Investigation of Cargo Tank Vent Fires on the GP3 FPSO, Part 1: Identification of Ignition Mechanisms and Analysis of Material Ejected from the Flare

Mark Pursell*, Simon Gant, Andrew Newton, Darrell Bennett, Louise O'Sullivan and Philip Hooker, Health and Safety Laboratory, Harpur Hill, Buxton, SK17 9JN, UK

David Piper, Maersk Oil North Sea UK Limited, Maersk House, Crawpeel Road, Altens, Aberdeen AB12 3LG

* Corresponding author: mark.pursell@hsl.gsi.gov.uk, 01298 218564

Maersk Oil operates the Global Producer III (GP3) Floating Production, Storage and Offloading (FPSO) vessel in the North Sea. During the course of normal operation, when crude oil is loaded into cargo tanks on the vessel, vapour in the ullage space is vented to the atmosphere. The outlet from the cargo tank vent pipe discharges the vapour part-way up the flare tower of the GP3, approximately 30 m above the deck level and 18 m below the flare.

Since April 2010, there have been four separate incidents where the vapour released from the cargo tank vent has ignited. In each case, the cause of the ignition has been unclear. To investigate the cause of these ignition incidents, Maersk Oil commissioned a programme of work at the Health and Safety Laboratory (HSL) in June 2013.

This paper describes the initial phase of the investigation work in which possible ignition mechanisms were identified. Results are then presented from a series of HSL experiments to assess whether burning droplets or hot particles falling from the flare could have ignited the cargo vent gas cloud. A companion Hazards 26 paper (Part 2) presents further analysis of vapour dispersion on the GP3 to assess whether the ignition incidents were caused by flammable vapour being drawn into the flare.

Keywords: FPSO, cargo vent, vapour cloud, ignition, experiments, burning droplets

Introduction

Maersk Oil operates the Global Producer III (GP3), a floating production, storage and offloading (FPSO) vessel, used to process and handle the oil and gas obtained from the Dumbarton, Lochranza and Balloch fields. During the course of normal operation the GP3 FPSO stores crude oil in the vessel's cargo tanks. To mitigate against the formation of a flammable atmosphere, the cargo tanks are purged with an inert gas. As crude oil is added to the tank, evaporation causes the quantity of hydrocarbon present in the vapour space to increase and due to compression of the vapour space, the overall pressure also increases. The cargo tanks are connected to a vent pipe system such that when the pressure inside the tank reaches a set point the vapour space is vented to atmosphere to relieve the pressure. In doing so, a mixture of inert and hydrocarbon compounds is released to atmosphere which upon mixing with air may form a flammable mixture.

Since April 2010, there have been four separate incidents where the vapour released from the cargo vent has ignited. In each case, the cause of the ignition has been unclear. In June 2013 Maersk Oil commissioned a programme of work with the Health and Safety Laboratory (HSL) to investigate possible causes of the ignition incidents. This paper and a companion paper presented at the Hazards 26 Conference by Gant *et al*. (2016) report the findings from this programme.

The present paper is organised as follows: the cargo vent ignition incidents are summarised followed by an overview of the initial investigation conducted by HSL that identified a number of feasible ignition mechanisms. The paper then proceeds to focus on one particular mechanism: ignition via burning droplets or hot objects ejected from the flare. The initial assessment work in relation to this mechanism is summarised and then a series of experiments are described that were undertaken to confirm whether or not this mechanism is feasible. The paper concludes with a summary of the findings relating to this ignition mechanism.

Background to Ignition Incidents

A picture of the GP3 is shown in Figure 1 which identifies the location of the cargo vent, part way up the FPSO flare tower. The flare tower rises 61 m above the ship's water line, with the flare tip assembly protruding a further 3 m, giving an overall flare height of 64 m. The cargo vent, which is a 150 mm diameter pipe, protrudes laterally 4 m outwards from the flare tower and is located approximately 18 m below the flare tip.

In the first ignition incident, the vapour ignited and continued to burn for around 23 minutes. A number of modifications to the vent pipe outlet were made following this incident, including installation of thermocouples at the vent exit (to detect fire), an associated trip to shutdown the plant and close the cargo tank vent control valve, and installation of a nitrogen snuffing system. Whilst these mitigate measures have been effective at minimising the duration of the fires in subsequent events, the cause of each ignition remains unknown.

