CHEMICAL ENGINEERING TRANSACTIONS

VOL. 48, 2016

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Eddy de Rademaeker, Peter Schmelzer

ISBN 978-88-95608-39-6; **ISSN** 2283-9216

DOI: 10.3303/CET1648074

Potential for Major Explosions from Crude Oil Pipeline Releases in Varied Terrain

Olav R. Hansen*, Malte T. Kjellander

Lloyd's Register Consulting – Energy, Fjøsangerveien 50B, 5059 Bergen, Norway
Olav.Hansen@lr.org

Crude oil is often transported by pipelines from remote production sites to refineries. Sometimes oil releases take place, caused by sabotage, corrosion or external impact. In a safety consequence study the main hazards considered are often pool, jet or flash fire. The integral models applied may give somewhat misleading hazard estimates, as a flat terrain surrounding the pipeline is assumed, and the models lack the ability to predict dense gas dispersion for calm and low wind scenarios. In a varied terrain an unrealistic large pool and following pool/flash fire, is often predicted. A major hazard often ignored is vapour cloud explosion. The fractions of volatile components in crude oil are limited. Still, as demonstrated by cascade flow experiments after the Buncefield accident, certain release mechanisms may lead to an enhanced evaporation and the likely generation of flammable vapour clouds. For an oil release it can be assumed that a pressurized oil release generating a vertical oil spray into the air, can lead to the evaporation of significant fractions of flammable vapours of propane, butane and pentane. For major pipeline releses during calm wind conditions (0-0.5 m/s) in a varied terrain, a CFD simulation study demonstrated that very large flammable vapour clouds could be generated and could fill lower lying areas of the terrain. The simulated clouds could be 5-10m deep with likely ignition sources as homes, farm houses and roads inside for 20-30 minutes. Areas with trees and dense vegetation were also inside the gas cloud, and could have led to significant flame acceleration, potentially deflagration to detonation transition (DDT) and severe consequences as seen for the Buncefield accident. For pipelines buried below the ground one possible way to prevent such a scenario will be to avoid the possibility for oil sprays upwards, for instance by covering the pipeline with plates which will remain in place during a major release. If this is not possible, vapour fences may be used to limit the gas cloud migration towards likely ignition sources or areas with dense vegetation. While such scenarios may be rare for unintended releases, the severity of the potential consequences should justify their evaluation as part of a safety study.

1. Introduction

Transportation of crude oil from the production site to the refineries can happen by ship, rail or pipeline, depending on transport route and volumes, e.g. access to sea or existing transportation infrastructure, challenges in topography or border crossings, climatic considerations and more. When practical, pipeline transportation will often be the preferred option due to lower cost and lower environmental or safety risk. Exxon Valdez, with estimated 30-80 t oil spilled in Prince William Sound, Alaska, 1989, and the more severe spills from Atlantic Empress, 1979, in Trinidad and Tobago (287,000 t) and Amoco Cadiz, 1978, outside France (223,000 t) are well known, and tanker explosions have also taken their life toll. In recent years due to the increasing tight oil exploration in USA and Canada a strong increase in crude oil transportation by rail has taken place. Among several derailings of crude oil trains in recent years, the 2013 Lac-Megantic accident demonstrated a severe accident potential as oil from several rail cars ignited and led to explosive fires killing 47 people, destroying numerous buildings and environmental consequences in the small town.

The potential consequences from crude oil pipeline releases are generally considered less severe, as a major release can be automatically detected and the amounts released limited. Due to a low volatility of crude oil, the explosion potential is considered limited with spray and pool fires as the most severe outcome in a hazard assessment. Still, when looking outside Europe and North-America, there are reports of explosions also related to oil pipeline releases, recent examples include the 2013 Bodo explosion in Nigeria, possibly caused by military supported theft/bunkering, see The Guardian (2013), and the 2013 Qingdao explosion in China.

