IGNITION HAZARDS AND AREA CLASSIFICATION OF HYDROCARBON COLD VENTS BY THE OFFSHORE OIL AND GAS INDUSTRY†

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- Vapours released from cargo oil tank 'inert gas' systems will contain considerable amounts of hydrocarbon vapours.
- The amount of hydrocarbon vapour present depends on the type of crude being handled, its storage temperature and the activity being undertaken in the tanks at the time. Levels of 50–70% by volume hydrocarbon are not uncommon.
- IMO codes detailing design requirements for cold venting systems on tankers were derived prior to the introduction of Floating Storage Production and Offloading installations (FPSOs) and may not be wholly suitable. They were developed for merchant tankers which generally have a relatively uncluttered deck where as an FPSO will have an extensive process plant built above the main deck. Also an FPSO remains at a fixed location and therefore is reliant on the prevailing winds to disperse vented vapours unlike a merchant tanker which when on passage will disperse vented vapours my means of its own motion.
- Instances are known where the static nature of FPSOs has led to the development of flammable clouds on the topsides of structures leading to confirmed gas detections and plant shut downs, also fires have occurred in cold vents.
- Computational Fluid Dynamics (CFD) studies have confirmed that topsides structures can complicate flow over the installation affecting dispersion.
- The hazardous area classification of such vents is not straightforward and a number of approaches could be used which contain differing guidance.

KEYWORDS: FPSO, Cargo venting, inert gas, oil vapours, flammability, dispersion, area classification, modelling, simulation, Computational Fluid Dynamics, CFD, integral models.

It appears commonplace in the offshore industry to regard cold vent systems, especially those venting 'inert' blanket gases from cargo storage tanks as being non-hazardous.

This paper describes a number of incidents where such vents have been ignited, describes the underlying circumstances which led to the incident, the properties of the vapours being vented and area classification schemes which could be applied to determine the size of the hazardous area.

Our work has identified that while tanks may initially be inerted, with little hydrocarbon content in the blanket gas, the introduction of oil rapidly displaces this blanket gas through a combination of physical displacement and the generation of hydrocarbon vapours from the off-gassing of the oil with the hydrocarbon content increases during loading or crude oil washing.

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Depending on the hydrocarbon content, which may be as high as 70% by volume, this inert gas/hydrocarbon mixture may be flammable and can present a fire or explosion hazard, as seen in the incidents described.

Predicting the behaviour, dispersion and hazards of this mixture on release is complicated by its changing composition and buoyancy, as well its changing flammability envelope.

The review of area classification schemes has shown that for fixed installations the most applicable code appears to be IP15, while for floating installations SOLAS, IMO Circular FP 48 and BS IEC 60092-502 are the most applicable. This latter document would consider the hazardous area to be an infinitely tall cylinder 10 m radius for large volume discharges, such as those formed during loading operations; while for small volume releases, such as vapour release due to thermal variation, it considers it to be a sphere, 3 m in radius.

Mathematical modelling of a release from a vent with a CFD model can provide insight into the dispersion of the flammable vapour. The dispersion will be strongly affected by the atmospheric conditions and the source of the gas. As there is likely to be significant uncertainty in these conditions this must be taken into account in the modelling by considering a range of parameters.

1. INTRODUCTION

Oil and gas production for marginal developments or deep water production is often undertaken using Floating Production Storage and Offloading installations (FPSOs).

Originally some of these may have been tankers which were later modified to introduce the production equipment on the topsides.

The problem of hydrocarbon evolution during tanker operations involving the transport of crude oil or other hydrocarbon cargos has been known for many years and, historically there have been a number of instances where internal explosions have occurred in tanks leading to fatalities and in some cases the loss of the vessel. This led to the present day practice of inerting cargo oil tanks which is being supplemented with VOC management systems for environmental reasons.

Due to the volumes of gas required this inerting is normally undertaken using boiler uptake flue gas or more commonly in FPSOs inert gas (IG) generators where diesel fuel is burnt to create an atmosphere rich in nitrogen and carbon dioxide, and low in oxygen.

When oil is introduced into the tanks hydrocarbon vapours emitted by the cargo become mixed with the IG to produce a cocktail of vapours/gases, the composition of which varies depending on the stage of the loading cycle and the properties of the oil being handled.

Excess pressure is released from the system via a means of pressure control to a vent system often referred to as a cold vent, or IG vent system.

Following recent incidents the UK Health and Safety Executive issued an Offshore Information Sheet (OIS 5/2010), and has conducted a survey of UK FPSOs to identify features such as design codes, vent locations, vent designs and methods of operation etc. to obtain more information in this area.

