Large scale pressurised LNG BLEVE experiments

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In recent years there has been a drive to use cleaner and more efficient fuels. Liquefied Natural Gas (LNG) is one of the fuels now being considered, especially for commercial vehicles such as trucks and ferries. LNG has a long and excellent safety record - it has been safely delivered across the oceans for over 50 years. In using LNG as a transport fuel, it is important to ensure continued safe operations in this new value chain. Next to liquefaction plants and regasification terminals this distribution chain also has retail fuel stations and bunker terminals relatively close to urban environments. Hence there are several questions that must be addressed: What are credible scenarios in this small scale distribution chain? Are the consequence models used today to safely manage risks appropriately validated? Do they predict the consequences correctly or are they too conservative and thereby adding unnecessary costs, to the investment, which do not result in improved safety?

One of these scenarios, a BLEVE (Boiling Liquid Expanding Vapour Explosion), has been the subject of much debate, particularly whether a catastrophic release from a vacuum insulated double skinned pressure vessel is credible. Industry has found it difficult to demonstrate that the loss of containment either through mechanical impact or via flame impingement is not credible, resulting in several Joint Industry Projects to quantify the likelihood. In addition, there are also uncertainties in the hazard consequence predictions for a LNG BLEVE. This arises because there is a lack of experimental data to validate, for LNG, models that have been developed for LPG. Even though the physical process of the BLEVE phenomenon would be similar to LPG, the actual thermodynamics and specifically the combustion properties of LNG may mean that any predictions based on LPG models may be more conservative than a dedicated LNG model and consequently could impact the design footprint of the retail operations.

To improve the prediction of potential BLEVE hazards from a pressurised LNG vessel, four large scale experiments have been performed. These tests were designed to be similar to the original LPG tests that Shell were involved with in the early 1990s and so using three 5 m^3 vessels the effect of fill level (33% and 66%) and pressurisation (6 and 13 barg) were investigated. The fourth test used a smaller 1 m^3 vessel to enable the results to be scaled. In these experiments the credibility of a double skinned vessel to catastrophically fail was not investigated; instead, single skinned pressurised vessels were artificially ruptured using a linear explosive cutting charge to initiate the BLEVE. The subsequent extent of the fireball, the thermal radiation and overpressure as a function of distance and time were recorded. This paper presents the results of these experiments and compares the hazard consequences to equivalent LPG tests. Overall the results show that using a LPG BLEVE model to predict the thermal radiation consequences of a LNG BLEVE will not generate overly conservative results.

Keywords: BLEVE, LNG, LPG, Experiment, Thermal Radiation, Overpressure, SEP

Introduction

A BLEVE (Boiling Liquid Expanding Vapour Explosion) is considered to be one of the most devastating major hazards and they have been extensively studied, especially for Liquefied Petroleum Gas (LPG). This industry has seen a number of fatal incidents, such as that seen in Mexico City in 1984 (Pietersen 1985). In contrast, a BLEVE hazard has historically not been viewed as a credible event for Liquefied Natural Gas (LNG) storage. This is mainly because LNG is usually stored at cryogenic temperatures at, or near, atmospheric pressure, but also because many tanks, particularly in the marine environment, are designed to fail at very low pressures, e.g. 0.28-0.30barg (Pitblado 1987).

In recent years there has been a drive to use cleaner and more efficient fuels, such as LNG, for commercial vehicles such as trucks and ferries. The majority of these systems that are in commercial use, or at the design stage, are pressurised to reduce natural boil off, as well as aid the pumping of the LNG product in some operations. It is therefore important to determine the credible hazardous scenarios in this small scale distribution chain to ensure continued safe operation. This distribution chain not only includes liquefaction plants and regasification terminals, but also retail fuel stations and bunker terminals that are in relatively close proximity to urban environments.

Consequently, the potential for a BLEVE has been the subject of much debate, particularly on whether a catastrophic release from a vacuum insulated double skinned pressure vessel is a credible scenario. So far industry has found it difficult to demonstrate that the loss of containment of these vessels, either through mechanical impact or via flame impingement, is not credible. Consequently, several Joint Industry Projects to quantify the likelihood of failure of these vessels and transfer hoses are either running, such as the LNG Safety programme in the Netherlands, or have been proposed, such as DNV GL's JIP to study the thermal radiation on double skinned vessels (Mohammed 2014). Separately, two incidents, involving single skinned LNG tanker trucks have been reported in Spain (Planas-Cuchi 2004, Bonilla Martinez 2011). In both these cases, eye witness accounts clearly described typical BLEVE behaviour when the pressurised vessels failed. If it is shown that a failure of double skinned LNG vessels is credible, then, there is a requirement to be able to predict the hazards from a potential LNG BLEVE.

Existing BLEVE models are predominantly based upon large scale LPG BLEVE experiments conducted in the early 90s (Johnson 1991), or earlier experiments on n-pentane (Hasegawa 1977), and although the physical processes of a LNG BLEVE would be similar to LPG, the actual thermodynamics and combustion properties of LNG are different. Therefore any predictions based on LPG models may be more conservative than a dedicated LNG model and consequently could impact the design footprint of retail operations.

This paper reports on four large scale experiments that have been commissioned by Shell to improve the prediction of BLEVE hazards from pressurised LNG vessels. In these experiments, the credibility of a double skinned vessel to catastrophically fail was not investigated; instead single skinned pressurised vessels were artificially ruptured using a linear explosive cutting charge to initiate the release. The subsequent extent of the fireball, the thermal radiation and overpressure as a function of distance and time were recorded. This paper presents the results of these BLEVE experiments and compares the hazard consequences to equivalent LPG tests.

