Explosion & Gas Release from LNG Carriers

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INTRODUCTION

There is a growing trend throughout industry towards using Liquified Natural Gas (LNG) as a potential source of energy. LNG is the liquefied form of natural gas and is predominately made up of Methane with the remaining small percentages made up of Ethane and Propane. This mix is transferred into a liquid form to allow it to be transported by ship to its final destination. This is carried out by lowering the temperature of the gas until it is cold enough to form a liquid (-162ºC).

Despite the excellent safety record of the shipping industry, there is still some concern about whether so much gas presents a risk of major explosion. It is easy to acknowledge that LNG does burn, it does form gas clouds, and it is extremely cold. However it has many qualities which limit the consequences of an LNG spill. This paper presents a high level overview of how LNG is likely to behave during a release from a ship. As such it puts in context the major explosion theory against what is known in practice.

The approach taken looks at evaluating a worst case scenario of a major release from a LNG tanker. Such releases are extremely unlikely in comparison to small scale releases. However examination of such large scale releases present a worst case scenario.

This includes evaluation of the loss of containment, the formation of LNG pools, gas plumes and ignition hazards.

The assessments of the consequences are backed up by an evaluation of historical and experimental evidence. This evidence has been presented to assist in the understanding of the nature of the consequences and to provide justification for certain conclusions.

GLOSSARY

Bund:- A retaining wall or dyke designed to contain liquid released usually as a result of the failure of a storage tank.

Deflagration:- The low speed combustion of a flammable gas cloud in which no damaging pressure wave is produced.

Detonation:- When the combustion flame speed in an ignited gas cloud increases up to or above the speed of sound in the gas, a detonation is said to occur. The flame front is directly coupled to the pressure profile which takes the form of a shock wave. Damaging overpressures can occur which are transmitted outside the region of the gas cloud.

Detonations generally occur in pipework or highly congested regions of process plant. To date no detonations have been produced in unconfined methane cloud tests.

Dispersion Models:- Mathematical models which are used to predict the spread and shape of a gas cloud. The models may be used to predict distances to specified concentration levels within the cloud and hence give concentration contour plots.

Emissive Power:- The heat flux measured at the surface of a flame.

Flame Speed:- The speed of propagation of a combustion flame through a gas cloud. The faster the speed the higher the associated overpressure produced. Flame speeds greater than 100m/s may result in damaging overpressures.

Lower Flammable Limit (LFL):- The minimum quantity of flammable gas (usually expressed as % by volume) which when mixed with air will support combustion. For methane air mixtures the LFL is 5% by volume, and for propane air mixtures the LFL is 2% by volume.

Overpressure:- for a pressure pulse (blast wave), the pressure developed above atmospheric pressure.

Upper Flammable Limit (UFL):- The maximum quantity of flammable gas (usually expressed as % by volume) which when mixed with air will support combustion. For methane-air mixtures the UFL is 15% by volume, and for propane-air mixtures the UFL is 8% by volume.

Unconfined Vapour Cloud Explosion:- An unconfined vapour cloud explosion (UVCE) describes an explosion of a flammable vapour-air mixture either in the open air or in partially confined circumstances due to the presence of buildings, structures, trees, etc.

HISTORICAL EVIDENCE

Modern LNG shipping has existed since 1965. Numbers have increased until there are now 149 LNG ships in active service, with another 27 on order. This number is likely to continue increasing as new LNG trades are started.

The review of the marine incidents for LNG carriers involving the loss of containment during loading, transportation and discharging confirms a good safety record. The rate of serious casualties per ship year for LNG carriers is approximately one half of that for other liquefied gas carriers. In addition the nature of the incidents involving LNG carriers were of a minor nature compared with those for other vessels.

A review of historical evidence (Ref. [1],[2]) indicates that since 1965, only a relatively small number of spillage of LNG have occurred. In all cases the spillage volumes were minor. In total these spills have resulted in:

- 2 cases of severe deck fractures
- 5 cases of minor deck/tank cover fractures
- 2 cases of Invar membrane rupture.

Four of the incidents were due to valve leakage. Such incidents have resulted in improved valve design. In the incidents that have been reported, there has been no loss of life, damage to land-based property or harm to the environment and on each occasion the LNG dispersed without igniting.

There are no recorded incidents of collision, grounding, fire, explosion or hull failure which have resulted in cargo spillage and no LNG carrier has been lost at sea.

Even in the two grounding incidents where bottom damage has occurred, there was no release of LNG.

