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Review

A summary of some experimental data on LNG safety

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Abstract

In a recent paper, Luketa-Hanlin reviewed the information in the public domain related to LNG safety. The purpose of this paper is to supplement that work by providing a summary of the experimental information that Advantica has collected on LNG behaviour over the course of the last 30 years. This summary includes previously unpublished information obtained as a result of a number of collaborative projects. Subjective comments are also made on the status of modelling for each of the topic areas and, in a discussion, views are provided on those areas where there are currently gaps that may have a major impact on evaluating the individual or societal risks associated with LNG operations.

Keywords: LNG behaviour; Experimental data; Risk assessment

Contents

1. Introduction

Studies on LNG behaviour have been undertaken by a number of organisations over a period of more than 40 years. The information in the public domain has been reviewed recently by

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Luketa-Hanlin [1]. Advantica has recently carried out a review of its own activities in this area on behalf of BP in order to help BP summarise the state of knowledge related to the hazards of LNG operations. This review considered previously unpublished material obtained by Advantica at its Test Site in the north of England. The purpose of this paper is to complement the work of Luketa-Hanlin, by providing a summary of the previously unpublished work. The status with regard to modelling each of the possible hazards is briefly addressed.

One of the main benefits of having carried out reviews of this nature is that areas where data is lacking or the behaviour is uncertain are highlighted. It is then necessary to decide on an appropriate course of action to take for each of these areas. One input that can be used to help make such decisions is to consider the impact of the uncertainties on the individual or societal risk posed by the LNG operations. Hence, the paper ends with a somewhat subjective view of those items that could have a potential major impact on risk and so are suitable topics for future work.

2. Experimental data

2.1. LNG outflow

The rate at which LNG is released from a storage container or pipe work is of critical importance in determining accurate estimates of the subsequent behaviour. The outflow of LNG from vessels and containers appears not to have been studied experimentally in its own right but as part of other projects investigating LNG vapour dispersion or pool spread, for example.

The factors that can influence the outflow rate include the following:

- the temperature and pressure of the LNG within the pipe work or vessel;
- the rate at which LNG is being transported within a pipe;
- the size and location of the hole;
- the orientation and layout of the pipe work and any vessels;
- the action taken in the event of spill detection.

The outflow will be larger if LNG is released in its liquid state. Under such conditions, significant flow rates can continue if LNG drains out of a vessel or hole in a pipe under gravity (for example, following valve closure or isolation of a storage vessel).

Advantica has obtained data for the outflow of pressurised LNG from small holes in pipe work or through pressure relief valves. The data covers a range of releases of up to about 75 mm in diameter at pressures of up to 70 bar. Flow from pipes connected to the base of storage vessels containing saturated or sub-cooled LNG has also been examined and the effect of an increase in the pipe length on the outflow has been examined. Cases of liquid outflow have been found, even for relatively long lengths of connecting pipe work between the vessel and the nozzle (5–10 m). This produces a higher outflow rate than might have been expected, for example, if the flow had been assumed to be homogeneous and in thermodynamic equilibrium.

Experimental studies have been undertaken to investigate the behaviour of the outflow from land-based storage tanks. The outflow of water into the atmosphere from a split at the base of large cylindrical tanks has been studied [2]. The outflow rate has been shown to be in agreement with the calculated, gravity-driven flow, based on the head of liquid inside the tank.

2.2. Liquid spread and boil-off

As the liquid LNG spreads on the underlying surface it covers more surface area. The larger the surface area covered, the more heat gained by the spreading LNG liquid from the underlying surface (water or land), and hence, the more vapour is produced.

The formation and spreading of the LNG liquid pool are influenced by many factors, as summarised in Ref. [3]. These factors include the following:

- the type, geometry, and conditions of the spill location/surface (land; soil, concrete, bunded or unconfined; open water; surface temperature; confinement);
- the composition and temperature of the LNG;
- the rate at which LNG is being released;
- the duration of the LNG spill;
- whether ignition occurs and, if so, where;
- the prevailing atmospheric conditions;
- spill control measures.

Experiments have been carried out to study the spreading of LNG spills on land or water (see [1,3]). Different series of small-scale studies has have been performed to measure the boil-off rates for LNG spills onto various surfaces including concrete, steel, wet or dry soil or clay and stones. Typically, measured initial boil-off rates (for the first 30 s) range from 0.15 to 2.0 kg m^{-2} s^{-1} for these surfaces [3]. However, care is required in interpreting some of the smaller scale work, involving spills of up to a few 100 l of LNG, as the boundary conditions may differ significantly from those that would be present in a real accident and also it may not provide a useful guide to behaviour in the later stages of the spill. Nevertheless, such results can be used to indicate the range of possible initial heat transfer rates, for example, and these can then be used in appropriate mathematical models to make predictions at the full-scale.