Experiment Setup

Four large scale BLEVE experiments using LNG fuel were commissioned at the DNV GL test facility at Spadeadam UK. These experiments were chosen to represent operating pressures for small scale LNG facilities, while at the same time enable a comparison to equivalent tests on LPG that were completed in a joint industry project in the early 90s (Johnson 1990, Johnson 1991). The details of each LNG experiment are given in Table 1.

Table 1: A Description of the LNG BLEVE experiments

Experiment #	Vessel Capacity (m^3)	Reservoir Pressure (barg)	Reservoir Temp (°C)	Final Fill Ratio	Calculated Release Mass (kg)
1	0.935	12.92	-120	66	247
2	5.055	13.01	-115	37	681
3	5.055	6.07	-131	67	1306
4	5.055	13.62	-115	69	1251

The base case, experiment 4, was tested last because it was assumed that it would generate the largest fireball and hence highest thermal radiation response. The base case was tested at approximately 14 barg and using a vessel capacity of 5.055 m^3. The equivalent test for LPG was performed at 15 barg and within a vessel with capacity of 5.659 m^3. However the lower liquid density of LNG (calculated to be 358 kg m^{-3} at these operating conditions) compared to the density of n-butane in the LPG tests resulted in a significantly lower mass; 1200 kg compared to 2000 kg in the base case for the LPG BLEVE tests.

Experiment 2 and 3 changed the fill level and the reservoir pressure respectively from the base case. In experiment 2, the fill level was reduced by approximately a half (69% to 37%) to understand the effects of liquid level and reduced mass on the resultant fireball at the same base pressure. This is analogous to LPG test 2, where the fill level was reduced from 77% to 39%. In experiment 3, the reservoir pressure was approximately halved to 6.07 barg, which enabled comparison to LPG test 3 at 7.5 barg. This reduced pressure also more closely matches the operating conditions on pressurised LNG tanker trucks, particularly if truck operators are over pressurising the LNG contents to offload LNG rather than use a pump. It therefore gives a direct measurement of the effects of a cold BLEVE.

In experiment 1, a smaller vessel with a volume of 0.935 m^3 was used to simulate the potential BLEVE for a typical fuel tank that is currently used within the industry for trucks fuelled by LNG. This experiment was also conducted to understand the effects of scale for subsequent model development.

Experimental Arrangement

The vessels were constructed from rolled 6 mm stainless steel plates and nominally had a length to width aspect ratio of 6:1. In practice, the resultant pressurised vessels that were designed and built had a length to width ratio of 6.5:1 and 5.5:1 for the larger and smaller vessels respectively. An image of the larger vessel prior to filling is shown in Figure 1, which shows the threaded and flanged ports used to both fill the vessel and allow entry for the instruments within the vessel.

Figure 1: One of the three 5.055 m^3 pressurised vessels.

The vessels were filled with commercial grade LNG that was sourced from the Avonmouth LNG terminal in the UK. The LNG was very lean with a composition ~96.7 mol% methane, ~3mol% ethane, <0.2mol% nitrogen and <0.1mol% propane. The vessels were cooled and filled using a vent-fill method by which LNG is injected at one end of the vessel and the pressure within the test vessel maintained below the supply vessel pressure using a remotely operated vent to discharge vapour from the opposite end of the vessel through a 1" OD stainless steel pipe.

The required fill level (either 33% or 66%) was obtained through the use of three tri-cock valves. The lower ends of these valves were set at three different levels within the vessel, such that the mid tri-cock was set at the desired percentage volume fill height and the low and high tri-cocks set at -2% and +2% respectively. Filling was stopped after the middle tri-cock discharged LNG to the outside and before any liquid came out of the highest tri-cock. The internal pressure was then allowed to rise to the value chosen in the experimental design and the resultant fill level calculated from the relative change in liquid density (see Table 1).

Instruments

The pressure in the vessel was measured using a 0-25barg range Druck UNIK5000 transducer at the top of the vessel. This has a quoted accuracy of ±0.04% of the full range. The temperature within the vessel was measured using 1.5 mm diameter, stainless steel sheathed, Type 'T' thermocouples. These thermocouples were located at five locations along the long axis and within both the liquid and vapour space of the vessels.

An array of sensors, both perpendicular and parallel to the axis of the vessel, were deployed to measure the characteristics of the resulting rupture. These sensors were positioned 10 m apart and at 1.5 m above ground level at the locations given in Figure 2. Video cameras were also positioned around the vessel, as shown in the diagram. Standard video recordings were made at the North West and East locations, while high speed video cameras (2000 fps) were positioned at the North and East locations.

The thermal radiation was measured at the locations indicated in Figure 2 using wide angle radiometers, with a field of view of 150° and a wide spectral response detecting wavelengths over 0.3 to 11.5 µm. The radiometers used a Schmidt-Boelter thermopile, which had a response time of less than 1s and an accuracy of ±5 %. A narrow angle radiometer was placed at the 20 m position along the East line, by installing a collimating shield to restrict the field of view to 0.055.

The overpressure at each location was measured via PCB 113B21 high frequency pressure transducers. The transducers have a resonant frequency of greater than 500 kHz and a non-linearity quoted by the manufacturer of <0.1% full scale range (13.7 bar).

Atmospheric measurements of the wind speed and direction were made using the same data acquisition system as the radiometers using anemometers located 100 m to the East of the vessel. A separate recording of the relative humidity during each experiment was made using the Spadeadam weather station located 500 m from the test site.