Discussions with operators, the survey results and information available in open literature would indicate that the potential flammability of these vapours is not always acknowledged, reflected by the cargo oil tank vent often being called the IG vent. This brings with it the natural assumption that inert gas mixtures do not burn, so differing methods of treatment of this problem are seen across operators, along with differing area classifications, and different vent locations depending on the degree of perceived hazard, sometimes based on asphyxiant considerations only.

2. CRUDE OIL PROPERTIES AND FLAMMABILITY

Crude oils are naturally occurring products which contain hundreds of hydrocarbon compounds, spanning a wide range of molecular weights and structures. Because of this range in composition the nature and volatility of different crude oils varies enormously, but in general they are often classified on a basis of their density and thus defined as light, medium or heavy crudes. Such is the volatility of even stabilised crudes, that light crudes can lose up to 75% of their original volume and heavy crudes 40% in a few days if left in the open air. (Fingas, 1994).

This variation in composition is illustrated in Figure 1 which shows the n-paraffin carbon chain lengths of species present in oils with a range of API specific gravities. (Boduszzynski et al., 1998).

The main feature to take in from Figure 1, apart from the complexity of composition, is the significant proportion of light, short chain, hydrocarbons present. This range of components and the volatilities means that even a stabilised crude will be continually evolving flammable hydrocarbon vapour. When in storage, these vapours will mix with the IG in the cargo tanks creating an IG/hydrocarbon mixture.

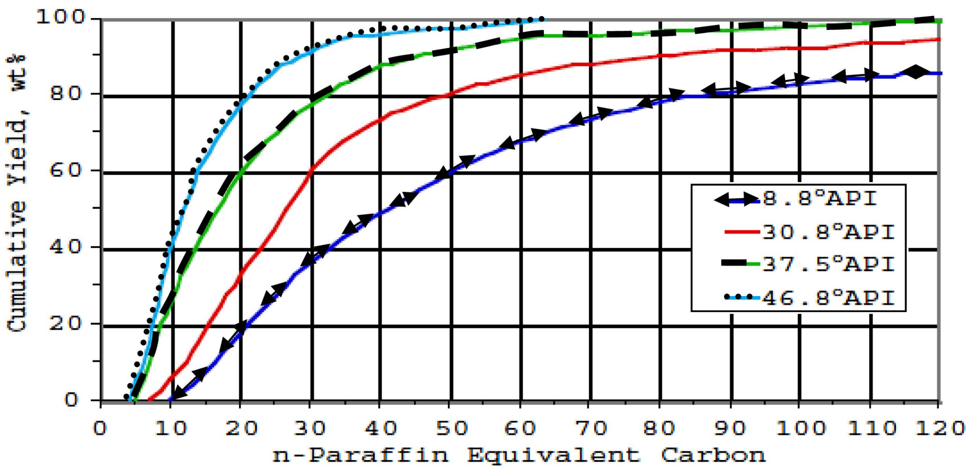

Figure 1. *n*-Paraffin content of different crudes

Table 1. Comparison of the dimensions of hazardous areas derived from different area classification standards for the same cargo tank vent

Code Reference	Requirement
IP15 #	10 m Hazard Radius Zone 1 at tank vent tip 10 m Hazard Radius Column Zone 2 extended down to grade
IEC 60092–502	6 m radius Zone I sphere around the cargo vent tip 6 m radius Zone I column extended indefinitely upwards 4 m radius Zone II column beyond the 6 m radius Zone I column the cargo vent tip extending down to tank top/deck and infinitely upwards
DNV OS A101	Hazardous area defined by recognised codes and standards Large releases should consider the extent of the zone larger than the boundary of 50% LEL concentration
SOLAS	Require discharges to be vertically upwards. Vent not located <6 m above cargo deck <2 m (Hi-jet types) Vent not be located <10 m horizontally from nearest intake or ignition source. Hazardous areas as per MSC/Circ 1120 Unified Interpretations of SOLAS II-2
ISGOTT	Vents to be sited in locations to prevent the accumulation of a flammable atmosphere and should be located as high as practical, unobstructed and away from potential ignition sources. Maximum flow rate 36 m/s. SOLAS to be complied with for the vessel.

Above figures given above are an example for a cargo tank vent based on values in IP15. Annex C – Part 3 of IP15 provides a series of tables to enable the calculation of hazardous areas based on fluid composition, release rate vent size for specific applications.

As well as being dependant on the type of crude present, the rate at which vapours are evolved will be dependant on the production and storage temperatures, as well as on the activity being undertaken in the tank at the time.

Typically, storage may be at a temperature of 40–50ºC, with production being at maybe 70ºC. This production temperature will drive off a proportion of the volatiles, but not all will be lost. Thus on arrival in the tanks, where it may be stored for several days at a temperature of 40–50ºC, vaporisation will continue until the hydrocarbon vapour reaches equilibrium with the stored oil. During operations such as tank washing where oil can be sprayed onto the tank walls to aid cleaning, this falling into equilibrium is reached far more quickly and levels as high as 70–80% volume hydrocarbons can be achieved: again depending on the type of crude, temperature etc.

