Discussion on the Possibility of BLEVE occurring in Liquefied Natural Gas Storage Tanks

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ABSTRACT

To safeguard workers and equipment at liquefied natural gas (LNG) terminals, the tanks are stored and operated under cryogenic conditions. However, fire accidents may affect the tanks' temperature and pressure, leading to a boiling liquid expanding vapor explosion (BLEVE). Thus, in order to evaluate the risks from BLEVEs of LNG storage tanks, this study first analyzes historical data (1920–2024) on BLEVEs involving any substance and identifies the key factors contributing to incidents. Then, we estimate the impact range of the overpressure generated specifically from vaporized LNG by utilizing the empirical formulas proposed by Prugh [1] and Hemmatian et al. [2], as well as the quantitative risk analysis (QRA) software Safeti/Phast developed by Det Norske Veritas (DNV). Our results indicate that, owing to the design of current storage tanks, the blast radius remains relatively small, limiting the extent of the damage.

Keywords: Liquefied Natural Gas (LNG), BLEVE, Overpressure

I. INTRODUCTION

A boiling liquid expanding vapor explosion (BLEVE) occurs when the liquid contents in a vessel reach or exceed their boiling point and rapidly vaporize and expand, causing the vessel to violently rupture [3]. Hence, fossil fuel facilities, including liquefied natural gas (LNG) terminals, must recognize the risk of BLEVEs arising during fire accidents, when the containers may be exposed to and consequently weakened by pool fires or jet flames. As these explosions are physical rather than chemical—i.e., caused by the release of mechanical energy—their hazards can be broadly categorized as overpressure shock waves, explosive fragments, or, when the event involves a persistent fire source and flammable materials, fireballs.

In this study, we primarily focused on the probability and magnitude of overpressure shock waves propagated by BLEVEs of LNG storage tanks. To accurately quantify the hazards in different scenarios, we compared and verified the results obtained with three methods:The equivalent-mass-of-trinitrotoluene (TNT) formula proposed by Prugh [1], the statistical model developed by Hemmatian et al. [2], and the quantitative risk assessment (QRA) and consequence analysis software Safeti/Phast, developed by Det Norske Veritas (DNV), are utilized in this study.

II. HISTORICAL BLEVES AND CAUSES

To identify the risk factors for BLEVEs, we examined 71 historical incidents inventoried in the Analysis, Research and Information on Accidents (ARIA) database, which is maintained by France's Bureau for Analysis of Industrial Risks and Pollutions within the Ministry of Ecology and has been recording incidents globally since 1950 [4]. To supplement these data and improve our analysis of the frequency of occurrence (Figure 1), the substances involved and the accompanying circumstances, we also consulted *The Handbook of Hazardous Materials Spills Technology* [5] and *Evaluation of the Effects and Consequences of Major Accidents in Industrial Plants* [6], which cover a period from 1920 to 2024 and include 65 incidents.

There were 136 accidents in total, of which 66 were BLEVEs during transportation, 64 were at fixed facilities, and 6 were other types, such as BLEVEs at road construction sites.