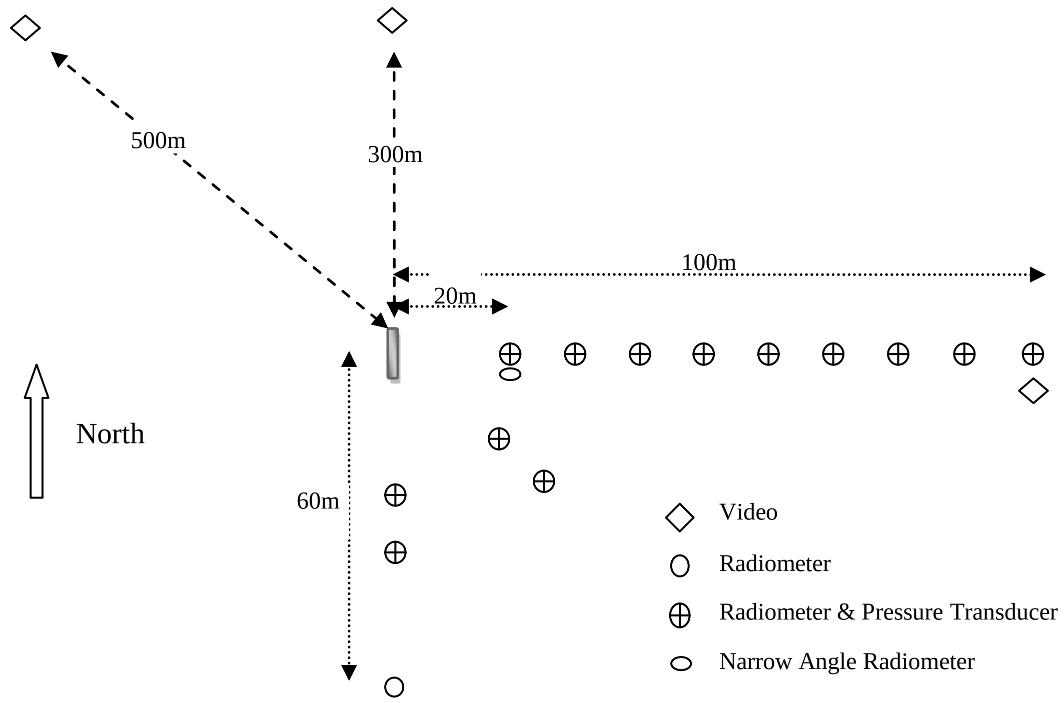

Figure 2: A schematic diagram of the field instrumentation layout. The camera positions to the North West and North are not drawn to scale.

Explosive Charge and Ignition

The rupture of the vessel was initiated by a copper based explosive cutting charge, which was sized to allow the rupture to propagate to the end caps and cause a catastrophic failure of the vessel. The charge was placed longitudinally along the top of the vessel when the correct reservoir conditions within the vessel had been achieved. A cable was attached to the triggering circuit to provide a trigger signal to the high speed cameras and field instruments.

A set of incendiary devices (roman candles and gerbs[1]) were installed around the vessel to ensure that the release was ignited. These devices were initiated a few seconds before the explosive charge was triggered.

Results

The results from all four experiments were obtained during the summer of 2014. A quick summary of each experiment is given initially before specific analysis from the instruments is discussed.

Overview

In experiment 1, the fracture ran along the full length of the top of the vessel, but arrested on the thicker material of the domed ends and so the vessel did not fail catastrophically. The resultant orifice, although large, forced the flashing LNG to be released as a jet. The gerb incendiary device also failed to trigger and the flammable cloud was only ignited by the secondary device three seconds after rupture. Consequently, the flammable cloud and subsequent fireball formed high above ground and to the right of the main instrument array. A still from the video just before, and after, ignition is shown in Figure 3.

It was observed that the flame produced by the experiment had a definite green colouration. This is believed to be attributable to the copper-based explosive cutting charge used to rupture the vessel. Although only small mass of copper is used, the explosive process forms a plasma and hence would allow elemental copper to mix uniformly during the release. In subsequent tests, the copper backing in the charge was reduced, and along with the increased LNG volumes, the green colouration was reduced significantly and was only apparent in experiment 2.

1 Gerbs are a type of firework that produces a jet or fountain of sparks at ground level.

Figure 3: The induced LNG BLEVE in experiment 1, showing the resultant flashing cloud (left) and fireball (right) approximately 3 seconds after rupture

The problems with the partial rupture and delayed ignition significantly affected the quality of the thermal radiation measurements. Hence only the fireball size results from experiment 1 have been used in the subsequent analysis in this paper.

The crack propagation was also limited in experiment 3 when the pressure was reduced to 6 barg, resulting in a 4 m^2 orifice. This orifice was large enough to discharge the LNG contents quickly in all directions, but with a preferential direction to the West. The resultant momentum of the release caused the vessel to roll 20m towards the Eastern arm of the instrument array. In experiments 2 and 4, the increased pressure, ~13 barg, was sufficient for the crack to propagate to circumferential weld at the end cap and severing the end cap from the rest of the vessel. In Experiment 4, one of the end caps was severed with enough energy to throw it 19 m. The video evidence also shows that two other missiles; pipework and a wooden sleeper used to support the vessel, were also thrown over fifty metres. Unfortunately the missiles were never found and the exact distance could not be determined.

Even though the LNG was subsequently released in all directions during experiments 2-4, there was still a preferential release direction in the East-West plane, e.g. perpendicular to the vessel axis, which runs along the North-South plane. This reflects a similar observation reported during the LPG experiments (Johnson 1991). The resultant release ignited within 0.5 s and produced a BLEVE with typical characteristics; a flashing release expanding outwards as a hemisphere, ignition followed by an increased expansion velocity as the fireball develops and a rising fireball forming a mushroom shape. A comparison of the resultant BLEVE for the three larger releases is shown in Figure 4. In each case the still image is taken from the video footage recorded 100 m East of the vessel and approximately three seconds after the rupture event.

