Review of recent incidents involving flammable mists

Philip Lees[1], Simon Gant[1], Richard Bettis[1], Alexis Vignes[2], Jean-Marc Lacome[2] and Olivier Dufaud[3]

[1] Health and Safety Executive (HSE), Harpur Hill, Buxton, SK17 9JN, UK
[2] Institut National de l'Environnement et des Risques (INERIS), Parc Technologique ALATA, BP 2, 60550 Verneuil-en-Halatte, France
[3] Laboratoire Réactions et Génie des Procédés, Université de Lorraine, CNRS, LRGP, F-54000 Nancy, France

Mists and sprays of high-flashpoint fluids can cause flash fires or explosions. However, guidance by industry on hazardous area classification to address these risks is limited. This paper presents a summary of recent work in this area and analyses three incident databases to establish common factors and trends in flammable mist incidents. The three incident databases are the UK Hydrocarbon Release Database (HCRD), the French ARIA and German ZEMA databases. The HCRD data shows that over a 30 month period starting in 2016 around 10% of reported releases on offshore oil and gas installations on the UK Continental Shelf involved mists or sprays. There were 25 incidents of which two ignited. The ARIA and ZEMA databases show that mist and spray releases of high-flashpoint fluids such as lube oil, hydraulic oil and diesel have led to significant incidents in a wide range of different industries.

Introduction

In 2009, the Health and Safety Executive's Laboratory published a review of flammable mists incidents, which identified 37 separate incidents, including 20 explosions, which together were responsible for 29 fatalities (Santon, 2009). The flammable mists in these cases were produced by pressurised sprays or condensation aerosols of high-flashpoint fluids, i.e. fluids whose vapours cannot be ignited and sustain a flame at normal room temperature (e.g. kerosene, diesel, lubrication oils and hydraulic oils). Prompted by that review, HSE and a consortium of other regulatory and industrial sponsors funded a Joint Industry Project (JIP) to further investigate flammable mist releases.

As part of that JIP, a comprehensive literature review was first undertaken (Gant *et al*., 2012; Gant, 2013), which found that existing guidance on area classification of flammable mists was limited. The review summarised data from previously published work on the formation of mists and their ignition characteristics, in terms of measurable quantities such as lower flammable limit, minimum ignition energy and minimum hot surface ignition temperature. Following the literature review, a classification system for flammable mists was developed, based on the flashpoint and ease-of-atomization (Burrell and Gant, 2017). The JIP then commissioned a series of experiments at Cardiff University on a simple, repeatable mist release configuration that consisted of a downwards-pointing, unobstructed spray release from a 1 mm diameter plain circular orifice (Mouzakitis and Giles, 2017a, 2017b). Test pressures ranged from 1.7 bar to 130 bar, although most tests were conducted at pressures of between 5 bar and 20 bar. Three fluids were tested, which represented three different categories of fluids according to the mists classification system: Jet A1 (kerosene), a light fuel oil and a hydraulic oil. The flashpoints for these three fluids were 38 °C, 81 °C and 223 °C, respectively. Some limited tests were performed with the light fuel oil heated to 70 °C or with an impingement plate. The ignition source was a 1 Joule electric spark igniter. A laser-based Phase Doppler Anemometer (PDA) system was used to measure mist concentrations and droplet sizes.

The Cardiff University experiments showed that the Jet A1 could be ignited at all pressures tested, including the lowest pressure of just 1.7 barg (the minimum pressure possible in the rig). The hydraulic oil and light fuel oil at room temperature could not be ignited. However, when the light fuel oil was heated or impinged onto a plate, the resulting sprays could be ignited at some of the pressures. The experimental work was complemented by CFD modelling (Coldrick and Gant, 2017), which found that atomised sprays could be modelled reasonably well, but that non-atomising sprays were not predicted well. Comparisons were made to the existing area classification guidelines published in the Energy Institute Model Code of Safe Practice, EI15 (Energy Institute, 2015). A summary of the JIP results was presented at the IChemE Hazards conference in 2016 (Gant *et al*., 2016), and full data reports have recently been published on the HSE website (links are provided in the References).

Whilst the JIP provided new data and important findings, particularly on the ease of ignition of Jet A1 at low pressures, the work was limited in studying just one orifice shape, size and release configuration. Important questions remain unanswered on several fronts, such as the ignition characteristics of other common fluids (notably, diesel) and the influence of irregular hole shapes on mist formation (e.g. corrosion holes, leaking flanges and cracks). The experimental rig at Cardiff also had limitations in terms of the height of the test enclosure (2.5 metres), which meant that the full vertical extent of the flammable mist could not be measured.

The JIP work finished in 2015 and since that time, HSE has sought to continue research on this topic, with the aim of producing more complete and comprehensive guidance on area classification of mists of high-flashpoint fluids. Compared to the decades of research on flammable gas releases, the work on flammable mists is still at an early stage. Moreover, flammable mists are considerably more complicated than gases or dusts, with the additional difficulties of spray breakup, droplet evaporation and surface-wetting effects.

The aim of this paper is to take a fresh look at recent flammable mist incidents and build upon the earlier review of Santon (2009). The objective is to assess whether there is clear evidence that mist fires and explosions continue to take place that justify further expense of another research project. The current review is primarily based on analysis of data submitted on ROGI forms (Report of an Oil and Gas Incident) provided by operators of oil and gas installations to the UK Offshore Safety

Directive Regulator (OSDR)[1]. Since 2015, the ROGI form has included a specific entry on flammable mists. In addition to analysis of these incidents on the ROGI forms, this paper also discusses other relevant incidents in the French ARIA incident database and German ZEMA database. Recent work undertaken by Université de Lorraine in collaboration with Université de Technologie de Belfort-Montbéliard, sponsored by General Electric, to support an incident in a gas turbine enclosure is briefly reviewed, and other recent HSE research on flange guards and mist detectors is summarised.

Analysis of Recent Mist Incidents in the UK Offshore Oil and Gas Industry

Following the Cullen Report into the Piper Alpha disaster (Cullen, 1990), dutyholders of offshore oil and gas installations on the UK Continental Shelf (UKCS) have voluntarily notified the Health and Safety Executive (HSE) of all potentially dangerous hydrocarbon releases, in addition to those that they are obliged to report under the Reporting of Injuries, Diseases and Dangerous Occurrence Regulations (RIDDOR). HSE compiles this information into the Hydrocarbon Release Database (HCRD), which is available on the HSE website: http://www.hse.gov.uk/offshore/hydrocarbon.htm (accessed 15 January 2019).

Dutyholders report via a standard form, which requires comprehensive information regarding the type of material, the temperature, pressure and rate and duration of the release, the type of equipment, cause of release, detection and subsequent action and investigation.

Since the start of 2016, the ROGI form has included the question: "Did a liquid spray / mist release occur?". Between January 2016 and July 2018, the duty holders answered this in the affirmative on 25 occasions. This represents 10% of all reported releases (258 in total) during this period and 21% of releases of liquid (120 in total) during this period. It should be noted that two of these incidents are described as process gas releases and it is not immediately clear from the descriptions what the nature of the observed mist was.

Fluids involved in spray / mist releases

Figure 1 below shows the types of fluids released in the reported spray / mist incidents. Less than half of the reported spray / mist releases are process fluids. In total, 20% of the reported releases were from diesel sources. Hydraulic oil and lubricating oil comprised another 20% of the releases. These findings are broadly in keeping with earlier analysis of the HCRD (Burrell, 2014) which showed that of 48 flash fires in the period from 2000 to 2005, 34 were of these substances (11 diesel, 3 hydraulic oil, 20 lubricating oil).

Size and pressure of releases

Figure 2 below shows the quantity of each of the spray / mist releases and the pressures at which the releases occurred. The majority of releases were greater than 10 kg, so could have produced a substantial flammable cloud. Approximately half of the releases were greater than 100 kg.