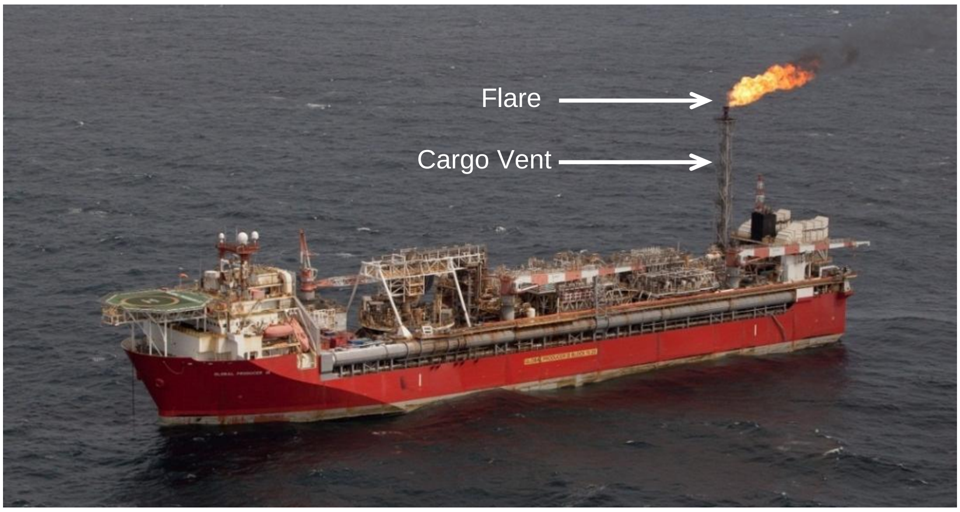
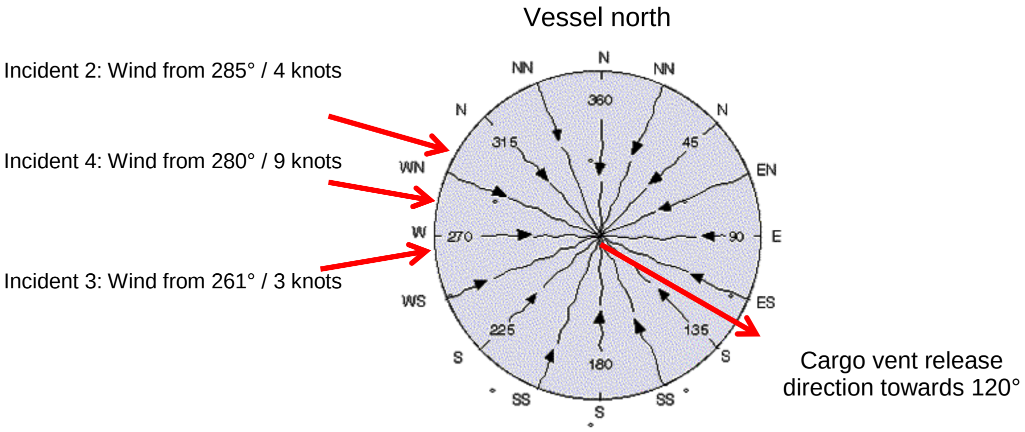


Figure 1 Location of the flare and the cargo vent on GP3 (Copyright: Maersk Oil)

Details of the wind direction and wind speed in the three subsequent ignition incidents are summarised schematically in Figure 2 (the specific conditions during Incident 1 were not well documented). A feature that was common to Incidents 1, 2 and 3 is that they all occurred in calm wind conditions. However, the most recent incident (Incident 4) was initially reported to be in a higher wind speed of 9 knots. During Incidents 2, 3 and 4 the wind direction was blowing in a similar direction to the vapour being discharged from the cargo vent pipe (Figure 2). The flames from the flare would therefore have been tilted over by the wind so that they were above the cargo vent outlet. This is an important observation with respect to the potential for droplets of burning liquid to have fallen from the flare through the vapour cloud from the cargo vent.


Vessel north

Incident 2: Wind from 285° / 4 knots

Incident 4: Wind from 280° / 9 knots

Incident 3: Wind from 261° / 3 knots

Cargo vent release direction towards 120°

Figure 2 Summary of wind speed and directions during cargo vent ignition Incident 2, 3 and 4

Assessment of Ignition Mechanisms

In 2013, Maersk Oil commissioned HSL to conduct an investigation into the potential credible ignition sources that could exist on GP3. Initially six possible mechanisms were identified, although two were quickly discounted: ignition via an electrical spark and ignition via radiation from the flare. The first of these should be controlled by suitable area classification and on-going testing, assessment and maintenance activities as part of Maersk's safety management procedures. Ignition via radiation from the flare was deemed not to be credible since the amount of thermal radiation absorbed by the gas cloud would be too low to lead to auto-ignition. The remaining four ignition mechanisms (summarised in Figure 3) were considered further.