Once the composition of this mixture is known it is possible to determine a number of factors important to safety. The most important being: flammable limits; flashpoint; and, vapour density.

Flammable Limits — In order to calculate the Lower Flammability Limit (LFL) of a gas mixture, it is necessary to apply Le Chatelier's Rule, which states that the LFL of a mixture can be calculated by:

Composite LFL = 100/(C1/LFL1 + C2/LFL2 + C3/LFL3……)

Where C1 is the percentage by volume of the component, once air or inert gases have been discounted. Table 1 below shows the composition of the VOC gas and calculates the LFL for this VOC gas stream.

The Upper Flammability Limit (UFL) is calculated in a similar way with the UFLs of individual components instead of the LFLs:

Composite UFL = 100/(C1/UFL1 + C2/UFL2+ C3/UFL3……)

Flashpoint – A useful summary on methods of calculation of the flashpoint of mixtures was given by Hristova and Tchaoushev (2006). One method contained therein defines the flashpoint of a mixture as the temperature at which the saturated vapour pressure is equivalent to the LFL of the composition:

$$LFL_i = \frac{P^{sat}_{i,fp}(T_f)}{P},$$

where $P^{sat}_{i,fp}(T_f)$ is the saturated vapour pressure at the flashpoint temperature, and P is the ambient pressure.

The situation for FPSOs or tankers is more complex, however, as not only must the properties of the hydrocarbon mixture be considered, but also the presence of the IG which will restrict the flammability of the mixture.

An example of a flammability chart for a propane/air atmosphere inerted using CO_2 or nitrogen is given in Figure 2.

Further information on the flammability of inerted or partially inerted gas mixtures can be found in the work of Gant et al. (2010, 2011), Purcell et al. (2011), and Thyer et al. (2009).

3. TYPES OF VENTING ARRANGEMENTS

Early generation FPSOs, were commonly converted very large crude oil carriers (VLCCs) and had a cargo tank venting arrangement essentially the same as that fitted for operation as a trading tanker, Figure 3, with modifications to take into account the topsides production facilities.

The vent system would either be a free flowing open vent or a high velocity pressure/vacuum (PV valve) vent

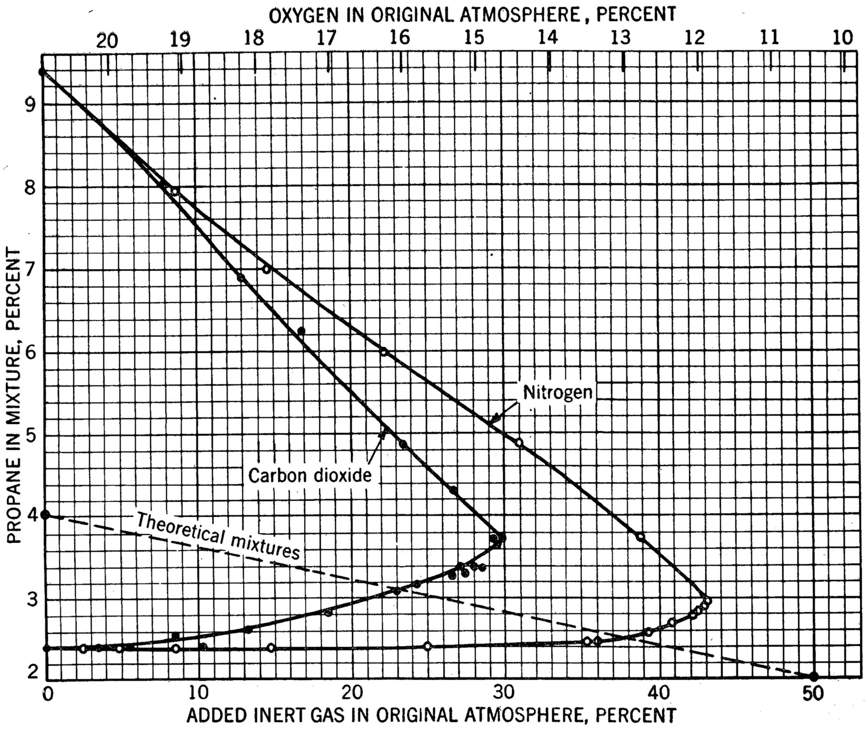

Figure 2. Flammability limits for propane in mixtures of air, CO2 and nitrogen (Coward and Jones, 1952)

arrangement to provide over and under-pressure protection to tanks during loading, discharge, or temperature variations within the tanks. The design being governed by the International Maritime Organisation (IMO) International Convention for the Safety Of Life At Sea 1974 (SOLAS) Regulation II-2/59 & 62 (Consolidated 1992) II-2 Pt B 4.5.3 & 4.5.5 (Consolidated 2009).

