Research Article

Evaluation of BLEVE and VCE Impacts from LPG Spherical Tank by ALOHA

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Abstract

Boiling Liquid Expanding Vapor Explosion (BLEVE) is an extremely violent explosion that can occur when a vessel containing a pressurized liquid is ruptured. The BLEVE gives rise to the following effects: (1) blast wave, (2) fireball, and (3) fragments. 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. This study aims to evaluate the BLEVE and VCE impacts from 1000 m^3 LPG spherical tank by an Areal Locations of Hazardous Atmospheres (ALOHA) program. ALOHA has been programed to estimate the BLEVE fireball thermal radiation and VCE blast wave overpressure. The BLEVE fire ball thermal radiation impacts and the VCE blast over pressure have been estimated at 10%, 20%, 30%, 40% and 50% of the capacity of LPG – 6. The farthest thermal radiation threat zones are identified in case of half full tank as follows: (i) the red zone (potentially lethal zone) extends up to almost one km, the workers and the neighboring community who are outside their offices and shelters will be at risk (ii) the orange zone (second degree burns zone) extends up to two km, and (iii) the yellow zone (pain zone) extends up to two kms. The VCE blast wave over pressure threat zones have been identified as follows: (i) the red zone extends up to almost 409 m which is likely to destruct building (ii) the orange zone extends up to 640 m which is likely to cause serious injury, and (iii) the yellow zone extends up to 1.1 kms where the glass is shattered.

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1. INTRODUCTION

Liquefied petroleum gas (LPG), also referred to as GPL, LP gas, liquid petroleum gas, propane, or butane, is a flammable mixture of hydrocarbon gases widely used as a fuel for heating appliances and vehicles. Approximately 60% of LPG is obtained from the extraction of natural gas and crude oil, while the remaining 40% is generated during the crude oil refining process [1]. In refineries and gas processing plants, LPG is stored in pressurized vessels, which are typically designed as either cylindrical or spherical tanks. These storage vessels are generally constructed from steel or other robust materials capable of withstanding the elevated pressures and low temperatures necessary to maintain LPG in its liquid state. Various types of LPG storage tanks are available; each intended for specific applications and differing in storage capacity. The classification of LPG storage tanks has been summarized by Lopez, A. G. [2].

The primary hazards associated with the operation of Major Hazard Installations (MHIs), including refineries and LPG plants, are fire, explosion, and toxic substance release [3]. Accidents resulting from LPG tank leakages can cause significant loss of life and substantial economic damage. Numerous incidents related to LPG storage and handling have occurred worldwide. The 1974 Flixborough Nypro UK) explosion involved the release of 30 tons of cyclohexane through a vertical crack in one of the on-site reactors, resulting in the deaths of 28 workers and injuries to an additional 36 individuals [4]. Another major incident was the 1984 PEMEX LPG Terminal disaster in Mexico City, which claimed more than 500 lives and left approximately 4,000 people injured. The first boiling liquid expanding vapor explosion (BLEVE) occurred 15 minutes after the initial release, followed by a series of subsequent BLEVEs. These explosions were so devastating that they caused extensive destruction in the surrounding area, with shattered glass projected as far as 4 km from the explosion source [5]. A similar event occurred during the 2005 BP Texas City Refinery explosion, which resulted in 15 fatalities and approximately 180 injuries [6]. Another LPG-related accident took place on July 16, 2015, in Shandong, China, when leakage occurred from an LPG spherical storage tank at a chemical engineering company. The incident generated a massive mushroom cloud over the site, while the ensuing explosion caused the collapse of buildings and walls and ignited nine spherical storage tanks. Consequently, all residents within a 5 km radius were evacuated [7]. These accidents were primarily attributed to vapor cloud explosions (VCEs) and boiling liquid expanding vapor explosions (BLEVEs). To help prevent the recurrence of such incidents, consequence assessments employing models related to VCEs are essential. Therefore, the objective of this study is to evaluate the consequences of BLEVE and VCE scenarios involving a 1000 LPG spherical storage tank using ALOHA.

2. Hazards from LPG

LPG is an essential energy source that is widely utilized in both domestic and commercial applications. However, it poses considerable hazards, as gas leaks can result in fires or explosions. Owing to its ability to be readily compressed under relatively low pressure, LPG is primarily stored in a liquefied state within pressurized tanks and vaporized before use. One cubic meter of liquid LPG expands to approximately 245-275 m' of vapor upon vaporization. In addition, the heating value of LPG is approximately 2.5 to 3 times greater than that of natural gas. Consequently, a substantial amount of potential energy is stored within a relatively small volume of LPG.

Accidents resulting from LPG tank leakages can lead to significant casualties and severe economic losses. The sequence of events following an LPG leak is illustrated in Figure 1. Once leakage occurs, the released vapor cloud may encounter an ignition source, leading initially to a flash fire. The flash fire can subsequently propagate back toward the leak source, resulting in a jet fire. The intense heat generated by the jet fire increases the temperature of the pressurized vessel, potentially triggering a boiling liquid expanding vapor explosion (BLEVE). Alternatively, a vapor cloud explosion (VCE) may occur when delayed ignition allows the flame propagation velocity within the vapor cloud to increase. The resulting consequences depend on both the timing of ignition and the size of the leak opening. In the case of a small leak, BLEVE represents the scenario with the greatest impact distance, regardless of whether ignition occurs immediately or is delayed. Conversely, for a large leak or complete vessel rupture, either a flash fire or a VCE resulting from delayed ignition can produce the greatest impact distance.