Figure 4: Induced LNG BLEVEs three seconds after rupture of the 5 m^3 vessels; Left - Experiment 2 (37% fill, 13 barg), Middle - experiment 3 (67% fill, 6 barg), Right - experiment 4 (69% fill, 13.6 barg).

The images in Figure 4 clearly show typical BLEVE phenomena, such as a luminous flame and a rising fireball. In all three experiments these images also show significantly less smoke generation than equivalent LPG BLEVEs, even at lower reservoir pressures, which will affect the Surface Emissive Power (SEP) and resultant thermal radiation.

Mass of fuel in fireball

When the vessel ruptures, the superheated liquid will flash and form a vapour. The assumption that is made is that, once formed, the liquid droplets flash adiabatically since there is insufficient time for heat to be transferred to the droplets and their surroundings. By assuming an isenthalpic flash to atmospheric pressure and temperature and using the latent heat of vaporisation, the proportion of liquid that will be expected to vaporise can be calculated. A flash fraction of 35% was calculated for the release in experiments 2 and 4, where the saturation temperature was approximately -115°C. This is at the limit identified by Hasegawa *et al*, above which all the fuel is considered to be burnt in the fireball (Hasegawa 1977). The video evidence supports this conclusion because there is no evidence of rainout and subsequent pool fire for either experiment 2 or experiment 4.

The result for experiment 3 is a little more interesting, because the calculated flash fraction is only 22% and therefore below the 35% limit. This is partly supported by the video evidence, which shows that there was a low lying flame below the main fireball. However this flame extinguished after only 4 seconds and consequently it can still be assumed that the majority of the liquid was consumed within the fireball.

Fireball duration

The dynamics of the fireball; its growth and subsequent decay, were studied by analysing the video information and using this data to determine the time for key events in the fireball development. This information in turn can be used to understand the physical processes that govern the growth of the fireball, such as the initial momentum following the vessel rupture, buoyancy effects when the fireball starts to rise and then radiative cooling. To predict the influence of these events, the timings of key stages with respect to the vessel rupture are given in Table 2. They correspond to the time of ignition, when the fireball reached its maximum size, the time that the fireball lifted off the ground and when the fireball was extinguished.

Table 2: Event timing during fireball development

Experiment #	Time from vessel rupture (s)			
	Ignition	Maximum size	Lift off	Extinction
1	3.0	4.5	n/a	7
2	0.5	1.7	2.8	5
3	0.4	3.4	3.3	7.5
4	0.5	2.7	3.6	5.5

The results from experiment 1 are also included in this table, but as can be seen from the large ignition timescale, a direct comparison to the other experiments is not possible. The results show that ignition for experiments 2-4 was consistently found to be about 0.5 s after the rupture event, however, the vapour cloud may have obscured the primary ignition location and these values should be considered as maximum times.

The data show that maximum fireball size is reached in a shorter time when a smaller fill level was used with the same operating pressure, comparing experiments 2 and 4. This matches the equivalent LPG results, where the time for maximum fireball reduced from 2 to 1.2 s as the fill level was reduced from 77% to 39% (Johnson 1990). In these experiments the time to extinction is also shorter when there is a reduced fill level, but not by the same margin.

A reduced pressure (in experiment 3) appears to slow the fireball process, increasing both the time to maximum size and to when the fireball itself will be extinguished, c.f. experiment 4 at a similar fill level, but twice the pressure. This supports the argument that there is a larger quantity of liquid within the initial flashing release, which subsequently takes time to fully vaporise (since, as already commented, any pool fire that was present only burnt for a few seconds). Again, this appears to match results in the equivalent LPG tests, where the longest time to maximum fireball diameter was recorded for the half pressure experiment (Johnson 1990).

The video analysis showed a clear lift-off period for experiments 2 and 4 (at the higher pressure), which was about 1 second after reaching the maximum fireball size. However this was less clear in experiment 3, where the maximum size and lift period appeared to occur at approximately the same time. This in part may be explained by combined fire/radiation from the "pool fire".

It has been noted that buoyancy controlled processes such as the liftoff of the fireball have a timescale proportional to $M^{1/6}$, where M is the mass of the fluid in the vessel (Hasegawa 1978, Fay 1977), whereas the timescale for the process controlling the initial momentum and radiative effects are proportional to $M^{1/3}$ (Roberts 1981). In addition, Roberts, suggests that the total duration of the visible fireball for releases from pressurised storage is dependent on the release conditions, because this will determine the relative strength of these two processes, and hence the total fireball duration will lie between $4.5\times M^{1/3}$ and $9.0\times M^{1/3}$ (where the mass is given in kg). To test this hypothesis, the total fireball duration for the LNG experiments ($T_{extinction} - T_{ignition}$) is plotted as a function of mass and shown in Figure 5. The results from the LPG experiments are also shown.