This system usually also forms part of the inert gas (IG) distribution system to the cargo and slop tanks, Figure 4. The tanks are usually all connected to a single main as shown in the simplified sketch below and have a vent outlet, usually in the form of a 'mast riser' which is required to have a minimum height of 6 metres above the main deck and to be fitted with an IMO approved flame arrestor. The vent system is required to have a capacity of at least 125% of the loading and discharge rate. The use of a high velocity type PV valve helps to (i) the dispersal of vented gases and (ii) prevent passage of flame back to the tanks due to the gas velocity being ensured to be greater than 30 m/s when the valve is discharging.

Figure 3. Typical deck layout of a very large crude oil carrier

These arrangements do not necessarily suit the manner in which an FPSO is constructed or operates. A VLCC will normally load a full cargo of crude at the loading port, this will occur quite quickly, possibly in less than 24 hours. This crude will have been *'stabilised'* by (i) potentially an efficient on shore process plant and (ii) by residence time in on shore storage tanks and therefore quantities of gas evolving should be quite small.

The vessel then will travel to the designated discharge port(s) and offload the whole cargo, again in a relatively short period of time e.g. 24 hours. It will then travel in ballast to a loading port to start the loading, shipment, discharge, return in ballast cycle. The ballast trips allow for gaining access to the cargo tanks for inspection, maintenance and/or repairs and have little impact in the VLCC operational cycle.

In comparison an FPSO does not have a relatively clear main deck, as this is where the process plant is situated, as can be seen in Figure 5. As well as this complication, FPSOs are static and thus does not create an airflow as would a VLCC to disperse any vented gases by means of their own motion, and can often experience calm weather conditions even in areas such as the North

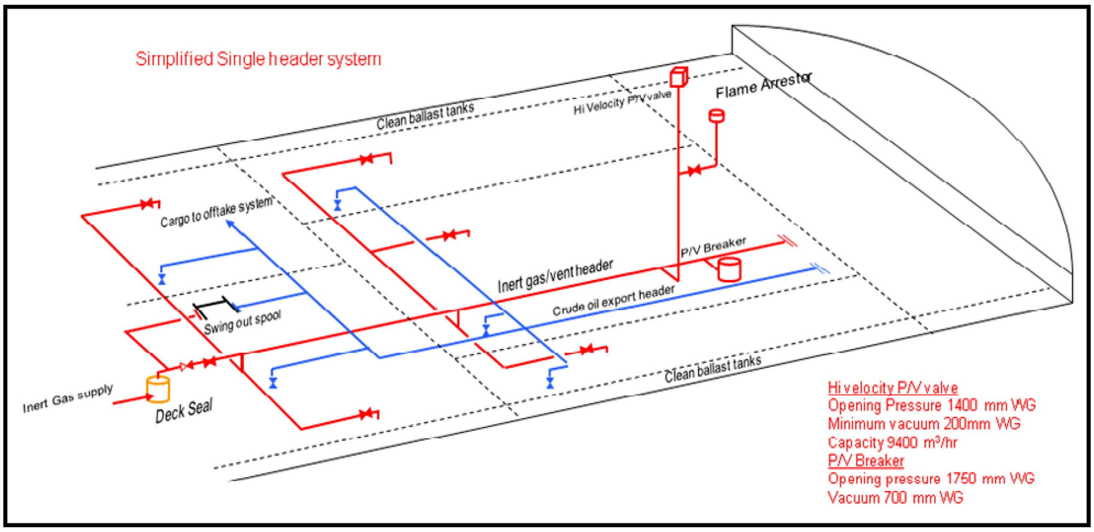

Figure 4. Layout of single header ventilation system

Sea, which would normally be considered to be an area subject to harsh weather conditions. These factors combine to give a situation whereby vented gases do not disperse readily and can accumulate in the congested process areas.

Again in contrast to a VLCC, the FPSO is normally storing a 'semi stabilised' crude oil as it processes the well fluids with a relatively small process plant which often relies on heat to drive off the lighter ends within the crude. The crude is then stored at a relatively high temperature in the tanks which gives rise to increased gas quantities evolving within the tanks prior to the offloading to a shuttle tanker.

The FPSO remains producing to the tanks almost continually so that, except when the installation is shut down there is always a need to have the vent system available for production.

With the traditional tanker vent system this continual production can create operational difficulties when access to a tank is required, as to gain access requires the tank to be subject to a series of washing, purging and gas freeing operations. The single header venting system is unlikely to be able to facilitate these operations at the same time as loading the oil production into the cargo tanks due to the gas freeing requirements of replacing low hydrocarbon ($<2\%$ vol) IG in the tank to be entered with air.