There are a wide range of release pressures. According to the Energy Institute's Model Code of Safe Practice, EI15 (Energy Institute, 2015), releases "under pressure" should be considered likely to give rise to a flammable atmosphere even if the liquid temperature is below the flashpoint, hence requiring hazardous area classification. EI15 does not specify the limits of the term "under pressure". However, only two of the spray / mist releases occurred at a reported pressure of less than 5 barg. Therefore, most of the releases should be considered to come under the EI15 definition of "under pressure". Five of the releases occurred at pressures in excess of 100 barg. Of these five releases, three involved the release of hydraulic oil.

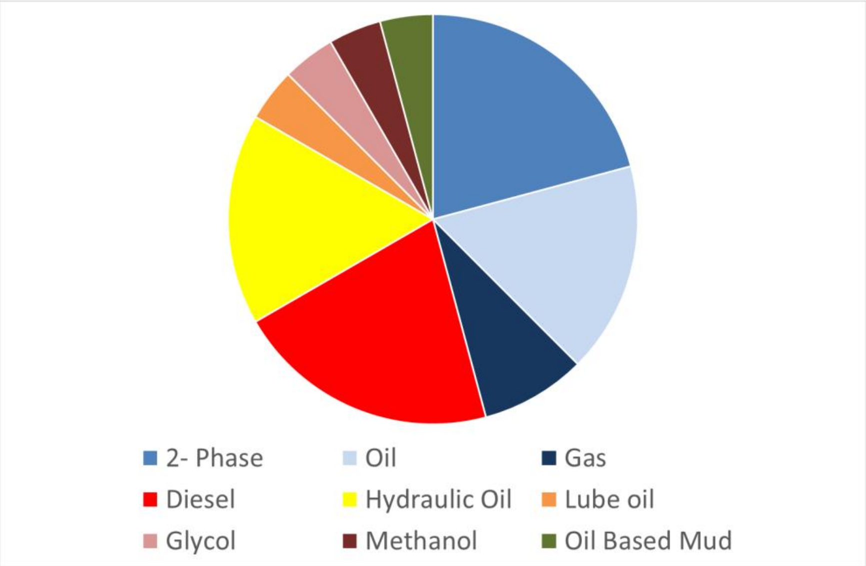

Figure 1: Proportions of the various fluids released in the HCRD spray / mist incidents

[1] For details, see http://www.hse.gov.uk/osdr/reporting/incidents-to-osdr.htm, accessed 7 June 2018.

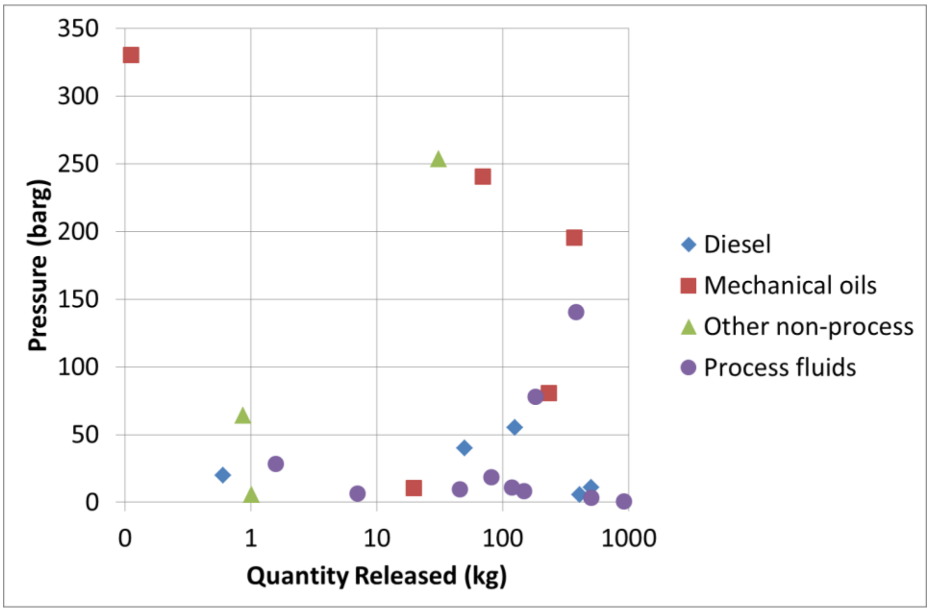

Figure 2: Quantity of releases and pressure of releases in the HCRD spray / mist incidents

Temperatures of liquids released

Information on the temperature of the liquid released is not always completed in the HCRD. For the 25 incidents where a spray / mist release was reported, the temperature of the liquid being released was only reported on seven occasions. Table 1 below gives details of the substances released. A tentative conclusion from this data is that most of the releases took place at temperatures above ambient. (The three relatively low temperature releases of these seven releases took place in winter: the diesel incident in 14 Jan 2016 and the two hydraulic oil incidents in February 2018 and November 2016.)

Table 1: Temperature of liquids released in the HCRD spray / mist incidents

Substance	Quantity (kg)	Pressure (barg)	Temperature (°C)
Hydraulic Oil	70	240	12
Hydraulic Oil	235	80	15
Diesel	125	55	20
Glycol	1	5.6	39
Lube Oil	20	10	80
Oil (process)	120	Not given	40
2-Phase (process)	7	6.0	78

Release hole sizes

Figure 3 below shows the hole sizes for the spray / mist releases. These are given as the equivalent diameter of a circular orifice required to give the same release rate as the measured release rate. Note that the X-axis has a simple number scale, to aid visualisation of the data by stretching out the data points. Seven of the equivalent diameters are close to 1 mm diameter (between 0.56 mm and 1.57 mm). Sixteen of the release diameters range from 1 mm to 10 mm, and eleven of these are greater than 3 mm in diameter.

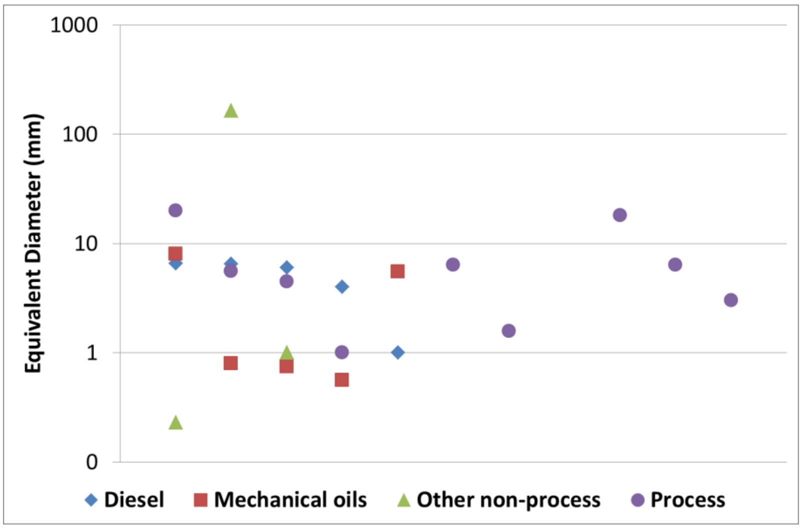

Figure 3: Equivalent diameter of the orifices for the HCRD spray / mist release incidents

Hole geometry

An attempt has been made to identify the shape of the holes based on the descriptions given in the HCRD. There are four categories of hole shape: fully circular, annular, slit shaped and diamond shaped. Figure 4 below shows the proportion of the holes in each category. For the purposes of shape classification, releases described as "pinhole releases" (4 in total) have been classed as circular. Nearly half of the releases had a circular shape (10 out of 23 releases). Details of the hole shape were not provided for three of the releases.

Further details of the HCRD mist incidents discussed above are given in Appendix A.