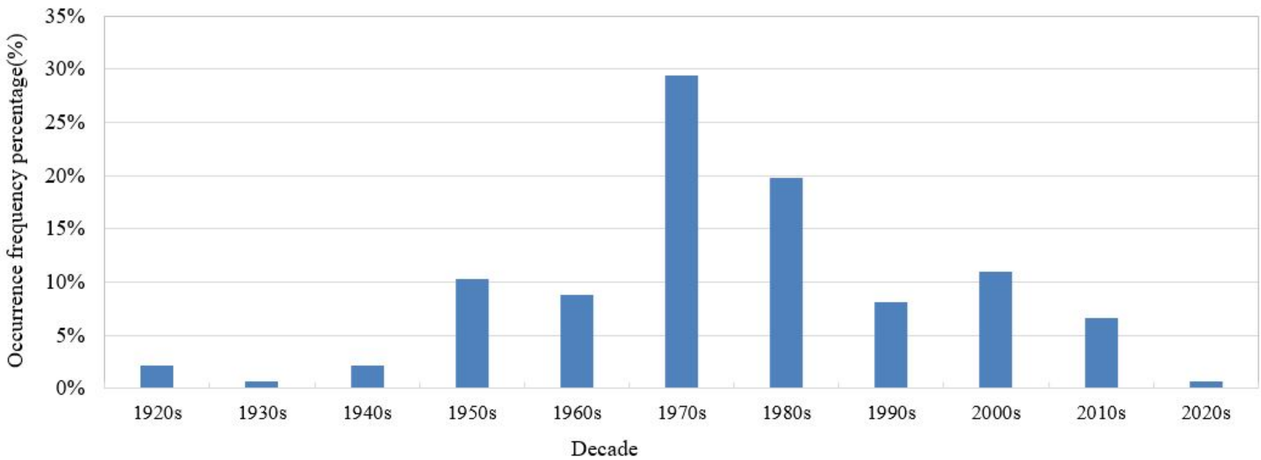

Figure 1. The distribution chart of BLEVE accident occurrence time and frequency

According to ARIA and the relevant literature, the causes of BLEVEs fall into five general categories, viz., impact failures, external events, human factors, mechanical failures, and severe reactions, which can be further divided into specific factors (Table 1). Impact failures, which comprise collisions, derailments, and road accidents, account for the largest proportion of incidents (~40%, or 51 incidents), followed by external events (~29%, or 39 incidents), which encompass earthquakes, explosions, and fires. However, external fires alone are responsible for more than a quarter of the total incidents (~27%, or 37 incidents), rendering them the most frequent cause among specific factors.

Table 1 Causes of BLEVE Accidents

General causes	Specific factors	Percentage of occurrences (%)
Impact Failure(39.71%)	Collision	8.1
	Derailing	16.2
	Road accident	15.4
External Event(28.68%)	Earthquake	0.7
	Explosion	0.7
	Fire	27.2
Human Factor(15.44%)	Overfilling	7.4
	Human error	8.1
Mechanical Failure(11.02%)	Overpressure	2.2
	Overheating	1.5
	Leak	2.9
	Corrosion	0.7
	Other	3.7
Violent Reaction (5.15%)	Runaway reaction	5.1

Additionally, we identified the 12 substances most likely to be involved in BLEVEs (Table 2), with liquefied petroleum gas (LPG) and propane appearing in half (or 68 incidents)) of the incidents. Gasoline and butane each contributed ~7% to the total occurrences (with 10 and 9 incidents, respectively), whereas LNG accounted for merely ~1% (with 2 incidents).

We also investigated the contributing factors in the disaster that unfolded on November 19, 1984, in San Juan Ixhuatepec, Mexico, when a ruptured pipeline at the Pemex LPG storage and transportation station released enough LPG to form a massive gas cloud, which eventually ignited, and, within minutes, triggered the first of multiple BLEVEs. Failed emergency isolation systems, nonfunctioning fire protection systems, and nonexistent gas detection systems in conjunction with poor facility location and traffic congestion exacerbated the severity of this industrial accident, which killed ~500, injured ~6,000, and destroyed almost all of the storage tanks at the station.

Although BLEVEs of LNG storage tanks seldom occur, mainly because these containers are generally constructed with thermal insulation and double walls (e.g., an outer shell of concrete and an inner shell of steel) as well as kept at a relatively low operating pressure, accidents involving LNG are still possible. For example, a road tanker transporting LNG in Spain during 2002 ignited after tipping over [7]. The heat of the fire caused the LNG to vaporize and, consequent to the high set pressure of the safety valve (nearly 8 bar), accumulate unchecked inside the trailer, resulting in a BLEVE [8].