Figure 5. Typical FPSO layout

More recent designs of vent systems for FPSOs take into account the limitations of the single vent header design and whilst specific arrangements may vary they follow the basic arrangements as shown in Figure 6.

The clean inert gas header is used to fill gas free tanks with clean IG prior to the initial loading of oil into the tank. It is also used in conjunction with the Purge Header to vent the tank contents when initially filling with IG and also when a tank is in the process of being gas freed.

The dirty inert gas header is used to vent tank atmosphere when the tank is being filled, and tank pressures are maintained within safe parameters using a pressure control valve, P/V valves and PV breaker to provide addition protection.

This arrangement makes the changing over of the system to undertake purging or gas freeing much simpler having dedicated purge and vent headers so that change over can be undertaken safely without the need to depressurise the whole system or isolate the tanks from the protective P/V valves even for a short period so that tank over or under pressurisation is unlikely and that tanks remain pressurised at all times except for when it is not necessary once gas freeing commences.

Having a degree of 'redundancy' within the system helps make maintenance simpler and also minimises single point failure risks. Despite this redundancy in pressure protection, recent incidents have highlighted concerns with the location of the cargo tank vent outlet itself on FPSOs which has often been found to be located on the flare stack. Whilst

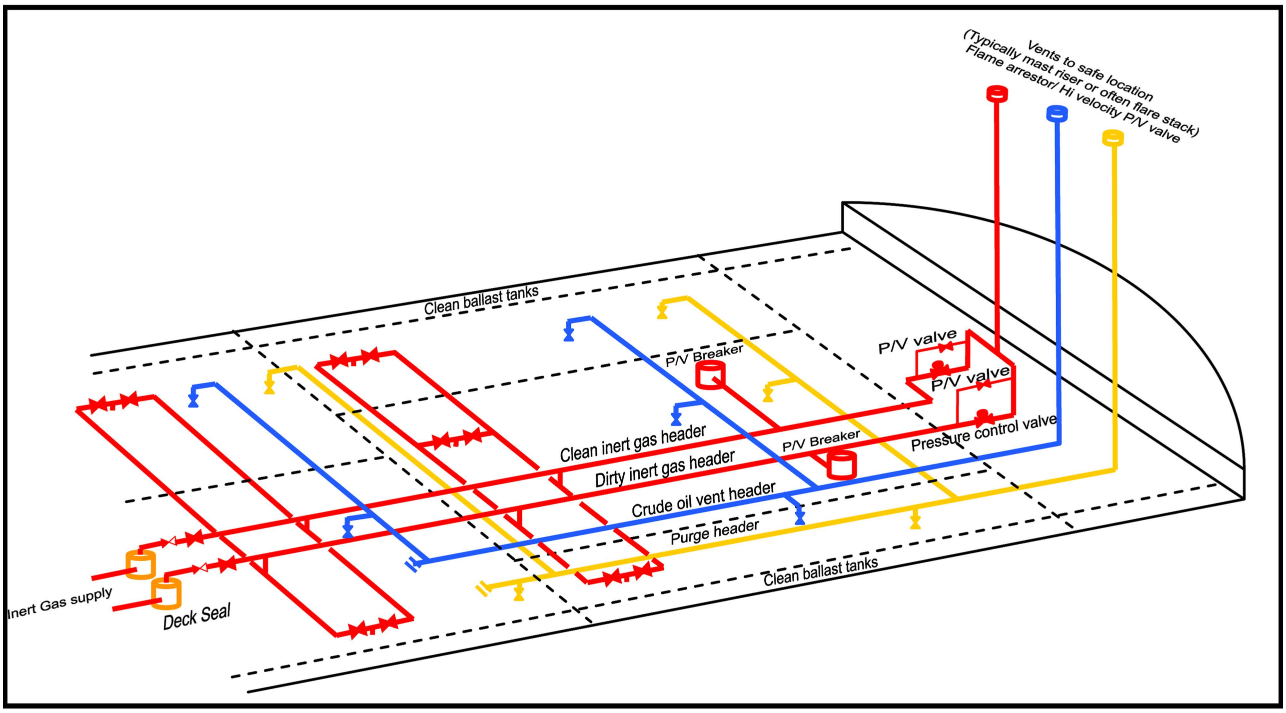

Figure 6. Layout of a three-header ventilation system

this does give opportunity to locate the outlet at a suitable height and away from the generally recognised sources of ignition it does, with a vertical flare stack place the vent outlet directly under the flare which experience has proven to be hazardous.

