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Potential for BLEVE associated with marine LNG vessel fires

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Abstract

Recent LNG marine shipping hazard studies have discounted BLEVE hazards associated with LNG vessels. This exclusion of a potential major hazard event has been queried, particularly since a recent LNG truck BLEVE-like event in Spain. This paper reviews the physical factors associated with the Spanish LNG truck event and accepts that this had features of a classical BLEVE event and that there is no inherent property of LNG excluding BLEVE-like events, although US LNG trucks would be safer due to design features. Marine LNG vessels have differently designed tanks and it is demonstrated that the combination of physical barriers makes direct thermal input to the LNG inner tank more limited than hypothesized by some, but if it occurs these tanks cannot rise to a pressure sufficient to cause a large flash of liquid and consequent BLEVE event of a scale hypothesized in the literature.

Keywords: LNG; Modelling; Risk; BLEVE; Marine transport

1. Introduction

There have been several recent studies assessing hazards associated with marine transportation of LNG [1–3]. These all demonstrated large hazards associated with tank leakage or discharge, evaporation, dispersion, ignition, flash fire, and pool fire. These studies did not consider boiling liquid expanding vapor explosions (BLEVE) events for marine transport. BLEVE events are well known hazards, often associated with transportation or storage of pressurized flammable liquids. The underlying theory for BLEVE events and several examples are summarized in Refs. [4,5].

Prof. Venart [6], a BLEVE researcher, has questioned the exclusion of BLEVE events from marine hazard studies, specifically quoting the DNV study by Pitblado et al. [1]. He noted that on 22 June 2002 a truck carrying about 20 tonnes of LNG at −161 °C and atmospheric pressure suffered a motor accident at Tivissa, Catalonia, Spain. This accident is analyzed in detail by Planas-Cuchi et al. [7]. Before this accident there is no record of an LNG BLEVE onshore, and there has never been a marine accident causing a serious release or thermal consequence of LNG of any type [1,12].

Prof. Venart, in his letter, makes several points:

- He disagrees with industry specialists who claim BLEVEs are not possible with LNG.
- LNG vessels may be exposed to long duration high thermal radiation pool fires.
- These vessels might not survive long pool fire impingement.
- His research suggests failures may be more related to the mechanism of vessel failure than the superheat limit.
- Pressure relief may not be able to limit the pressure rise in a full fire impingement case.
- The tank might BLEVE, involving the entire inventory onboard the vessel, and create a fireball over 2.5 km in diameter with a surface emitted power of about 350 kW/m^2 lasting 54 s.

The purpose of this paper is to respond to Prof. Venart's published letter. The Spanish accident is reviewed and factors contributing to the BLEVE of LNG material are identified. This paper then determines whether these factors can apply to the tanks on board marine LNG vessels and whether a BLEVE is a realistic possible outcome.

2. Short review of BLEVE theory

BLEVEs are a well known major hazard. They can pose significant risks to firefighters as they usually have a delay period

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of some 5–25 min before occurring and in that time firefighters can arrive and be in a position of danger. For this reason BLEVE phenomena have been well studied and communicated by organizations such as NFPA—National Fire Protection Association. BLEVE events have three main associated hazards: thermal radiation, overpressure, and fragments.

Good summaries of well known BLEVE events and overviews of mechanisms are given in Lees [4] and of the mechanisms in CCPS [5]. A simple definition of BLEVE is given by CCPS.

> BLEVE: "any sudden loss of containment of a liquid above its normal boiling point at the moment of its failure. It can be accompanied by vessel fragmentation and, if a flammable liquid is involved, fireball, flash fire, or vapor cloud explosion."

A fuller BLEVE definition is given in Lees [4] as follows:

> "When a vessel containing liquid under pressure is exposed to fire, the liquid heats up and the vapor pressure rises, increasing the pressure in the vessel. When this pressure reaches the set pressure of the relief valve, the valve operates. The liquid level falls as the vapor is released to the atmosphere. The liquid is effective in cooling that part of the vessel wall which is in contact with it, but the vapor is not. The proportion of the vessel wall which has benefit of liquid cooling falls as the liquid vaporizes. After a time, metal which is not cooled by liquid becomes exposed to the fire; the metal becomes hot and weakens and may then rupture. This can happen even if the relief valve is operating correctly. A pressure vessel is designed to withstand the relief valve set pressure, but only at the design temperature conditions. If the metal has its temperature raised, it may lose its strength sufficiently to rupture."

