 7: VCE thermal radiation at different degree of fill percentage

Degree of fill %	**Thermal radiation (kW/m^2)**					
	Mass (kg)	**100 (m)**	**200 (m)**	**300 (m)**	**400 (m)**	**500 (m)**
1	5300	27.397	9.615	4.619	2.674	1.734
10	53000	64.619	36.026	20.735	13.006	8.792
20	106000	76.078	48.785	30.530	20.035	13.894
30	159000	82.469	56.904	37.520	25.404	17.951
40	212000	86.850	62.826	43.001	29.825	21.396
50	265000	90.164	67.460	47.517	33.608	24.418
60	318000	92.819	71.249	51.357	36.925	27.124
70	371000	95.030	74.444	54.696	39.883	29.583
80	424000	96.922	77.197	57.645	42.555	31.839
85	450500	97.774	78.442	59.000	43.801	32.903

Figure 13 shows the VCE thermal radiation levels at several degrees of fill percentage of the tank and various distances far from the tank.

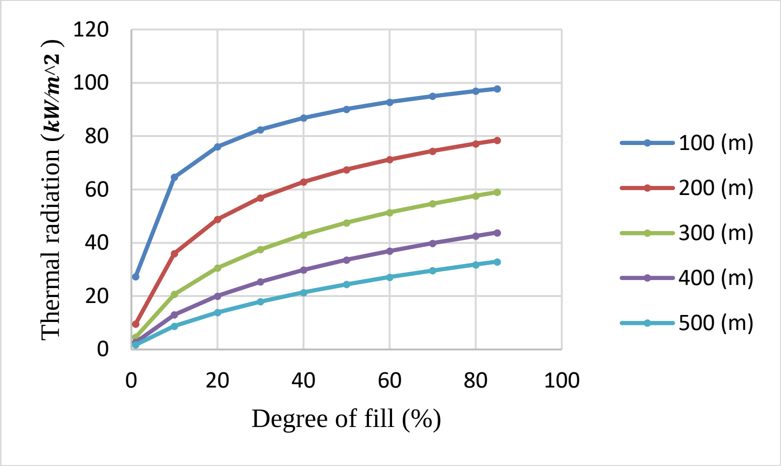


Figure 13: Thermal radiation versus the degree of percentage of the tank

11. Discussion of Results

The findings of this study highlight that VCEs associated with LPG storage generate two principal consequence domains: blast wave overpressure and thermal radiation. Among these, the blast wave effect represents the most critical hazard due to its rapid propagation and severe structural damage potential.

A key parameter governing blast severity is the side-on peak overpressure, which was evaluated at a radial distance of 500 m from the explosion source. The side-on peak overpressure generated from the modelled VCE scenario was estimated at incremental tank fill levels ranging from 10% to 85% of the total storage capacity, utilizing both the TNT equivalency and TNO models.

The analysis demonstrates a clear positive correlation between tank inventory and explosion severity. As the stored LPG volume increases, the available combustible mass participating in the vapor cloud formation also rises, resulting in higher explosion energy release. Consequently, both the predicted peak overpressure and the spatial extent of blast wave consequences increase proportionally with tank fill level.

The associated damage spectrum spans multiple structural vulnerability thresholds. At lower fill percentages, the predicted impacts are generally limited to light structural damage, including partial rupture of industrial cladding and non-load-bearing components. However, at higher inventory conditions, the blast intensity escalates significantly, reaching levels capable of causing severe structural impairment and, in extreme cases, total destruction of exposed facilities within the high-impact zone.

A comparative evaluation of the two modelling approaches indicates that the TNT equivalency model consistently predicts higher side-on peak overpressure values than the TNO model across all assessed fill levels. This variation reflects the conservative nature of TNT-based energy conversion assumptions relative to the more scenario-sensitive multi-energy methodology.

Thermal consequences were also assessed using the point source radiation model across inventory levels spanning 1% to 85% capacity. Radiation intensities were calculated at setback distances of 100 m, 200 m, 300 m, 400 m, and 500 m from the tank. The results, summarized in Table 7. The analysis indicates that the thermal radiation intensities generated from the modelled VCE, evaluated across multiple tank fill percentages, present significant hazard implications for both onsite personnel and offsite populations.

The predicted radiation levels demonstrate the potential to produce severe thermal impacts on exposed workers within the facility, particularly those not protected by structural shielding or emergency refuge systems at the time of the event. In addition, the surrounding residential communities located within a radial distance of up to 500 m from the LPG storage tank are also subject to considerable thermal exposure risk. Such radiation intensities may lead to serious burn injuries, ignition of combustible materials, and escalation of secondary fire scenarios, thereby amplifying the overall consequence severity of the VCE event.

12. Conclusions

VCEs represent one of the most catastrophic explosion scenarios within the chemical and hydrocarbon process industries due to their combined blast and thermal destruction potential.

In this study, the consequences of a VCE originating from a 1000 m³ LPG spherical storage tank were quantitatively assessed using both the TNT equivalency and TNO models. Blast wave impacts were estimated across multiple fill levels ranging from 10% to 85% of tank capacity at a distance of 500 m from Tank LPG–6. The predicted peak side-on overpressure of 85% of tank capacity was estimated to be 27400 pascal which is sufficient to cause rupture of lightweight industrial cladding and significant structural damage.

Thermal radiation effects associated with the VCE fireball were also evaluated up to 500 m from the tank. The results indicate that both onsite workers and surrounding communities would be exposed to hazardous radiation levels in the absence of adequate shelter or protective barriers.

The applied VCE consequence models provide valuable decision-support tools for:

- Industrial risk assessment and hazard zoning
- Worker safety planning
- Emergency preparedness and response design
- Regulatory land-use control near major hazard installations (MHIs)

From a risk mitigation perspective, it is strongly recommended that high-hazard industries:

- Maintain hazardous material inventories at the lowest practicable levels
- Implement robust onsite and offsite emergency response plans in coordination with regulatory authorities
- Establish adequate safety buffer zones separating industrial facilities from residential developments

Furthermore, architectural and civil engineers involved in early facility design should possess foundational knowledge of process hazards. This enables optimized decisions regarding building location, orientation, and construction materials particularly for critical infrastructures such as control rooms and administrative buildings to minimize explosion impact consequences.

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