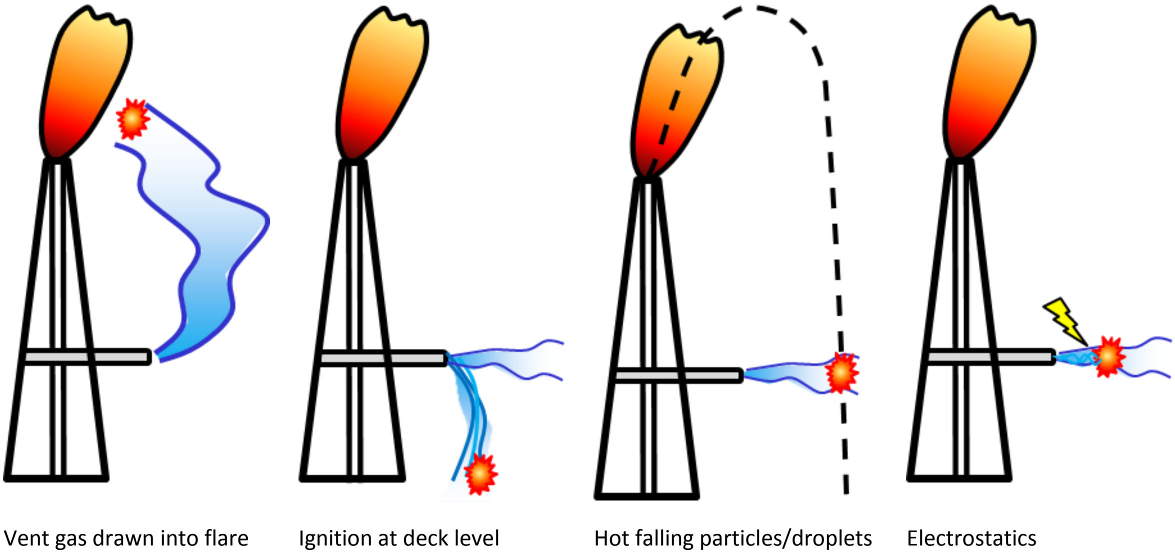


Figure 3 Summary of the four main ignition mechanisms that were investigated

In the first ignition mechanism, flammable gas from the cargo vent is drawn up into the flare. This had previously been investigated using Computational Fluid Dynamics (CFD) modelling by engineering consultants working for Maersk, and further CFD modelling was conducted by HSL. The model predictions showed that the flow behaviour was very complex. Heat sources, exhaust outlets and the flare all affected the flow behaviour in low wind speeds. It was considered likely that the dispersion behaviour could also be affected by small gusts of wind and local air currents, which were not well accounted for by the CFD model (which only simulated the mean flow behaviour). For these reasons, it was deemed necessary to investigate the dispersion behaviour using a combination of indoor and outdoor reduced-scale physical experiments and further CFD modelling. Details of this work can be found in the companion paper (Gant *et al*., 2016). The work concluded that whilst it was unlikely that the vent gases could be ignited by the flare, the possibility could not be completely discounted.

In the second ignition mechanism, flammable liquid released from the cargo vent is ignited at deck level and the flames burn back to the vent outlet. It had been observed on the GP3 that liquid was sometimes released through the cargo vent pipe during venting. Videos taken on the GP3 showed on some occasions a constant flow of liquid leaving the end of the vent pipe and oil droplets on the surface of the sea, close to the GP3, where the liquid stream hit the water. Calculations performed by HSL indicated that this liquid was probably produced by condensation of the hydrocarbon vapour within the vent line. Since it had been demonstrated that the liquid could rain-out onto the sea, it therefore seemed possible that the liquid could rain-out on the deck of the GP3 near the flare tower in a different wind direction. If this rained-out liquid came into contact with a hot surface close to its auto-ignition temperature, it seemed feasible that the liquid could vaporise and ignite. In 2014, Maersk undertook remedial work to insulate and trace heat the vent pipe to prevent any condensation and liquid rain-out. This second ignition mechanism was therefore not studied any further.

The third ignition mechanism involves hot particles or burning droplets ejected from the flare falling through the flammable gas cloud from the cargo vent and causing an ignition. There had been some mixed reports from the GP3 of liquid traces on the deck that may have emanated from the flare. There were also concerns that small metal fragments from the flare assembly could detach and pass through, and be heated by, the flare itself before falling towards the cargo vent gas cloud. Further analysis of this mechanism was undertaken, initially through a theoretical consideration of the relevant physical factors and then subsequently through a series of experiments. Full details of this research are given below.

The fourth ignition mechanism is for the vapour cloud to be ignited by an electrostatic discharge. This had been investigated previously by an engineering consultant and further “order of magnitude” calculations were performed by HSL. Brush discharges from an insulating liquid slug could not be ruled out by a worst-case analysis but the likelihood of this as a credible ignition mechanism was rated as minimal. All other electrostatic ignition methods were considered as either not feasible or as having a negligible likelihood providing that standard electrical bonding was in place.

Hot Particle Ignition Mechanism

Ignition Mechanism

In this ignition scenario, shown schematically in Figure 4, a particle (either liquid or solid) is ejected through the flare where it may be ignited or heated to a temperature approaching that of the flare (up to ca. 900 °C to 1200 °C). Upon leaving the flare, the object falls under the influence of gravity (and the prevailing wind) towards the region where the cargo vent vapours are released. If the object is either hot enough or still burning when it reaches this region, then it may ignite the cargo vent vapours if a flammable mixture is encountered. For ignition to occur, the particle must:

1. be projected into the flammable region of the released vapour;
2. have sufficient heat to be able to ignite the flammable mixture;
3. be resident in the vapour for long enough to initiate ignition; and
4. transfer sufficient energy to a flammable mixture for a stable ignition kernel to be formed.

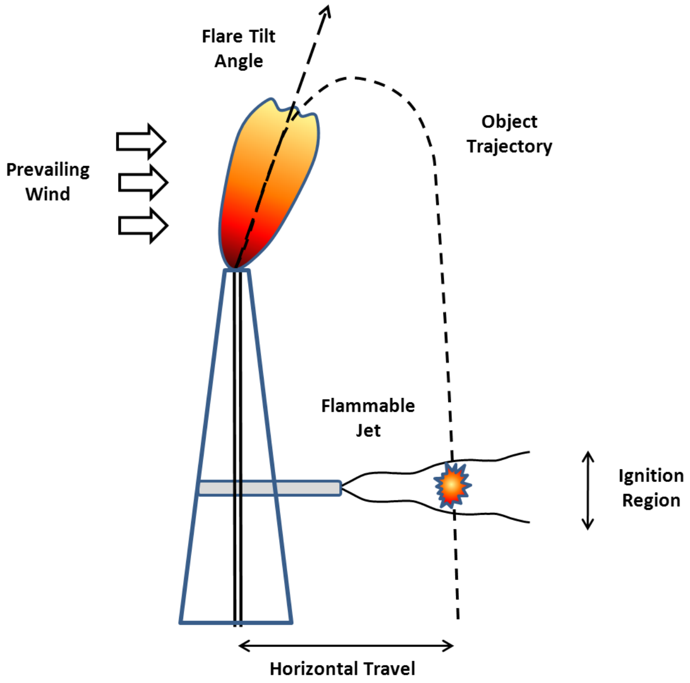


Figure 4 Schematic of Mechanism 3: Ignition of the GP3 cargo vent via hot or burning objects ejected from the flare

Initial Assessment

To determine the feasibility of this ignition mechanism, a search of relevant literature was performed and the main physical processes were analysed using simple models. Each of the four criteria identified above was assessed and it was concluded that:

- Objects ejected under low wind speed conditions or where the initial release direction is close to vertical will fall within the flammable region; furthermore all objects with low initial velocities will fall within a flammable region.