2. Frequency and Hazard Potential from Crude Oil Pipeline Releases

Concawe (2015) has developed estimates for leak frequencies from onshore crude oil pipelines. Over the past 20 years the typical leak frequency from larger oil pipelines (>16") has been of the order 0.2 per 1000 km pipeline and year, among these 19% are defined as rupture, giving the largest spill rate, often of the order the transport rate of the pipeline after an initially higher transient leak rate. 17% of the holes were defined as "split", with an opening of 75-1000mm x 10% of diameter, which could also give release rates similar to the pipeline flow rate. This would correspond to a total release frequency of $2x10^{-4}$/y and rupture+split frequency of $7x10^{-5}$/y per km pipeline. Almost half of the releases were categorized as caused by 3rd party, a small, but a strongly increasing fraction last couple of years was found to be intentional, primarily due to theft (kept out of statistics used in this paper). In a varied terrain the pipeline pressure must be chosen high enough for oil to scale hills ahead, and the oil release can be expected to continue with almost the same release rate for some time after a successful shut-down, as oil may flow by gravity from higher elevations along the pipeline. Thus a quite typical major release scenario from a large crude oil pipeline in varied terrain could be 1000 kg/s release (somewhat higher initial transient) with duration of 15-30 minutes. The evaporation from a crude oil pool w hich is not burning will normally be slow, and the generation of significant flammable clouds will not be likely. Like demonstrated in the Buncefield accident and following investigation (HSE, 2012), there may under certain circumstances be a significant evaporation from moderately volatile liquids. In the post-Buncefield experiments it was demonstrated that cascade mechanism sending fine droplets into the air could make 17% of the petrol (by weight) remain airborne, corresponding to all hydrocarbon components butane and lighter (C1-C4), and 50% of pentane. If the release mechanism for crude oil could generate fine droplets in a spray up in the air, which might be a quite typical scenario for significant releases from covered pipelines damaged by impact from above, it could similarly be expected that around 5% (wt) of a typical crude oil may remain airborne as vapour or fine mist. For major pipeline ruptures, this could correspond to around 50 kg/s vapour/mist generation contributing to flammable mixtures with air. OGP (2010) gives an estimated ignition probability for large crude oil releases of 0.70% (OGP Table 2) in rural areas, while the same releases in urban or industrial areas have an ignition probability of 7%. By studying the report (UKOOA, 2006) from which the OGP tables are extracted, a somewhat higher ignition probability (2-5%) can be found for low wind scenarios in rural areas.

The most commonly used tools for consequence studies have several limitations, these integral models i) cannot take into consideration varied terrain and obstructions and ii) cannot predict dispersion consequences in calm weather (< 1 m/s wind), and dispersion studies will often consider 2 m/s Pasquill F as a representative worst-case scenario. The results from a traditional crude oil pipeline assessment might then be a predicted worst-case LFL-distance for oil vapour of the order 150m (250m if ½ LFL is conservatively used), and a flashfire distance 150-250m from the pipeline may be concluded to be among the risk driving scenarios. The pool modelling of such integral tools may be even less suitable for pipeline scenarios in varied terrain, as the models will assume average pool thicknesses of the order 1-10mm, thus the predicted pool diameter from a major pipeline scenario may be of the order 500m. Hazard distances from pool fires, 100-200m for radiation levels of concern, may then end up as the second risk driving scenario. In reality, crude oil will accumulate in lower lying terrain, it may penetrate the soil, and an average pool thickness may more likely be of the order 1m, which would give a pool diameter around 50m, and much shorter hazard distances, for the same release scenario.

Ignited vapour clouds are normally concluded to become flashfires, and explosion pressure effects are seldom considered. For an explosion of concern to take place there is in addition to a flammable mixture and an ignition source, a need for turbulence generating mechanisms which can help initiate or maintain high flame speeds through the flammable mixture. The Buncefield accident and following investigaton (BMIIB, 2008) confirmed that the reactivity of the volatile hydrocarbon vapour is high. Hansen and Wilkins (2004) further demonstrated that the reactivity of airborne crude oil mist can be high, provided that droplet break-up is achieved, or that hydrocarbon vapour concentration around the mist is above LFL (lower flammable limit). With a given source term for hydrocarbon vapour and mist, the gas cloud size will depend on the terrain and wind speed and direction during the incident. Finally, to obtain an explosion turbulence generation may be required to accelerate the flames. Near the release there will be some jet induced turbulence that might accelerate flames, however, a more substantial and important mechanism will appear if the flammable cloud will enter dense vegetation like trees and bushes. As was demonstrated in the Buncefield accident and following experiments at Spadeadam test site, see e.g. Hansen and Johnson (2015), trees may even be capable of accelerating a deflagration into a detonation (DDT), which may result in very severe consequences.