4. INCIDENTS ASSOCIATED WITH CARGO VENTING SYSTEMS

INCIDENT 1

In 2010 a fire was noted at the tip of the so-called inert gas vent outlet on an FPSO. This outlet was located part-way up the vertical flare tower and was approximately 10 m below the flare tip. Vented gases were directed downwards via a gooseneck arrangement fitted to the end of the 6″ pipe.

The fire was eventually extinguished by isolating the vent and hence the fuel supply at the pressure control valve and surveys confirmed that no structural damage had been caused to the steelwork of the flare tower.

Subsequent investigations identified a number of possible ignition mechanisms including direct ignition by the flare above, hot or burning particles falling from the flare, lightning, static discharge, or ingress of a flammable vapour cloud into the intakes for the gas turbines.

Following the incident production was shut down for a number of months and a limitation placed on production should wind speeds fall below 4 knots.

Prior to the fire it had been previously noted that a flammable gas cloud had been detected at deck level during still weather conditions.

INCIDENT 2

Whilst not on an FPSO, a second recent example of an incident with an ignited vent is a fire which occurred in a vent stack following a fire in a nearby crane diesel engine. Red hot particles from ignited items on the diesel engine were thought to have blown across the deck, thus igniting the flammable gases being released from the vent stack. Extinguishing the flames proved difficult, which required the application of water from monitors on the standby vessel. The fire lasted for over 90 minutes and production was shut down for 9 weeks.

INCIDENT 3

Another source of cold venting of hydrocarbon may come from fuel storage tanks and also from associated cargo pumping systems such as automatic vacuum stripping systems which remove the need to have separate stripping pumps and lines. This is achieved by priming the centrifugal cargo pumps and thus preventing ‘gassing up’ and loss of suction on a tank.

A recent incident arose through the combination of operator error and poor location of a vent from the vacuum stripping system drain tank which allowed a large volume of gas to be drawn into a pump room when the pump room door adjacent to the vent was opened. Fortunately the gas detection system picked up the gas release before it was able to find a source of ignition. To remedy this design failure will require the vent being re-located in a safer location. An estimated 73 kg of gas was released in this incident which if it had found a source of ignition could have lead to a considerable explosion.

5. CODES STANDARDS DESIGN GUIDELINES AND AREA CLASSIFICATION SCHEMES

Within the marine industry hazardous area classification has been defined and developed to suit the normal operational requirements of the industry. The petrochemical process industry similarly has developed a considerable amount of guidance for its own specific purposes. However where the 'marine' and 'process' requirements 'overlap' there is little guidance as to the most appropriate arrangements to put in place. In terms of area classification for the marine sections of an FPSO, it is considered by the authors that the most appropriate code to apply is BS IEC 60092 − 502:1999, Electrical installations in ships — Part 502: Tankers — Special features. This standard reflects the SOLAS requirements for merchant tankers. It is also referred to in the Area classification code for installations handling flammable fluids: Model Code of Safe Practice Part 15, 3rd Edition, as being applicable for tankers. IP15 also refers to ISGOTT for suitable operational precautions that should be taken and ISGOTT in turn also refers to the IEC for the identification of hazardous areas and the determination of suitable electrical equipment for use.

An FPSO is essentially a combination of a merchant tanker with a petrochemical process plant on top of it, for which there is even less guidance available. For marine systems SOLAS takes primacy, this is reflected in Classification Society Rules for the construction of ships and also within the International Chamber of Shipping (ICS), Oil Companies International Marine Forum (OCIMF) and International Association of Ports and Harbours (IAPH) document the International Safety Guide for Oil Tankers and Terminals (ISGOTT).

However once an FPSO process plant has been fitted on the main deck of an FPSO the guidance contained with SOLAS as well as other documents needs to be considered taking the combined equipment requirements into account.

Simplistically the greater the physical separation by vertical and horizontal distance separation between vent outlet and potential sources of ignition the better.

Knowing and understanding the physical properties of the vented gases can also assist in the decision making process for the locating of these cold vents.

The dimensions of possible hazardous areas derived using the above standards are given in Table 1.

6. DISPERSION MODELLING STUDIES

Simple illustrative diagrams showing vent plumes are given in publications such as ISGOTT or ISGINTT, see Figure 7. These serve to demonstrate that, as would be expected, plumes of denser than air gases tend to sink downwards on release, and lighter than air vapours tend to rise. Structures, for example the FPSO itself and equipment on its deck, can greatly affect the wind field and the dispersion behaviour of the plume of flammable gas. This also is illustrated in publications such as ISGOTT and ISGINTT, see Figure 8. These figures can only ever give a qualitative appreciation of the plume dispersion behaviour and then only for the illustrated scenario. The situation for a different release rate, wind speed and/or wind direction is not covered. However, it is not feasible or possible to perform experiments of actual releases on FPSOs. Obviously, this simple picture is insufficient to provide a basis for safety and, as such, in many cases mathematical modelling may be used to predict downwind concentrations and dispersion patterns. Mathematical modelling provides a means to obtaining more quantitative information such as the mass and volume of the flammable gas cloud. The models will also provide an insight into where the flammable gas goes after leaving the pipe.