This definition explains many BLEVE events, but Venart et al. [8] have developed a new event sequence—BLCBE. This model combines fluid dynamics inside the fluid with progressive failure mechanics of the pressure vessel. The BLCBE event is summarized in Ramier [9].

> "Boiling Liquid Compressed Bubble Explosion (BLCBE) is stated to result from an initial partial failure of the vessel, the rapid depressurization of its already nucleated liquid contents due to prior pressure relief valve action, the initiation of, inertial and then thermal bubble growth in the depressurized fluid, followed by its rapid swell and then constraint of the two-phase mixture within the confines of its damaged vessel shell. This process may result in the coherent inertial collapse of the two-phase mixture which causes a power-amplified conversion of thermally developed bubble energy. The conversion generates high local dynamic pressures which catastrophically fail the already damaged vessel and subsequently release the vessel's contents as a rapidly evaporating superheated mechanically formed aerosol."

This type of event will not occur in all BLEVEs and may only occur in a few—but it is an important category of BLEVE. It suggests the failure mechanism for the vessel shell may not only be thermal weakening from external fire, but also mechanical force due to water hammer effect as the rapidly expanding two-phase mixture inside the vessel strikes the shell. This would apply where a vessel is leaking through a crack and this crack then catastrophically fails. Experiments by Ramier [9] confirm this possibility using Refrigerant-22, a material similar to propane. Vennart [11] also proposes thermal quenching leading to thermal stresses in the steel shell also associated with the two-phase swell.

Steel yield stress varies with the specific steel and temperature. Many construction steels are reported by FEMA in its analysis of the World Trade Center fire to reduce to 90% of ambient yield stress at 200 °C and 50% at 550 °C. Birk [10] reports that steel used for rail car pressure vessels is reduced to 80% of its ambient yield stress at 427 °C. Many pressure vessels have a safety factor of 2, thus when the temperature of the steel shell rises to 550 °C due to external pool fire or jet fire thermal radiation, then the internal pressure load stress equals the steel yield stress and the shell will fail along its weakest line. This mechanism does not require a BLCBE event to fail the vessel shell.

Table 1
Spanish LNG tanker incident

Accident key features	Tanker design matters
• An LNG road tanker rolled over onto its side	• Tank dimensions: 13.5 m long, 2.33 m diameter, volume 56 m^3
• The accident dislodged thermal insulation over a space now occupied by vapor	• Normal fill was 85% liquid (47.6 m^3) and 15% vapor (8.4 m^3)
• Flames appeared immediately between the driver cab and the trailer tank	• Tank walls—ANSI-304 stainless steel, cylindrical wall thickness 4 mm, ends 6 mm
• Initially the flames were reported as smokeless	• Insulation—130 mm expanded polyurethane foam, self-extinguishing
• Soon after the vehicle tires became involved and both black and white smoke evolved	• Tank and insulation cover—2 mm aluminum
• The tank exploded in two steps 20 min after the initial accident	• Design pressure 7 bar, hydraulic test pressure 9.1 bar
• Initially there was a small explosion followed by a hissing sound	• LNG cargo conditions (before accident): temperature under −160 °C, pressure just under 1 bar
• Subsequently there was a large explosion which created a large white cloud	• Five safety valves—vapor space: 2 × 1 in. @ 7 bar, 1 × 3/4 in. @ 9 bar, liquid pipe 2 × 1/2 in. @ 10 bar
• This white cloud ignited immediately and a fireball ensued	• No manhole
• The driver was killed and two persons were burned approximately 200 m from the truck	• Heat sources (other than LNG cargo): diesel fuel tank capacity 0.5 m^3, tanker tires, aluminum cover and cab materials

3. Spanish LNG truck BLEVE-like event

Planas-Cuchi et al. [7] describe an LNG road tanker accident that occurred on 22 June 2002 near Tivissa, Catalonia, Spain. They argue that this event exhibited key characteristics of a BLEVE and could thus be the first example of an LNG BLEVE event. Prof. Venart quotes this accident to demonstrate that LNG material is potentially subject to BLEVE events. Key facts and tanker design matters are summarized in Table 1 from Ref. [7]. There is no prior incident (as demonstrated by the MHIDAS accident database) that has characterized an LNG truck accident as causing a BLEVE.