3. Potential for Generation of Large Vapour Clouds and Explosions

To illustrate potential weaknesses of traditional pipeline risk assessments an example study will be presented in the following. A 28” (700mm diameter) crude oil pipeline has to cross a 30 km stretch of varied terrain. As the pipeline has to scale some hills, 100m higher than the lower sections of the pipeline, the pipeline pressure along much of the route will be 15 bara. For a typical split type hole size of e.g. 70mm x 500 mm (same area as a 200mm circular hole) a release rate of 800 kg/s can be estimated, this rate will also be representative for full bore releases. The estimated release rate for a 100mm hole size is 200 kg/s. The frequency for 800 kg/s release (rupture+split) is estimated to 2.2×10^{-3}/y, as these worst-case scenarios represent 36% of all release scenarios, they also dominate the estimated risk. From a traditional, simplified pipeline assessment the flashfire hazard distance (LFL) is 160m, with a frequency of 1.1×10^{-5}/y (0.5% probability for delayed ignition, 25% probability for 2F wind speed) and assumed lethal outcome for people trapped inside the flammable cloud. Similarly, pool fires from major releases with an estimated frequency 4.3×10^{-5}/y give hazard distances around 80-90m for 12.5 kW/m^2 (assumed fatal) and 150-180m for 7 kW/m^2 (some fatalities). These estimates are based on the assumption that the terrain is flat, a pool thickness of 1-10mm, and no risk for calm days/nights with wind less than 1 m/s.

The pipeline studied goes through a varied rural terrain with valleys, vegetation, roads, some houses and farms and a statistical probability of calm weather (wind < 1 m/s) of around 10%. An estimated 40% of the pipeline route is located in terrain formations in which dense vapour may accumulate in calm weather. In order to better assess the risk from major release scenarios consequence modelling has been performed with the CFD tool FLACS (www.GexCon.com), which has shown good validity for gas dispersion, see Hanna et al. (2004) and Hansen et al. (2010). FLACS has previously been used e.g. for chlorine dispersion (Hanna et al. 2009) and stack dispersion (Hansen, 2013). The scenario selected to model the pipeline releases in valleys is shown in Figure 1, centrally in the upper pictures a 40 kg/s (5% of oil release rate) vertical oil vapour release is modelled, consisting primarily of butane and pentane, and some lighter and heavier oil components, with an average molecular weight is 62 g/mole. There are a few houses and a barn in the selected valley, and also a small wood with around 50 trees, up to 15-20m tall. If it is conservatively assumed that 50% of the major scenarios considered will be released upwards and send a spray of oil into the air, 40% of the scenarios will take place in valleys, and 10% of the time will be calm weather, the scenario frequency for 40 kg/s oil vapour generation in one of the valleys along the pipeline route in calm weather can be estimated to 4.3×10^{-5}/y.

In order to assess the accumulation of flammable vapour from the release under calm conditions, simulations in various wind conditions have been performed. The domain simulated spans 850m x 800m x 150m, with grid resolution of 1m around the release, increased to 2m in the horizontal directions within the valley, and thereafter stretched outside. In Figure 1 the gas dispersion during the 20 minutes release and 10 minutes thereafter, is shown for a 0.5 m/s wind from WSW, similar simulations were performed for no wind as well as 0.25, 0.5, 1.0 and 2.0 m/s wind from SE. In Figure 2 the transient development of flammable cloud volumes and Q8 energy based equivalent stoichiometric clouds (Hansen et al., 2013), can be found for 0, 0.25, 0.5, 1.0 and 2.0 m/s wind scenarios. Figure 1 and 2 indicate that for wind speeds up to 0.5 m/s, independently of wind direction, very large flammable clouds (200,000m^3) are developed within 10 minutes and reaches a maximum above 500,000m^3 shortly after the releases are stopped at 20 minutes. Within the following 10 minutes the cloud size is only reduced by 20%, indicating that massive clouds may be expected to remain for 30-60 minutes. As much as 65% of the potential combustion energy of the released vapour is within flammable parts of the cloud, and could be released in an explosion. The flammable cloud fills most of the valley to a depth of 5 to 10m, covering most of the walls of the homes, the barn, and the lower parts of the trees.