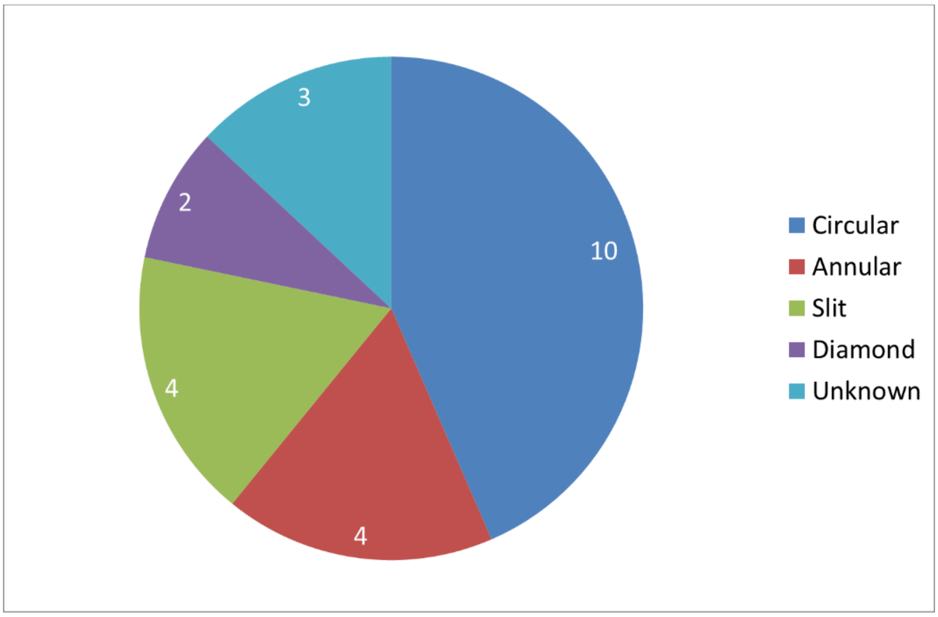

Figure 4: Hole geometry for the spray / mist releases

Review of Incidents in the ARIA and ZEMA Databases

Additional accidents were also collected from two databases: the French ARIA (Analysis, Research and Information on Accidents) database and the German ZEMA (Zentrale Melde- und Auswertestelle für Störfälle und Störungen in verfahrenstechnischen Anlagen) database. These databases present a catalogue of industrial accidents and incidents that occurred in France, in Germany and abroad. Their basic objective is to gather information and experience and help provide feedback and support to risk prevention. Neither database is intended to be exhaustive.

The French Ministry of Environment's organisation (Bureau d'Analyse des Risques et des Pollutions Industrielles, BARPI) publishes the ARIA database online[2]. It contains a short summary of all the recorded accidents in France since 1794, and also includes important accidents abroad. In total, there are approximately 47,000 accidents and incidents listed. Some 1,200 new events are added to the database each year. It became standard practice since 2003 to systematically make an inventory of new accidents that occur at high-risk facilities, or accidents that occur at any classified facility if they involved fatalities. Here, "classified" refers to a site that presents either a high environmental risk or a high risk to human health and safety. The information is mainly collected by fire and rescue services and by the regional environment agencies.

The German ZEMA accident database is published by the German Environmental Agency and contains accidents in Germany notified according to the German Accident Regulation (Stoerfallsverordnung)[3]. It is also linked to the German Committee for Incident Evaluation (AS-ER) of the Commission on Process Safety (KAS) which is in charge of the evaluation of non-reportable incidents with hazardous substances in accordance with German accident regulations. The primary purpose of the work is the collection, evaluation and dissemination of all information from incidents to help improve the state of safety technology.

These databases were searched for industrial accidents involving high-flashpoint fluids in fixed installations in France and Germany for the time period between 1965 and 2017. Materials, type of activity, causes and main consequences were gathered to identify relevant accidents. The analysis of the identified events consisted then in extracting from the accident reports some explicit criteria (date, activity, dangerous goods/substances, consequences, causes, etc.).

These two databases have different scope and coverage and in order to allow comparison:

- Only accidents that induced two-phases / spray / mist releases into air were considered. Soil or water releases as well as transport accidents have been excluded;
- To complete this first screening, the following terms were also used and combined: "aerosol, spray, two-phase release, mist, cloud, oil, leak and pressure";
- The following types of industries were assessed: oil and gas, oil refineries, petrochemical, and chemical industries. Other various industries could also be identified in ARIA database;
- Typical high-flashpoint fluids were also specifically searched for, to improve the completeness of the identified events. These fluids included: oil-based materials (diesel, crude oil, thermal oil, fuel oil, hydraulic oil, pyrolysis oil, tar oil) and other additional materials prone to mist release (methanol, phenol, toluene, phthalic anhydride).

The evaluation of the relevance of many accidents was often difficult as it is very rarely mentioned explicitly when an aerosol / mist / spray of fluid is involved, which introduces some uncertainty in the assessment. Unlike the HCRD, there is no specific section requesting dutyholders to identify mist / spray release events. Only the description of the event can be used to identify specifically a mist release (and, in relevant cases, a subsequent fire or explosion). Generally speaking, the ARIA database contains much more detailed information than the ZEMA database. The level of detail also varies significantly from one accident report to another, often depending on its severity. Release pressure, quantities and orifice characteristics are occasionally mentioned, but not as a general rule. As a consequence, the data interpretation is much more incomplete than what is possible with the HCRD. However, it is still relevant since it complements and reinforces some of the conclusions from the analysis of the HCRD, while also highlighting the fact that accidents related to mists concerns a broader range of industries than just the oil and gas industry.

We have identified 19 mist incidents out of 464 incidents in the ZEMA database that involved a release of material into the atmosphere, and 40 mist incidents out of 9,725 incidents in the ARIA database that were related to the potential release of flammable liquids or pressurised gases (including those where there was a fire or explosion, or a release of the fluid without ignition).

Some general trends were extracted from the analysis of the events from the databases, despite the limits mentioned above concerning interpretation due to the lack of sufficiency / completeness of quality and depth of information.

Accidents from the ZEMA and ARIA databases mainly concerned oils (thermal, hydraulic or lube oils – 27 cases out of 40 for the ARIA database), liquid fuel hydrocarbons (crude oils, diesel, gasoline, fuel oil, kerosene – 8 out of 40 cases) or other minor compounds such as methanol, liquefied ethylene or propane. Figure 5 shows these incidents according to the material released

[2] https://www.aria.developpement-durable.gouv.fr, accessed 15 January 2018.

[3] http://www.infosis.uba.de/index.php/de/zema/index.html, accessed 15 January 2018.

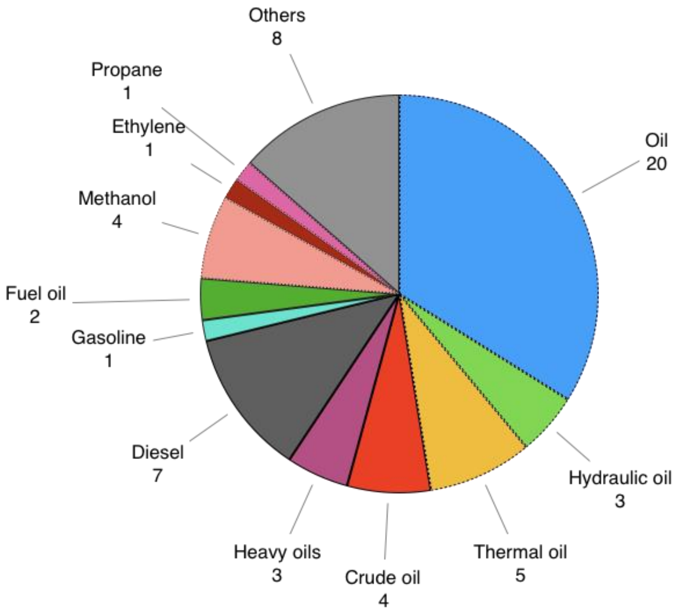

Figure 5: Proportions of the various fluids released as a spray / mist from ZEMA and ARIA database

In view of the analysis of the quantitative data collected in the ZEMA and ARIA databases, it appears that the quantity of fuel emitted was always greater than 100 kg, whatever the case considered. In addition, 8 of these accidents reported releases greater than a ton of material. These large quantities are of course probably not statistically representative of the actual cases of hydrocarbon mist generation, but are rather characteristic of how the data are collected and selected for the databases, which highlights larger accidents, i.e. of stronger severity.