The road tanker was of special design for its LNG cargo (material of construction and insulation), but in other respects (size, pressure vessel design) it was conventional. Planas-Cuchi et al. suggest a two-stage failure mode similar to that proposed by Venart [11]. This is an initial crack in the heat affected zone, associated with rapid cargo discharge, followed by crack propagation.

The event had three distinct impacts: over-pressure, thermal radiation and fragments. Planas-Cuchi et al. reviewed pressure damage impacts and based on windows remaining intact at 125 m, back calculated a TNT equivalence of 75 kg and an internal pressure in the tank of 8 bar. The API 520/521 pressure relief standards for sizing relief valves allow a small internal tank pressure of rise to around 110–120% of the relief valve set point under fire exposure. Given the set point of 7 barg, this would equate to 7.7–8.4 barg. This is in good agreement with the authors' over-pressure calculations.

The trailer tank disintegrated into a small number of large fragments—mostly thrown in alignment with the cylindrical tank. The motor was ejected the greatest distance 257 m, tank fragments were ejected about 125 m. Four internal tank baffles were ejected 50–125 m sideways. This small number of fragments and orientation mostly along the cylindrical axis is typical for BLEVE events.

Thermal effects were estimated by Planas-Cuchi et al. based on the total initial contents of the tank. Using the method of CCPS [5] this came to a fireball diameter of 150 m, centered at a height of 113 m, lasting 12 s. The authors estimated a surface emitted flux of 260 kW/m^2 and this correlated well to the first and second degree burns suffered by two bystanders located 200 m away.

Planas-Cuchi et al. summarize several definitions of BLEVE, and conclude it would not qualify based on the more restrictive definition of Reid [14], but the definition of CCPS allows this event as a BLEVE.

Some debate exists as to the sources of heat for this event. A typical transport BLEVE event is heated by ignition of leaking fuel or pressure relief from the tank itself. There is doubt here as to whether there was sufficient energy available to cause the LNG to rise to a temperature to BLEVE. Heat sources available include: the truck diesel fuel and other combustible material (e.g. tires), the tank insulation and aluminum cover, the drivers cab, and the LNG fuel itself.

The temperature rise required in the LNG fluid is debatable. Planas-Cuchi suggests the Reid [14] superheat criteria for BLEVE is reached at −117 °C, a rise of 44 °C. The LNG fluid vapor pressure is sufficient to lift the relief valves at around −128 °C a rise of 33 °C. If the relieved vapors were ignited, this would greatly increase the heat source and temperature, and hence increase the potential for thermal weakening of the steel shell.

A simple scoping heat transfer calculation is presented below. Using the convective heat transfer equation (Perry):

$$Q = UA\Delta T$$

where U = overall heat transfer coefficient = 570 W/m^2 K (Perry's Chem Eng Handbook); A = exposed area (m^2); ΔT = temperature gradient (°C).

Assuming an average temperature seen by the exposed tank surface of 600 °C (i.e. some hydrocarbon flame at 1100 °C and some cool sky), the temperature gradient is around 760 °C. For 1 m^2 exposure this would require 1.6 h to raise the entire LNG mass to a temperature sufficient to lift the relief valve. An important point is that the entire mass of LNG need not be heated by this amount. If the heat is passing through the upper surface of the tank, then the LNG fluid may become stratified with an upper layer warmer than the lower layer. The vapor pressure inside the tank will reflect the upper layer properties, not the bulk cooler LNG below. Thus, there are two unknowns—how much insulation was exposed and how much of the LNG is raised in temperature. As the tank was destroyed these cannot be known. However, if 2 m^2 of tank were exposed and one quarter of the LNG formed an warmer upper layer then the time required is one eighth = 0.2 h or 12 min. If these values were larger or smaller the time required varies proportionately as per the heat transfer equation.

Once the relief lifts then the pressure in the tank should not rise above 120% of the relief set point and tank failure would be due to thermal weakening of the unwetted steel shell and possibly by the mechanism proposed by Venart. Ignition of the relieved vapor would add to the heat source and thermal input.

While this information is not known, the scoping calculations show that the event can be explained by heat initially from combustible materials and possibly from leaking LNG due to the original accident, but added to from the pressure reliefs when these are actuated. To the degree that the aluminum cover and combustible insulation may have contributed to the event, the USA LNG truck design involving steel cover and fiberglass insulation would have reduced the heat input and constitutes a safer design—less likely to suffer this type of incident.