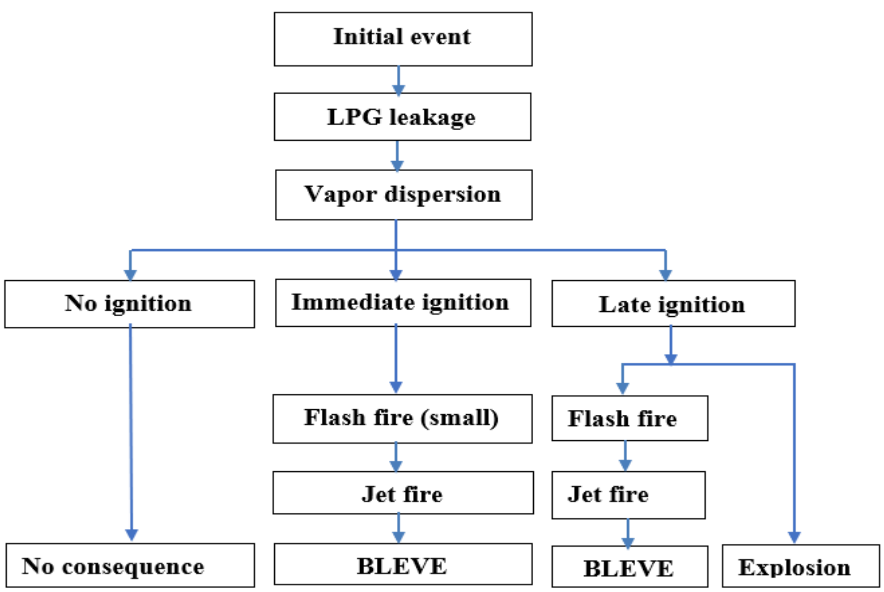


Figure 1: Event sequences of LPG leak [7].

3. BLEVE

The Centre for Chemical Process Safety (CCPS) [8] defines a boiling liquid expanding vapor explosion (BLEVE) as "an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure." Similarly, CCPS [9] describes a BLEVE as "a sudden release of a large mass of pressurized superheated liquid to the atmosphere." Such a release may occur following containment failure caused by factors including fire engulfment, missile impact, corrosion, manufacturing detects, or internal overheating, among others [10]. Furthermore, [11] classified BLEVEs into three categories-BLEVE, hot BLEVE, and cold BLEVE-based on the type of event or underlying mechanism.

A BLEVE typically occurs when a pressure vessel containing a flammable liquid is exposed to fire, causing the vessel material to lose its mechanical strength and eventually rupture [12]. Any process involving significant quantities of liquefied gases, volatile superheated liquids, of gases maintained at elevated pressures and temperatures is considered susceptible to BLEVE occurrence. The development of a BLEVE can be described through a sequence of stages, as illustrated in Figure 2, which presents the mechanism of BLEVE development [13,14].

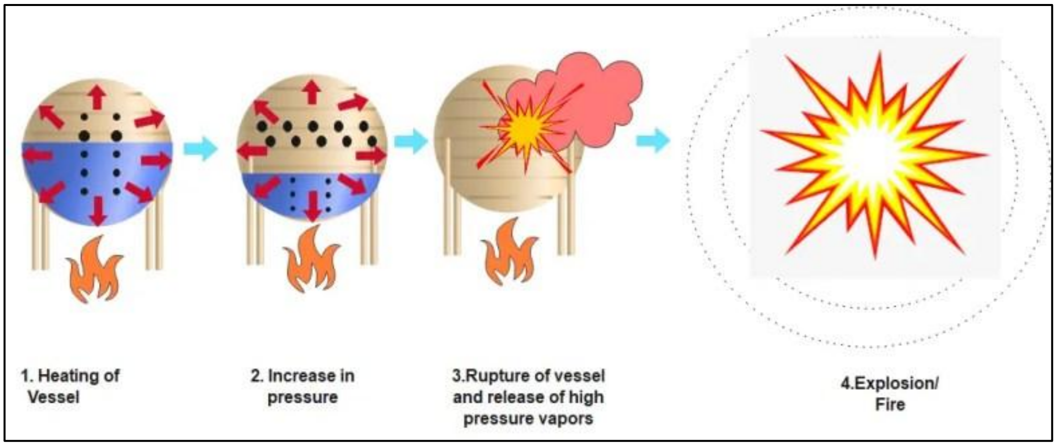


Figure 2: Mechanism of BLEVE [13].

4. Vapor Cloud Explosion

An explosion is defined as the rapid expansion of gases that generates a fast-moving pressure or shock wave [15]. The explosion of a fuel-air mixture is commonly referred to as a vapor cloud explosion (VCE). When a large quantity of flammable vaporizing liquid or gas is suddenly released, a vapor cloud is formed and subsequently disperses into the surrounding atmosphere. If the cloud is ignited before its concentration decreases below the lower flammability limit (LFL), either a VCE or a flash fire may occur. For an incident to be classified as a VCE, the following conditions must be satisfied:

1. Cloud formation
2. Presence of flammable material
3. Flammable concentration limits
4. Blast effect
5. Presence of turbulence

The flame front, defined as the interface between burned and unburned material, can propagate during a VCE through two distinct modes: deflagration and detonation.

In a deflagration, flame propagation occurs through heat and mass transfer into the unburned mixture. Because energy transfer is relatively slow, the flame propagation velocity remains below the speed of sound in the unreacted medium. In contrast, detonation propagates through shock-induced compressive heating. Owing to the rapid transmission of mechanical forces, detonation advances at velocities that exceed the speed of sound. Consequently, the overpressure characteristics of deflagrations and detonations differ considerably over time. Representative overpressure profiles for both phenomena are presented in Figures 3(a) and 3(b). For an equivalent explosion energy, deflagrations generally exhibit a gradual increase to peak overpressure, followed by an extended duration and a gradual decay in pressure. This type of pressure profile is commonly referred to as a pressure wave. Conversely, detonations are characterized by an almost instantaneous rise to peak overpressure, followed by a steady decline, producing the more idealized shock front.