The fluid release pressures that generated the mists ranged from 3.6 bar to 200 bar. However, half of the events with quantifiable data involved an initial fluid pressure between 5 bar and 30 bar. Only one accident related to a pressurized release of a hydraulic oil at more than 100 bar. As for the orifices, their size ranged between 6 mm and 300 mm with an average diameter of 10 mm. It is difficult to be more precise about their shape. Indeed, the causes of rupture, and thus the shapes of the orifices, were very different from one accident to another, including: corrosion, seal rupture, valve opening, pierced filters, faulty flanges, etc.

Table 2 Summary of releases for which detailed information is available in the ARIA and ZEMA databases

Substance	Quantity (kg)	Hole size (mm)	Pressure (barg)	Temperature (°C)
Thermal Oil	2,200	-	-	274
Thermal Oil	4,400	-	-	275
Oil	170	-	-	290
Oil	-	51	18	50
Oil	2,400	6	13	40
Oil	-	6.5	8	-
Oil	600	-	-	60
Hydraulic Oil	-	-	200	450
Diesel	-	-	50	230
Diesel	-	205	48	343
Methanol	-	-	3.6	149

Table 2 shows that the temperatures of the fluids emitted are, for 10 of the cases, higher than 200 °C, and up to 450 °C for a hydraulic oil. For four of the cases, the temperature of the mist before its ignition was lower than 60 °C. The so-called thermal oils were generally released at a higher temperature than the other oil mists.

For 36 out of 40 hydrocarbon mist incidents collected from the ARIA database, an ignition occurred, which was followed by a fire (in 19 cases) or an explosion (in 15 cases). This demonstrates the potential severity of spray / mist releases of high-flashpoint fluids.

Further details of the ARIA and ZEMA incidents discussed above are given in Appendix B and C.

Other Related Work

Research at the University of Lorraine, France

Studies have been performed at University of Lorraine to study the generation of oil mists and to characterize their droplet size distribution, their lower explosive limit, minimum ignition energy, explosion severity and flame propagation velocity (Dufaud *et al*., 2015). Tests were carried out on fresh / unused oil, on oil collected after one life-cycle in a gas turbine (after aging) and on lube oil containing additives against corrosion. Degraded conditions were also simulated by mixing flammable products (principally, cleaning solvents or liquid fuels) with the oils.

The samples could not be ignited by disruptive discharges of energies lower than 1 Joule in a semi-confined configuration (a modified Hartmann tube). However, explosion tests in the standard 20 L sphere showed that these oil mists could be ignited with a much stronger 2500 J ignition source for droplets of a few tenth micrometres in diameter, or even at 2000 J for smaller droplet size distributions (6 µm in diameter). The lower explosive limits ranged from 80 g/m^3 to 250 g/m^3, which was consistent with data from the literature. It therefore appeared that pure lubricating oil mists were flammable and could cause explosions, but that they required high or very high ignition energies.

The effect of oil aging was not noticeable with regard to the flammability limit and the minimum ignition energy of the unused oil. Moreover, the addition of flammable volatile compounds such as iso-octane and methyl butanoate, was found to greatly change the explosive behaviour of these mists. For solvent / fuel concentrations lower than 10% to 20 % by volume, the decrease of the MIE and LEL was not significant. However, when the concentration was increased up to 30% to 35% by volume, the MIE decreased from 2 kJ to 6 mJ or 10 mJ, which is very low in the context of the ATEX Directives. It should be added that these experiments were only conducted on specific products / mixtures and that their results cannot be directly extrapolated for other oils / fuels. For instance, in the ARIA database, the case of an explosion of a 600 kg lube oil tank is described. The generation of electrostatic discharges by blowing air through a filter was sufficient to ignite the oil mist. It is considered that contamination of the oil with toluene (4%) lowered its flash point from 220 ° C to 55 ° C and is one of the main causes of this accident.

Flange Guards

One potential method of controlling oil mist hazards by preventing production of mists at source is the use of “flange guards”. These are devices fitted around flanged joints to prevent a mist forming spray being produced by any leak at that flange. In 2015, GENSIP (the Thermal Generators Safety and Integrity Programme - a non-commercial grouping of thermal power generation companies) commissioned HSE's Health and Safety Laboratory to undertake a “state of the art” review of available flange guard systems. In particular, this looked at standards and testing available to demonstrate the effectiveness of different flange guard products. The review identified more than 40 suppliers of flange guards with products addressing a range of leak issues not just flammable mist formation. It found that there is no standardised testing of products, although some suppliers stated they had carried out “in-house” or third-party testing of their product’s effectiveness. Little, if any, of this data is openly available. Anecdotal evidence suggests that performance is variable, with some commercial products performing poorly when exposed to even moderate pressure leaks.

Mist Detectors

Detection of an oil mist at an early stage may allow control of the leak or isolation of potential ignition sources before the mist can be ignited. HSE is completing an as yet unpublished study of oil mist detector systems and their testing. Many detector systems are optically based, using technologies such as obscuration or diffraction which are affected by droplet size as well as concentration. Where systems are designed for a particular type of droplet (such as condensation aerosols formed when oil evaporates from hot surfaces into colder air) they may not respond correctly to mist clouds formed in different ways (e.g. leaks from pressurized systems). Current standards for testing appear to be based around the hazards found in marine engine crankcases, where droplet sizes are very small (< 5 µm). The HSE work has also been considering how standardised testing of oil mist detectors for spray releases might be undertaken.

Discussion and Conclusions

Previous analysis of the HCRD (Burrell 2014) and the present analysis both indicate that a substantial number of liquid releases in the offshore industry (around 10% of all releases) result in the generation of a spray or mist. The EI15 guidance conservatively suggests that such releases should be regarded as flammable. However, there is little scientific basis for determining whether a specific release condition will give rise to a spray or mist which is flammable.

High-flashpoint fluids such as lube oil, hydraulic oil and diesel have wide-ranging applications. The HCRD incidents highlight these fluids as being of particular concern. It is clear also from the incidents analysed in the Aria database that spray / mist releases occur throughout a wide range of industries.

The flammable mists JIP led by HSE between 2009 and 2014 investigated the flammability of hydraulic oil mists and found that it was not possible to ignite the mist even at a discharge pressure of 130 barg. Similarly, the experiments were not able to ignite a light fuel oil mist when discharged at ambient temperature at pressures of up to 20 barg. However, it is self-evident that fuel oil must be flammable under a certain set of conditions. Previous analysis of UK offshore incidents (Burrell 2014) showed that hydraulic oil and lubricating oil mists can ignite (they produced 3 and 20 fire or explosion incidents, respectively). Similarly, analysis of the ARIA database presented here found two incidents of a hydraulic oil mist igniting Furthermore, half of the incidents extracted from the ARIA database are simply described as "oil". The JIP research should not be considered the final, definitive work on the mist flammability of these substances. Compared to the decades of research on flammable gas releases, the work on flammable mists is still at an early stage.

A trend that emerges from both the HCRD and the ARIA database is that real-life spray / mist releases are often from orifices with an equivalent diameter much larger than 1 mm: half of the releases are from orifices in the range 3 – 10 mm in the HCRD, whilst incidents in the ARIA database had orifices larger than 6 mm in diameter, with 10 mm being the average. In comparison, the JIP research used an orifice of just 1 mm diameter. The authors are not aware of any research into the flammability of mists from such large orifices, and indeed it is difficult to undertake such large-scale tests in a controlled environment.