- Large liquid droplets are likely to break up due to aerodynamic forces and the maximum stable droplet size for lightweight hydrocarbons will be in the region of 3 mm in diameter.
- It is uncertain how a small burning droplet would behave during free fall i.e. would the flame be extinguished?
- A falling burning liquid droplet could transfer sufficient energy to a flammable mixture to create a stable ignition kernel, but the convective energy losses due to the cross flow of the cargo vent vapour plume may prevent stable kernel formation.
- The ignition behaviour of a burning solid particle will be similar to burning droplets.
- The ignition of flammable mixtures by hot solid particles requires the particle temperature to exceed the auto-ignition temperature of the vented gases.
- The temperature of a smouldering solid may be insufficient to ignite a flammable gas mixture.

The initial assessment demonstrated using simplified models that it is feasible for objects ejected from the flare to fall through a region of flammable gas, and that sufficient energy may be transferred from burning objects to the gas to produce an ignition kernel. However, uncertainties remained that related to the combustion process, droplet break-up and heat losses.

Based on these findings, experiments were carried out to determine whether or not it was feasible for a hot or burning particle to ignite a flammable gas jet under conditions comparable to GP3. Specifically, the test series had the following objectives:

1. To visualise the behaviour of burning liquid droplets during free fall.
2. To assess whether a burning liquid drop could ignite flammable gas.
3. To assess whether a single liquid droplet could remain ignited over a drop height of a magnitude comparable to the GP3.
4. To examine whether the presence of condensed flammable liquids in the cargo vent gas cloud would affect the ignition potential of flammable gas.
5. To assess the potential for a hot or burning solid to ignite a flammable gas jet.

Experimental Design

The behaviour of hot or burning particles was examined using a bespoke experimental rig that utilised a temporary scaffolding tower to provide a drop height of 8 m. The test rig was located in HSL's Burn Hall facility, where tests could be conducted in a stable environment with no cross wind. The experiment, shown schematically in Figure 5, allowed burning droplets or hot solids to be created at the top of the tower before being released to fall freely through the flow field of a flammable gas.

Droplets were formed on the end of a vertical needle attached to a gravity fed solvent supply chamber. The rate of droplet generation was controlled through a series of needle valves. Following its detachment, an individual droplet passed through a burner tip where the droplet's surface vapour was ignited. Heptane, which is representative of natural gas condensate, was selected for use in the experiments. Heptane has an appreciable vapour pressure such that a falling droplet would readily produce a flammable vapour (i.e. the liquid had to have a low flashpoint temperature). Two needle sizes (2 mm and 8 mm diameter) were used to generate droplets and it was found through gravimetric analysis that these needles produced droplets with diameters of 2.5 mm and 4.4 mm respectively.

For the tests on falling hot non-burning material, solid metal cubes were heated at the top of the tower using a propane burner torch. During heating the temperature was monitored using a thermocouple located in the centre of the cube. When the temperature reached the set point the cube was detached from the thermocouple and then released from the retaining clamp. Two sizes of mild steel cubes were used with side lengths of 1 cm and 2 cm.

On the GP3, the vented gases exit through a 150 mm orifice at velocities between 13 m/s and 21 m/s (these values correspond to the upper and lower volumetric flow rates of gas from the cargo vent). The experiments replicated, where possible, the conditions on GP3 whilst operating within the constraints of the Burn Hall. The diameter of the release pipe was reduced to 7 mm whilst maintaining the exit velocity equal to that on GP3 so that the centre line momentum would be preserved. The location of the release orifice was adjustable so that the hot and burning objects could fall through different downstream positions both inside and outside of the flammable region. The flammability limits and density of the vent gases released on the GP3 are similar to butane, so for simplicity pure butane was used to simulate the GP3 vented gases. The butane was supplied from small pressurised gas cylinders and piped to the release orifice. The overall flow rate was controlled manually using a rotameter. To achieve the higher flow rate, four 9 kg butane cylinders were manifolded together. During initial tests it was found that the butane cylinders cooled (due to vaporisation/boiling of the liquid contents) which led to a reduction in the flow rate. To counteract this cooling, the bottles were placed in a moderately warm (≈ 20 °C) water bath.