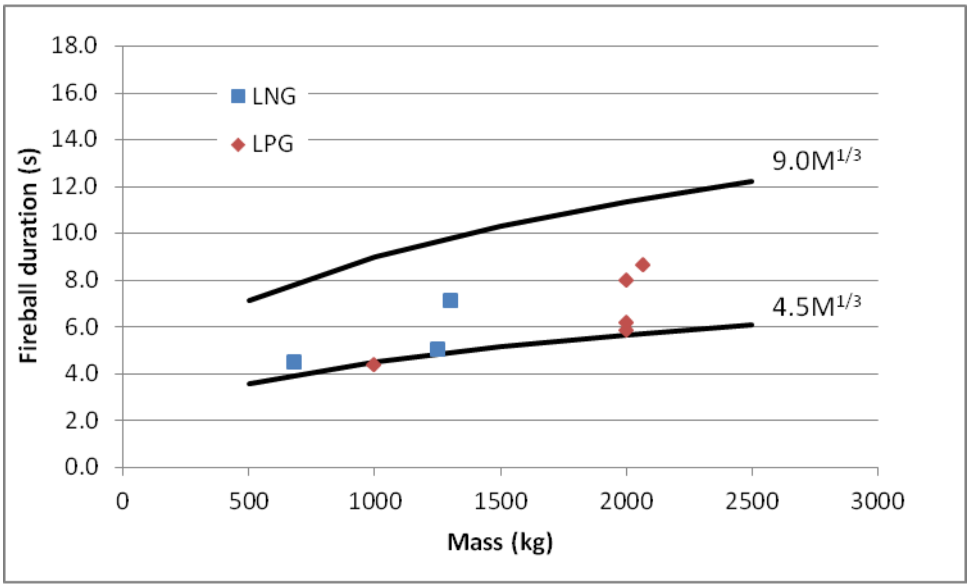

Figure 5: The fireball duration as a function of LNG and LPG mass

The results show that LNG follows the same trend as the previous LPG experiments and suggest that the fireball duration is controlled by the initial momentum process in these experiments. However if the model is extended to much larger fuel volumes, the effect of buoyancy may become more significant and a modified correlation, based upon $M^{1/6}$, may need to be applied.

Fireball size

The size of the vapour cloud and subsequent fireball as a function of time were determined from the video recordings of each experiment. This was achieved by generating still images from the video at regular intervals and measuring the area of the outer extent of the cloud/fireball with respect to the initial vessel size. In this process, the calculated area was adjusted for the orientation of the vessel axis with respect to the camera location. It was also assumed that the outer extent of the fireball was in the same plane as the vessel itself and that as the wind speed was low no adjustment was required for the relative position of the fireball. The diameter was calculated from the fireball area by assuming an equivalent circular area and this is shown for experiment 4 as a function of time in Figure 6.

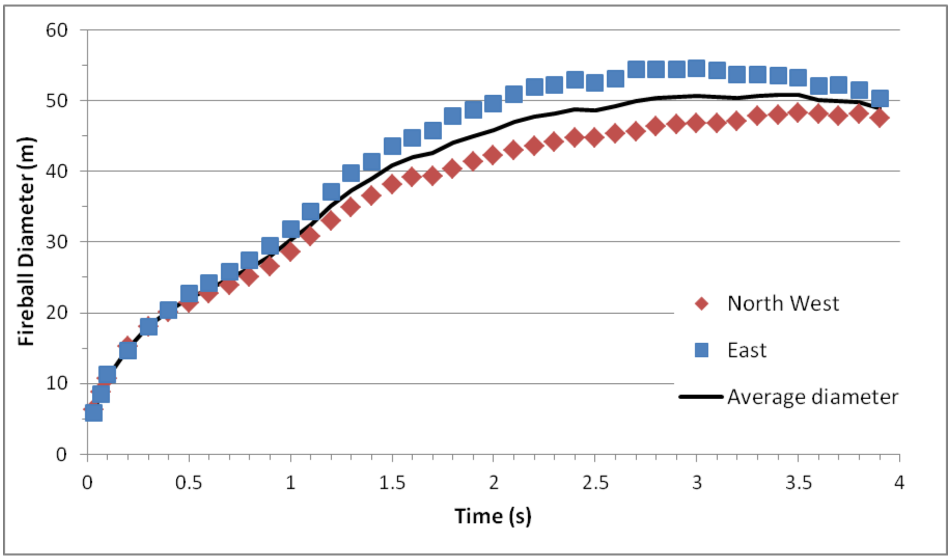

Figure 6: Calculated fireball diameter for expt. 4, as measured from cameras positioned East and North West of the vessel

The graph shows a number of features that were typical for the other two experiments.

- An asymmetry in the fireball area depending on the viewing position, which, as discussed previously, depends on how the vessel initially failed. The calculated average diameter was accurate to ±5 m.

- An initial expansion phase after the vessel ruptures as the LNG contents flash, but then slows down as air is entrained. The velocity of this expansion was measured to be greater than 60 ms^{-1} for experiments 2 and 4, but as expected, it is closer to 25 m/s for experiment 3, which is at a lower pressure. These velocities are significantly lower than obtained using a similar analysis of the LPG experiments, where velocities of approximately 200 ms^{-1} were recorded.
- A second acceleration phase starts after approximately 0.5 s as the flammable cloud is ignited. The velocity of the expansion was measured to increase from about 8 to 12 ms^{-1} during this period. Again this is lower than that measured during the LPG experiments, where velocities from 20-32 ms^{-1} were recorded (Johnson 1991).
- There is only a limited time period where the fireball maintains a constant size. Instead the expansion continues slowly and then diminishes at the same rate as the fuel is consumed. This last observation appears to be different to the LPG experiments, where a longer steady state period was achieved (Johnson 1990).

The maximum fireball diameter for all four LNG experiments is plotted as a function of liquid mass in Figure 7. This includes experiment 1, where the momentum release does not significantly alter the final fireball size. It is clear from this graph that the maximum fireball size increases with the mass originally contained in the vessel. However, the maximum fireball diameter for LNG appears to be 10-20% smaller than that obtained during the LPG experiments for n-butane for the same equivalent mass. The relative difference in fireball size is less clear for the single propane experiment, which appears to not follow the same trend as n-butane.