A further issue raised by analysis of the HCRD incidents is that around half of the incidents involved a release from an orifice that was non-circular in shape. The previous JIP only considered releases from a plain circular 1 mm diameter orifice, with a length to diameter ratio of 2. Whilst work has been done on sprays from different-shaped orifices, this has primarily been driven by different types of applications, e.g. fire suppression and fuel injectors. It is unclear if this data can be applied equally within the context of process safety, where releases may be produced by leaking flanges or corrosion holes.

To address these knowledge gaps, HSE is currently leading a second JIP that aims to make further progress in understanding the flammability of mists of high-flashpoint fluids. This project will have three work streams (HSE 2018):

- Assessing the ignitability of diesel mists;
- Exploring how the shape of the orifice affects the mist ignition characteristics;
- Larger-scale experiments to measure the full extent of the flammable mist produced by spray releases.

The work will help to advance the scientific understanding of mist flammability and underpin new guidance.

Disclaimer

This report and the work it describes were co-funded by the Health and Safety Executive (HSE), INERIS and Université de Lorraine. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

References

Bettis, R., Burrell, G., Gant, S.E., Coldrick, S., Mouzakitis, K. and Giles, A., 2017, Area classification for oil mists - final report of a Joint Industry Project", Health and Safety Executive, Research Report RR1107. Available from: http://www.hse.gov.uk/research/rrhtm/rr1107.htm, accessed 7 June 2018.

Burrell, G. and Gant, S.E., 2017, Liquid classification for flammable mists, Research Report RR1108. Available from: http://www.hse.gov.uk/research/rrhtm/rr1108.htm, accessed 7 June 2018.

Burrell, G. and Jagger, S., 2014, Flammable mists from accidental hydrocarbon releases offshore. Health and Safety Executive, Research report R1001. Available from: http://www.hse.gov.uk/research/rrhtm/rr1001.htm, accessed 7 Jan 2019

Coldrick, S. and Gant, S.E., 2017, CFD modelling of oil mists for area classification, Health and Safety Executive, Research Report RR1111. Available from: http://www.hse.gov.uk/research/rrhtm/rr1111.htm, accessed 7 June 2018.

Cullen, W. D. 1990. The public inquiry into the Piper Alpha disaster. London: H.M. Stationery Office. ISBN 0101113102. Available from: http://www.hse.gov.uk/offshore/piper-alpha-public-inquiry-volume1.pdf, accessed 15 January 2019.

Dufaud, O., Charvet, A., Mougel, G., Luthun, S., Molière, M., Brunello, D., Perrin, L., Delimoges, S., and Couchot, M., 2015, Generation, characterization and ignition of lube oil mists, ASME Turbo Expo 2015: Turbine Technical Conference and Exposition, Volume 4B: Combustion, Fuels and Emissions, Montreal, Quebec, Canada, 15-19 June 2015.

Energy Institute, 2015, Model code of safe practice: Area classification code for installations handling flammable fluids, Fourth Edition, Energy Institute, London, UK. Available from: https://www.energyinst.org/technical/safety/ei-15-hazardous-area-classification, accessed 7 June 2018.

Gant, S.E., 2013, Generation of flammable mists from high flashpoint fluids: literature review, Health and Safety Executive, Research Report RR980, 2013. Available from: http://www.hse.gov.uk/research/rrhtm/rr980.htm, accessed 7 June 2018.

Gant, S.E., Bettis, R., Santon, R., Buckland, I., Bowen, P. and Kay, P., 2012, Generation of flammable mists from high flashpoint fluids: Literature Review, IChemE Hazards XXIII Conference, Southport, UK, 12-15 November 2012. Available from: http://www.icheme.org/~/media/Documents/Subject%20Groups/Safety_Loss_Prevention/Hazards%20Archive/XXIII/XXIII-Paper-43.pdf, accessed 7 June 2018.

Gant, S.E., Bettis, R., Coldrick, S. Burrell, G., Santon, R., Fullam, B., Mouzakitis, K., Giles, A. and Bowen, P., 2016, Area classification of flammable mists; summary of joint-industry project findings, IChemE Hazards 26 Conference, Edinburgh, UK, 24-26 May 2016. Available from: https://www.icheme.org/~/media/Documents/Subject%20Groups/Safety_Loss_Prevention/Hazards%20Archive/XXVI/XXVI-Paper-38.pdf, accessed 7 June 2018.

HSE, Hydrocarbon Release Database (HCRD), 2017. Available from http://www.hse.gov.uk/offshore/statistics.htm, accessed 9 Jan 2019.

HSE, Further work towards area classification for oil mists (MISTS2), HSE, 2018. Available from www.hse.gov.uk/aboutus/assets/docs/shared-research-flammable-mist.pdf , accessed 8 Jan 2019

Mouzakitis, K. and Giles, A., 2017a, Experimental investigation of oil mist explosion hazards (Phase 1), Health and Safety Executive, Research Report RR1109. Available from: http://www.hse.gov.uk/research/rrhtm/rr1109.htm, accessed 7 June 2018.

Mouzakitis, K. and Giles, A., 2017b, Experimental investigation of oil mist explosion hazards (Phase 2), Health and Safety Executive, Research Report RR1110. Available from: http://www.hse.gov.uk/research/rrhtm/rr1110.htm, accessed 7 June 2018.

Santon, R. C., 2009, Mist fires and explosions — an incident survey. Proc. IChemE Hazards XXI Symposium & Workshop, Manchester, UK. Available from: https://www.icheme.org/~/media/Documents/Subject%20Groups/Safety_Loss_Prevention/Hazards%20Archive/XXI/XXI-Paper-054.pdf, accessed 7 June 20

Appendix A: Summary of mist incidents reported to OSDR from 2016 to 2018

URN	Where on the site did the dangerous occurrence happen?	What type of work was being undertaken at the time of the event?	Cut down description of circumstances	Non Process Type	Process Type
6879	Well B25 Conductor, Wellhead Module (M01), Drilling Module (M22).	The subsea cutting of the well B25 conductor/multistring.	During well shut down operations, mist was observed discharging from the top of the proving string at the drill floor.	N/A	OIL
6877	2" Helifuel transfer line above Main Deck	Daily Helifuel checks and sampling.	During daily helifuel checks, the pumps on the helifuel package were started and a sample obtained up on the helideck. At the same time, deck crew were on the main deck and noticed a smell of 'diesel / heli-fuel'. Subsequent investigation found a pin hole leak on the 2" helifuel line to the helideck package running along the main deck	HELIFUEL	N/A
6871	Main Deck - Forward	Process star-up following June 2018 shut-down	Positive displacement pump for methanol was started up, inadvertently pumping against a dead head due to closed shut down valve. A 3/4" Swagelok fitting parted resulting in methanol release. Pump was manually shut down almost immediately by Production Technician.	METHANOL	N/A
6846	Process Module C5 Mezz	No work was being undertaken, routine production operations	During routine production operations, a pin hole hydrocarbon leak was spotted by the area technician in module C5Mezz. The pin hole leak was identified to be on GC2-04 Production routing valve.	N/A	2-PHASE
6845	Outside, open process module adjacent to FCV-10004	Platform restart and testing of recently replaced cartridge seal on P-1031.	Failure of stem gland packing securing mechanism led to a leak from FCV during platform restart	N/A	OIL
4905	Well A41 Wellhead Hydraulic Control Unit (Brisco Unit)	Routine production operations	A release of hydraulic oil from underneath the wellhead control unit cabinet. A 1/4" NPT fitting was determined to have failed.	HYDRAULIC OIL	N/A