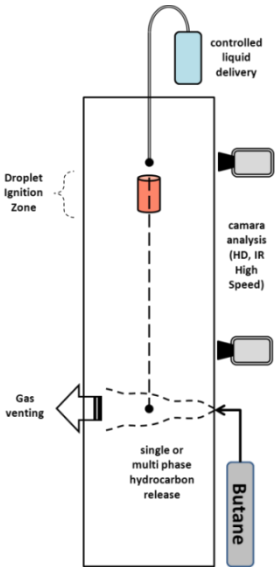


Figure 5 Schematic of the drop tower experimental set-up

On the GP3, there was evidence that condensed liquid mists or droplets were produced during operation of the cargo vent. To assess the effect that a condensed liquid phase may have on the ignition process, two-phase butane releases were conducted. A two-phase flow was generated by fitting an atomisation nozzle to the end of a liquid butane take-off from the supply bottle. The output from the nozzle produced a fine spray that followed the bulk momentum of the gas jet. The flow rate of the two-phase releases was selected to produce a similar size and shape of the burning jet to that obtained from an ignited gas-only release. It was subsequently found during trials with the low flow rate condition that the unignited two-phase release lost momentum quite quickly and slumped prior to reaching the extraction hood. Due to the uncertainty over the flow behaviour and the potential for butane accumulation in the experimental facility, this condition was not examined and only tests with the higher flow rate were conducted.

The ignition behaviour of the flammable release was observed directly and recorded using standard and high speed video cameras and still photography. The outcome of each experiment was assessed based on observations of the ignition response behaviour and classified as follows (these categories are used later when presenting the experimental results):

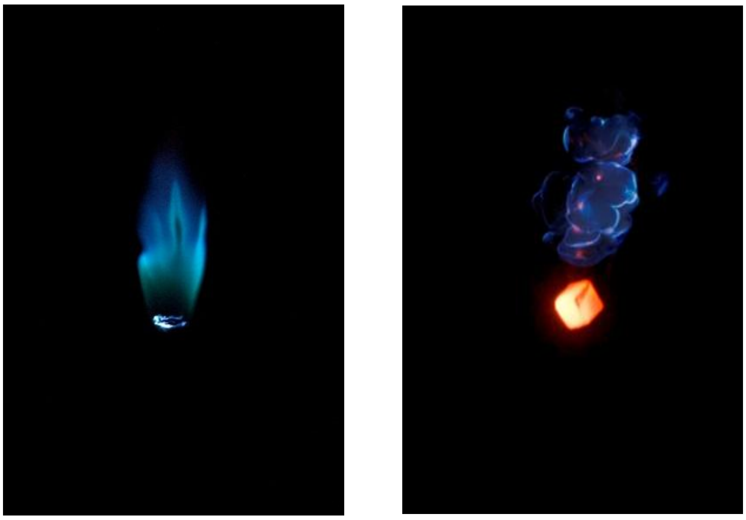
1. No ignition.
2. Intermediate behaviour - Ignition kernels were formed but they did not burn back to source, or the jet only lit after a large number of burning drops.
3. Jet easily ignited and flames burnt back to the release orifice.

Behaviour of Burning Droplets / Hot Solids

Initial test work examined the behaviour of burning droplets in the absence of a flammable release. The behaviour of the droplets whilst being ignited by the burner flame was examined to determine if there was any substantial droplet break-up or change of volume. In all cases, no substantial change in the droplet size was observed. Further tests quickly established that burning heptane droplets would continue to burn throughout the 8 m fall height from the drop tower. Still images of the burning droplets at the bottom of the drop tower (e.g. Figure 6a) showed that the burning portion of the droplet existed in the wake behind the droplet. As the droplet fell from the drop tower, the air flow over the droplet surface forced the flame front to the rear of the droplet. The air flow caused the flammable vapour generated from the surface of the droplet to flow towards the flame front and support the combustion process.

The ignition tests performed in this study were conducted over a drop height of 8 m, whereas on the GP3 the distance between the flare tip and the vent pipe is 18 m. An important aspect, in relation to the ignition on the GP3, is whether the droplets would continue to burn over an additional fall height of 10 m. Observation of the experiments indicated that the droplets were still quite large as they fell to the bottom of the drop tower (having lost/burnt minimal volume), and they could easily be observed and tracked. Calculations of the expected droplet fall time suggested that a large droplet falling at its terminal velocity would take an additional 1.3 seconds to travel a further 10 m. On this basis, it was considered that the droplets would have sufficient fuel to continue burning if allowed to fall a further 10 m. Therefore, it was concluded that droplets of the sizes studied here would continue to burn over an 18 m fall height (as encountered on the GP3).

During the experiments with burning liquid droplets it was not possible to capture the specific moment when a burning droplet ignited the flammable gas. However, ignition events were captured for tests conducted with hot solids. Figure 6b shows the formation of the ignition kernel in a volume of gas traversed by a red hot metal cube.



(a) **(b)**

Figure 6 Images of **(a)** a burning droplet of heptane in free fall at the bottom of the drop tower, and **(b)** the formation of an ignition kernel as a hot solid passes through the butane release

Ignition Assessment – Burning Droplets

Ignition tests were performed using two droplet sizes: 2.5 mm and 4.4 mm diameter. These two droplet sizes are nominally referred to as small and large droplets respectively. Tests were also performed using high and low butane release flow rates that correspond to the upper and lower cargo vent exit velocities encountered on GP3. The outcome of each ignition test condition has been classified according to the ignition response criteria given earlier.

Figure 7 presents the test results for both droplet sizes passing through the higher flow rate butane release. Similar experimental results (not shown) were obtained when conducting experiments with the low flow rate butane release. The estimated locations of the upper and lower explosive limit (UEL and LEL) mean concentrations and the ½ LEL concentrations on the centreline axis are also shown in Figure 7. The locations of the UEL, LEL and ½ LEL were calculated using the DNV GL Phast dispersion model. For the higher velocity release, they were located at 0.23 m, 0.94 m and 1.39 m downstream of the orifice, respectively.