Planas-Cuchi et al. do not specifically conclude the truck event was a BLEVE. They suggest it meets the criterion for BLEVE as defined by CCPS, but not that of Reid. This may be too formal. The event shared key characteristics of BLEVE events:

- overpressure,
- large fragments,
- fireball and thermal impact,
- delay of 20 min.

These are important factors to be considered by emergency responders, regardless of the whether the event is characterized as a BLEVE or more generally as an ignited explosive rupture. This author agrees with Planas-Cuchi et al. that this tanker truck event had characteristics of BLEVE involving LNG. The actual susceptibility depends strongly on the tank design, and good design can significantly reduce the likelihood of BLEVE, but it is not sustainable to argue that LNG cannot either BLEVE or fail in a manner that causes outcomes essentially indistinguishable from BLEVE.

4. LNG marine vessel design

In principle, any flammable material can result in BLEVE if it is contained within a pressure vessel significantly above its atmospheric boiling point and the container fails in a near instantaneous manner. The issue with LNG marine vessels is not whether the LNG material can BLEVE, but rather whether the physical conditions of the cargo and its container just before failure could result in major flash (i.e. conversion of liquid to vapor by latent heat) in a fire scenario that would result in BLEVE when immediately ignited. This section reviews LNG vessel tank design and how this might respond in a major fire situation.

Vaudolon [12] identifies several marine LNG vessel designs, but the two most common both in the past and likely for the future are the prismatic membrane design and the spherical tank design. These are different in configuration and require separate discussion to identify conditions necessary for failure.

4.1. Membrane vessel

These vessels contain typically four to five membrane tanks totaling 125,000–160,000 m^3. Current vessels typically have individual 25,000 m^3 tanks, but newer vessels employ up to 40,000 m^3 tanks. These are straight sided tanks with horizontal top and bottom, vertical ends, and vertical sides but with angled shoulders and footings. These assist in minimizing the effect of cargo sloshing while at sea. Typical tank dimensions for a single 40,000 m^3 tank might be $L = 41$ m, $W = 34.5$ m, $H = 31$ m. The vessel itself carrying four of these LNG membrane tanks might have overall dimensions as follows: length 278 m, breadth 42.5 m, and draught 11.2 m.

The stainless steel membrane wall material is designed for LNG cargo internal pressure only, not for structural support which is provided by the insulation/hull. For this reason the tank wall thickness can be quite thin, 0.7–1.2 mm. One design uses flat membrane plates made of invar—a very low thermal expansion stainless steel. The more common design employs stainless steel double folded to allow for thermal expansion in two directions simultaneously.

The membrane design incorporates twin wall membranes with insulation between the two membranes and structural insulation around the outside. The more common insulation is perlite contained in plywood boxes. Perlite is an inorganic, non-combustible insulation normally in expanded pellet form. Other wood is used for structural support as well. This design has been in use for 40 years.

Pressure relief is installed for several fault modes—including external fire as required by the IMO International Gas Carrier code [13]. Fire relief requirements derive from standard oil industry practice—API 520/521. This employs an empirical formula for pressure relief requirements, well validated as to sufficiency over many thousands of fires affecting pressure vessels. Pressure relief set points for LNG tanks are 0.25 barg, and during fire situations the maximum internal pressure could be 10–20% above this. This is based on the API 521 assumption of 10% heat input for an insulated tank compared to a bare steel tank. It is not easy to conceive how a membrane tank could have 10% of its surface exposed without some form of failure, as the insulation contributes to its structural integrity.

The insulation is held in place by the double hull structure. Single hull plating covers the roof. Hull plates are typically 15–20 mm thick, but will be thicker at and below the waterline than high above sealevel—reflecting the different loads imposed by seawater pressure and wave action. Hull plates are made of normal marine steel and cannot withstand very cold temperatures. These can be subject to brittle failure below −40 °C. For this reason the insulation is designed to preserve cold in the LNG tanks and prevent extreme cold in the hull plates. A gap of up to 2 m separates the inner from the outer hull. Mostly this is an air gap but there will be intervening hull structural elements and also some of the space may be used for service tanks (e.g. ballast water). Insulation might be 0.6 m thick (including the internal secondary membrane barrier) all around the tank. Thus, there would typically be around 2.6 m between the external hull and the LNG cargo. The top deck would be about 27 m above the waterline allowing for the double hull, insulation all around, the LNG tank itself, a gap at the top deck less the vessel draught. This upper deck is subject to thermal radiation from a large LNG pool fire, but the deck is steel plate over tank insulation and while this might sag onto the insulation, this will not lead to high heat input.