Mathematical models for the dispersion of flammable vapour typically falls into one of two categories: integral and Computational Fluid Dynamics (CFD) models.

CFD models generally offer the most complete and detailed description of the flow physics and provide a wealth of information about the flow in terms of flow velocities, temperature, fuel concentrations and so on. CFD modelling is a knowledge-based process and requires the user to understand the fluid flow behaviour. The flexibility comes at a cost as the set-up process can be lengthy. CFD modelling is the most appropriate technique to investigate dispersion of a flammable vapour cloud on an FPSO as the dispersion will be strongly affected by the interaction of the wind field with the FPSO. The CFD model can take into account the wind direction/speed, atmospheric stability, and the presence of any complicating features such as local air intakes/exhausts, or heat sources such as gas turbine exhausts or flares.

It is not possible to simulate every combination of release rate, wind direction and wind speed. In order to reduce the number of simulations required, experience and engineering judgement are used to try to identify a reasonable worst-case scenario. This is not straightforward since the scenarios and the flow behaviour are likely to be very complex due to the great number of factors that play an important role in the dispersion behaviour.

Incident 1 occurred at quiescent or very low wind speeds. However, releases into higher ambient wind speeds could disperse the flammable cloud back onto the FPSO depending on the direction and speed of the wind. Atmospheric dispersion models based on the integral model approach are not applicable for quiescent or very low wind velocities, say below 0.5 m/s. CFD models, while more generally applicable, can be difficult to run for very low wind speeds or for unstable atmospheric conditions. The CFD models are unlikely to have been validated against very low wind speed data.

The computational domain must include the FPSO and also significantly extend beyond the tanker in all directions. An atmospheric boundary layer approach should be used to describe the variation in the stream-wise velocity with height. In many cases a simple 1/7-th power law profile will be sufficient. It is also important to impose the correct

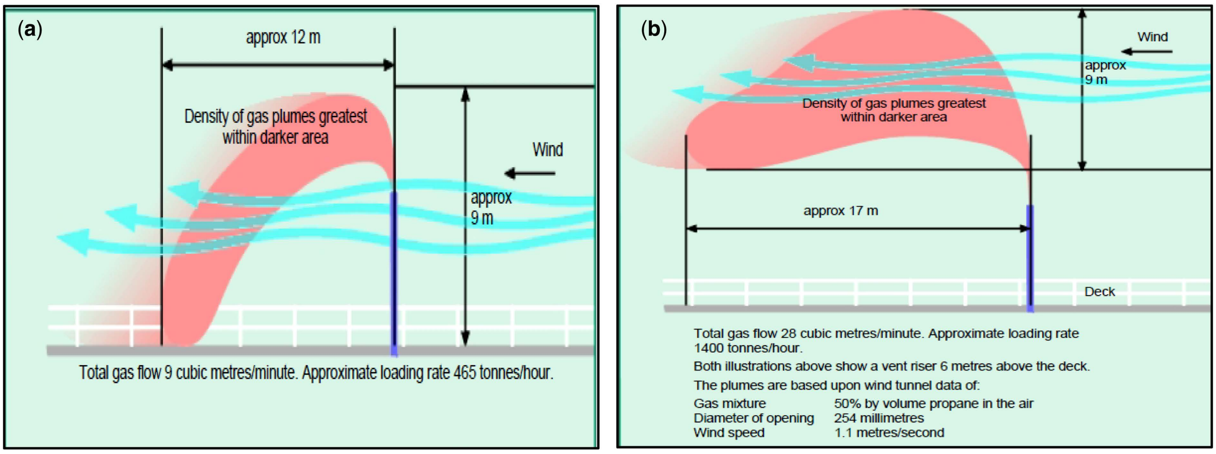

Figure 7. Behaviour of vented hydrocarbon plumes (Oil Companies International Marine Forum, 2010)

atmospheric conditions, referred to as the Pasquill class, for example Pasquill class D2 — a stable atmosphere with a 2.0 m/s wind speed at 10 m height. Structures, such as the FPSO itself and equipment on its deck, greatly affects the velocity field by changing the flow direction and giving rise to regions of recirculating or stagnant flow or shedding of vortices behind the structures, as illustrated in Figure 8.