Tests in the rich region between the release orifice and the UEL mean concentration all led to successful ignitions (Figure 7). At this location in the release, the burning droplets would have to pass through lower concentrations that are away from the centreline before they reach the core of the jet where concentrations above the upper limit will exist. Therefore it is not possible for a burning droplet to fall through the UEL region of the jet without encountering a flammable mixture and thus igniting the release.

All of the tests for both droplet sizes (Figure 7) conducted between the UEL and the LEL mean concentrations led to ignition of the butane gas cloud. Failure to ignite the release was not observed until downstream of the LEL boundary. In the region between the LEL and the ½ LEL mean concentrations, positive ignitions were also recorded. However, as the mean concentration approached ½ LEL, failed ignitions and intermediate ignition behaviour were observed.

The experimental results (Figure 7) appeared to show a dependency on the droplet size, with the larger droplets achieving ignitions further downstream. The cause of this behaviour was unclear, but it may be due to larger droplets being able to heat a larger volume of gas, so that in an inhomogeneous gas cloud with pockets of flammable gas the larger droplets have a greater chance of producing a stable ignition kernel.

No previous reports of liquid droplets igniting flammable gas jets with similar characteristics to the GP3 were found in a survey of the literature. The initial assessment of whether a burning droplet could ignite a flammable gas stream concluded that the energy that a droplet could impart would be sufficient to form a stable ignition kernel. The main area of uncertainty with the analysis was related to the interaction of the moving droplet within a cross-flow of gas and convection of heat away from the ignition kernel. The experimental results presented here clearly demonstrated that a burning droplet of sufficient size would easily ignite the gas if it passed through a flammable region with a mean concentration above ½ LEL. The contact time between the burning droplet and the combustible gas was sufficient for ignition to occur in these experiments. Under other conditions, such as where the velocity of the release jet is higher, then convective heat losses during kernel formation may quench the ignition.

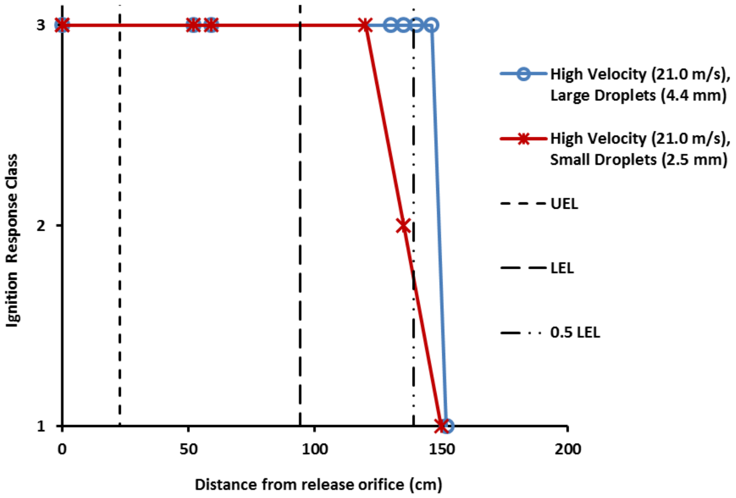


Figure 7 Ignition test results for 2.5 mm and 4.4 mm burning droplets of heptane passing through a butane release (exit velocity = 21.0 m/s)

Ignition Assessment – Two-Phase Releases

Tests using small and large burning droplets were conducted using a two-phase release of butane, where the flow rate of butane was chosen to given equivalent burning characteristics (flame size and length) to the ignited higher velocity butane gas releases. Figure 8 presents a summary of the results which show that for both droplet sizes, it was possible to ignite the flammable two-phase release at locations beyond the LEL, and in the case of the smaller droplets up to the location of the ½ LEL mean concentration. Comparison of these results with those presented for the gas-only releases (Figure 7) shows a similar ignitable range for the smaller droplets. However, for the larger droplets, ignition was only possible a short distance beyond the LEL boundary and not up to the ½ LEL mean concentration, as was found for single phase gas releases. The location of the flammable region given in Figure 8 is estimated based on gas-only releases. While the flow rate of butane in the two phase releases was calibrated by comparing the resulting flame size to that found in the single phase case, the gas produced in the two-phase plume may have a lower concentration than the equivalent gas-only releases; therefore the location of the flammable limits may occur over a shorter range for the two-phase releases compared to the gas-only ones.

For the two-phase releases, the smaller burning droplets achieved ignitions further downstream than the larger burning droplets. This behaviour is opposite to that observed for the gas-only releases, where the larger burning droplets were able to ignite the jet further downstream than the small droplets. The reason for this behaviour is unclear. One explanation could be that due to the greater surface area of the larger droplets there would be a higher degree of surface quenching from the liquid phase in the two-phase butane release, leading to the burning droplet being extinguished before a flammable gas region was encountered.