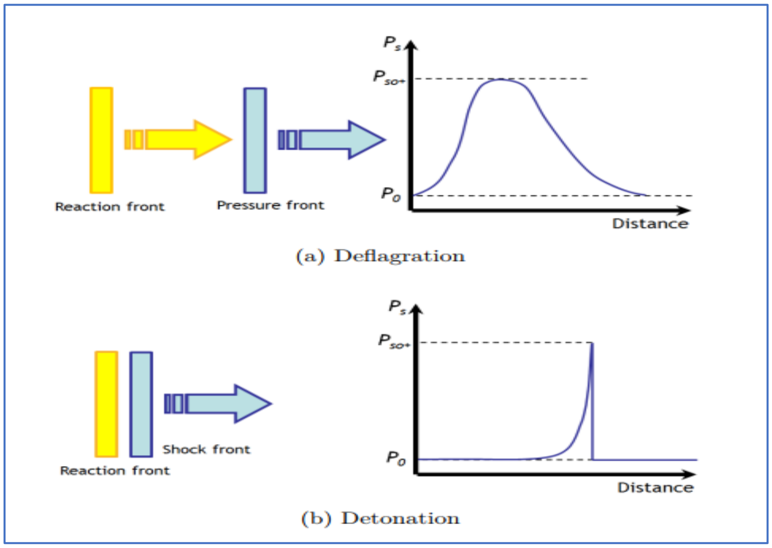


Figure 3: Pressure-distance shape following an explosion [16].

4.1. Mechanism of VCE

When a flammable substance is released into the atmosphere, it forms a vapor cloud that disperses as it moves downwind. If the cloud encounters an ignition source during dispersion, the portions of the cloud with concentrations within the flammable limits Will ignite and burn. Under certain conditions, combustion may occur at a sutticiently rapid rate to generate an explosive force in the form of a blast wave [17]. In a vapor loud explosion (VCE), the intensity of the resulting blast wave is governed by both the rate at which the fuel is consumed and the total quantity of fuel involved in the combustion process. The fuel consumption rate is primarily influenced by flame speed, which is significantly enhanced when flame propagation occurs through congested environments or when the expansion of burned gases is confined. Generally, the flame must accelerate to a velocity exceeding approximately 0.2 times the speed of sound in air (about 70 m/s) before a blast wave capable of causing structural damage can be produced. When the vapor cloud burns at flame speeds below this threshold, the event is typically classified as a flash fire. Although flash fires can result in direct flame contact and thermal radiation damage, they generally do not generate significant overpressure effects. The sequence of events leading to a VCE is illustrated in Figure 4.

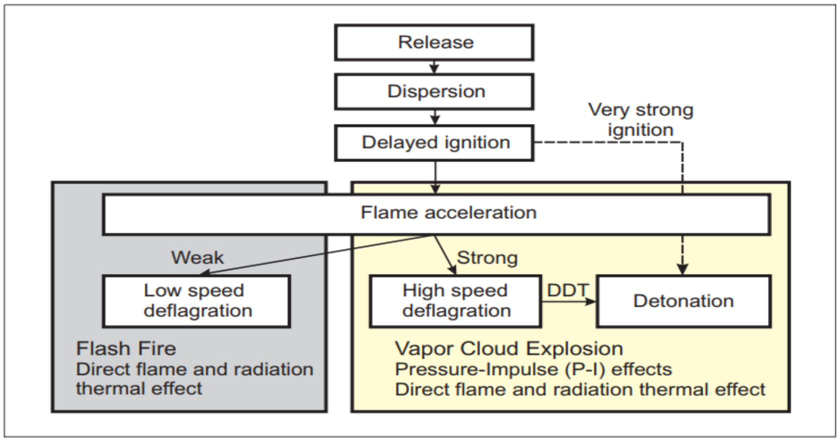


Figure 4: VCE mechanism [18].

5. ALOHA

Areal Locations of Hazardous Atmospheres (ALOHA) is a software program jointly developed by the United States Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) to support emergency planning and response for hazardous chemical releases. Designed by NOAA, the program is capable of evaluating accident scenarios occurring on both land and at sea.

Although ALOHA does not provide the same level of accuracy as commercial software packages such as PHAST and TRACE (SAFER), it remains a valuable tool for consequence assessment [19].

ALOHA is freely available and designed with a user-friendly interface. Technical support is also available through the Reporting Center to assist users in resolving operational issues. Furthermore, the software incorporates an extensive database that has been continuously updated since its initial development. Its modeling capabilities account for key atmospheric parameters, including wind speed, wind direction, atmospheric stability, surface roughness, and the atmospheric inversion layer.

To deliver rapid assessments, ALOHA employs predictive models that generate results efficiently. These predictions have been validated through comparisons with similar modeling approaches and field experiments conducted during the software's valuation to ensure the reliability of the generated results. Moreover, effective use of ALOHA requires users to possess a basic understanding of atmospheric parameters and their influence on dispersion modeling. Overall, the software provides significant practical value due to its ease of use and its capability to estimate hazardous emissions efficiently [20].

5.1 ALOHA thermal radiation impact criteria

Table 1 summarizes the BLEVE fireball thermal radiation impacts criteria.

Table 1: ALOHA thermal radiation impact criteria and threat zones [19].

Threat zone	Thermal radiation level (kW/m^2)	Impacts
Red	10	Potentially lethal within 60 sec
Orange	5	2nd degree burns within 60 sec
Yellow	2	Pain within 60 sec.

5.2 ALOHA blast wave impact criteria

Table 2 summarizes the VCE blast wave impacts and threat zones criteria

Table 2: ALOHA blast wave impact criteria and threat zones [19].

Threat zone	Over pressure (psi)	Impacts
Red	8	Destruction of buildings
Orange	3.5	Seirus injury likely
Yellow	1	Shatter glass

6. Case Study

A refinery is equipped with six LPG spherical storage tanks designated as LPG-1 through LPG-6 for the storage of liquefied petroleum gas products. Among these, four smaller tanks (LPG-1, LPG-2, LPG-3, and LPG-4) each have a storage capacity of 500 m', while the remaining two larger tanks (LPG-5 and LPG-6) each have a capacity of 1000 m'. The arrangement of the LPG spherical tanks and the separation distances between them are illustrated in Figure 5.