4.2. Spherical vessel

Spherical LNG vessels are quite different to membrane vessels. The tanks are single tank wall and have a single layer thermal insulation. The insulation may be polystyrene or polyurethane material. This is combustible—but usually it would be self-extinguishing if the heat source were removed. The LNG marine vessel dimensions tend to be a little wider and higher than for membrane vessels as the spherical shape is inherently less efficient volumetrically than the rectangular prismatic shape.

A similar capacity spherical vessel to the above membrane example might employ four spherical tanks. For 40,000 m^3 the spherical tank would be 42.3 m in diameter. The vessels dimensions would be length 288 m, breadth 48.2 m and draught 11.2 m.

At its closest approach to the side, the LNG sphere would be 3 m from the outer hull, but at other positions it would be considerably further due to the spherical shape.

The sphere is usually made of aluminum as this has excellent cryogenic properties and it weighs much less than an equivalent stainless steel tank. The wall thickness is much greater than the membrane at 30–65 mm (depending on location in the sphere) because aluminum is not as strong as steel and the sphere is self-supporting for itself, the LNG cargo and its external insulation. The spherical tank is connected to the vessel through a specially engineered cylindrical skirt from its waist down to the hull base which provides both structural support and thermal insulation and ensures the hull members are never subjected to cryogenic temperatures. One effect of the skirt would be to limit fire impact from an external fire. As for the membrane tank, the spherical tank upper surface is protected by an upper deck made of steel.

As before, thermal relief for fire exposure as specified in the IGC Code is derived from API520/521. Tanks are fitted with at least two relief valves @ 50% capacity each.

4.3. Comparison—LNG tanker truck to LNG marine vessels

A comparison between the barriers presented to an external fire event between an LNG road tanker and LNG marine vessels is shown in Table 2. A normal LPG tanker truck would have only a single barrier—the tank wall.

In summary, an LPG truck has one barrier against thermal impingement, an LNG tanker truck has three barriers, while both LNG marine vessel types have seven barriers. Every one of these barriers contributes to reducing the risk. A further protection is the limit on internal tank pressure to 0.28–0.30 barg—it will be shown later this is a major limitation on cargo flash and hence BLEVE potential. The initiating events and durations are different and the quality of the barriers are not identical—but they do give an indication that the two situations transport truck versus marine LNG vessel are quite different.

5. Fire event

For transport trucks the precursor fire events often occur in the first 5–25 min of exposure—the time for unprotected steel to rise to a temperature where thermal weakening is sufficient for failure. Pitblado et al. [1] give three realistic maximum credible events for marine LNG vessels and for each of these present discharge rates for above waterline punctures and predicted pool fire dimensions using the PHAST code (see Table 3). Underwater punctures are similar but last a little longer. The long durations are due primarily to the rate of LNG discharge onto the sea surface, the LNG once spilled burns relatively quickly. The PHAST model is well known in the process industry and is the most used commercial consequence model for process chemical hazards associated with loss of containment. It has been extensively validated with published papers describing its operation. It scored well in the Hanna et al. [16] review of dispersion models. The model was significantly enhanced to address Hanna's findings and validated by Witlox and Holt [17]. A subsequent survey by Britter [18] as part of the EU SMEDIS project was positive. The model is termed a similarity model and uses a continuous transition between momentum, dense gas and neutral buoyancy phases. Special source term modelling is applied based on experimental data for spills of cryogenic gases onto water.