The probability of delayed ignition for a 300,000-500,000m^3 flammable cloud, remaining in the valley for more than 30 minutes, likely penetrating cellars and living rooms of several houses, and covering potentially busy roads to 5m height, will likely be close to 100%, not 0.5% or 2-5% as assumed from OGP/UKOOA guidance.

For 1 m/s wind the cloud size is reduced by factor of four to around 100,000m^3, still significant. For 2 m/s wind, which is the low wind scenario and often the highest risk contributor in traditional studies, the flammable cloud size is below 10,000m^3 and of marginal concern. The 100mm hole size no wind scenario (200 kg/s oil release, 10 kg/s oil vapour assumed generated) gave a maximum flammable cloud of 30,000m^3, while still a significant volume severe consequences will be less likely as the cloud is shallow.

The vapour cloud sizes from the low wind scenarios (0 to 0.5 m/s) are more than double the size of the flammable cloud exploding at Buncefield (estimated to 240,000m^3), where a TNT-equivalent energy of 20-30 ton was estimated. The potential energy of the predicted maximum of 31 ton of hydrocarbon vapour mixed with air in this study could potentially represent TNT-equivalenf of more than 100 ton, if the energy release is efficient and 40% of the combustion energy becomes blast energy.

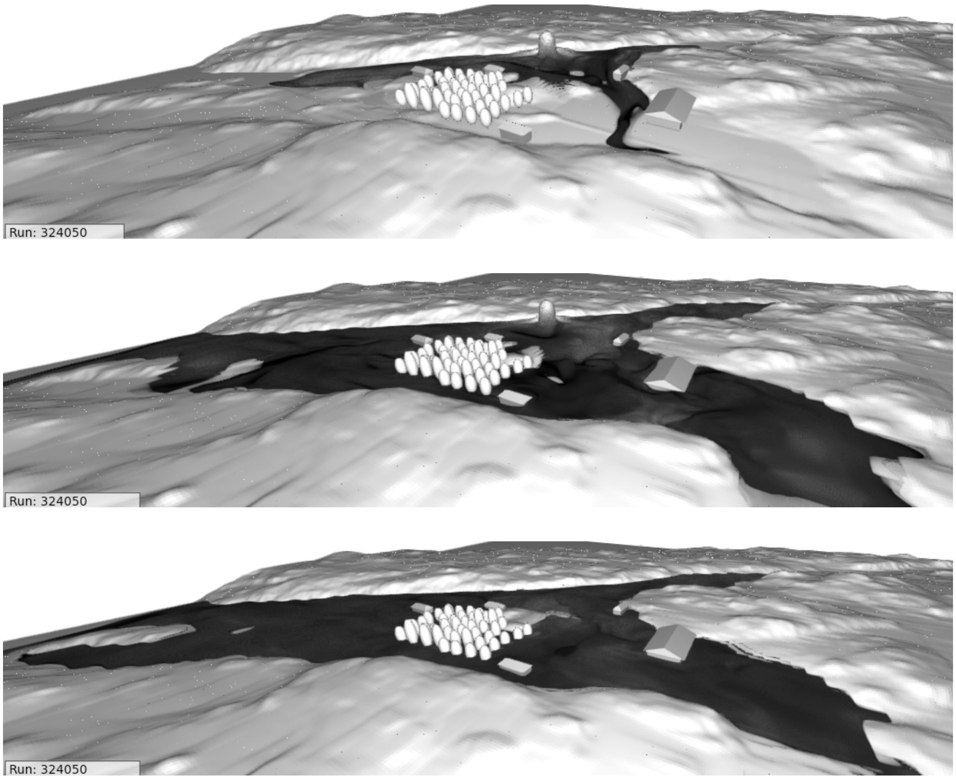

Figure 1: Valley along pipeline route selected for dispersion study, the pipeline goes from the fjord left (South) into the valley to upper right corner (NW), the flammable vapour cloud is shown after 5 min, 20 min (end of release) and 30 min from the onset of the release