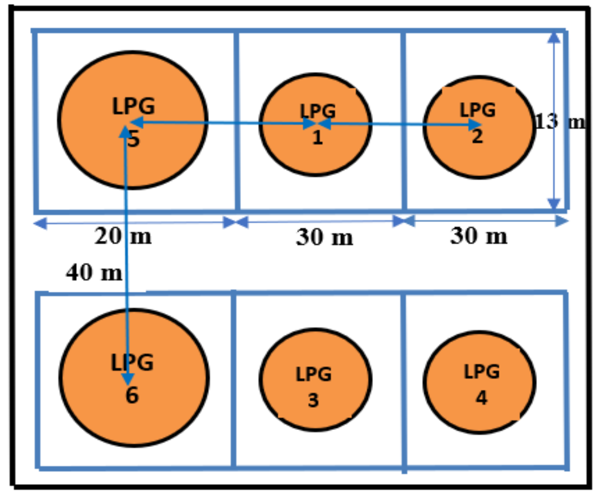


Figure 5: The lay out of the LPG spherical tanks

Figure 6 (a) shows the Goggle earth aerial view of the LPG spherical tanks, and Figure 6 (b) shows the distance from LPG – 6 to the nearest housing accommodation which is 504 m.

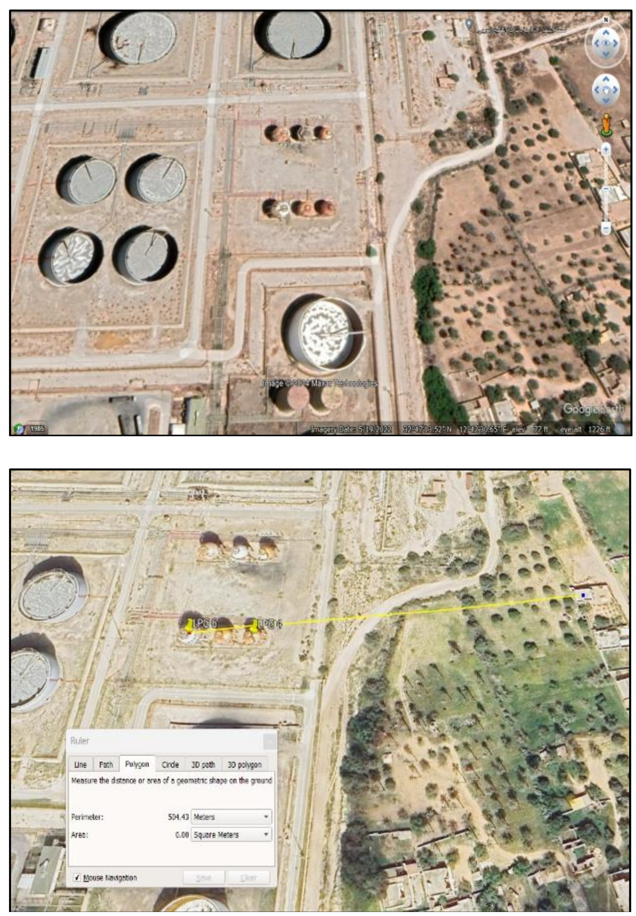


Figure 6: Goggle earth Areal view of the LPG spherical tanks, the distance between the LPG spherical tanks and housing accommodation

The LPG spherical tanks are fitted with inlet, suction, transfer, return, balance, drain, and discharge piping systems. Figure 7 presents the configuration of a typical LPG spherical tank. The inlet line supplies LPG to the storage tank, whereas the suction line facilitates the simultaneous execution of two operational functions. The transfer line enables the movement of LPG from one spherical tank to another during maintenance activities or emergency situations. Return lines are provided to redirect LPG products that do not satisfy the required quality specifications. The balance line transfers LPG to empty storage tanks when an overfilling condition occurs. In addition, the circulation line recirculates the product from the bottom of the tank back to the top until a homogeneous composition is achieved. This circulation process typically requires approximately four hours. Upon completion, an LPG sample is collected and analyzed in the laboratory to verify compliance with the required product specifications. Once conformity is confirmed, a certification is issued indicating that the LPG is suitable for domestic cooking applications.

The LPG spherical tanks are also equipped with control, protection, and firefighting systems to enhance operational safety. As shown in Figure 5, four gas detectors are installed at ground level near the corners of the containment dike to provide early detection of any LPG leakage.

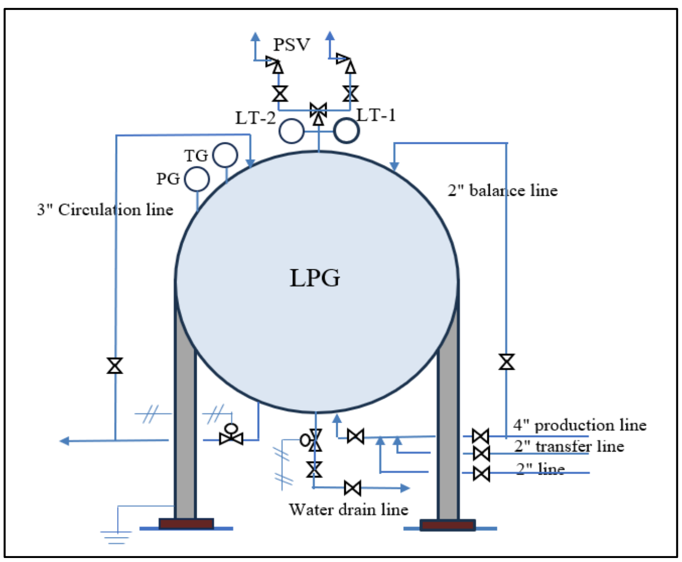


Figure 7: LPG spherical tank

The Characteristics of LPG spherical tank has been summarized in Table 3.

Table 3: 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

7. ALOHA Estimation of BLEVE and VCE

The ALOHA software was employed to estimate the thermal radiation effects of a BLEVE fireball and the blast wave overpressure associated with a vapor cloud explosion (VCE) originating from the large LPG spherical storage tank, L.PG-6.

7.1 ALOHA Fireball Thermal Radiation from LPG-6

A BLEVE scenario was simulated at 10%, 20%, 30%, 40%, and 50% of the storage capacity of LPG-6. The ALOHA output is presented in the form of thermal radiation threat zones. The software identifies three concentric thermal radiation hazard zones: the red (innermost) zone denotes the highest hazard level, while the orange (intermediate) and yellow (outermost) zones represent progressively lower hazard levels. The thermal radiation is predicted to propagate in all directions, with a slightly greater extent in the downwind direction. ALOHA can also be integrated with Google Earth to visualize the predicted thermal radiation threat zones geographically. Figure 8(a) illustrates the BLEVE fireball thermal radiation threat zones generated by ALOHA, whereas Figure S(b) presents the corresponding thermal radiation threat zones overlaid on a Google Earth aerial image.