The impact of a pool fire onto an LNG vessel is speculative as these vessels have many thermal barriers and the sequence of these being challenged and potentially failing is uncertain. Of the three leak size events defined, only the first has any experimental data of comparable size—the Montoir fire experiments [15] which were for a pool of burning LNG 35 m diameter are close to the 250 mm hole case which gives a 29 m pool. The larger fires have no experimental or accidental basis for direct comparison. Also, very large long lasting LNG pool fires on water have much uncertainty. LNG fires initially burn faster and hotter than other hydrocarbons with less smoky flames, but at the largest sizes this may not be true due to the scale of fire and the inability of air to mix fully with the evaporating LNG fast enough to allow

Table 2
Comparison of protective barriers LNG truck and LNG marine vessels

	LNG truck	LNG membrane vessel	LNG spherical vessel
Threat—external fire	Two threats can cause BLEVE: pool or jet fire at base or jet fire from relief valve	One threat: pool fire on water; jet fire from relief valve cannot lead to BLEVE on its own	Same as membrane vessel
Barrier 1	Insulation cover—2 mm Al (EU) or steel (USA)	Hull plating—20+ mm steel	Same
Barrier 2	Insulation	Air gap—2000 mm (maybe water if ballast tank)	Same
Barrier 3	Steel wall: 4–6 mm	Hull plating: 15–20 mm steel, also steel plate above top of tank	Same, but different geometry
Barrier 4	–	Insulation 0.3 m—plywood box filled with perlite beads	Air gap due to tank curvature 500–5000 mm
Barrier 5	–	Stainless steel membrane about 1 mm	Skirt plating—steel >10 mm (Note 1)
Barrier 6	–	Insulation 0.23 m—plywood box filled with perlite beads	Insulation—combustible
Barrier 7	–	Stainless steel membrane—about 1 mm	Tank wall—aluminum 30–65 mm
Cargo	LNG	LNG	LNG
Maximum pressure at failure (Note 2)	Up to 8 barg pressure	0.28–0.30 barg	0.28–0.30 barg

Notes: (1) The situation differs a little for heat entering through the top of the Moss LNG tank as barrier 5 does not apply, but this heat is less (radiant only, not in contact with flames). (2) This assumes operational pressure relief, but reliefs are of standard design used in industry where reliefs are extremely reliable, and all LNG tanks have multiple reliefs.

Table 3
Thermal hazard range for maximum credible events

LNG marine event[a]	250 mm hole	750 mm hole	1500 mm case
Possible cause	Puncture due to striking	Collision/grounding	Terrorism
Initial discharge rate	226 kg/s	2030 kg/s	8130 kg/s
Duration of event	19 h	2.2 h	0.5 h
Sustainable pool diameter	29 m	86 m	171 m
Thermal hazard range to people	190 m	440 m	750 m

[a] All punctures above waterline, hole size as diameter, radiation to 5 kW/m^2, wind 3 m/s, hazard range measured from center of pool. It is believed that the hazard ranges presented are conservative as the pool flame is likely to be smokier than the luminous assumption used.

complete combustion. Smoky pool fires generate much less thermal radiation than bright pool fires as smoke is both incomplete combustion and an absorber of much of the radiation giving hotter combustion products but significantly less emitted thermal radiation.

The duration of this sequence is unknown, but it would probably be of the order of hours rather than 20–30 min as typical for a transport vehicle BLEVE scenario. Also not evaluated here is the effect of the pool fire on the vessel structure. Clearly some structural members will fail, but load redistribution will occur and it is unclear how the ship will respond. As buoyancy is lost on the fire impacted side, the ship would roll partly and water might cover the thermally exposed portion of the tank. The cycle of damage may then start again. For the larger hole sizes the duration of event is likely to be insufficient for further damage of the type described. Thus, smaller events could have the potential to last long enough to create the damage sufficient to defeat all the barriers and thermally impact the tank. However, smaller events are of a scale to which emergency response could be effective by cooling the exposed surface with water jets or applying foam to the pool fire itself. Emergency fire response is normally readily available for marine LNG vessels in port transits.

A slightly different situation exists for the upper surface of the LNG vessels, but this surface is high up and away from direct pool fire contact, but subject to thermal radiation. The top deck is steel and this may start to sag when subject to high thermal flux. This might sag onto the LNG membrane insulation boxes or onto the Moss LNG insulation directly. This would not result in high heat transfer to the LNG tank or its contents.

5.1. *Can fire impact lead to BLEVE?*

Assuming the fire can breach all the ship's structural defenses, and that emergency response is not effective, calculations can demonstrate whether BLEVE is a possible outcome. The hull structure prevents 100% envelopment and the pool fire will only be active on one side of the vessel. The exposed portion of the tank would be well below 10% of the tank area—this is considered in the relief system design.