Advantica carried out two studies at field scale in 1984 and 1993 to investigate LNG spread velocities on land and water. Up to 1 m^3 of LNG was released instantaneously or LNG was released continuously at rates of up to 0.1 m^3 s^{-1}. A subsequent study in 1997 investigated the spreading of continuous horizontal releases of LNG driven by a pressure of up to 5 bar through a nozzle with a diameter of 75 mm situated close to the ground. These releases produced longer, narrower pools. Initial rates of the order of 2 and 1.5 m s^{-1} were measured for the radial spread of LNG produced by a continuous release onto concrete and onto water, respectively. The UK Health and Safety Executive funded a more recent study [2]. This used water as the test medium to assess spreading rates and the potential for overtopping to occur in the event of catastrophic tank failures within a bunded (or dyked) area. In these studies, carried out at a reduced scale that

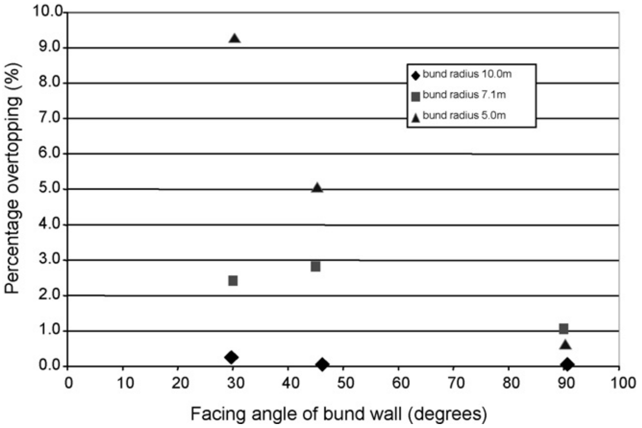

Fig. 1. Percentage of tank contents overtopping a retaining wall for releases into a circular bunded area, with the tank contents equivalent to 90% of the free volume of the bund.

was nominally 1 in 20, initial radial spreading rates of the order of 3 m s^{-1} were measured for releases from a narrow slot around the base of the tank. The amount overtopping the retaining bund depended on the shape of the retaining wall, the profile and height of the wall and the distance to the wall. However, some overtopping could occur even when the spilled volume was less than the capacity of the bunded area, as illustrated by the set of results reproduced in Fig. 1.

Further details are given in Ref. [2], along with results for other bund configurations. The Health and Safety Executive has subsequently funded more experimental and theoretical work in this area, including further smaller-scale experiments involving a wider range of release conditions [4].

2.3. Dense gas dispersion

The vapor that evolves from a spreading LNG pool on land or sea will evolve at the boiling point of LNG initially. As a result, its density will be in excess of that of the surrounding ambient air. The dispersion of such ‘dense gas’ clouds in the atmosphere is very different from that of neutrally buoyant (same density as the surrounding air) or positively buoyant (lighter than air) clouds, as entrainment rates of air through their upper surface may be reduced significantly by the stable density gradient that is formed. Further, if the gravity driven motions are large enough, such a dense gas can spread horizontally in an upwind, as well as downwind and crosswind direction.

A number of major programmes of field trials, such as the Shell Maplin Sands trials, the HSE Thorney Island trials, the LLNL–DOE, DOT, GRI and other agency sponsored tests programmes at the Nevada desert (such as the Burro, Coyote and Falcon trial series) and EU sponsored programmes (propane dispersion) have been conducted. Luketa-Hanlin [1] provides details of many of these programmes. Advantica has been involved in many specific wind tunnel (and water flume) studies in which dense gas behavior has been simulated. This has included studies of releases at a simulated LNG import terminal, complete with jetty and model of ship [5], and also studies of releases from storage tanks and export pipework at a model of an LNG peak shaving site. Such work was used to investigate the effects of obstacles, such as the storage tanks themselves (land), or the ship (sea), on the dispersion process. The results were in qualitative agreement with the findings of the Thorney Island trials, see, for example [6], or the later Falcon trial series [7]. However, it is acknowledged that there are many scaling issues related to the use of wind-tunnels (and water-flumes) and, in general, information from such small-scale studies should be regarded as indicative rather than definitive.