Table 2 Substances Involved In BLEVE Accidents

substance	Percentage of occurrences (%)
LPG, Propane	50
Gasoline	7.35
Butane	6.62
Ethylene, ethylene oxide	5.15
Ammonia	5.15
Chlorine	5.15
Propylene	2.94
Vinyl chloride	2.94
Carbon dioxide	1.47
LNG	1.47
Water	0.74
Other chemical substances	11.02

III. ESTIMATING THE IMPACT FROM BLEVES OF LNG STORAGE TANKS

Using three methods and comparing their results, we assessed the impact range of a potential BLEVE if an LNG storage tank with a capacity of 160,000 m^3 (diameter = 76 m, length = 35.26 m) were filled to 80 %. The first method applied Prugh's equivalent-mass-of-TNT formula [1], which relies on the assumption that vapor expands isentropically; the second employed the statistical approach pioneered by Hemmatian et al. [2], which predicts the magnitude of the overpressure based on simple inputs; and the third utilized the Safeti 8.71/Phast software developed by DNV, which integrates QRA and consequence analysis. Based on typical storage conditions and the standard tank design, a rupture would ensue when the temperature of the LNG reached −157.8 °C (above the boiling point) and the pressure inside the tank equaled 0.26 bar—1.21 times the level that would trigger the tank's pressure safety valve (a general gauge pressure of 0.22 $kg \cdot cm^{-2}$, or ~0.216 bar) [9]. Furthermore, adopting Zipf 's scale of overpressure thresholds or effects on structures and human bodies (Table 3)[10], we estimated the distances at which minor injury (1 psi), severe injury (2 psi), and fatality (3 psi) would occur (Table 4).

Table 3 Damage Standards for Overpressure

Overpressure	Impact on Equipment	Impact on Personnel
1 psi	Window glass shatters	Minor injuries caused by flying glass shards
2 psi	Moderate house damage (doors/windows destroyed, severe roof damage)	Injuries caused by flying glass shards
3 psi	Collapse of residential structures	High likelihood of severe injuries or fatalities
5 psi	Most buildings collapse	Severe injuries and fatalities common
10 psi	Damage or collapse of reinforced concrete structures	Most people will die
20 psi	Heavily built concrete buildings are severely damaged or demolished	Fatality rate approaches 100%

Table 4 BLEVE Impact Radius (m) for LNG Storage Tanks Simulated by Different Methods

Consequence Analysis	Impact radius (m)		
	Prugh	Hemmatian et al.	Safeti/Phast
Minor injury radius (1 psi)	164.5	313	164.5
Severe injury radius (2 psi)	91.4	174	100
Fatality radius (3 psi)	73	139	79.2

III.A. Application of Prugh's TNT Equivalent Formula

As detailed by Planas-Cuchi et al.[11], the amount of energy released during a BLEVE, E_V (kJ), is the product of the vapor's mass and the vapor's change in internal energy:

$$E_V = m(U_1 - U_2) \tag{1}$$

where m is the mass of vapor already existing in the vessel at the moment of the failure(kg), U_1 is the internal energy of the vapor preceding the rupture (kJ·kg^{-1}), and U_2 is the internal energy of the vapor following the rupture once the vapor has expanded and achieved equilibrium with the atmospheric pressure (kJ·kg^{-1}).

Adopting Prugh's empirical approach, we assumed the vaporization and expansion of the LNG to be isentropic (i.e., adiabatic and reversible) and calculated the energy of the BLEVE as an equivalent mass of TNT, W_{TNT} (kg), by inputting values for methane, the primary component of LNG, as parameters:

$$W_{TNT} = 0.021 \times (\frac{P \times V^*}{\gamma - 1}) \times (1 - \left(\frac{P_a}{P}\right)^{\frac{\gamma-1}{\gamma}}) \tag{2}$$

where P is the vapor pressure (bar), P_a is the atmospheric pressure (bar), V^* is the total volume of the vapor (including that produced by instantaneous vaporization) inside the tank (m^3), and γ is the heat capacity ratio (1.31).