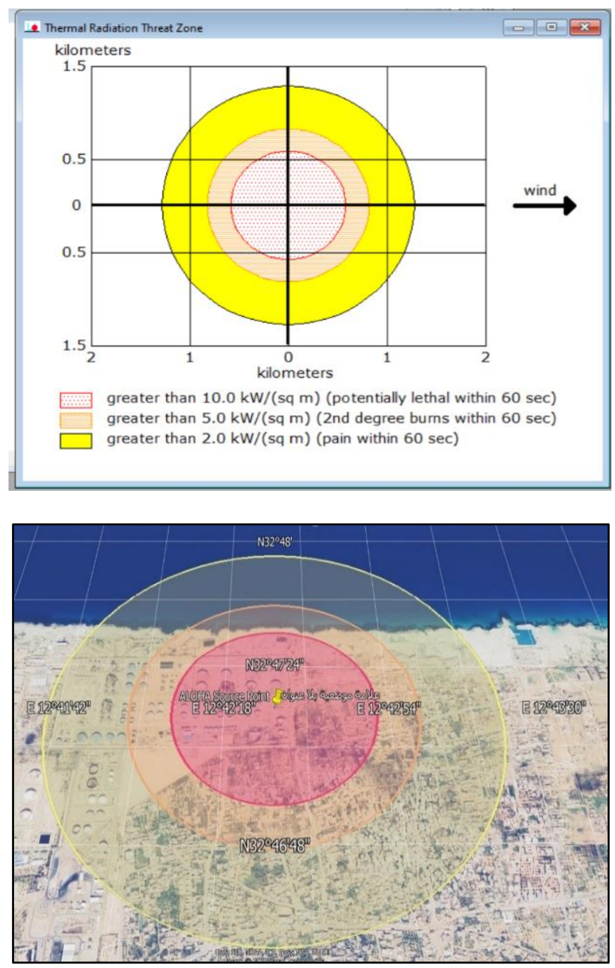


Figure 8: (a) ALOHA BLEVE fireball and (b) Google Earth aerial view thermal radiation threat zones at 10% capacity of LPG tank.

Figure 9 shows the BLEVE fireball thermal radiation contour at 20% of the capacity of the LPG spherical tank

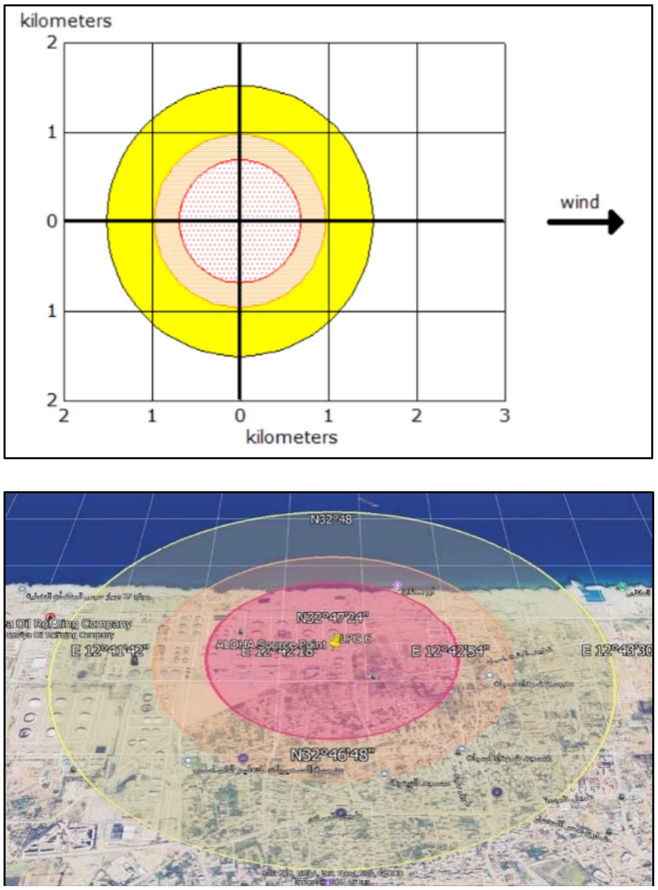
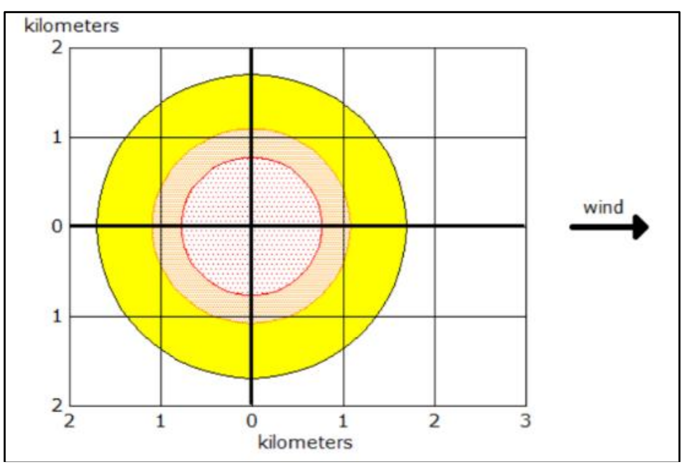


Figure 9: (a) ALOHA BLEVE fireball and (b) Goggle earth aerial view thermal radiation threat zones at 20% capacity of LPG tank.