In one particular wind tunnel trial series, the ignitability of the dense gas cloud was examined. This test programme gave results that were in qualitative agreement with the findings of the Shell Maplin field trial series [8]. That is, a dispersing cloud could be ignited at its edges at locations where the mean concentration was below the lower flammable limit, due to turbulent fluctuations in concentration. Nevertheless, on the centerline, the cloud could only be ignited and light back to the source at locations where the mean concentration was above about 90% of the lower flammable limit concentration. Reservations about scaling issues in such experiments means that such findings are best viewed as providing qualitative support to the field trial information elsewhere in the literature.

2.4. Pressurised releases of LNG

As LNG is stored or transmitted through pipelines under pressure, there is a possibility that a small hole may lead to a continuous jetted release. Such a release may ‘flash’ within the pipework upstream of the release location or may expand rapidly immediately outside the orifice as the LNG relaxes to atmospheric pressure. The release process is likely to lead to the break up of the jet into droplets. In the experiments that have been performed at the Spadeadam Test Site, it has been observed that, for unobstructed releases, all of the LNG remains inside a directed jet, rather than raining out to form a spreading pool of the type discussed in Section 2.3. However, if obstacles are present in the path of the jet, then some of the LNG has been observed to rain out of the jet to produce a spreading pool on the ground nearby. If the releases are ignited then because of the higher velocity of the flow, just as for other hydrocarbon jet fires [9], the convective component can make a significant contribution to the overall thermal flux experienced by an object within the flame.

The factors that have appeared to influence the behaviour in the experiments performed to-date include the following:

1. the temperature and pressure of the release;
2. the size of the release;
3. the flow regime in any pipe work upstream of the release location;
4. the atmospheric conditions (wind speed and direction) and surrounding geometry (obstacles, surface type).

Two of the three previously unpublished experimental studies concerned unignited pressurised releases of LNG in either a horizontal, vertical or inclined direction. Fig. 2 shows

Fig. 2. LNG jet dispersion—horizontal release through a 10 mm nozzle shown.

an example of a release driven at a pressure of approximately 70 bar horizontally through a 10 mm diameter nozzle.

The mass release rate was determined and concentration measurements were made in the dispersing gas cloud. The horizontal tests showed that for pressures of between about 3.5 and 7 bar, the flammable zone may extend a considerable distance downstream, with concentrations of over 5% being measured 80 m downstream for the case of a mass flow rate of approximately 5 kg s^{-1}, released through a 25 mm diameter nozzle. LNG droplets were also detected within the dispersing plume at similar distances downstream. The elevated releases in a vertically upward direction were very wind affected and in low wind conditions the flammable cloud could descend to ground level. The LNG droplets did not ‘rain out’ of the flow close to the source however.

In the third study, the release was ignited and the hazards presented by a horizontal LNG jet fire assessed. Measurements were made of the flame length, shape and the thermal radiation. A flame length of typically 25 m was measured for a release rate of about 5 kg s^{-1}. Visually, the fires appeared to resemble a combination of a jet fire close to the source of the release producing a pool fire further downstream, with the latter portions of the fire being affected by the wind. The radiation that was measured in a nominally crosswind direction for one of the experiments is shown in Fig. 3. This experiment involved a horizontal release of approximately 4 kg s^{-1} through a 25 mm nozzle at a height of 1.3 m above the ground from a storage pressure of 7 bar and temperature of −151 °C. The wind was blowing in the same direction as the release at a relatively low speed.

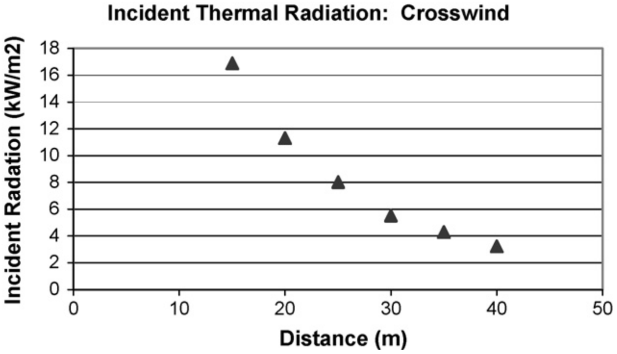

Fig. 3. Thermal radiation received in a cross-wind direction at different distances from an LNG jet fire.