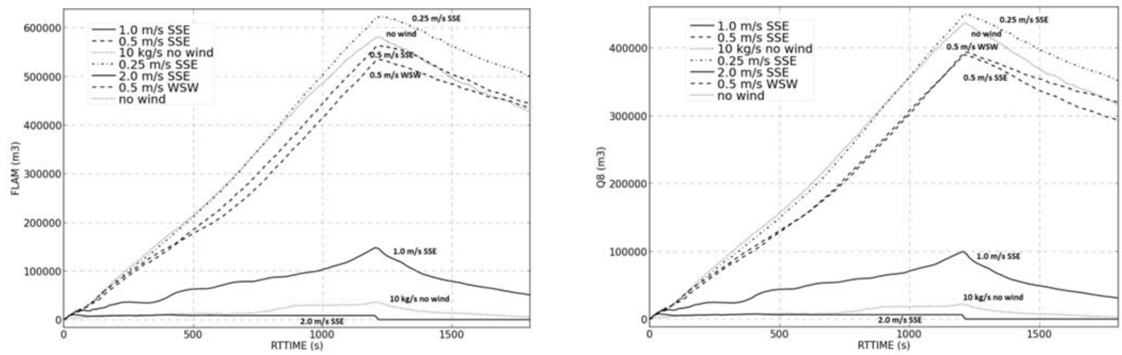

Figure 2: Development of flammable volume (left) and Q8 equivalent stoichiometric volume (right, energy), digits 2 and 3 is wind direction (15=>150 deg, 24=>240 deg) and last 3 digits wind speed (cm/s)

At Buncefield the flame acceleration inside dense tree vegetation was concluded to initiate DDT, which may make the remaining flammable cloud detonate. Without DDT the expected explosion consequences would be limited, as turbulence generation from vegetation or buildings will only accelerate flames very locally. In the pipeline terrain studied, there is quite frequently dense vegetation in the lower lying areas of the valleys, which might accelerate flames in a similar way that was seen at Buncefield. Since the areas with dense vegetation are often larger than at Buncefield, and the vapour cloud depth significantly thicker than at Buncefield, there is reason to believe that the potential for DDT will be at least as high as for Buncefield and the Post-Buncefield tree-detonation experiments, see Hansen and Johnson (2014). To illustrate the potential consequences of such a scenario, DDT in the dispersed gas cloud seen in Figure 1 will be simulated using the gas cloud after 25 min as starting point, i.e. 5 min after the release is stopped. At this stage the cloud has filled several houses and much of the dense vegetation in the small forest. In Figure 3 the result of the DDT simulation can be seen, in the pressure plot the bright area in the valley is inside the detonating gas cloud, and, due to the large dimensions of the cloud, the hazard distances to 0.2 barg and 0.5 barg are very significant, blast pressures of 0.2 bar were predicted in most directions around 400m from the centre of the explosion. When taking into consideration that the scenario simulated is seldom evaluated in any risk assessment, while it may have an estimated frequency above $1x10^{-5}/y$ (assuming 50-100% ignition probability and that 50-75% of the low wind scenarios will generate clouds large enough to fill areas with dense vegetation and detonate).