Figure 10 shows the BLEVE fire ball thermal radiation contour at 30% of the capacity of the LPG spherical tank



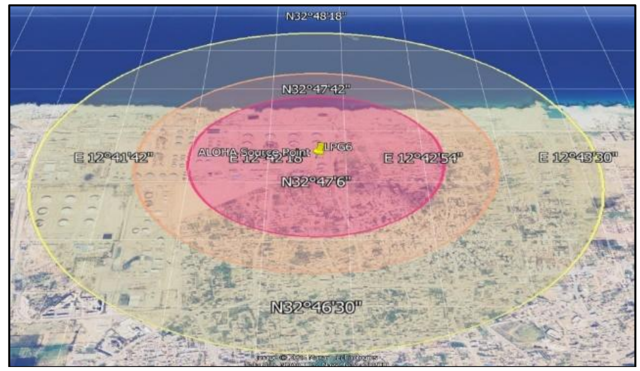


Figure 10: (a) ALOHA BLEVE fireball and (b) Goggle earth aerial view thermal radiation threat zones at 30% capacity of LPG tank.

Figure 11 shows the BLEVE fire ball thermal radiation contour at 40% of the capacity of the LPG spherical tank

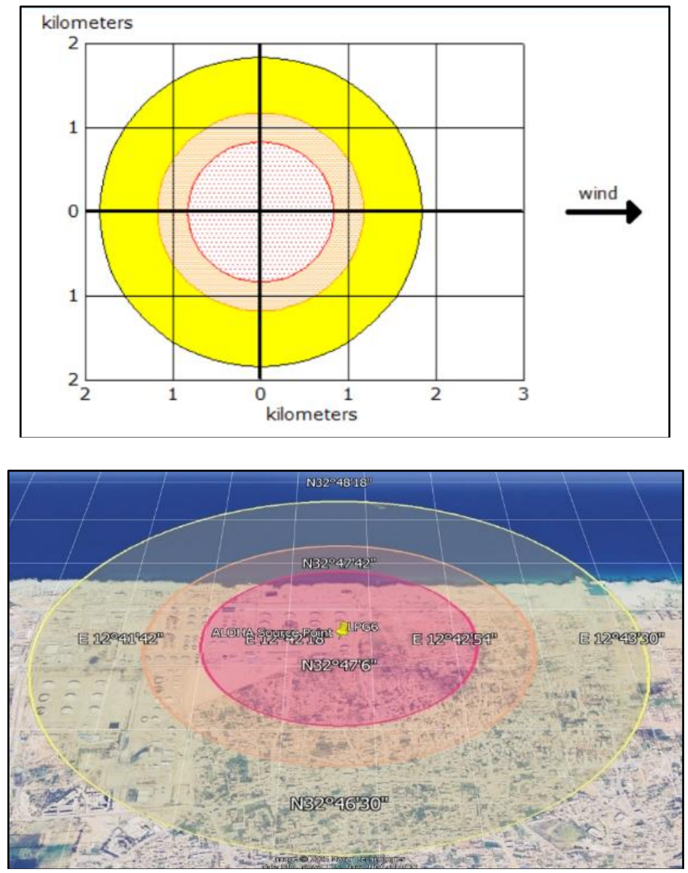


Figure 11: (a) ALOHA BLEVE fireball and (b) Goggle earth aerial view thermal radiation threat zones at 40% capacity of LPG tank.

Figure 12 shows the BLEVE fire ball thermal radiation contour at 50% of the capacity of the LPG spherical tank

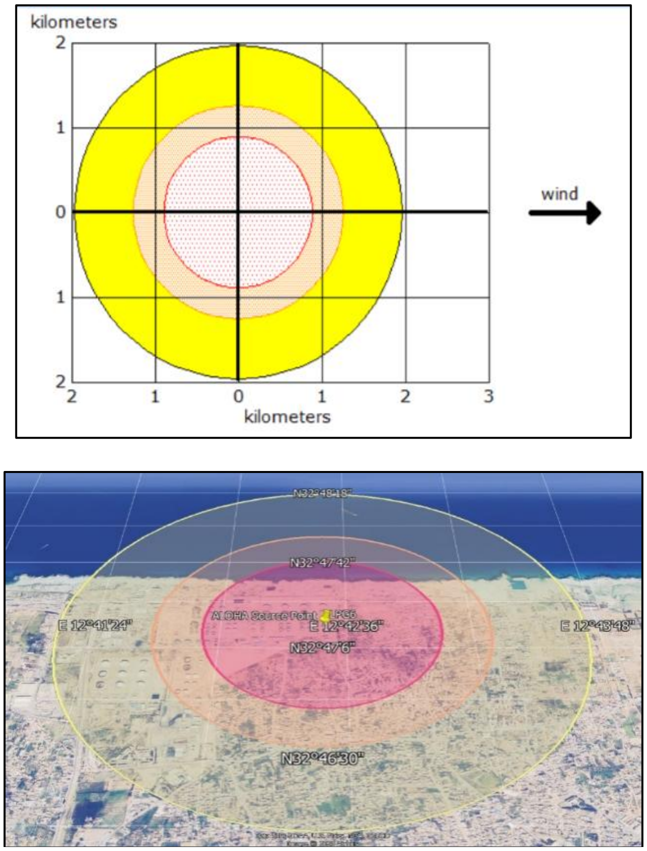


Figure 12: (a) ALOHA BLEVE fireball and (b) Goggle earth aerial view thermal radiation threat zones at 50% capacity of LPG tank.

Table 4 summarizes the fireball thermal radiation impacts and threat zones at different levels of the capacity of the spherical tank.

Table 4: The summary of the fireball thermal radiation impacts and threat zone at different levels of the capacity of LPG – 6.

Tank capacity	Threat zone	Distance (m)	Thermal radiation threat
10%	Red	580	Potentially lethal within 60 sec.
	Orange	818	2nd degree burns within 60 sec.
	Yellow	1278	Pain within 60 sec.
20%	Red	688	Potentially lethal within 60 sec.
	Orange	971	2nd degree burns within 60 sec.
	Yellow	1500	Pain within 60 sec.
30%	Red	768	Potentially lethal within 60 sec.
	Orange	1100	2nd degree burns within 60 sec.
	Yellow	1700	Pain within 60 sec.
40%	Red	833	Potentially lethal within 60 sec.
	Orange	1200	2nd degree burns within 60 sec.
	Yellow	1800	Pain within 60 sec.
50%	Red	890	Potentially lethal within 60 sec.
	Orange	1300	2nd degree burns within 60 sec.
	Yellow	2000	Pain within 60 sec.