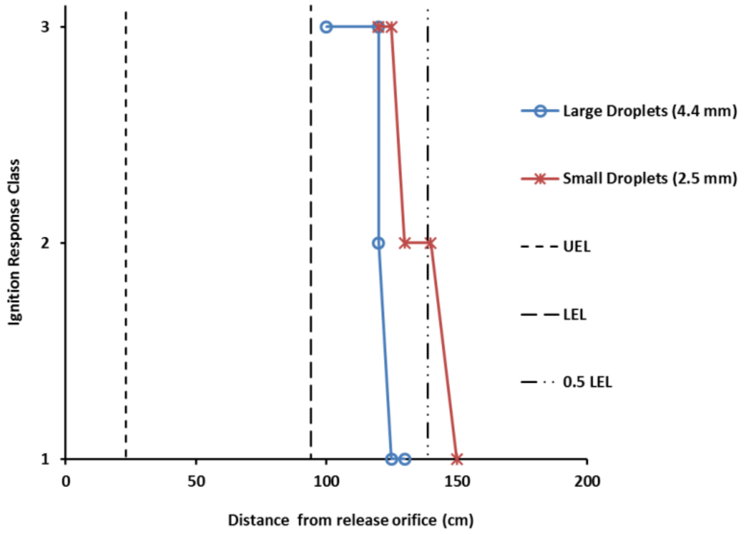


Figure 8 Ignition test results for 2.5 mm and 4.4 mm burning droplets of heptane passing through a two-phase butane release.

Ignition Assessment – Hot Solids

The potential for hot, non-burning material to ignite a flammable release was examined using heated cubes of mild steel. An initial series of static tests was conducted at ground level where both small and large metal cubes were heated and then placed directly into the flammable region of the butane release around the centre of the LEL region (approximately stoichiometric concentration). Both the small and the large cubes were capable of igniting the butane release if they had been heated sufficiently. In these tests, the large cubes had to be heated to 895 °C before the jet would ignite, whereas with the smaller cubes ignition was recorded at 980 °C (but not at the next lower temperature tested of 900°C). Ignition of the gas stream by a heated cube will occur when sufficient heat transfer occurs from the cube surface to the surrounding gas to raise the temperature of the gas above the auto-ignition temperature (which is 405 °C for butane). The auto-ignition temperature quoted in the literature is obtained in idealised quiescent conditions; however, in practice a higher value would be required. Due to the gas flow, the time available for sufficient heat transfer would be short and therefore a temperature substantially above the auto-ignition temperature will be required to drive rapid heat transfer. Similarly, the reduced surface area of a smaller cube would require a higher surface temperature so as to provide a greater temperature driving force to start the ignition process. The behaviour observed here is comparable with test results published by Babrauskas (2003) that demonstrated the dependence of particle surface area on surface temperature for ignition of a number of flammable gases. Babrauskas reported similar behaviour for town gas or hexane with ignition temperatures between 900 °C and 1000 °C with particles ranging in surface area from 10 mm^2 to 100 mm^2. The particle surface areas used in the current work are larger (600 mm^2 and 2400 mm^2 for the small and large cubes respectively), but the measured ignition temperatures of 980 °C and 895 °C correlate with the data presented by Babrauskas (2003).

The static tests were conducted to provide a temperature baseline for the subsequent drop tower tests. Given the marginal difference in temperature recorded for the small and large cubes, subsequent tests from the drop tower were only conducted using the larger cube. The larger cube was safer to manipulate when hot and it was possible to obtain greater control over the target heating temperature. Tests were undertaken from the top of the drop tower at a height of 8 m, but these were unsuccessful because it was not possible to drop the cube with a high degree of accuracy, and the cubes did not fall through the central flammable region of the jet. Further drop tower tests were undertaken from a lower level of the tower, approximately 1.3 m above the level of the release orifice. From this reduced elevation, a higher degree of consistency over the fall location of the hot cube was obtained. These tests showed identical behaviour for both gas release flow rates; the jet was ignited by cubes heated to 1050°C, but not those heated to 1030°C. This result suggests that a variation in the flow rate does not affect the overall ignition process, but it is still possible that some degree of cross flow has an effect on the temperature threshold. Figure 9 compares the ignition response behaviour for the large heated cube that was placed into the flow at ground level (static tests) with that when dropped from 1.3 m above the release plane. The temperature required for ignition to occur was 155 °C higher for the cubes dropped from the elevated position than those inserted into the jet at ground level. In the elevated tests, no ignition was recorded at temperatures that led to ignitions at ground level. It was not possible to record the temperature of the cubes during or after they were dropped from the tower; however it is expected that a degree of cooling occurred during the short period between being dropped and reaching the level of the butane release.

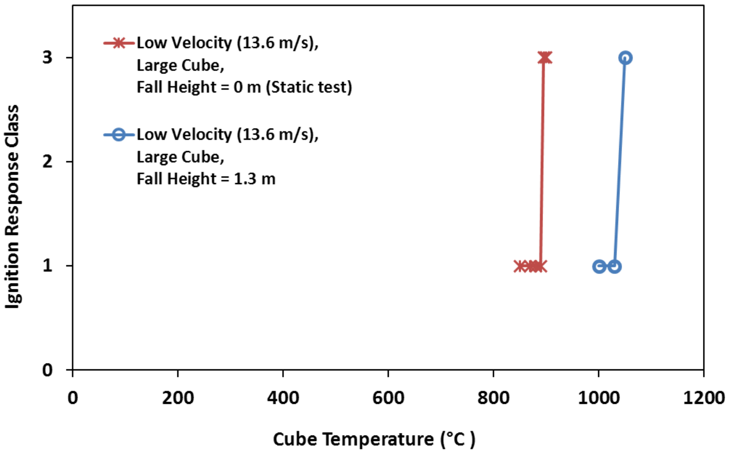


Figure 9 Comparison of the ignition response for large heated cube from either ground level or dropped from 1.3 m above the release plane.