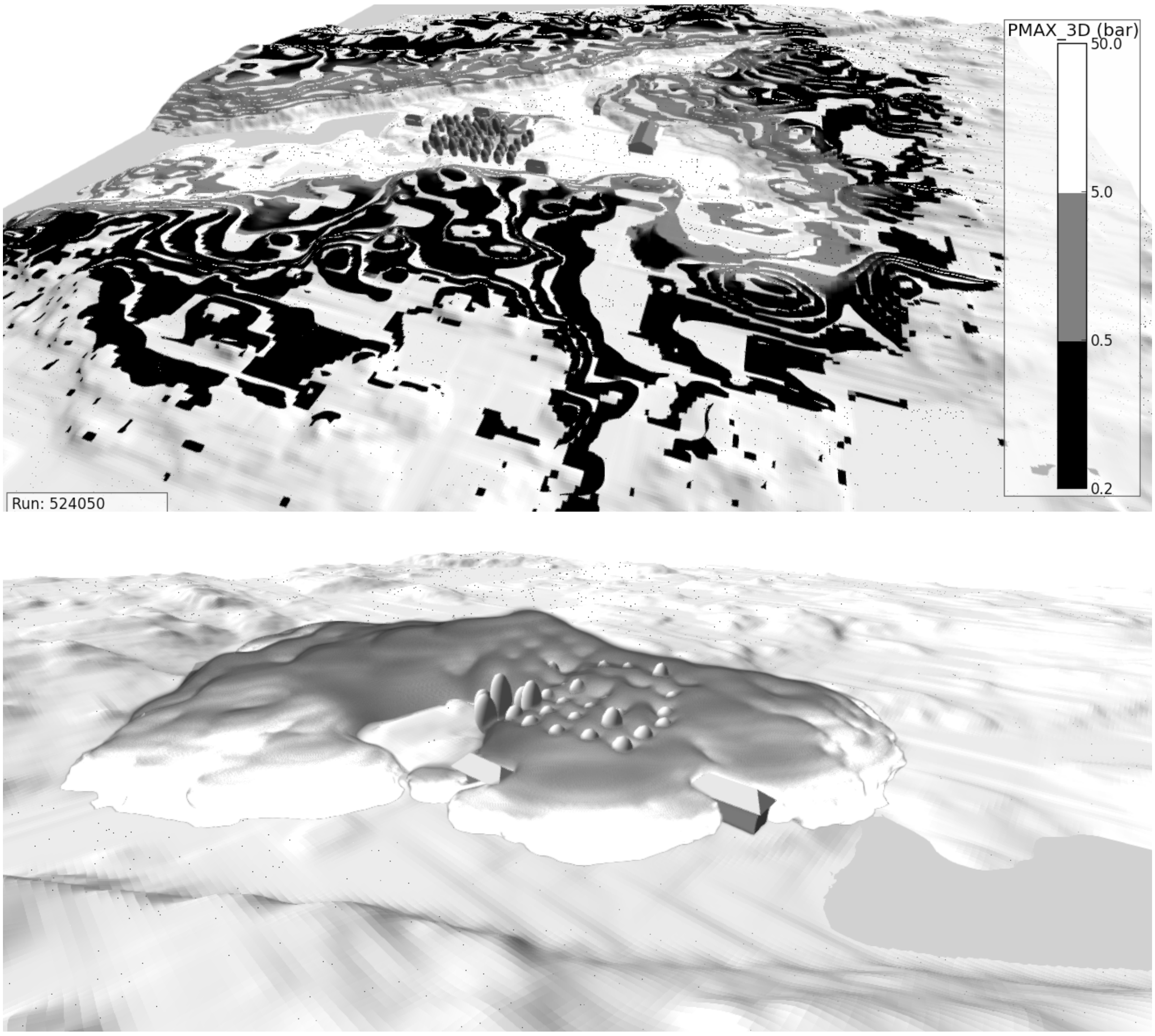

Figure 3: Upper picture shows maximum pressures in the explosion, the bright colour in the valley is the footprint of the detonating gas cloud, the dark colour is the extent of 200 mbar contour. In the lower picture the predicted flame ~100 ms after initiated DDT is shown, bright areas indicate the high intensity detonation front.

4. Conclusions

This work has highlighted weaknesses with traditional risk assessments for oil pipelines, and potentially other pipelines transporting toxic or flammable substances that may generate dense vapour clouds if released. These assessments may have major flaws when the pipeline route is through varied terrain with valleys and vegetation. While consequences of pool fire scenarios may be exaggerated with the too simple modelling tools, a greater concern is that significant and long lasting dense vapour accumulation in valleys and lower lying terrain during calm weather, with potentally high ignition probability, and severe explosion concequences often is completely ignored in such analyses. A main reason for this is the inability of the simple consequence tools to predict gas dispersion during low winds (< 1.0 m/s) and in particular in non-flat terrain.