Heat from the pool fire, once in contact with the unprotected LNG tank wall, would enter the tank and cause the LNG to boil locally. Over a short period of time, this will be sufficient to lift the LNG tank pressure relief valves—set for 0.25 barg. Allowing a tank maximum pressure of 0.28–0.30 barg it can be calculated that the flash amount on relieving to atmospheric pressure would be 2.4% (i.e. 2.4% of the slightly pressurized LNG liquid would flash to vapor). In practice much less than the whole tank would flash due to the hydraulic head of the LNG liquid. Commercial LNG has a range of densities depending on the quantity of ethane and heavier components, for conservatism a lower range density for nearly pure methane under half that of water is used. For this, each 1 m of liquid exerts a static pressure of 0.045 barg. Thus, at a depth of about 6 m the pressure rises to 0.28 barg and no flash will occur. Thus, the flashing is restricted to the top 6 m and averages half the flash at the surface, or 1.2% (i.e. 2.4% at the surface and 0% at 6 m depth). In mass terms 1.2% of the top 6 m corresponds to 38 tonnes of LNG and might create a sphere of 100% methane vapor about 34 m diameter. A figure showing the process is given in Fig. 1.

This is about the same size as the tank itself and is the same order of size as a propane tanker truck and its consequences might be expected to be similar in terms of thermal radiation from the immediately ignited gas puff. There should be virtually no overpressure as there is no massive tank contents flash expanding at near sonic velocity. There is no confinement at the top of the vessel that could lead to what is known as a partially confined vapor cloud explosion.

There is no credible mechanism causing all 4–5 LNG tanks to fail simultaneously, although longer term cascading damage of several tanks is possible as the first failure damages the protection of its neighbors and causes it to be subject to failure. Simultaneous failure would require a major over-pressure to physically damage several tanks at once. Thermal impact alone would not cause simultaneous failure as the undamaged tanks still have their deck plate, air gap, and insulation layers. As the tank which failed will generate a cloud which is consumed in 30–60 s, probability rules out simultaneous involvement.

A possible scenario for BLEVE would be if the internal LNG tank pressure were to rise well above 0.28 barg, closer to the several bar pressure observed in normal BLEVE events. The membrane tank cannot sustain this pressure as it is an atmospheric tank supported by the vessel structure. It will fail with significant internal pressure giving a result similar to that already described with thermal tank rupture. The spherical tank is different, it is self-supporting and can withstand a significant internal pressure, possibly 3–4 bar if the aluminum shell was not weakened by fire in the unwetted portion. If its relief system failed then it could rise to a pressure high enough to BLEVE. This is hypothetical as there are always multiple relief valves on LNG tanks and simultaneous failure of all reliefs is not credible. There is extensive process industry experience with relief valves and these are highly reliable. Two or three independent relief valves