4865	Gas Turbine 1 accessory compartment	Normal operations	On investigation it was identified that there was a leak of diesel inside the turbine enclosure coming from the area of the liquid fuel pump. Weld joint on diesel supply pipework to GT1 failed due to misalignment of pipework causing stress on weld	DIESEL	N/A
4848	Gas Turbine 1 Accessory Compartment	Planned maintenance routine to changeover fuel from fuel gas to diesel	A watchkeeping check during a planned activity to transfer Gas Turbine 1 from fuel gas to diesel fuel identified a spray of diesel from the lid of a filter housing in the accessory compartment of the turbine. The turbine was shutdown and all diesel release was safety contained within the enclosure, and subsequently to closed drains system.	DIESEL	N/A
4845	A5Z Wellhead	None in this area	An audible gas leak was present on the unmanned platform after helicopter had departed. 2 men were dispatched to investigate the leak and confirmed that a Grayloc fitting had failed on well A5Z. Topside venting of the production header was then manually initiated and the gas release was monitored from a safe area.	N/A	GAS
4839	South end of C1-Mezz / Flow Control Valve FCV-10005	Normal Production - Process re-start following a planned outage (unrelated to area of the event)	Operator noticed a mist coming from an oil metering skid caused by an oil leak from around the MOL pumps discharge valves. This was the result of mechanical failure of main valve body.	N/A	OIL
4838	Auk Module U1/Turbine Hall	BLANK	A crew member noticed excessive fume from the turbine enclosure ducting outlet. After visually inspecting the turbine enclosure through the windows, an internal inspection was conducted. A small pin-hole leak was observed allowing a small spray of diesel, giving off smoke. This soon ceased. Cause of failure: Loose exhaust cladding vibrating against diesel fuel pipe caused pin-hole leak.	DIESEL	N/A
4835	Module 3 - on the discharge line of the LP separator Crude Oil Transfer Pump	Normal Operations	Plant operating under normal conditions. Operations technician was in the area undertaking normal duties on the plant when he noticed dripping onto the forward edge of the bund below the LP separator. He quickly investigated the source of the leak and radioed in to CCR to report the issue. Operations supervisor called to the scene who instructed the CCR to shutdown production and then had the operations technicians drain the line down to the LP separator bund. No emergency response was required.	N/A	2-PHASE

4829	Douglas Accommodation Platform main deck area within the compressor enclosure.	None - steady production operations. Both Alpha and Bravo Plant Air Compressors operating as normal.	GPA initiated by indication of smokes on multiple detectors on Douglas Accommodation Plant Air Compressor enclosure B. ERT confirmed smoke/mist from the package. Proceeded to investigate and on opening enclosure package door, confirmed no fire in enclosure but full of oil mist/smoke and compressor lubricant on the package floor. Machine has lost lubrication oil contents via a sheared oil receiver sight glass fitting with approximately 25ltrs of hot lubrication oil (~80degC at normal operating conditions) contained within the enclosure on the floor and evidence of oil spray throughout the enclosure.	LUBE OIL	N/A
4823	East skid deck. Hydraulic work-over unit BOP over GA-23 production well.	Run in hole with fishing assembly.	Mixture of gas, oil and brine released when topping up drill string during running in of hole.	N/A	2-PHASE
4817	GTG Turbine C - Main Deck - Aft / Starboard corner	Start-up-procedure - Commissioning Phase. Lead up to introduction of hydrocarbons to the platform	Release of diesel supply within small bore tubing within diesel generator. At 23:30, an alarm of confirmed flame indication was received in the CCR and the turbine shutdown automatically. Diesel fuel ignited on contact with hot surface of engine core.	DIESEL	N/A
4813	Module 3 - Mezzanine Level	Production Operations	Loss of containment due to a perforation on crude oil outlet header located on the oil metering skid on Module 3 Mezzanine. Following the observation of the release an ESD was initiated by the MCR following notification and the crude oil outlet header was manually isolated to reduce the loss of hydrocarbon inventory to the module.	N/A	OIL
4807	ST-3 weather deck North side on the top of a coiled tubing rig tower	Well clean up operations using concentric coiled tubing.	During well clean up operations, gas was observed to vent from the top of the coiled tubing equipment during the process of Pulling Out of Hole. The inspection team determined that the release had been from the Coiled Tubing itself as the outer (2 inch) sheath had split, releasing gas which was inside the annulus between the inner (1 inch) and outer (2 inch) tubing and from the stuffing box.	N/A	GAS
4792	CP73 8m Impulse line within module 02/07	Production Operations	During a site tour a scaffolder noticed fluid jetting from an instrument impulse line that appeared to have detached from the flow line on well CP73. He immediately contacted the control room to report the release. The control room operator shut-in the well and requested the area tech to investigate the source of the release. Upon inspection of the 8mm impulse line, it was confirmed that it had sheared at a connector. No fixed detection systems were activated as a consequences of the release and all other platform operations remained online.	N/A	2-PHASE

4789	Sub Structure BOP Deck	Drilling Operations	With regard to RIDDOR this incident is not considered as reportable based on the conclusion that the non-petroleum hydrocarbon fluid is not hazardous for this incident.	OIL BASED MUD	N/A
4780	A' Turbine Accessory compartment	Normal Operations	Operator found Turbo T32 turbo oil to be leaking from small bore pipework on the hydraulic supply to the liquid fuel pump in the GE-1201A Turbine ancillary enclosure. The leak path was isolated, reported and the accumulated fluid cleaned up.	HYDRAULIC OIL	N/A
4775	Between the control panel and Xmas tree	Normal Production	Leak developed in Module 1 on the DHSV control line for SP80, between the control panel and xmas tree. As the location of the leak was over open grating, 130 litres of T32 hydraulic oil was lost to sea.	HYDRAULIC OIL	N/A
4760	ESDV HPU Skid	Plant Start-up	During start-up, hydraulic fluid was sprayed from a fitting onto surrounding pipework. Cause not described.	HYDRAULIC OIL	N/A
4718	Mezz level of Glycol skid - Glycol filter V-3604A	Normal platform production - no work being carried out on skid	Lid from a glycol filter released, causing rich glycol to be ejected - the result of wrong material being used for the tie down boss. Gas detectors initiated emergency shutdown.	GLYCOL	N/A
4715	Wellbay Area	Production Operations	Gas release leading to a production shutdown initiated manually from Main Control Room MCR. GPA initiated and personal muster to TR.	N/A	2-PHASE
4681	Power Generation Module	Operation of the power generator	A diesel leak from the B Power Generator enclosure was noted by the operations team during a routine walk about. The power Generator was manually shutdown immediately. Approximately 75kg was contained within the Power Generator enclosure, with the remainder released to the deck and open drains system.	DIESEL	N/A

URN	Estimated quantity released KG	Equivalent hole diameter [mm]	Duration of leak (min)	Hazardous Area Classification (1 / 2 / unclassified) (Directive 1999/92/CE)	Actual Pressure (barg)	Actual temperature (Deg C)	Did ignition occur?	A3 Preliminary direct and underlying causes
6879	926.00	18.00	19.00	1	Ambient - Very Low - Discharge hose is open to sea, landing string open to atmosphere therefore no contained pressure. No pressure noted on B annulus when well handed over to drilling.	BLANK	NO	Unidentified residual well bore fluids within the conductor annulus.
6877	0.04	1.00	1.00	1	6.00	BLANK	NO	Internal corrosion of the pipeline
6871	0.87	20.00	<0.17	2	64.00	BLANK	YES	Preliminary investigation indicates valves were not in alignment during start-up resulting in dead-heading resulting in failure of SBT fittings. The independent Petrofac investigation team identified the immediate cause as attributed due to a dynamic shock when the positive displacement pump P-2587B being started against a closed Actuated Shutdown valve near the pump head combined with under tight Super Duplex compression fittings.