Obtaining $V^*$and its prerequisites required two additional formulas:

$$V^* = V + V_l \times f \times (\frac{\rho_l}{\rho_V}) \tag{3}$$

where V and V_l are the volumes of the vapor (m^3) and the liquid (m^3), respectively, inside the tank prior to the rupture; ρ_l and ρ_V are the densities of the liquid (443 kg·m^{-3}) and the vapor (2.44 kg·m^{-3}), respectively; and f is the vapor fraction of the liquid, i.e., the proportion of liquid that vaporizes during flash evaporation, and:

$$f = 1 - \exp(-2.63 \cdot (C_p/H_v) \cdot (T_c - T_b) \cdot (1 - ((T_c - T_o)/(T_c - T_b))^{0.38})) \tag{4}$$

where T_c, T_b, and T_0 are the critical temperature of the substance (190.56 K), the boiling temperature of the substance at atmospheric pressure (111.55 K), and the temperature of the substance at the time of rupture (−157.8 °C, or 115.35 K), respectively; C_p is the specific heat capacity at constant pressure (2.232 × 10^3 J·kg^{-1}·K^{-1}); and H_v is the enthalpy of vaporization for the substance (5.11 × 10^2 kJ·kg^{-1}).

Hence, f and V^* equal 0.0167 and 420,097 m^3, respectively, yielding a W_{TNT} of 1,908.4 kg. Since breaking the tank alone would require a significant amount of energy, we multiplied W_{TNT} by an adjustment factor, β, of 0.4 (which is suitable when the overpressure involves ductile materials)[12] to estimate the remaining available energy for the blast, $(W_{TNT})_{overpressure}$: 763.4 kg.

Lastly, we evaluated the scaled distance, d_n (m·kg$^{-1/3}$), to determine the impact radius of the BLEVE for different levels of harm:

$$d_n = \frac{d}{(\beta W_{TNT})^{1/3}} \tag{5}$$

where d is the actual distance (m). Calculating the pressure wave as a function of the scaled distance (Figure 2), we thereby found the impact radii for minor injuries, severe injuries, and fatalities to be ~164.5 m (d_n = 18), ~91.4 m (d_n = 10), and ~73 m (d_n = 8), respectively.

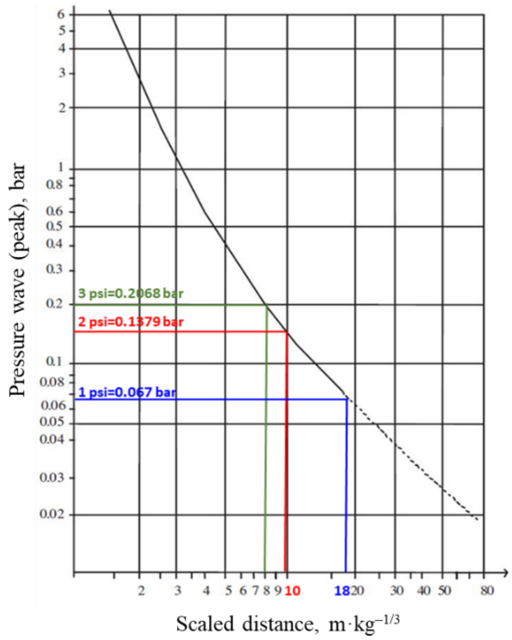

Figure 2. Pressure Wave as A Function of The Scaled Distance[13]

III.B. Statistical Overpressure Estimation Based on Hemmatian et al.'s Model

Hemmatian et al. used MATLAB's Curve Fitting Toolbox 3.4.1 and related statistical models to develop an easy-to-use formula that requires only the initial filling degree of the tank (FD) and the temperature at which rupture occurs (T, K). This approach assumes that the expansion of the vapor is irreversible and adiabatic (in contrast to Prugh's method) .The comparison of its predictions with the values corresponding to experimental data gives very positive results, this validating the reliability of the method.