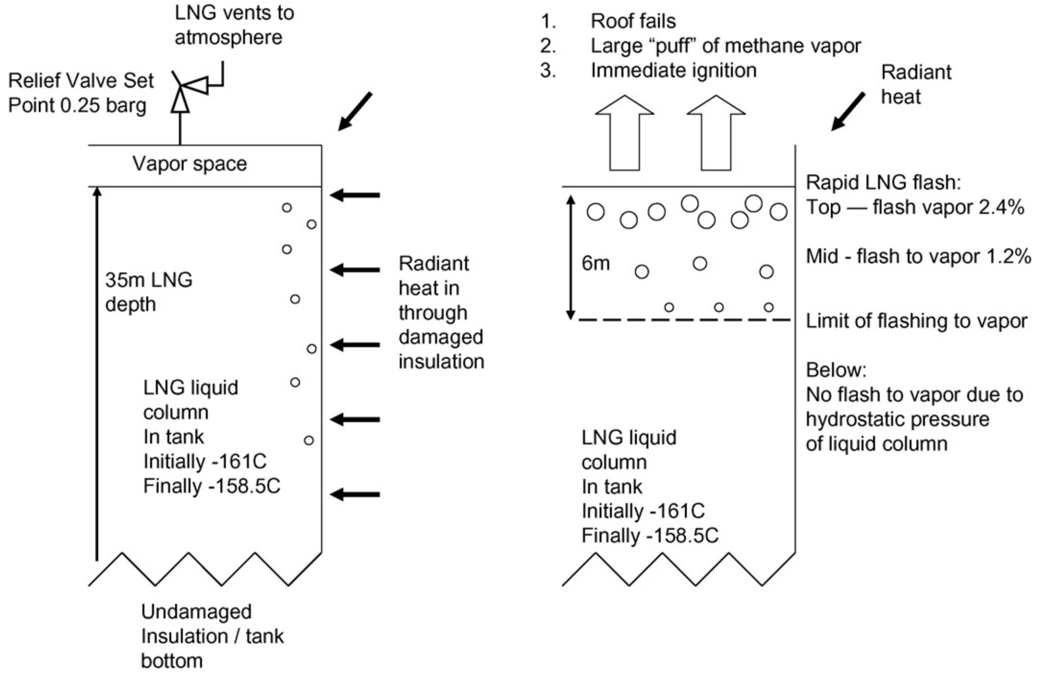

Fig. 1. Heating of LNG tank.

reduce the probability of failure even further. Reliefs are sized assuming 10% heat input past failed insulation (compared to an bare tank) thus the fire situation is properly accounted for. The 10% value is typical in API 521 relief calculations for insulated vessels. Here, the vessel structure, insulation, the skirt for a sphere and the insulation boxes for the membrane, and the fact that the fire is on one side only of the vessel greatly impede thermal input compared to a bare tank completely enveloped in a pool fire—which is the 100% basis assumption.

There is the potential for some liquid entrainment in the relief stream and if this were ignited this would increase the heat input onto the top of the tank, but through the several barriers noted earlier. Heat input onto the top of the tank would not result so much in heating of the bulk fluid, rather this would tend to raise the shell temperature in the upper unwetted zone leading to thermal failure at the current relief pressure when the rising shell temperature lowers the material yield stress to match the internal pressure loading. This is particularly relevant to the spherical design as these have a higher inherent strength than membrane tanks. Undoubtedly, the combination of a pool fire and an ignited two-phase relief discharge is a major heat input to the tank area. However, there are multiple thermal barriers for the top of the tank and these barriers should not be affected to the same degree as the lower portion whose external barriers have been damaged in the collision or other event which caused the original pool fire.

6. Conclusion

The Spanish LNG truck incident has been reviewed and this shows that LNG fluid in certain circumstances can give rise to BLEVE-like outcomes, however US LNG truck design is different and safer against threats of this type.

This paper has reviewed a serious pool fire event affecting an LNG vessel. This would damage the vessel in as yet unproven manner—but a reasonable sequence of events can be hypothesized. This would occur over a significant period of time, of the order of hours, and normal emergency response should ensure no public remains in any significant hazard zone. The pool fire event is serious, but it has been hypothesized that a BLEVE outcome is possible and this is even more serious in consequence zone, up to 2.5 km.

This paper has reviewed the potential for a BLEVE of the damaged tank or one of its undamaged neighbors. While tank failure is possible, it would not give rise to a major BLEVE of the type seen in Mexico City. The design of the tank and its relief system limits the flash of slightly pressurized LNG (0.28–0.3 barg) to only 1.2% of the upper 6 m of tank. Thermodynamic calculations show this could cause only a cloud of 38 tonnes of methane vapor, or a sphere of 34 m diameter. This is similar in scale to a transport accident and would create a hazard zone of 200 m, less than the hazard zone from the pre-existing pool fire.

During a major pool fire event, no unprotected person is likely to approach within 200 m of the vessel. Fire fighters in full protective clothing and stationed on a fire tug should be able to shelter safely much closer than 200 m away.

Undoubtedly, a major LNG accident or terrorism event will give rise to serious dispersion or thermal hazards from the resultant pool fire but these should be localized to the area around the ship and out to several hundred meters. However, a BLEVE event causing a thermal hazard zone in excess of 2.5 km is not credible. There is no mechanism for the tank to reach a high enough internal pressure to result in a BLEVE which the design has not eliminated.

As prior studies have noted [1,2], there are many uncertainties associated with accidental events to large marine LNG vessels.

Some selected experimental or theoretical calculations would be beneficial for to better establish vessel structural response to external pool fire events.

This paper has demonstrated that the BLEVE potential of large LNG marine vessels, with properly sized relief valves as specified in the applicable IGC code, is greatly reduced in consequence due to design considerations and relief, well below the scale of the initiating pool fire event. Spherical tanks might be subject to a large BLEVE if their relief system failed as the spherical tank has greater internal strength to be self-supporting, but this would require multiple simultaneous failures of the double or triple relief system, conceivable but virtually unheard of in the process industry.

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