The most commonly used relationship for calculating the fireball diameter is given in Equation 1, where M is in kg. This relationship is reported to be relatively insensitive to fuel type and cloud formation mechanism (Johnson 1990) and although it does give a good correlation for LPG (n-butane), it is over predicting the maximum fireball size for LNG by about 15%

$$D = 5.8M^{1/3} \qquad \text{Equation 1}$$

As can be seen in the graph, a better fit to the LNG data can be obtained when the constant is 4.8, rather than 5.8. However this appears to be inconsistent with the stoichiometry of methane because additional air is required for the complete combustion compared to other hydrocarbons. For instance the air-to-fuel ratio for methane is 17.2, compared to 15.7 for propane, 15.4 for butane and between 15.1 and 15.3 for heavier hydrocarbons. The original Hasegawa formulation, from where Equation 1 is derived, would also suggest a larger fireball size for methane, again due to the difference in stoichiometry (Hasegawa 1977). Consequently further analysis is required to explain the smaller fireball size that has been observed for these releases.

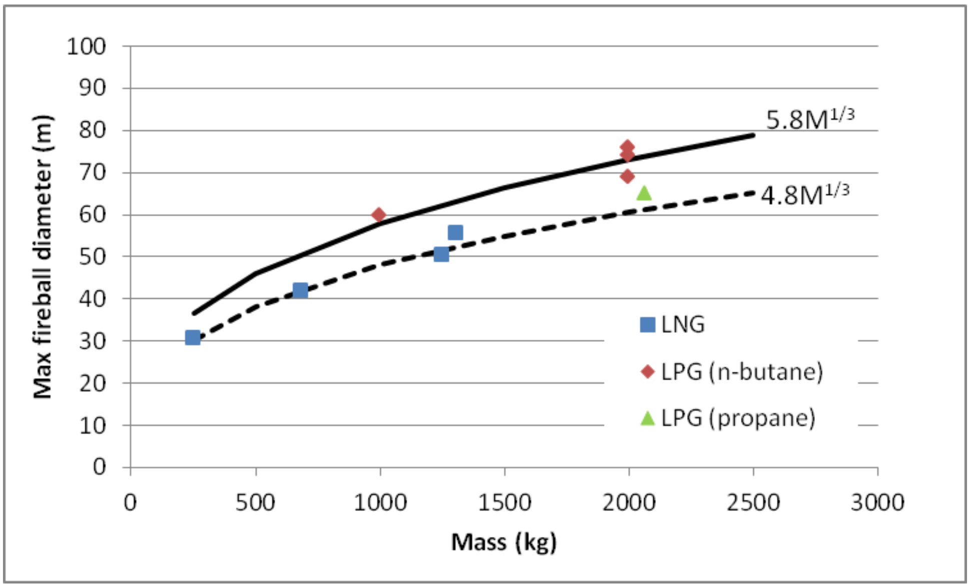

Figure 7: Maximum fireball diameter as function of liquid mass

Fireball height

As discussed earlier, a clearly defined fireball was generated in all experiments. At the lift off time, it separated from any remaining LNG burning near ground level (or at ground level in the case of expt. 3) and its height increased until it finally broke up. The impact of the fireball height on thermal radiation was assessed by calculating the fireball position as a function of time. The height of the fireball at a given time was defined to be the centre of the equivalent spherical fireball following the methodology of Johnson *et al* 1991.

The maximum heights for each fireball are given in Table 3. The absolute maximum height occurs for expt. 3, which is perhaps not surprising as it is likely to contain more liquid droplets and hence the fireball will have sustained burning for a longer period (as can be seen from the fireball duration times) and hence will rise further above ground level. Overall the maximum height for the LNG tests was found to be lower than the equivalent LPG tests, but the ratio of the height to the maximum fireball diameter is more consistent and was found to lie in the range 1.0 to 1.2 (c.f. 0.8 to 1.35 for LNG experiments). Indeed these values add further evidence to support the hypothesis by Moorhouse *et al* 1982; that the maximum fireball height should be taken to be the maximum fireball diameter.

Table 3: Calculated values for the fireball height

Experiment #	Maximum height of fireball centre (m)	Height to diameter ratio
2	50	1.2
3	61	1.1
4	52	1.0

Surface Emissive Power

One of the important parameters to characterise a BLEVE and predict thermal radiation is the Surface Emissive Power (SEP) of the fireball itself. Unfortunately the narrow angle radiometer positioned 20 m from the vessel along the East axis did not generate useable results. Consequently an average surface emissive power was calculated using the wide angle radiometers and adjusting the measured thermal radiation by the view factor of the fireball (using measurements of the fireball diameter as a function of time). These values were also corrected to account for atmospheric absorption. The results for radiometers along the East axis were used, because the thermal radiation could be directly correlated to the fireball size measured from the camera positioned at 100 m. In addition, the results from radiometers at 20 – 40 m were excluded because these radiometers were either engulfed by the fireball or did not see the full extent of the fireball as it rose into the air.

The predicted SEP values for experiments 2 – 4 are given in Table 4. It was found that the predicted SEP changed over time and generally increased as the fireball grew in size. There was also some unexpected variation in the SEP between radiometers located at 90/100 m and those radiometers situated nearer the fireball at 50-70 m. Further analysis is required to understand the physical origin of this discrepancy. Consequently a range of values for each experiment has been reported, as well as the average value calculated three seconds after ignition. This spot value at three seconds covers a time when the fireball is near or has reached its maximum size and is therefore more representative of the maximum SEP for these LNG fireballs.

Table 4: The calculate range of SEP values and average value three seconds after rupture

Experiment #	SEP Range (kW m^{-2})	SEP 3 s after rupture (kW m^{-2})
2	450-650	540
3	250-350	290
4	400-550	475

The values reported for experiments 2 and 4, 475 – 540 kW m^{-2} respectively, are significantly higher than reported for the LPG BLEVEs, which had average SEP values in the range of 340-370 kW m^{-2} (Johnson 1991). From the images in Figure 4 it is clear that very little or no smoke was generated and that the LNG fireballs were optically thick. In addition previous analysis has shown that LNG pool and jet fires have higher SEPs than equivalent LPG fires (Cowley 1991, Mizner 1982). Therefore the calculated values from these experiments seem reasonable.