7.2 ALOHA Blast wave from LPG - 6

The blast wave has been estimated at different tank levels. Figure 13 shows the ALOHA blast wave threat zones at 10% of the capacity of LPG - 6

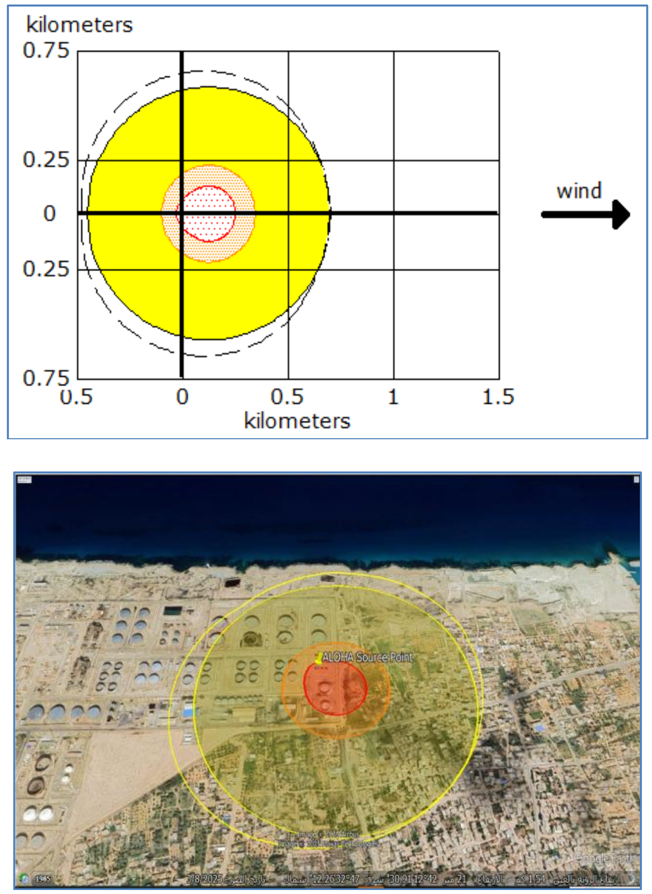


Figure 13: (a) ALOHA blast wave and (b) Goggle earth aerial view threat zones at 10% of the capacity of LPG – 6.

Figure 14 shows the ALOHA VCE blast wave threat zones at 20% of the capacity of LPG – 6

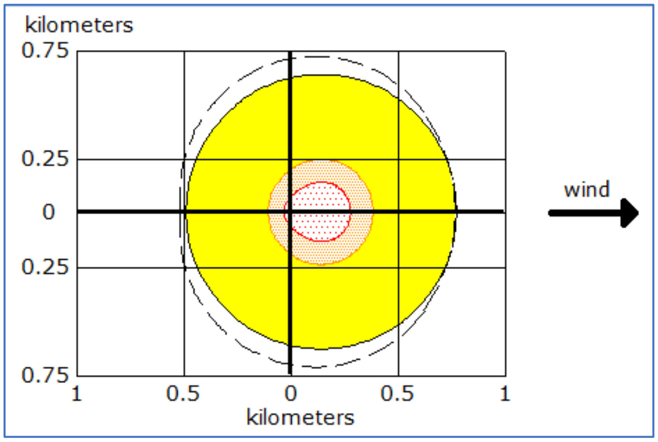


Figure 14: (a) ALOHA blast wave and (b) Goggle earth aerial view threat zones at 20% of the capacity of LPG – 6.

Figure 15 shows the ALOHA VCE blast wave threat zones at 30% of the capacity of LPG - 6

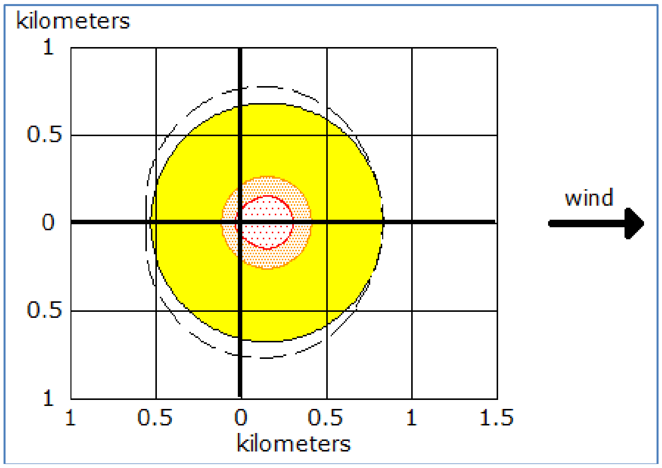


Figure 15: (a) ALOHA blast wave and (b) Goggle earth aerial view threat zones at 30% of the capacity of LPG – 6.

Figure 16 shows the ALOHA VCE blast wave threat zones at 40% of the capacity of LPG - 6

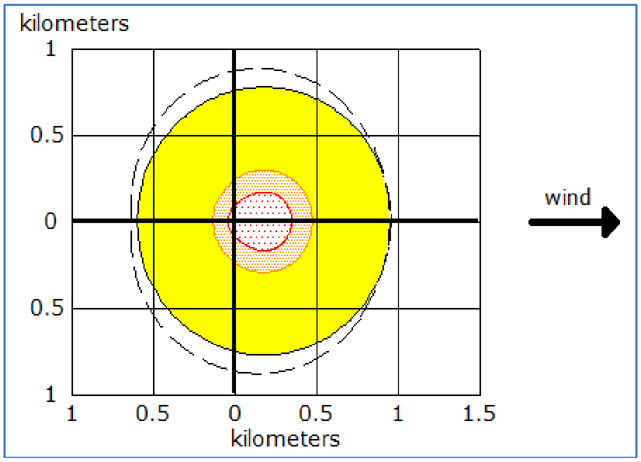


Figure 16: (a) ALOHA blast wave and (b) Goggle earth aerial view threat zones at 40% of the capacity of LPG – 6.