6846	1.59	0.56	39.00	2	28.00	BLANK	NO	The direct cause of the leak was due to erosion of the valve inlet due to high velocity gas containing sand. The underlying cause was failure to adequately inspect the valve using NDT techniques during operation.
6845	82.40	5.60	1.95	2	18.00	BLANK	NO	Failure of stem gland packing securing mechanism.
4905	70.00	0.80	16.00	2	240.00	12.00	NO	Investigation on-going. It was noted that the fitting had PTFE tape applied as a thread sealant, a method which is no longer used. The casual factor is determined to have been either a failure of the thread sealant or the threads within the solenoid block. The onshore failure mode analysis will aim to determine this.
4865	504.00	6.50	10.00	UNCLASSIFIED	10.90	BLANK	NO	Misalignment of pipework causing stress on weld
4848	410.00	6.58	11.00	UNCLASSIFIED	5.50	BLANK	NO	O ring sealing arrangement on filter housing lid has failed. Design of diesel fuel check valve arrangement suspected to have caused back pressure in filter due to passing check valve.
4845		UNKNOWN	6480.00	2	31.72	13.00	NO	Need to be assessed by investigation team.
4839	385.00	3.00	10.00	2	140.00	BLANK	NO	Mechanical failure of main valve body. Unable to determine root cause until valve can be removed for further inspection
4838	49.83	0.75	21.00	UNCLASSIFIED	40.00	BLANK	NO	BLANK

4835	150.00	4.00	10.00	2	8.00	BLANK	NO	Incident caused by failure of pipe integrity specifically external corrosion under pipe support. Inspection data is available and preliminary investigations reveal that the inspector deemed the spool to be in adequate condition. An investigation team has been established and the expectation is that the investigation team will establish the facts and provide recommendations by 14/6/17. Following an investigation and completed Incident review Panel (IRP) the findings are as follows: Immediate Cause - There was a total failure of integrity of 8"-F-10012-HA2D. The pipework had failed due to crevice corrosion localised to the pipe support at TP-113. Underlying Causes · Through-out the inspection history of this line excessive pipework movement and vibration has referenced multiple features (including TP-113) across multiple reports. This pipe work movement will have exacerbated the wall loss in this area. · An earlier MCDR raised against the failed line (for FM and movement) was closed with incorrect justification for both damage mechanisms. Root Cause - During the 2015 Inspection activity, the failure point (TP-113) was reported as having 3mm scale height. From the report, the reported defect was significantly higher than 3mm and closer to 12mm. This should've been the trigger for an MCDR escalation and Integrity review. · This misreporting was subsequently not picked up during the inspection report review cycle. Anomaly underestimation is also apparent on other features contained within this report e.g. TP-126. · Any MCDR raised at this point would certainly have led to further CUPS inspection and relevant mitigation.
4829	20.00	6.35	1.00	UNCLASSIFIED	10.00	80.00	NO	Analysis of fitting failure is to be undertaken. Likely to be vibration fatigue failure of fitting. Possible incorrect design as level glass mass may, in conjunction with vibration in this package - excessive without additional support. TBC

4823	508.00	165.00	0.50	1	40.00	BLANK	NO	The tubing had previously been cut before the hydraulic work-over unit arrived on location and it had therefore not been possible to confirm communication through the SSSV for bull-heading hydrocarbons into the formation. The gas bubble break out at surface is suspected to be from gas bubble migration from a stored column of hydrocarbons under the SSSV flapper.
4817	0.60	6.35	60.00	UNCLASSIFIED	20.00	BLANK	YES	Incorrect maintenance procedures.
4813	120.00	6.00	4.00	2	10.40	40.00	NO	Root cause identified as Microbial-Induced Corrosion (MIC). The release is estimated to have occurred for about 3 minutes and was brought to a safe conclusion with both the initiation of an ESD and manual isolation applied locally to reduce the volume of hydrocarbon loss. There were no reported operational deviations within the metering stream that may have given cause for the incident. The metering stream has been subject to previous inspection and has was to have been checked again in by July 2017. The spool in question has not previously been subject to an MCDR.
4807	185.00	5.50	1.33	2	77.38	BLANK	NO	The cause of the gas release was the 2” coiled tubing splitting at the Coil tubing connector. This was caused by the bottom hole assembly (BHA) (which is not flexible) trying to go around the goose neck of the injector head. This was caused by the BHA passing through the Stripper Brass bushings. The Brass bushings should be a smaller ID than the BHA OD in order to prevent this, however these were found to be worn.
4792	46.00	8.00	118.00	1	9.00	BLANK	NO	BLANK
4789	31.00	1.00	4.00	2	253.38	BLANK	NO	The exact failure mechanism is not known at present but will be clearer once the fitting is broken apart and sent onshore for further examination. The incident is still under investigation

4780	235.00	1.57	29.00	UNCLASSIFIED	80.00	15.00	NO	The section of tubing that ruptured to cause the incident was a short spool with a non-formed bend. It is assumed that on installation the spool in question would have been a straight spool. It is likely that over time and with through traffic it has suffered this non-formed anomaly.
4775	0.11	0.23	300.00	UNCLASSIFIED	330.00	BLANK	NO	Mode of failure unknown at present, Inspection in progress.
4760	374.10	10.00	10.00	2	195.00	BLANK	NO	BLANK
4718	1.01	203.00	1.30	2	5.60	39.00	NO	Wrong material selection when manufacturing replacement tie down boss
4715	7.14	4.50	15.00	2	6.00	78.00	NO	Failure of valve seal mechanism (grease port valve) Leaking Valve seal mechanism on HDR2 diverter valve
4681	125.00	1.00	45.00	2	55.00	20.00	NO	Pin hole leak - Due to rubbing on thermal jacket tie-down stud

Appendix B: Summary of spray / mist incidents in the ARIA database

Date	Substance	Activity (location)	Causes / Consequences
2018	Diesel	Oil refining (Port-Jérome-sur-Seine, FR)	Corrosion of a pipe (50 bar, 230 ° C) / Spray - Leaking fuel oil.
2017	Thermal oil	Wood panel manufacturing (Rambervillers, FR)	Maintenance operation on a pump, disassembly of a temperature sensor without checking the fluid pressure. No drain / Spray - leakage of 5 m^3 of thermal oil heated to 275 ° C
2017	Oil	Textile fabrication (Nucourt, FR)	Leak on the oil network. Projection on a boiler with smoke tubes / Fire of the boiler
2016	Oil	Textile fabrication (Nucourt, FR)	Clogging of boiler expansion tank with mud / Opening of the anti-explosion valve on the roof and ejection of 4t of oil
2016	Hydraulic oil	Waste treatment (Vert-Le-Grand, FR)	Breakage of a welding of the pipework. Leakage on hydraulic oil supply piping of the cylinders of a hopper / Mist ignition and fire
2015	Ethylene	Oil industry (Gonfreville-L'Orcher, FR)	Mechanical failure of the hatch of one of the compressor valves / Leakage of 8t of ethylene due to the failure of a compressor. Formation of a mist with visible droplets. Concentration greater than LIE. No ignition.
2015	Hydraulic oil	Metal industry (Nuits-Saint-Georges, FR)	The crimping of a high pressure hydraulic hose (200 bar) of a press breaks causing a cloud of oil aerosol on a hot tool / The oil mist ignites immediately and creates a fireball with 8 m high flames causing a fire
2014	Oil	Cement plant (La Couronne, FR)	Oil leak on a hose. Projection of oil on a heat exchanger at 225 ° C / Ignition. Compressor fire
2014	Lube Oil	Chemical Industry (Lauterbourg, FR)	A pulse of compressed air through the module filter of the recirculation - filtration circuit. Oil mist generation. Oil was contaminated with 4% of toluene. Generation of electrostatic charges by blowing air through the filter / Explosion of the oil dilution tank containing 600 kg of lube oil
2013	Oil	Chemical industry (Marseille, FR)	A poorly tightened temperature probe is ejected. Oil leak at 40 ° C and 13 bar / Fire of the steam boiler. 2750 L of oil burned.
2012	Thermal oil	Printing on plastic films (Argentan, FR)	Thermal Oil leak at a gasket or flange of the Boiler - Oil overheating and spraying / Explosion at the level of boiler retention