The third experiment has a much lower SEP (290 kW m^{-2} at 3 seconds) than the two other experiments, but shows a good correlation to the equivalent LPG BLEVE at half pressure, which also has the lowest SEP within the LPG dataset (306 kW m^{-2}) (Johnson 1991). In these cases, the lower pressure appears to reduce the turbulent mixing of the flashing liquid/vapour as it leaves the vessel and so reduces the efficiency of the subsequent combustion. Further analysis is on-going to understand why the SEP is comparatively low relative to the two other LNG BLEVEs.

Thermal radiation

The variation of incident thermal radiation as a function of time is shown in Figure 8. The graph on the left shows a comparison of the thermal radiation at different distances during experiment 4. It shows a relatively smooth decay in the maximum thermal radiation as a function of distance – similar to equivalent measurements in experiments 2 and 3. At distances shorter than 40 m, some variation from this smooth trend was noticed for all three experiments. This was because the expanding fireball engulfed the detectors and was also calculated to rise above the detectors' field of view. A comparison of the thermal radiation at equal distances along the East, South East and South axis shows that the highest thermal radiation was recorded along the East axis. This is to be expected considering the asymmetry in the expanding fireball and correlates with the calculated fireball diameters, which were also larger when measured from the camera along the East axis.

The second graph on the right in Figure 8, shows the variation in thermal radiation at 100 m between the three experiments. At this distance, experiment 3 has the highest thermal radiation, although this is atypical when the radiometers between experiment 3 and 4 are compared at shorter distances. A comparison with the thermal radiation recorded during the LPG experiments shows a similar level of thermal radiation at 100 m, e.g. a peak of ~ 25 kW m^{-2}, but significantly higher values at distances less than 100 m and hence closer to the fireball.

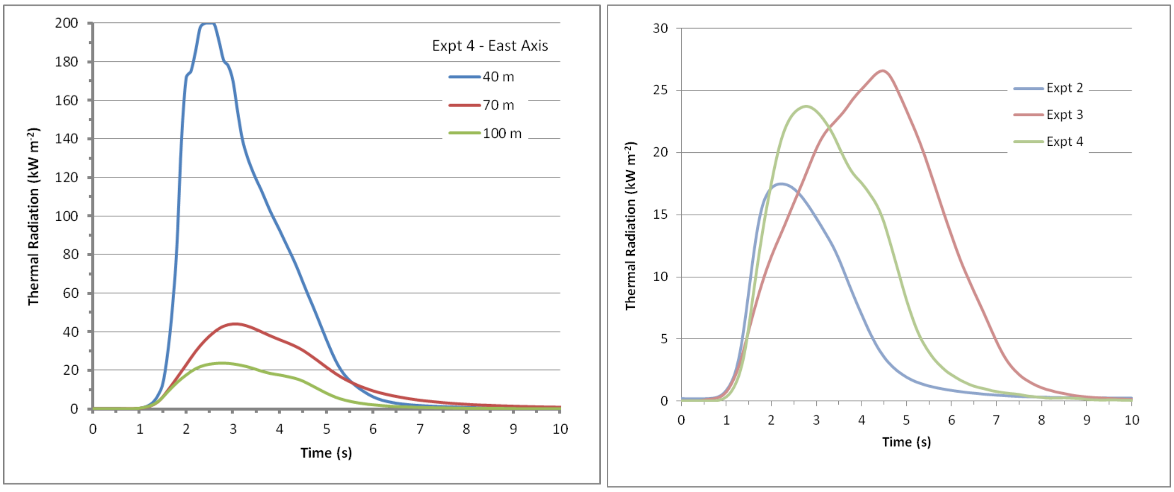

Figure 8: Incident thermal radiation at three locations during expt. 4 (left) and a comparison of the results from expts. 2-4 at 100 m (right)

Overpressure

Pressure transducers were installed at a number of locations around the vessel to try to detect the three phases in the BLEVE lifecycle that can generate an overpressure. These phases are the initial rupture of the vessel and the expansion of the pressurised vapour, the expansion of the liquid as it flashes to a gas and the combustion of the flammable cloud (Shield 1993).

Unfortunately in all four experiments it was difficult to distinguish the first two potential overpressures from the detonation charge required to rupture the vessel. The charge itself was 210 g equivalent TNT and modelling the overpressure decay of this TNT charge shows a peak overpressure of up to 30 mbar at a distance of 20 m. In all the experiments, the maximum initial peak was no greater than 30 mbar at 20 m and consequently it can be deduced that the overpressure from the first 2 phases is no greater than this value. This is less than the 60-90 mbar predicted for the equivalent volume of pressurised gas using the vessel burst model within the Shell consequence package, FRED, which is derived from the model published by Lees 1995. Further analysis is planned to understand why the results are lower than expected, although similar results were seen during the LPG tests (Johnson 1991).

The clearest pressure trace was obtained for expt. 2 and the measured overpressure at a distance of 40 m, 70 m and 100 m along the East axis is shown in Figure 9. In this image the initial overpressure pulse corresponding to the detonation charge can clearly be seen at each position. However a lower second peak with a similar short duration can be seen immediately after the initial peak and this may correspond to the expansion of the pressurised vapour to atmospheric pressure. The maximum overpressure of this second peak is about 5 mbar at 40 m, when the 20 ms rolling average is removed.