To estimate the mechanical energy released per cubic meter by the BLEVE, e (MJ·m^{-3}), we simply input our values for FD and T (0.8 and 115.35 K, respectively) into the formula provided for methane (Table 5):

$$e = 6.13 - 42.71 \times FD - 0.06558 \times T + 0.5629 \times FD \times T - 0.0001499 \times T^2 - 0.001647 \times FD \times T^2 + 2.327 \times 10^{-6} \times T^3 \quad (6)$$

Obtaining an e of 0.387 MJ·m^{-3} enabled us to calculate the total amount of released energy, E (MJ):

$$E = e \times V_T \quad (7)$$

where V_T is the volume of the tank (160,000 m^3). E therefore equals 61,920 MJ.

Converting E to the equivalent mass of TNT (the energy released by 1 W_{TNT} = 4,680 kJ·kg^{-1}) yielded a W_{TNT} of 13,230 kg and consequently a (W_{TNT})overpressure of 5,292 kg (β = 0.4). We then solved Equation (5) with the latter value, obtaining ~313 m (d_n = 18), ~174 m (d_n = 10), and ~139 m (d_n = 8) as the impact radii for minor in as the impact radii for minor injuries, severe injuries, and fatalities, respectively.

Table 5. Mechanical Energy Released Per Cubic Meter of Vessel As A Function of Explosion Temperature and Initial Filling Degree (Expressed in Parts Per Unit Instead of Percentage) For Different Substances

Substance	Released mechanical energy ($MJ \cdot m^{-3}$)
Propane	$e = 43.97 - 213.9 \cdot FD - 0.152 \cdot T + 1.349 \cdot FD \cdot T - 0.0004361 \cdot T^2 - 0.002045 \cdot FD \cdot T^2 + 1.55 \cdot 10^{-6} \cdot T^3$
Butane	$e = 21.32 - 87.2 \cdot FD - 0.136 \cdot T + 0.4756 \cdot FD \cdot T + 0.0001885 \cdot T^2 - 0.0005805 \cdot FD \cdot T^2 + 9.693 \cdot 10^{-6} \cdot T^3$
Methane	$e = 6.13 - 42.71 \cdot FD - 0.06558 \cdot T + 0.5629 \cdot FD \cdot T - 0.0001499 \cdot T^2 - 0.001647 \cdot FD \cdot T^2 + 2.327 \cdot 10^{-6} \cdot T^3$
Water	$e = 56.36 - 275.6 \cdot FD - 0.2341 \cdot T + 1.076 \cdot FD \cdot T + 0.0001696 \cdot T^2 - 0.0009183 \cdot FD \cdot T^2 + 1.626 \cdot 10^{-6} \cdot T^3$
Vinyl chloride	$e = 20.71 - 92.48 \cdot FD - 0.1206 \cdot T + 0.5346 \cdot FD \cdot T + 9.836 \cdot 10^{-5} \cdot T^2 - 0.0006987 \cdot FD \cdot T^2 + 2.503 \cdot 10^{-7} \cdot T^3$
Ethylene oxide	$e = 23.61 - 119.4 \cdot FD - 0.1182 \cdot T + 0.6295 \cdot FD \cdot T + 4.505 \cdot 10^{-5} \cdot T^2 - 0.0007463 \cdot FD \cdot T^2 + 2.946 \cdot 10^{-7} \cdot T^3$
Propylene	$e = 104.9 - 86.15 \cdot FD - 1.035 \cdot T + 0.5013 \cdot FD \cdot T + 0.00329 \cdot T^2 - 0.0005726 \cdot FD \cdot T^2 - 3.321 \cdot 10^{-6} \cdot T^3$
Ammonia	$e = 28.34 - 168.4 \cdot FD - 0.1447 \cdot T + 1.048 \cdot FD \cdot T - 6.71 \cdot 10^{-5} \cdot T^2 - 0.001471 \cdot FD \cdot T^2 + 7.984 \cdot 10^{-7} \cdot T^3$
Chlorine	$e = -2.469 - 81.17 \cdot FD + 0.08234 \cdot T + 0.4975 \cdot FD \cdot T - 0.0005088 \cdot T^2 - 0.0006739 \cdot FD \cdot T^2 + 8.889 \cdot 10^{-7} \cdot T^3$
Ethylene	$e = 9.356 - 69.53 \cdot FD - 0.04289 \cdot T + 0.6194 \cdot FD \cdot T - 0.0003058 \cdot T^2 - 0.001262 \cdot FD \cdot T^2 + 1.454 \cdot 10^{-6} \cdot T^3$