2.5. LNG pool fires

If a liquid pool of LNG is created and not ignited immediately, the pool will start to boil as a result of heat transfer from the underlying surface. The vapours present at the LNG liquid pool surface are in equilibrium with the liquid LNG on the liquid surface. If these vapours are ignited, the flame will also radiate to the pool surface and provide additional energy for vaporization. Whether this contribution dominates depends on the size of the fire and the nature of the underlying surface. For example, the contribution from the radiation will dominate for a pool fire of LNG in a bunded area having an underlying surface of low-density concrete.

If ignition of a liquid release is immediate, the ignited pool will spread less than an unignited pool. If ignition occurs at a later time in the spill, the maximum pool spread may well be limited by the pool size at the time of ignition. As a result, early ignition may produce a smaller fire that lasts longer, whereas late ignition may produce a larger fire that lasts for a shorter time. Which of these is the ‘worst’ depends on the location of the surrounding people and the action they take as the pool spreads.

Advantica has carried out numerous investigations into pool fires over the years [10–14]. Data have been collated on the thermal characteristics of these fires. Almost all of the pool fire field trials have provided data on the flame emissive power and the liquid burning rates.

One particular series of co-funded, collaborative experiments in which Advantica participated took place in Montoir, France and represents the largest LNG pool fire field trial on land that has been reported to-date [12]. A maximum flame emissive power of 300 kW m^{-2} and an average burning rate of 0.14 kg m^{-2} s^{-1} were reported. The three tests were carried out on a 35 m diameter pool. The total quantity of LNG that was used in each test was up to 238 m^3, with long test durations (up to 235 min).

In general, it has been observed in all of the experiments that the pool fires are affected by the wind and can be influenced by the shape of any surrounding bund. The surface emissive power tends to increase with size of the pool and maximum local values up to about 300 kW m^{-2} have been measured. However, significant smoke shielding was observed in the largest tests. The behaviour of tank roof fires was also examined at a reduced scale in a container with a diameter of 10.6 m and height of 3 m. At high wind speeds, it was found that the flame could be drawn down into the recirculating region in the wake of the tank (or high-walled bund), as shown in Fig. 4.

2.6. LNG vapour cloud explosions

Particular conditions that must be realised in order for an LNG vapour cloud to produce an explosion. In an otherwise empty, confined volume, once a flame is generated, the products

Fig. 4. Tank roof fire (or fire in high-walled bund), during high wind speed conditions.

of combustion are hot and occupy a larger volume than the original mixture. If the rate at which combustion products are being generated exceeds the rate at which the products or mixture are being expelled through available openings or vents in the enclosure, the pressure will rise and a damaging overpressure can be produced in what is referred to as a 'confined' explosion. The pressure rise can be sufficient to cause the enclosure itself, or at least the more vulnerable parts of it, to fail catastrophically. This may also lead to an external vented explosion, in which the flame propagates out of the enclosure at a significant speed into a highly turbulent mixture that has been expelled earlier in the combustion process, producing a further 'external' explosion extending the effects of the original incident outside of the confined volume.

On the other hand, if the gas cloud is unconfined the products behind the flame front will expand more freely and will generate an outward flow ahead of the flame. The speed of this flow will be small initially if ignition is from a low energy source, but if the flame front encounters an obstacle, the flame area will increase in its wake and also the turbulence present in the wake of the obstacle will increase the local burning rate of the flame. Both of these factors combine to produce a higher rate of combustion at the flame front and more products behind the flame, which then push the flow ahead of the flame to a greater extent. This can produce a positive feedback mechanism should the flame encounter repeated obstacles, producing successively higher speeds of flame with associated high levels of overpressure in a 'congested' explosion. Particularly severe explosions may result if the congested region is also partially confined, as both of the above mechanisms come into play.

It is at this point that the properties of LNG vapour are important. Methane is normally the main constituent of the vapour and methane is the least reactive of the common hydrocarbon fuels. It has a lower burning velocity, a tendency to undergo flame quenching at high turbulence levels and a large detonation cell size. Fundamental work in establishing the flammability limits, detonability limits and flame speeds of natural gas and other fuels has appeared in the academic literature. Work of a more pragmatic nature by Advantica, Shell and TNO in Europe and the research work in USA and Canada identified the importance of congestion in generating turbulence and high flame speeds (see Luketa-Hanlin [1], for further details of the openly published work and Refs. [15–17], for the earlier work by Advantica).