Design factors have minimised the consequences of these incidents. These include:

- double hull protection
- containment systems specifically designed for the transportation of LNG at low temperatures
- transportation at atmospheric pressure

The above safety record demonstrates that maintaining safety is a principal aim of the LNG marine transportation industry. The IMO Gas Carrier Code and LR's Rules for Gas Ships [3] provide requirements for design, construction and the equipment these vessels should carry so as to minimise the risk to the ship, its crew and the environment with regard to the hazards involved.

Thus LNG has an extremely safe record in terms of accidental release. When the very few occasions when accidental release has occurred, the consequences have been minor.

RELEASE CONSEQUENCES - LNG EXPERIMENTS

Much of the experimental work associated with LNG was carried out in the 1970's and 1980's. Experiments were undertaken to gain a better understanding of the behaviour of cold dense gases when released from containment. A further objective was to study the combustion characteristics of LNG vapour. The results from the experiments were used in the validation and development of computational methods for predicting the behaviour of these substances. There was also a need to confirm the feasibility of jettisoning cargo safely if required.

The tests concentrated on vapour cloud dispersion, vapour cloud ignition, pool fires and rapid phase transition i.e. the instantaneous change from liquid to vapour.

Dispersion

Note that the following dispersion theory deals purely with gas cloud movement. It does not take into account the ignition of a gas cloud prior to it reaching its full dispersion range.

Dispersion trials on water (Maplin Sands, Thorney Island, China Lake and Burro/Coyote) [4],[5],[6],[7],[8],[9]) show that an LNG release results in a low lying heavy cloud of vaporised LNG with well defined edges made visible by condensed water vapour. This gas cloud can be used to indicate where the dangerous Lower Flammability Limit (LFL) is following a release of gas.

The LFL is the smallest amount of gas:air ratio that can support combustion (5% for LNG vapour). Hence it is important as it indicates the area where ignition of the gas cloud could occur resulting in a fire. Generally when analysing gas cloud dispersion, the limit of the danger zone is taken to be half the LFL (i.e. 2.5% of volume). Both the 5% LFL and the half LFL occur within the area of the visible condensed water cloud. Hence the ignitable dangerous area of a gas plume is visible at ground level.

Experiments have shown that the LFL for vaporised LNG for a $20m^3$ release over 10 minutes is typically between 110m and 150m (propane ranged between 210m and 400m). These distances increase up to 400m for a $40m^3$ spill.

Larger spills of up to $200m^3$ over a similar period from a shipboard jettison system also resulted in inferred downwind distances to LFL of up to 400m although a visible cloud extending up to 2000m is possible. In each test the cloud height was found to be in the order of 10 to 12m.

Larger releases produce larger gas clouds and hence longer release distances. Distances of around 6km have been suggested as a potential range from a $25,000m^3$ spill. This figure does vary widely depending on the calculation method used.

Bifurcation of a gas cloud can produce fingers of higher concentration gas than the average predicted for that distance.

All vapour dispersion tests carried out on flat ground and water surfaces are acknowledged to give conservative results. The effect of obstructions, barriers, etc., would have the effect of reducing the spread of the cloud due to improved mixing and higher atmospheric turbulence levels.

Ignition

Ignition trials on dispersed unconfined LNG vapour clouds have confirmed that no *significant* overpressures are developed [4],[5]. Flame speeds are in the order of 10m/sec and measured overpressures less than 1mbar and the flame may not be sustained throughout the whole cloud.

In order to produce high flame speeds (i.e. > 100m/sec) in a methane gas cloud a high degree of confinement and congestion is required, for example in and around buildings, process plant and pipework. Overpressures in this event would be damaging but restricted to within the confined region, dying away rapidly in the unconfined part of the cloud. To date there have been no reports of a detonation in an unconfined methane gas explosion. Flame fronts in unconfined LNG vapour clouds have been observed to extinguish and not propagate through the whole cloud, or stop and be held stationary by the wind at some point away from the source. In seven LNG cloud ignition tests the flame burnt back to the source on only one occasion.

Pool Fires

Fire tests using pools of LNG up to 35m diameter have been carried out [10] and measurements of emissive power show that above 20m pool diameter the emissive power reaches a maximum of approximately $250kW/m^2$. It should be noted that the value of emissive power obtained from test measurements is dependant on an idealised flame shape which must be adopted for the calculations. Values of emissive power from different tests should only be compared if the same idealised flame shape is adopted.

For very large fires the generation of smoke limits the amount of radiated heat. This can result in much lower emissive heats in the range of around $50kW/m^2$.