The density of the vapour also greatly influences the behaviour of the plume. A buoyant gas, i.e. one with a density less than that of the ambient air at a given temperature and pressure, will rise on release. A dense gas with a density greater than the ambient air will slump down under the influence of gravity. A buoyant release directed downwards may rise once buoyancy becomes greater than the plume/jet momentum. A buoyant gas ejected upwards will continue to rise upwards, but may be bent over by the ambient wind, see Figure 7a. Conversely, a dense plume initially ejected vertically upwards will slump downwards when its upward momentum goes to zero see Figure 7b. In the case of a horizontal release a higher momentum release will penetrate further into the atmosphere than a low momentum one, irrespective of whether the gas is dense or buoyant, before gravity begins to dominate the momentum.

It should be borne in mind that the CFD modelling provides time-averaged concentrations. Hence it is possible ignite a flammable gas cloud with a mean concentration below LFL due to the instantaneous concentration being in the flammable range. This is very important to remember when using the results of the CFD modelling with ignition probabilities in a risk assessment study.

CFD modelling offers physical realism and can provide a wealth of information about the flow. Even so,

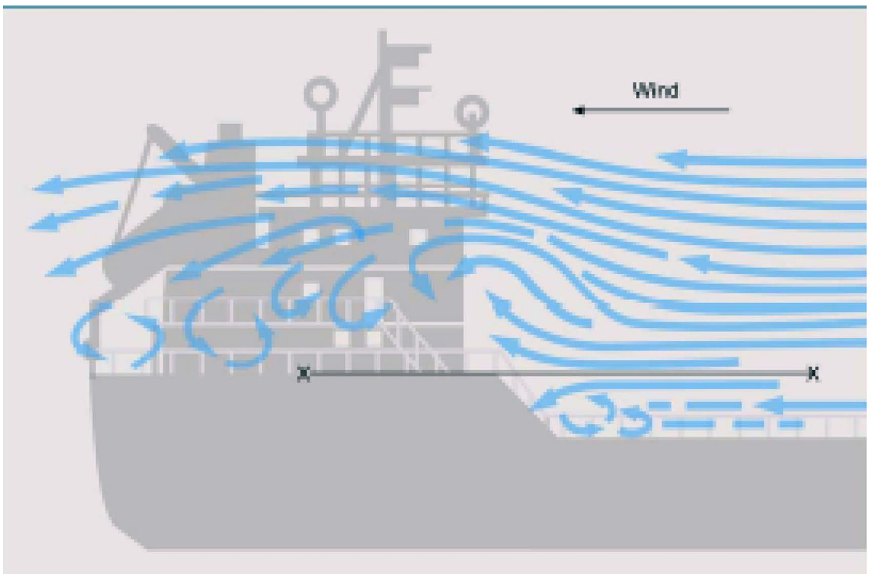

Figure 8. Effect of structures on the ambient wind field and gas plumes (Oil Companies International Marine Forum, 2006)

caution should still be exercised with even the most up to date and complex of models as circumstances can arise where obtaining accurate predictions is difficult. Such situations may be very low or zero ambient wind speeds and or unstable atmospheric conditions.

7. CONCLUSIONS

The information drawn together in this paper demonstrates the sometimes neglected fact that crude oil is capable of generating a flammable atmosphere when stored, and that any vent system associated with storage tanks should be regarded as hazardous and included in hazardous area drawings, whether or not, it may also be discharging inert blanket gas from the cargo tanks. The blanket gas for the tank is inert purely due to lack of oxygen and may contain potentially flammable hydrocarbons which when vented may form flammable mixtures once able to commingle with the air.

The incidents summarised show that there have been a number of fires associated with cargo or tank vents discharging hydrocarbon vapours, or hydrocarbon inert gas mixtures, as well as a number of instances where poor dispersion has led to the formation and detection of a flammable atmosphere on the topsides of the installation, with resulting process shutdowns and upsets.

In some cases fires could have been avoided through the application of the correct area classification scheme. The summary presented in this report demonstrates that not all widely used schemes are applicable to FPSO, and identifies the most appropriate code as BS IEC 60092 – 502:1999, Electrical installations in ships — Part 502: Tankers — Special features.

Even when area classification is correctly applied there is a residual risk that vapours may be ignited, and also that vapours may not disperse as readily as expected.

Experience from North Sea operations have shown that low wind speeds (<5 knots) occur far more frequently than may be expected in an area known to be prone to adverse weather. These low wind speeds, combined with the complex and often congested geometry of the topsides of FPSOs can result in a situation where vent plumes may fall or be pulled to deck level.

One way of determining the likelihood of this and the extent of possible vapour plumes is to undertake computer modelling. Such an approach can give a detailed indication of where plumes may be driven, but the predictions derived will obviously be highly affected by the quality of the input data, as well as the inherent difficulty in obtaining accurate predictions under conditions of very low wind speeds or unstable atmospheric conditions.

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