There are only a few existing experimental studies related to hot particle ignition of hydrocarbon gas. A study by Coronel *et al*. (2013) investigated the ignition of quiescent n-hexane/air mixtures using falling hot metal spheres. The spheres were much smaller than the present work (diameter = 4 mm) and the drop height, whilst not explicitly stated, would have been in the order of 20 cm. In the work by Coronel *et al*. (2013), spheres were heated to temperatures in the range 750 °C to 1250°C. It was found that the minimum temperature required for falling particle ignition was in the region of 875°C, which was substantially above the static ignition temperature of 637°C. Due to the different scales, a direct comparison between the present work and the study of Coronel *et al*. (2013) is not possible. However, they both required a similar magnitude of temperature difference between the temperatures required for ignition in the static and transient tests, which clearly demonstrates that a temperature substantially above the static ignition and auto-ignition temperature is required for a falling solid to ignite a flammable release.

Discussion

The experimental work presented in this paper has examined the possibility that during low wind speeds a hot object or burning droplet could be ejected from the flare on the GP3, fall towards the deck of the ship and pass through the flammable cloud produced by the cargo vent release, igniting the vent gases in the process.

To assess the credibility of this ignition mechanism, experiments were conducted with two burning droplet sizes (initial diameters of 2.5 mm and 4.4 mm) over a fall height of 8 m. When droplets of either size fell through the flammable region of a simulated vent release, where the mean concentration was above ½ LEL, the gas cloud was ignited. The test programme demonstrated extensively that ignition by burning droplets was a feasible ignition mechanism.

On the GP3, the difference in height between the flare tip and the cargo vent outlet is 18 m, whereas in the experiments the height difference was only 8 m. An area of uncertainty is whether droplets that were demonstrated to burn through a fall height of 8 m, would continue to burn over a height of 18 m. Based on observations of the residual burning droplets once they had reached the base of the tower in the experiments and calculations of the time taken to fall a further 10 m it was concluded that the droplets would indeed continue to burn if allowed to fall a further 10 m. The final conclusion was therefore that if flammable liquid was ejected and ignited by the flare, and it subsequently fell through the flammable region of the cargo vent gas cloud, then the gas cloud would be ignited. However, the likelihood that such an event could occur, and that a volume of liquid would persist through the flare (i.e. not be completely vaporised) remains uncertain.

It was observed on the GP3 that liquid was sometimes released through the cargo vent pipe during venting. The ignition of two-phase mixture of flammable gas and liquid droplets from the vent was examined experimentally using burning droplets. These tests found no substantial difference in behaviour when compared to the gas-only vent releases. Therefore it was concluded that ignition of two-phase vented releases by burning droplets ejected and ignited by the flare was also feasible.

It was demonstrated experimentally that the vent gas cloud could be ignited by pieces of metal that were heated considerably above the auto-ignition temperature. Two sets of tests were performed: static tests where a metal cube was inserted into the gas flow, and drop tests in which a metal cube fell through a height of approximately 1.3 m before reaching the gas cloud. The solid temperatures required for ignition were 895 °C in the static tests or 1050 °C in the drop tests, which are both considerably higher than the butane auto-ignition temperature of 405 °C. In the static tests, smaller pieces of metal required a greater temperature to ignite the gas cloud.

In relation to GP3, if a piece of metal was ejected through the flare (or had broken off from the flare tip) then it would need to be heated to a temperature greater than 1050 °C, and in all likelihood considerably above this temperature (>1200 °C) as the drop distance is 18 m. The adiabatic flame temperature for natural gas (being burnt through the flare) in air is 1960 °C, but the actual temperature that could be expected on the GP3 when aspects such as incomplete combustion and heat losses are taken into account would give a maximum flame temperature in the region of 900 °C to 1200 °C. Furthermore, unlike liquid droplets that may be ignited almost spontaneously, the time required to heat a piece of metal would be longer than the transit time through the flare. Even if elements of the flare tip structure were preheated through radiation and conduction it is unlikely that they could be heated to such a high temperature in such a short space of time (≈3-5 seconds). Therefore, on this basis it is unlikely that a piece of metal could be heated to a sufficiently high temperature to cause ignition of the cargo vent gas.

Conclusions

The overall objective of this study was to determine whether material that could originate from the flare on the GP3 could be either heated or ignited such that when it fell close to the cargo vent release pipe it could ignite the flammable vent gases.

It was found experimentally that material that does not readily combust, such as solid metal pieces, are unlikely to attain a sufficiently high temperature to ignite the cargo vent gas cloud. However, it was demonstrated that material that freely burns, such as droplets of flammable liquids, could remain burning whilst in free fall and ignite a flammable jet. The conclusion of the work is that burning droplets falling from the flare are deemed to be a credible cause of the ignition incidents on the GP3.

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References

Babrauskas, V., 2003, Ignition Handbook: Principles and Applications to Fire Safety Engineering, Fire Investigation, Risk Management and Forensic Science.

Coronel, A., Menon, S., Mevel, R., Blanquart, G., and Shepherd, J. E., 2013, Ignition of n-Hexane-Air Mixtures by Moving Hot Spheres. 24th International Colloquium for Dynamics of Explosions and Reactive Systems (ICDERS), Taipai, Taiwan.

Gant, S.E., Pursell, M., Newton, A., Bennett, D., O'Sullivan, L. and Piper, D., 2016, Investigation of Cargo Tank Vent Fires on the GP3 FPSO, Part 2: Analysis of Vapour Dispersion, IChemE Hazards 26 Conference, Edinburgh, UK, 24-26 May 2016.