Advantica found during explosion experiments in large congested regions that venting of the combustion products from behind the flame balances their rate of production at the flame front and the forward speed of the flame so that an approximate equilibrium can be reached within a large enough congested region. The equilibrium speed that was measured for natural gas explosions was typically 100–200 $\mathrm{m\,s^{-1}}$, although an average limiting speed of about 500 $\mathrm{m\,s^{-1}}$ was observed in the worst case [15]. Transition to detonation has not been observed, despite these high speeds and compressible nature of the flow. Therefore, once the flames leave the congested region, they are observed to decelerate rapidly, with a result that it is only the portion of the cloud that overlaps the congested region that contributes to the generation of significant overpressure. This is in marked contrast to fuels such as ethylene, propane or cyclohexane—all of which have been observed to undergo a transition to detonation in congested explosions. Such transitions have been observed in experiments involving these fuels in which deflagration flame speeds in excess of about 250 $\mathrm{m\,s^{-1}}$ and overpressures of above about 1 bar have been produced. It is postulated that, under these conditions, the reflections of shock waves from obstacles and the ground can produce a transition to detonation at the flame front. This is then a self-sustaining mode of combustion, in that the compression of the flow ahead of the flame is sufficient to auto-ignite the mixture just ahead of the flame and the flame front and shock front become linked. Once fully initiated, such flames continue to propagate through clouds having concentrations in the detonable range, irrespective of whether congestion is present or not. Hence, in unfavourable circumstances, there is the potential for more of these clouds to contribute to the pressure generation, extending the hazard range. Such detonations have been observed in experiments at a large scale to travel at speeds of typically 2000 $\mathrm{m\,s^{-1}}$, with associated shock loading to the surroundings.

The factors that would influence the severity of the explosion include the following:

(1) the concentration and composition of the gas within the mixture;
(2) the amount and type of any congestion present (size, orientation);
(3) the amount and type of confinement present (size, failure pressure);
(4) nature of the ignition source;
(5) size of the cloud.

Factors such as the volume blockage and size of the obstacles within the congested region were identified as important parameters in congested explosions. In particular, two European Union (EU) funded projects (MERGE and EMERGE), involving experimental work by TNO, Shell and Advantica, provided extensive data on this aspect [18,19] including information on

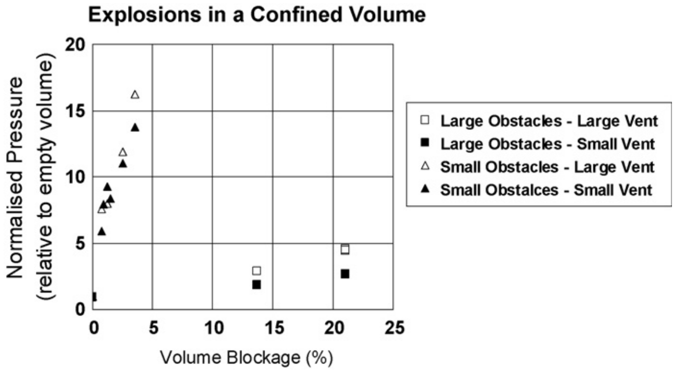

Fig. 5. Results demonstrating the sensitivity of the overpressures that are generated to the type of obstacles within the enclosure.

the behaviour of different fuels and also the effect so initial turbulence on the evolution of explosions.

More recent work by Advantica has included studies to see the effect of a range of obstacle sizes on the overpressures (see [20], for an overview of the experimental programme). In one set of experiments, an enclosed volume was fitted with a low failure pressure panel fitted in one face to provide explosion relief. Obstacles of different sizes and type were placed inside the enclosure and the pressure that was generated as a result of the ignition of stoichiometric natural gas–air mixtures inside the enclosure was measured. It was found that the overpressure levels generated inside the enclosure were sensitive to the nature and location of obstacles within it, with a small number of large obstacles resulting in significantly lower pressures than a large number of small obstacles providing equivalent volume blockage, as demonstrated in the graph in Fig. 5.

2.7. Rapid phase transitions

When LNG is spilled on land or water, LNG is initially very cold (say 110 K). The spill surface (land or water) is initially very hot compared to the temperature of LNG, with the initial difference between the LNG and the water surface being of the order of 175 K.

This high temperature difference causes the LNG to start boiling. Because the difference in temperature is so high initially, a vapor film is formed between the LNG and the underlying spill surface. As long as, the vapor film exists between the LNG and the spill surface, heat transfer is greatly reduced. However, if the vapour film is disrupted, a transition to a different (faster) heat transfer mode of nucleate boiling can begin. As a result, the LNG is heated very rapidly and a rapid phase transition (RPT) can occur.