Figure 17 shows the ALOHA VCE blast wave threat zones at 50% of the capacity of LPG – 6

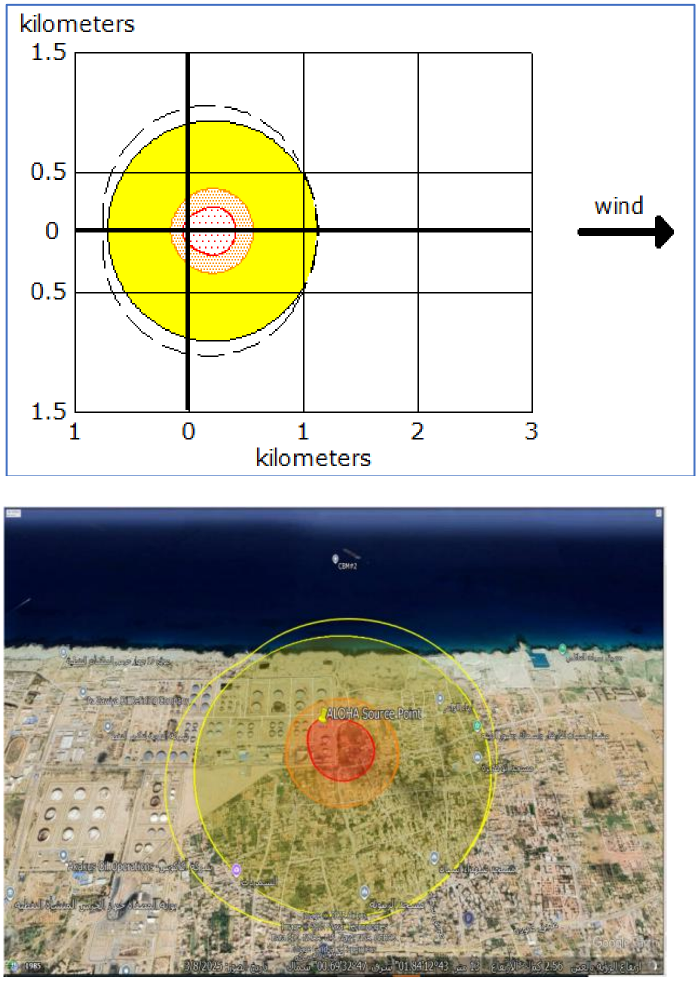


Figure 17: (a) ALOHA blast wave and (b) Goggle earth aerial view threat zones
at 50% of the capacity of LPG – 6.

Table 5 summarizes of the blast wave threat zone for LPG – 6

Table 5: The summary of the Blast wave threat zone for LPG – 4 & LPG – 6.

VCE at	Threat zone	LPG - 6 Distance (m)	Thermal radiation threat
10%	Red	271	Destruction of buildings
	Orange	369	Serious injury likely
	Yellow	735	Shatters glass
20%	Red	303	Destruction of buildings
	Orange	408	Serious injury likely
	Yellow	812	Shatters glass
30%	Red	329	Destruction of buildings
	Orange	445	Serious injury likely
	Yellow	880	Shatters glass
40%	Red	375	Destruction of buildings
	Orange	508	Serious injury likely
	Yellow	1000	Shatters glass
50%	Red	409	Destruction of buildings
	Orange	559	Serious injury likely
	Yellow	1100	Shatters glass

8. DISCUSSION

This study evaluated the extent of radiant heat damage resulting from a BLEVE involving the LPG-6 storage tank. The fireball thermal radiation effects predicted for the LPG spherical tank are presented in terms of threat zones and corresponding impact distances. Both the ALOHA output and the Google Earth visualizations classify the affected areas into red, orange, and yellow threat zones. The red (innermost) zone represents the highest hazard level, while the orange (intermediate) and yellow (outermost) zones indicate progressively lower levels of thermal radiation hazard.

Table 4 summarizes the fireball thermal radiation impacts and the corresponding threat zones at 10%, 20%, 30%, 40%, and 50% of the storage capacity of the spherical tank. At 10% capacity, the lethal thermal radiation zone extends to an approximate radius of 0.5 km, with the affected area increasing as the tank inventory increases. At 50% capacity, the lethal thermal radiation zone expands to nearly 1 km. Although the duration of fireball thermal radiation is limited to only a few seconds, its consequences can be fatal for refinery personnel working outside office buildings during the incident, as well as for members of the surrounding community who are not protected within shelters.

The orange threat zone, which corresponds to thermal radiation capable of causing second-degree burns within 60 seconds, extends to approximately 818 m when the tank is filled to 10% capacity and increases progressively with increasing tank inventory. At 50% of the tank capacity, the second-degree burn hazard extends to nearly 2 km.

Table 5 summarizes the VCE blast wave impacts and associated threat zones for storage levels of 10%, 20%, 30%, 40%, and 50% of the spherical tank capacity. The results indicate that the red threat zone extends to approximately 409 m, where structural destruction of buildings is likely. The orange threat zone reaches approximately 640 m, where serious injuries are expected, while the yellow threat zone extends to approximately 1.1 km, within which glass breakage is anticipated.

9. CONCLUSION

BLEVE represents one of the most catastrophic explosion phenomena encountered in the chemical process industry. Although Major Hazard Installations (MHIs), including refineries, chemical processing plants, and LPG production and storage facilities, increasingly employ advanced specialized software to conduct comprehensive safety assessments, ALOHA remains a practical tool capable of providing consequence predictions with reasonable accuracy. It can therefore serve as an effective means of enhancing awareness of potential hazards among industrial personnel and supporting authorities responsible for protecting communities located near hazardous installations. To minimize both onsite and offsite risks, high-risk industries are advised to maintain hazardous material inventories at the lowest practicable levels and to coordinate offsite emergency response plans with the relevant authorities. In addition, regulatory authorities should discourage residential development in close proximity to the boundaries of Major Hazard Installations. Furthermore, architectural and civil engineers involved in the design of industrial facilities should possess a thorough understanding of process hazards—including fire, explosion, and toxic releases—to ensure that the location, orientation, and construction materials of critical buildings, such as control rooms and office facilities, are selected to reduce the potential impacts of explosion events.

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