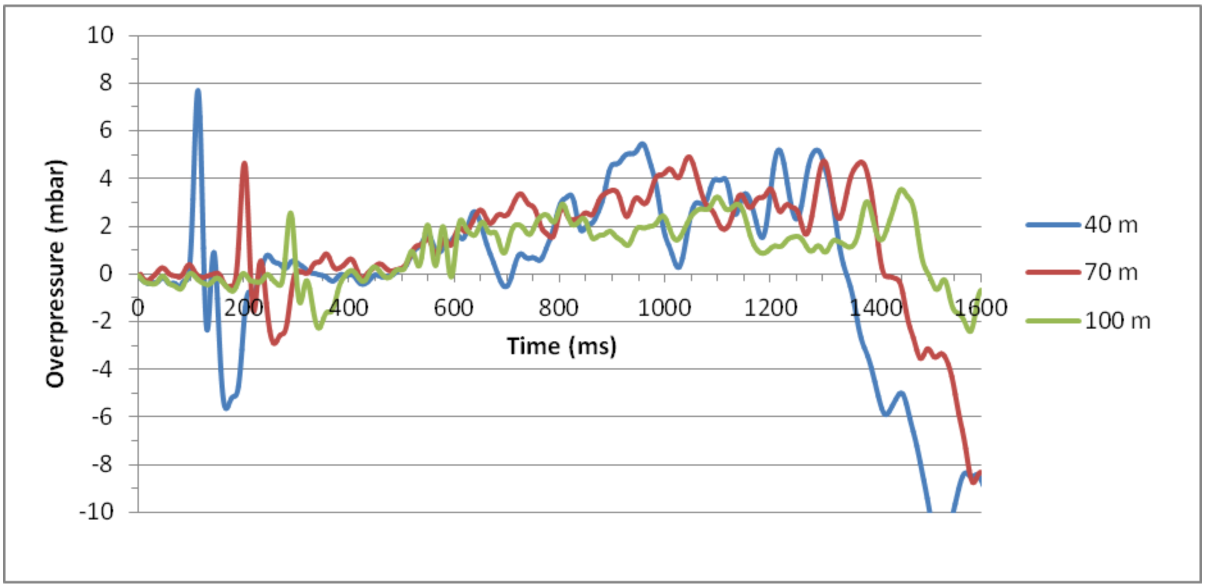

Figure 9: Overpressure measured at 3 locations during expt. 2. A 20 ms rolling average has been applied to clean the signal.

After 0.5 seconds, an overpressure corresponding to the combustion of the cloud can be seen. As expected, this has a much longer duration, representing the much slower combustion process compared with the initial rupture. The maximum overpressure of this combustion process is on average 5 mbar at 40 m, reducing to 3 mbar at 100 m. The duration of this impulse is longer than the equivalent combustion impulse in the LPG experiments, which is under 0.5 ms, but the actual value for the maximum overpressure (LPG Test5) is higher than those measured during these LNG experiments.

Conclusions

Shell has commissioned a series of large scale tests to characterise the thermal radiation and overpressure consequences should a pressurised LNG vessel fail catastrophically. These tests were designed to represent the typical and maximum design pressures that would be expected in normal operations at small scale LNG facilities, while at the same time enable a comparison to equivalent BLEVE tests using LPG that were completed in the early 90s. In these experiments, the credibility of a double skinned vessel to catastrophically fail was not investigated; instead single skinned pressurised vessels were used for all four tests to ensure that a catastrophic release could be initiated.

A BLEVE was successfully generated in each test, with physical characteristics, such as flashing liquid, expanding vapour cloud and a rising fireball, that have been seen previously in tests on other fluids. However the results for experiment 1, using the smaller 1 m^3 vessel, were only partially successful. This is because the crack generated by the explosive charge did not propagate to the vessel end caps, resulting in a directional rather than a hemispherical cloud. A second problem delayed the ignition by about three seconds and consequently only limited data could be recovered. In the three other tests, there was sufficient crack propagation along the vessel to ensure that the LNG was released instantly. Although in each case the resultant vapour cloud and fireball was not completely uniform, resulting in some asymmetry in the recorded results.

The consequences were compared to data recorded for the previous LPG tests and the following conclusions can be drawn:

- The diameter of the LNG fireball was found to be approximately 15% smaller than the fireball from a LPG BLEVE with equivalent mass. Therefore the commonly used relationship $D = 5.8M^{1/3}$ will over predict the fireball size and a better fit for LNG would be obtained using $D = 4.8M^{1/3}$.
- Measurements of the fireball duration show that LNG follows the same trend as the previous LPG experiments and the data lies between $4.5M^{1/3}$ and $9.0M^{1/3}$. This suggests that the fireball duration is controlled by the initial momentum process in these experiments.
- The expansion velocity was found to be smaller during both the initial flashing phase and the subsequent combustion expansion. This is reflected in smaller overpressures for the combustion phase compared to LPG. The overpressure results for the vessel burst phase were also lower than measured previously and were found to be smaller than the explosive charge used to rupture the vessels.
- The maximum LNG fireball height was found to have a consistent ratio to fireball diameter of 1.0 – 1.2 for all three experiments and hence was similar to the LPG tests.
- The SEP of the LNG fireball was calculated to be approximately 300 and 500 kW m^{-2} for the low and high pressure experiments respectively. This matches an equivalent relationship seen for LPG. However the SEPs for expts 2 and 4 were found to be significantly higher than the average LPG value of 350 kW m^{-2}.

- The thermal radiation of the LNG fireball was found to be 17 - 26 kW m^{-2} at 100 m and hence was similar to LPG (25 kW m^{-2}. While at shorter distances, the thermal radiation from LNG was found to be smaller than LPG.

Overall, these results show that using a LPG BLEVE model to predict the thermal radiation consequences of a LNG BLEVE will not generate overly conservative results. However, there are indications that the thermal radiation from a LNG BLEVE is smaller than LPG and further work is planned to extend the BLEVE model in FRED using these results. This will enable the hazards for a range of vessel sizes and conditions to be quantified and subsequently used to develop more accurate safety cases for the small scale LNG distribution business.

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