IoMosaic has provide a more detailed explanation and proposal for modeling such behaviour on their web site, along with a comprehensive summary of the openly available experiments in this area [21]. The majority of the experimental studies undertaken by Advantica were performed as part of three collaborative projects. The other partners in the collaboration, including Gaz de France and Statoil, also carried out extensive studies. Only the openly published results are referred to here (see [22,23]).

In general, it was found that irrespective of the experimental procedure, the resulting overpressures are very variable. RPTs do not always occur in apparently identical experiments and the severity of the RPTs is not the same, with different fractions of the LNG being involved in the RPT. When pools of LNG are formed on water, an RPT appears to be more likely when there is some turbulence or mixing of the LNG/water interface. The propagation speed of RPTs through a pool of LNG was determined and found to be of the order of 240 m s^{-1}.

During the collaborative projects, liquid nitrogen (LN) was jetted into water and measurements of the mixing region made. The depth of penetration of the jet was oscillatory in nature. Further tests in which LNG was released from a pressurised container vertically downwards to impact on the water surface showed that, in this case, RPTs tended to occur within the spreading pool rather than within the jet-mixing region. Once again, the severity of the RPTs was found to be variable and, as has been observed by others earlier, RPTs are significantly more likely with ‘aged’ LNG where the methane concentration is lower (see, for example, the discussion by IoMosaic on the effects of LNG aging).

2.8. Rollover

LNG rollover can occur if a stratified layer within an LNG storage tank breaks down and allows the relatively hot LNG from the lower parts of the tank to come to the surface, liberating large quantities of vapour. The most usual way in which a stratified layer is produced is through filling. If the filling operation does not intimately mix the new cargo with the heel (residual LNG in the tank), the LNG could stratify into two distinct layers. Once formed, the apparently stable interface restricts the transfer of heat and mass from the lower layer to the upper surface. As a result, heat absorbed by the heel partly accumulates there. Eventually, the density of the heel can be reduced to the extent that the interface destabilises. The breakdown of stratification results in a rapid mixing of the two layers, a dramatic increase in vapour evolution rates, and a potentially hazardous rise in tank pressure. The main hazard arising out of a rollover incident is the rapid release of large amounts of vapor and, if the venting system is not adequate, possible damage to the storage tank.

A number of Advantica’s experimental studies have been published in the open literature. In the experiments reported in Ref. [24], different fluids were used to simulate the layers that could be formed. Measurements include details of the initial compositions and size of the layers and how the interface evolves in time. A number of rollover incidents also provide information on how stratified layers evolve and the vapour generated by rollover.

3. Modelling issues

3.1. LNG outflow

The outflow of LNG from a small hole in a vessel or in pipe work into free air can be predicted using relatively simple methods. For example, considering the experiments referred to in

Sections 2.1 and 2.4, Bernoulli's relationships has been used successfully to predict the liquid outflow rate for the experiments in which flashing within the pipe does not occur and the homogeneous equilibrium outflow model has been used for cases involving two-phase outflow.

One area of uncertainty is the chain of events that might occur following the creation of a hole in an LNG ship at or below the water line. Pitblado et al. [25], address this situation in their paper and provide some predictions for the outflow from a hole below the waterline of an LNG tanker. In general, if the inner and outer containment of the LNG tank and ship are both breached there is a possibility initially that opposing jets of LNG and water may interacting in the ballast space inside the ship. Once the level within the ballast space is equalised with the water outside, there is now a possibility of an exchange flow with the denser water following into the LNG tank and the LNG flowing out into the sea. However, as the LNG comes into contact with ambient temperature seawater, there will be some heat exchange and vaporisation of the LNG. This may cause the pressure to rise within the ballast space or the LNG tank to such an extent that the inflow may be temporarily halted. It is possible that an unstable flow may be set up, with alternate entry of water and pressurisation within the LNG tank. Three may also be the risk of a rapid phase transition occurring. This is an area where more data would be useful, as it could have a direct impact on the duration and amount of material that is released, compared to the simpler approaches in which it is assumed that the LNG is released directly into the atmosphere, for example.