$250kW/m^2$ is the maximum emissive power from the flame itself. This is an extremely high value (approximately 1000°C) when compared to other chemicals. To put this into context, a human immediately next to such a flame would be killed instantly. However the value drops the further away people are. $50kW/m^2$ causes fatality after 10 seconds, $20 kW/m^2$ is enough to cause pain on exposed human skin after 2 seconds. $1.5kW/m^2$ is considered safe. For a small fire (25m diameter) this safe distance would be around 250m away from the edge of the flame.

Rapid Phase Transitions

Rapid Phase Transition (RPT) occurs when LNG that has aged in storage, due to relief venting of vapour, is released onto water. Alternatively, if a volume of LNG ($0.5m^3$ and above) is released onto water it ages due to evaporation and can undergo a RPT after a delay of several seconds. No ignition is associated with the RPT effect and it has a limited capability for damage to structures due to the physical explosive effects [9].

Multiple RPTs of varying strengths can occur over the area of the release, the shock waves from each contributing to the initiation of others. Damaging overpressures occur only very close to the source. No ignition of vapour has been observed during an RPT. However, ignition of the gas cloud as a result of RPT damage to neighbouring equipment or instrumentation has occurred [11].

Releases onto water around jetties of a piled construction may involve the flow of the LNG pool and vapour cloud beneath the jetty. The vapour in this case could engulf the construction and any sheltering effects will prolong the duration of the cloud. In the event of an RPT beneath a jetty, damage could occur. However, a potential danger resulting from RPTs is cracking of the ship's hull as a result of low temperature embrittlement due to contact with the LNG.

Experimental Results in Context

The experimental work conducted throughout the last 25 years has resulted in a comprehensive understanding of the hazards associated with LNG and the consequences of both ignited and non-ignited releases. This understanding has therefore led to greater confidence in the accuracy of the models developed to analyse the effects of LNG releases. The results of the tests have also had an impact on the development of operational and emergency procedures associated with the transfer and transportation of LNG.

These tests must be placed into context with the situation after a release of LNG. If the ship is at sea then there is unlikely to be any local ignition sites. However there are also no general public or equipment in the local vicinity which could be damaged.

If the release occurs close to shore then there is likely to be many sources of ignition once the LNG vapour cloud reaches land. These sources of ignition are highly likely to cause the gas cloud to ignite before it travels any significant distance. Thus the damage will likely be limited only to the immediate shore area and no further beyond.

Although such combustion may not burn back to source, it is likely that the sheer size of the spill, along with the number of local ignition sources will cause multiple ignitions of the gas cloud. It is expected that at least one ignition will burn back to the source causing a pool fire to develop.

This review has drawn from a number of sources, both historical evidence, experiments and theoretical modelling. This has resulted in the following conclusions:-

CONCLUSIONS

Historically for all types of LNG shipping there has been no reported incidents of loss of life onboard the LNG ship, damage to land based property ,or damage to the environment. Design and operating standards onboard LNG ships have allowed only a small number of releases to occur. In each case there has been minimal damage to the ship.

Ignition and sustained combustion of a vaporised LNG cloud under normal release conditions is difficult. However the given a large number of ignition sources the gas cloud will probably ignite and eventually burn back to the liquid pool it was vaporising from. This will cause the pool to ignite.

Unconfined LNG vapour cloud detonation type explosion has not been demonstrated in experimental work and is most unlikely in practice.

Confined explosions could result in overpressures, but these effects are limited to the confined space, and the effects would dissipate away from the event.

The LFL for methane air mixtures is 5% volume so the LFL boundary is well within the visible cloud at ground level.

If a gas cloud is formed, and assuming that no ignition occurs, the flammable limits have been suggested as reaching a substantial distance from the source. **Such a value is only valid for a ship at sea. It is extremely unlikely that these distances would be reached whilst close to shore or at berth due to local ignition sources being readily available.**

As the gas cloud warms up the gas will become lighter than air and will rise away from the surface.

As LNG will vaporise and is non-toxic there is no significant direct environmental damage caused by a spill and hence no clean up costs other than those arising from secondary escalation factors.

Thus it can be concluded that LNG has specific parameters which make the likelihood of a major explosion remote. Ignition sources proportional to the sensitivity of the location mean that gas plumes are extremely unlikely to pass long distances through cities before igniting. As the gas cloud warms up it will rise away from the surface until it dissipates into the atmosphere.

These features combined with the high standards of design and operation throughout the industry mean that compared to other chemicals LNG poses one of the lowest threats to the general public and property.

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