2012	Thermal oil	Wood panel manufacturing (Sully-sur-Loire, FR)	Draining thermal oil from boiler expansion vessel - generation of fog and oil vapors / Oil mist ignition. Thermal flash
2012	Oil	Metal industry (Issoudun, 36)	Extraction fan malfunction - fumes generated by the quenching of hot metal parts in oil / Explosion of an extractor
2012	Mineral oil	Food industry (Saint-Cyr-en-Val, FR)	Oil leak on a flange of mineral oil pipe (heat transfer fluid of fryers) / Fire
2011	Olefins	Oil refining (Berre l'Etang, FR)	Degraded olefin line due to severe vibrations of a pump - breakage by fatigue of a connection - Olefin mist / Mist ignition on a hot element of a pump
2010	Oil	Electricity production (Bouchain, FR)	Communication between two circuits of high pressure oil and lubricating oil (poor design). Leakage on a hydraulic circuit with a 23 m^3 tank of oil / Fire
2009	Oil	Metal industry (Saint-Jean-de-Maurienne, FR)	Leakage of oil under pressure on a jack / Fire powered by the oil flow thrown by the jack
2007	Oil	Thermal power station (Le Port, FR)	An oil purifier feed hose suddenly broke, releasing superheated oil at 5 bar on an exhaust pipe downstream of the turbocharger / Ignition of the oil mist at the contact of the overheated surface (400 °C)
2006	DFO Fuel oil	Thermal power station (Lucciana, FR)	Line/pipe leak (crack causes by engine vibrations) / Mist ignition - explosion - fireball
2006	Hydraulic oil	Aeronautic industry (Gennevilliers, FR)	Large leakage of hydraulic oil under pressure and at high temperature / Fire on a gas turbine
2005	Oil	Wood panel manufacturing (Bazeilles, FR)	Presence of water in the primary circuit of the boiler - overflow of hot oil, foaming, depressurization, opening of the rupture disc, rejection of a mist - Ignition and explosion on contact with a hot surface
2002	Oil and R22 (refrigerant)	Automobile industry (La Verrière, FR)	Head gasket torn on a compressor / Oil jet - spray
2001	Oil	Synthetic fiber fabrication (Longlaville, FR)	Deterioration of filters by electrochemical corrosion - oil mist on fan and soundproof box / Fire in an oil filter box
2000	Gasoil	Waste treatment (Lillebonne, FR)	Purge of a filter - Overflow of a tank and projection of a diesel mist by bubbling with compressed air / Ignition of the mist in contact with hot piping
1999	Oil	Oil refining (FR)	Maintenance operation. Vibration fatigue. Rupture of the 5 cm diameter connection of the emergency pump valve / Oil leak at the compressor (18 bar and 50 ° C). Fire
1998	Oil	Glass industry (Givors, FR)	Oil leak that ignites in a technical duct / Fire
1996	Oil	Coating plant (Blainville sur Orne, FR)	Increased pressure in the boiler oil compartment and malfunction of the valve - Opening of the

			ferrule / Oil spray, ignition on burner - explosion
1995	Oil	Metal industry (Hayange, FR)	Emission of oil vapour in a rolling mill / Explosion
1994	Lube oil	Urban heating (Allemagne)	Lube oil leak on the mechanical speed reducer of the gas turbine / Explosion of the gas turbine
1993	Oil	Computer industry (Toulouse, FR)	Rupture of a pipe on a welding machine / Spray of hot oil in the workshop
1991	Used oil	Waste treatment (Dieulouard, FR)	Presence of water in the incinerator, spraying of used oil / Ejection of 1 m^3 of oil on neighbouring buildings
1991	Gasoline	Fuels trade (Saint-Herblain, FR)	Leakage on a fitting (rubber seal) of a 12" draw line at the bottom of the fuel tank Formation of an aerosol / Aerosol ignition. Explosion.
1990	Oil	Wood panel manufacturing (Sully-sur-Loire, FR)	Oil leak under pressure heated to 240 ° C / Electrical contact - short circuit
1988	Fuel oil	Electricity production (Amagasaki, JAP)	Clogging of a boiler catalyst by a fuel mist / Explosion of the boiler
1984	Diesel	Oil refining (Venezuela)	Vibrations. Rupture of a line of 8 "Projection of diesel at 48 bar and 343 ° C / Formation of an aerosol. Inflammation in contact with hydrogen lines
1982	Lube Oil	Thermal power station (Blanzy, FR)	Breaking of solder due to vibrations / Lube oil ignites on contact with superheated steam line
1977	Diesel	Oil refining (FR)	Bride badly tightened. Flexible under 6 bars breaks. Projection of diesel / Fire
1974	Oil	Oil refining (FR)	Human error. A technician removes a cap on a filter in use. Projection of oil under 8 bars / Formation of an aerosol. Ignition in contact with the hot lines of the turbine.
1970	Propane	Gas production (Perpignan, FR)	During unloading of a 45-t propane tank car, a hose (50 mm diameter) breaks / Propane leak: 8kg/s. Mist generation. UVCE and BLEVE
1965	Diesel	Oil refining (FR)	Pressure tests on an exchanger. Rupture of a seal / Jet of fuel. Ignition in contact with hot lines. Fire.

Appendix C: Summary of spray / mist incidents in the ZEMA database

infosis / ZEMA

Major Accidents and Incidents

General

Welcome to ZEMA

The Central Reporting and Evaluation Office for Major Accidents and Incidents in Process Engineering Facilities (Zentrale Melde- und Auswertestelle für Störfälle und Störungen in verfahrenstechnischen Anlagen - ZEMA) records, evaluates and publishes in annual reports all events which must be reported to the authorities pursuant to the 12th Federal Immission Control Ordinance. Such reportable events are sub-divided according to their hazard potential into major accidents and disturbance of normal operation. The systematic recording and evaluation of events will provide information which acts as an important basis for a further development of the state of the art of safety technology.

Further information under:

ZEMA
Safety of Installations

Date	Substance	Activity (location)	Causes / Consequences
2018	Flammable liquids	Plant for distillation and refining (Vohburg, GE)	Leakage / Release - fire - explosion
2015	Crude oil	Pumping station of a petroleum tank farm (Schwedt, GE)	System error during maintenace / Release (air)
2015	Diesel	Plant for distillation and refining (Leuna, GE)	Leakage due to corrosion / Release (Air)
2015	Naphta / Aromatic oil	Petrochemical plant (Wesseling, GE)	Corrosion / Fire of a diphasic mixture
2012	Crude oil	Pumping station of a cargo terminal (Schwedt, GE)	Human error - unlocked relaxation line / Release (air)
2011	Crude oil	Refinery (Cologne, GE)	Technical error (inappropriate welding of a pipe) / Mist release
2011	Phthalic anhydride	Polyol plant (Wesseling, GE)	Leakage on a flange / Release (air) - Fire
2004	Methanol	Distillation column (Frankfurt, GE)	Human error during maintenance on a valve / Release (air)
2001	Tar oil	Transfer pump (Wülknitz, GE)	Unknown / Release (air)
2001	Methanol	Plant for distillation and refining (Wesseling, GE)	Corrosion pipeline / Release(air) - Fire
1998	Diesel	Installation of storage (Rostok, GE)	Corrosion / Release(air)
1994	Methanol	Chemical plant (Gross Umstadt, GE)	Chemical runaway linked to a badly tightened flange / Release (air)
1993	Nitroanisole/méthanol	Chemical plant (Frankfurt, GE)	Operator error - chemical runaway / Release (air)
1993	Toluene	Chemical plant (Ludwigshafen, GE)	Corrosion on a pipeline / Release (air)

1992	Pyrolysis oil	Plant for distillation and refining (Gelsenkirchen, GE)	Technical error - Leakage of a pipe at a connection point / Release (air) -Fire
1992	Methanol	Plant for the production of dimethyl terephthalate (Gersthofen, GE)	Ignition of condensated methanol vapors / Release (air) - Fire - explosion
1992	Phenol	Nitrosophenol plant	Pipe bursting / Spray release
1987	Crude oil	Refinery (Gelsenkirchen-Horst, GE)	Human error - Cutting ring fitting unsufficiently tightened / Mist release under 50 bars - Fire