3.2. Liquid spread and boil-off

The main technical uncertainties for LNG pool spread relate to the dynamic relationship at the front of the spreading pool and the heat transfer rate to apply for spread on water. A shallow-water model was developed by Cambridge Environmental Research Consultants [26], that is able to model such flows and incorporate additional factors such as the formation of bubbles within the LNG. Simpler box models and correlations are also available, see, for example [1,25]. Most models assume film boiling occurs for spills on water and postulate a fixed heat transfer rate from the underlying water. This is reasonable in deep water, when the convection currents set up in the water ensure that the surface of the water is maintained at an approximately constant temperature and ice formation does not occur. Such values can be used to infer a steady-state pool size for continuous spills of LNG at a constant rate. However, as Luketa-Hanlin noted [1], the influence of waves on the front of a spreading pool introduces some uncertainty. Also, currents may be important for long duration events as they have the potential to extend the range that is affected by a release.

3.3. Dense gas dispersion

In parallel with the various field programmes, many different models for dense gas dispersion have been produced, ranging from the initial 'box' models through the phenomenological or similarity models to the complex, three dimensional computational fluid dynamics (CFD) models. Given this wealth of information, there has been no shortage of model validation exercises both in Europe, sponsored by the European Union, or in the USA, in collaboration with the EPA. As a result of this, there appears to be a degree of consensus that the better of the more, practical models (box or similarity models) should be within a factor of 2 of the observed concentrations for a straight-forward situation within the bounds covered by the experimental data (see, Hanna et al. [27] in the USA and Daish et al. in Europe [28]).

The issues that are raised from time to time as requiring more information or study include the effects of surface roughness and site obstacles, the formation of a vapour 'blanket' over a spreading pool, heat transfer effects and the transition to passive behaviour. Specific aspects that are relevant to dispersion from a liquid pool on the sea are the effects of the large LNG ship itself on the dispersion, heat transfer from the sea to the vapour cloud and the atmospheric stability that is appropriate in coastal or inland waters. It would require considerable expenditure on field trials to provide evidence to improve modelling significantly in this area.

3.4. Pressurised releases of LNG

The results obtained in the experiments referred to in Section 2.4 are useful for checking the calculation of the LNG outflow rate and also the subsequent jetting behaviour in the near field. The experiments demonstrate that rainout of liquid droplets does not occur directly under the release location for an unimpeded release and this observation has been used to help define the initial conditions for use in a jet dispersion model. Another use of the data is to study how the impact of the release on the ground or a nearby obstacle influences the dispersion. This data complements the experimental information available from many other sources for the dispersion of low momentum releases of LNG vapour (e.g., vapour clouds produced by spreading pools, such as studied in the Shell Maplin Sands field trials). The data can also be use to test the validity of two-phase jet dispersion models, such as those referred to by Witlox [29], for example.

3.5. LNG pool fires

LNG pool fires have been studied extensively. The technical issues that arise in modelling large LNG pool fires on water arise mainly through the potential scale of the fire. It is beyond the database for empirical models and this immediately introduces some uncertainty. It could be argued that this is no different to the situation for LNG vapour dispersion where the largest experiments performed to-date relate to dispersion distances of the order of 400 m. However, in the case of LNG vapour dispersion, there are no underlying physical reasons that preclude the use of physically based or similarity models to larger releases. In contrast, oxygen starvation in the centre of pool fires, smoke generation and a possible reduction in the emissive power of the larger fires are physical phenomena that have been suggested become progressively more important in larger pool fires. Hence, extrapolation from results of smaller pool fires may be misleading, although such errors are more likely to result in some degree of overestimation of the hazard from a specific pool fire.

3.6. LNG vapour cloud explosions

The MERGE/EMERGE data referred to above has been used to help derive a number of different simpler, phenomenological models or correlations to predict overpressures in congested explosions. For example, TNO have developed one such model in the GAMES project [30]. Advantica has fitted a correlation to the MERGE data for use in the phenomenological model, linking the flame speed to the pressure generation through a simplified form of the fluid flow equation (see [31,32]).

Data from experiments on piperacks was used to define a similar correlation for flame speed for planar propagation along the axis of a piperack. The realistic geometry data was used to derive a method for mapping the 'real' obstacle geometry, containing a range of size and direction of obstructions, onto its equivalent idealised case. This then enabled the correlations for flame speed to be used and hence a prediction for the associated overpressure to be obtained. The effect of one or two perimeter walls was included by changes to the phenomenological model and the flame speed correlation [20].

Other modellers have adopted a more sophisticated approach, including the development of computational fluid dynamic models, such as FLACS [33]. Such approaches have the potential to provide more detail for specific cases and can provide detailed information on the load received by key structures or buildings, for use with finite element response models, for example.