The largest potential uncertainty in the assessment of this paper is probably the likelihood for a major crude oil release (~1000 kg/s) from a pressurized pipeline to create a spray of droplets with sufficient evaporation to generate a large, flammable vapour cloud. The evaporation from the unleaded petrol at Buncefield was much higher than anticipated upfront, and the assumptions done in this paper (5% evaporation by mass) should be consistent with the 17% evaporation observed in post-Buncefield cascade experiments, with a more volatile liquid. Keeping in mind that severe oil vapour explosions have happened in connection with crude oil pipeline leaks e.g. in Nigeria, and the violent fire inferno caused by the derailing crude oil trains in Lac-Megantic, the potetial for major accidents from crude oil pipelines should not be ignored. Another reason for concern is the significant rise of leak incidents resulting from theft from pipelines, combined with the general perception that the risk for terror is increasing. It may thus not be sufficient to study historical data to estimate the risk for major events.

To do a pipeline assessment along the lines described in this article does not require advanced CFD modelling. It should be sufficient studying the map of the route, identify areas with potential for dense vapour accumulation, and thereafter assume that low wind scenarios (less than 0.5 m/s to 1.0 m/s) will lead to very significant vapour clouds with most of the released gas inside the flammable clouds, and with a probability of ignition close to 100% if the clouds would engulf houses or roads for a significant period of time. If there are significant areas with dense vegetation (bushes or trees) inside the gas clouds, DDT should be feared, and it can be assumed that the entire vapour cloud might detonate. If a better precision in this this assessment is reqired one could consider to apply CFD.

The most important is of course to prevent such incidents from happening. One challenge is the increasing amount of incidents caused by theft or sabotage. One potentially effiient measure to reduce the propensity of leaks to become oil sprays into the air, and generate large amounts of vapour, will be to protect the pipeline from above with large, stiff plates. Such plates would likely also make it more challenging to steal oil or perform sabotage to the pipeline. If this solution is not feasible, it could be consdered to cut or thin the vegetation, or alternatively protect the vegetation with vapour fences at exposed locatons.

Until good solutions are found and implemented, it is recommended to not to understimate the risk from oil pipr

References

BMIIB (2008): The Buncefield Incident 11 December 2005, The final report of the Major Incident Investigation Board, Volume 1 and 2 Buncefield investigations

Concawe (2015): Performance of European cross-country oil pipelines, Statistical summary of reported spillages in 2013 and since 1971, www.concawe.org (last accessed August 30, 2015)

Guardian (2013) www.theguardian.com/global-development/2013/oct/06/oil-theft-costs-nigeria (last accessed August 22, 2015)

Hanna, S.R., Hansen, O.R. & Dharmavaram, S., (2004). FLACS CFD air quality model performance evaluation with Kit Fox, MUST, Prairie Grass, and EMU observations. Atm. Environment, 38: 4675-4687.

Hanna, S.R., Hansen, O.R, Ichard, M. & Strimatis, D. (2009). CFD model simulation of dispersion from chlorine railcar releases in industrial and urban areas. Atmospheric Environment, 43: 262-270.

Hansen, O.R. & Wilkins, B. (2004). An experimental study on oil mist explosions. International European Safety Management Group (ESMG) Symposium, 16-18 March 2004, Nuremberg, Germany: 10 pp.

Hansen, O.R., Gavelli, F., Ichard, M. & Davis, S.G. (2010). Validation of FLACS against experimental data sets from the model evaluation database for LNG vapor dispersion. Journal of Loss Prevention in the Process Industries, 23: 857-877.

Hansen, O.R., Gavelli, F., Davis, S.G. & Middha, P. (2013). Equivalent cloud methods used for explosion risk and consequence studies. Journal of Loss Prev. in the Proc. Industries, 26: 511-527. ISSN: 0950-4230.

Hansen, O.R. (2013) Stack Releases During Low Winds, Evaluation of Hazards and Mitigation Using CFD, Chemical Engineering Transactions 31:91-96

Hansen O.R and Johnson, D.M. (2015), Improved far-field blast predictions from fast deflagrations, DDTs and detonations of vapour clouds using FLACS CFD, Journal of Loss Prev. in the Proc. Industries 35:293-316

HSE (2012), Buncefield investigation, Liquid flow and vapour production, HSE research report RR936, Health and Safety Laboratories, 2012

OGP (2010), Risk Assessment Data Directory, Report No 434-6.1, Ignition Probabilities, International Association of Oil and Gas Producers, March 2010.

UKOOA (2006), IP Research Report: Ignition Probability Review, Model development and Look-Up Correlations, Energy Institute, London, January 2006