III.C. Application of Safeti/Phast Software in QRA (by DNV)

We simulated the consequences of an LNG tank explosion by running the BLEVE blast model in Safeti 8.71/Phast.The impact range of BLEVE in LNG storage tanks causing minor injuries (1 psi), serious injuries (2 psi) and death (3 psi) is shown in Figure 3. The blue color represents the 1 psi contour map, and its influence radius is ~164.5 m; the green color represents the 2 psi contour map, and its influence radius is ~100 m; the red color represents the 3 psi contour map, and its influence radius is ~79.2 m.

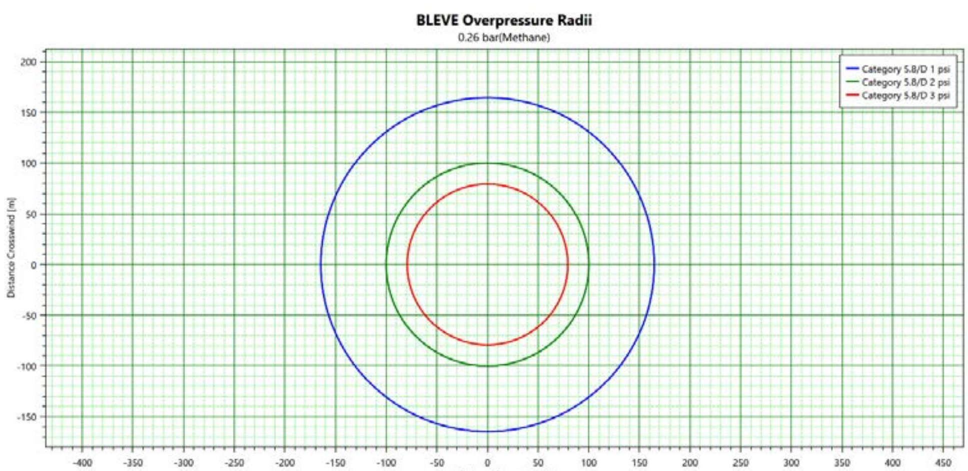

Figure 3. BLEVE Overpressure Contour

IV. DISCUSSION

Under the same initial conditions (temperature, pressure and the volume of tank), although the impact radii obtained using Prugh's empirical formula and Safeti/Phast show good agreement for all three damage levels, the method of Hemmatian et al. produces significantly higher values - up to ~148.5 m - which may be attributed to the differences in thermodynamic assumptions mentioned earlier. Among them, Prugh's empirical formula assumes ideal gas and isentropic expansion;

Hemmatian et al.'s method assumes real gas and adiabatic irreversible expansion; Safeti/Phast assumes real gas and isentropic expansion. The three different thermodynamic assumptions lead to slightly different results.

V.CONCLUSION

Historically, two BLEVEs involving LNG have been recorded, but both incidents occurred with trailers, which can transform into high-pressure vessels when exposed to heat. By contrast, LNG storage tanks maintain an extremely low internal pressure at all times (the standard set pressure of the safety valves is ~0.216 bar, or less than 3% of that for trailers), minimizing the fraction that flashes during a rupture (which is only ~0.03 times that of LPG). Furthermore, the multi-layered construction of these containers resists heat transfer, reducing the rate of vaporization. However, in spite of BLEVE being unlikely to occur—and being limited in magnitude when they do—storage tanks and related equipment should be regularly inspected to ensure safety at LNG terminals.

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