Correlations and simple models have been produced by many authors for predicting the overpressures generated in explosions in empty, confined volumes. The data that Advantica has collected was used to extend one such model [34], by including a correlation for the flame speed enhancement factor, attributable to the obstacles. This type of approach is only valid for relatively low flame speed cases, where the pressure developed within the confined enclosure is approximately uniform. This is in contrast to the case of explosions in regions that are both significantly confined and congested. In this latter case there is a need to consider pressure generation by confinement of the products and through the inertia of the flame together. This situation has been studied extensively in the context of safety studies for offshore gas or oil production facilities and appropriate models, including CFD models, have been developed for this situation (see [35], for example).

One uncertainty in the application of any of the models is the simplification required in order to represent a real distribution of obstacles by a small number of parameters. Calculations with computational fluid dynamic models may allow many of these obstacles to be represented directly in the calculations, although uncertainties may still arise from issues such as grid resolution and the degree of empiricism in any subgrid model that is applied for a real case. A similar source of uncertainty is the representation of non-homogeneous mixtures in explosion calculations and the link to the inventories and overpressures produced by realistic releases.

3.7. Rapid phase transitions

The participants in the collaborative project reported above have used the data to develop predictive models for RPTs. For example, Advantica produced an empirical model for the pressure generated by the occurrence of an RPT, following a release of LNG onto water. The current model does not attempt to quantify the likelihood of the RPT occurring, although the data could be used to investigate this in a more probabilistic assessment. Gaz de France and Statoil have worked to produce a CFD type of model for RPTs. In the literature, IoMosaic have shown that its also possible to link an RPT model to a liquid pool spread model to provide a method for predicting if conditions can be reached in which an RPT can occur (see [21], for an example).

It is noted that if an event does occur in close proximity to, or within, the ship, it is possible that the water born pressure wave experienced in the immediate neighbourhood of the event may be significant. Detailed finite element calculation can be used to indicate whether a single RPT event may have the strength to cause further damage to a ship's outer structure and lead to escalation of an event. There may be a need to extend such studies to examine the further response of the inner LNG tanks in detail.

3.8. Rollover

Simple models based on heat and mass balances, including tracking of compositional variations and densities, allow both the prediction of the approximate time until rollover occurs and the total amount of vapor that will be released in the rollover [36]. The dimensions and initial compositions of the two layers need to be determined as a starting point. The heat leak through the tank insulation into each layer is an important parameter, driving the process, and this may be different for the sides of the tank and the bottom of the tank, or may vary with location in the case of certain novel designs of tanks. Criteria taken from studies of mixing in stratified layers in the oceans can be used to determine when the layer erodes as the layer densities get close to each other. Some more recent models include a second phase during which the layers move, due to penetrative convection as the fluid from the lower layer partially mixes with the upper layer to weaken the interface. Alternatively, more complex CFD or finite element type of models have been applied in order to simulate in more detail the convective motions within the tank and their interaction with any density interface [37].

4. Discussion and conclusions

The experimental work carried out by Advantica on LNG related issues has been summarised in this paper. Because much of this information has not been published previously, this supplements the more comprehensive literature review provided by Luketa-Hanlin [1]. Subjective comments have also been made on the modelling of each of the areas addressed in the paper. Whilst this shows that there may still be areas in which large-scale data is in short supply or even lacking, it is argued here that the uncertainty in prediction should be a major factor in determining the need for future work. If the effects of the uncertainty in a topic do not significantly influence the level of risk calculated for a facility, then it is suggested that such a topic should be of lower priority. Conversely, if the risks are particularly sensitive to a poorly understood phenomenon then this should be investigated as a matter of some urgency.

With this in mind, it is suggested that the behaviour immediately after any breach of the inner tank of an LNG ship would repay closer attention, as would RPT behaviour. Both of these have the potential to alter the course of an event and hence the individual and societal risks that follow from it. Conversely, the effort required to achieve an improvement in predictive capability to determine the maximum possible dispersion distance from an LNG ship spill in unfavourable weather may not represent a cost effective use of resources. Although, the latter may provide a 'headline' value for the maximum possible hazard range, it is of such low frequency (combination of the initiating event, coincident weather conditions and ignition at exactly the time that the maximum hazard distance is reached) to accept the current degree of uncertainty in the prediction of a numerical measure of the resulting risk. Adopting this pragmatic, risk-based approach to deciding in the areas for future study is likely to produce a different ranking to one based on uncertainties in the consequence modelling. At the very least, it should be one input into the decision process for determining the course of future studies on the individual and societal risks that the LNG facilities pose.

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