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Pipeline puncture scenarios near fuel depots - contribution to risk and implications for land use planning

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This paper is concerned with accidental pipeline puncture events that lead to spray evaporation of moderately volatile liquids, gasoline in particular. The paper argues that both likelihood estimates and hazard ranges of pipeline puncture scenarios, and hence their contribution to risk, exceed those of tank overfill scenarios. This is particularly true for fuel depots which have implemented improved overfill protection measures in response to revised recommendations because of the 2005 Buncefield incident.

The paper briefly examines the regulatory permitting regime for pipeline transport of dangerous substances. Pipelines are not covered by the Seveso III Directive. At the EU level, there are no requirements for systematic risk analysis, land-use planning and information to the public, amongst others. Furthermore, the current practice for carrying out pipeline risk analysis appears to largely overlook evaporation from puncture scenarios.

The contribution of pipeline punctures to risk in a land-use planning procedure may therefore go unrecognized. The omission is important if such scenarios can generate very large vapour clouds that contribute significantly to overall risk. Many ports in Europe are losing traditional industrial enterprises. There is often a desire to develop and revitalize vacated lots at ports relatively close to expensive land near urban centres, for instance construction of upscale residential housing or office buildings near waterfronts. Fuel depots stay in the harbour however, to supply fuel to the urban centre.

The inclusion of pipeline puncture scenarios may have major implications for risk mitigation measures and/or land-use planning around fuel depots, in particular for depots located in ports.

Keywords: Major accident hazard; Onshore pipelines; Fuel depot; Land-use planning; Urban development.

Introduction

Before 2005, the storage of gasoline in large aboveground tanks was thought to present rather limited risks to neighbours. For land-use planning (LUP) purposes, the worst credible design event (dimensioning scenario) was a pool fire resulting from an ignited release of product. Predicted hazard distances rarely exceeded 200 m (BMIIB, 2008a, 2006; Hedlund et al., 2019). In December 2005, an incident at the UK Buncefield fuel depot fundamentally changed these ideas. A gasoline tank overflowed, there was extensive evaporation and the vapours exploded violently.

In a land-use planning context, it is important that much incremental commercial development had taken place near the Buncefield depot. When it began operating in 1968, there were very few buildings in the surrounding area. At the time of the explosion, there were some 630 businesses employing about 16,500 people in the depot's neighbourhood. Many of the premises were destroyed or severely damaged. Costs were estimated at about £1 billion (BMIIB, 2008a), about USD 1.75 billion with the exchange rate at the time.

The Buncefield explosion fundamentally changed risk analysis practice and land-use planning considerations for fuel depots – the dimensioning scenario now became a tank overfill event, late ignition and a so-called Open Flammable Cloud Explosion (OFCE) (BMIIB, 2008a; Hailwood et al., 2009; Herbert, 2010; Johnson, 2010). How to determine adequate separation distances between fuel depots and neighbouring residential and commercial development, and how to manage the cumulative effect of incremental developments, became major land-use planning issues.

This paper draws attention to another scenario, potentially capable of producing a large vapour cloud although the liquid involved is only moderately volatile: puncture of a pressurized import pipeline. If a release of liquid gasoline discharges upwards, liquid fragmentation, spray generation and fountain effects will form many droplets that can lead to extensive evaporation of the lighter components of gasoline. As reported in a recent paper (Hedlund et al., 2019), hazard analysis suggests that such a scenario may evaporate significantly more fuel than a Buncefield-type overfill event.

A review of the literature suggests that the evaporation of moderately volatile liquids due to spray effects resulting from pipeline puncture scenarios is currently given little or no consideration in pipeline risk analysis studies. Moreover, a brief review of the current regulatory permitting regime for fuel depots suggest that the contribution to risk from pipeline puncture scenarios may well be overlooked. As such, pipeline puncture may potentially constitute a new dimensioning scenario for land-use planning, perhaps leading to a new round of revised land-use planning guidance concerning adequate separation distances between fuel depots and neighbouring residential and commercial development.

Background

Drivers for land-use planning for fuel depot near urban centres

In 2005, Ritt Bjerregaard, the Lord Mayor of Copenhagen, announced an ambitious plan to provide homes for 'ordinary citizens'. The plan called for 5,000 homes to be built, the monthly rent should not exceed 5,000 DKK, and construction should be complete within five years. Property prices had risen to such an extent that only high-income citizen could afford to live in the capital, the mayor argued, and it was a political priority that Copenhagen should continue to provide affordable homes to citizens in the mid-income bracket. The area set aside for the project included parts of the green area Kløvermarken. The project area was near the tank farm Prøvestenen with about 150 tanks, many with oil products, located on an artificial island. Some project proposals contemplated land reclamation of parts of the 200 m wide channel that separates Prøvestenen from the mainland and many homes at the waterfront would be within 300 m of the fuel depot. The recent Buncefield incident had challenged commonly held views of the inability of fuel depots to be a source of major hazards and preliminary consequence analysis studies were carried out to assess hazards. The studies suggested, amongst others, burial of pipelines at road crossings. Legal obstacles and political infighting eventually killed the project in 2007 before any serious assessment of risk was carried out. It is clear though that risk issues would have played a significant role in land-use planning decisions.

In 2004, Kemira (formerly Superfos) announced that the production of NPK fertilizer, sulfuric and nitric acids at Fredericia Harbour (Denmark) would terminate due to sluggish economic performance. Demolition of the production facilities would open a large part of the harbour for new developments. The city council decided to seize the opportunity and launch an ambitious urban development project involving homes, commercial development and cultural institutions with the aim to vitalize the nearby old town and transform the former industrial waterfront to an upscale lifestyle district. As part of the project, in 2008, the city terminated a land lease agreement with Frederica Værft, a major repair shipyard, forcing it to relocate. This left the oil terminal servicing the nearby Shell refinery as the only remaining large industry at the harbour. Again, risk issues collided with urban development.

Similar risk issues currently confront urban development plans in the harbours of other Danish cities, e.g. Aarhus. Ambiguous land-use planning guidelines and ill-defined criteria for tolerable harm complicate matters. We note that modern upmarket urban development often involves extensive use of large glass façades, which are particularly vulnerable to overpressure damage. We also note that the resolution of conflicting interests in land-use planning decisions is inherently complicated and public opinion tend to make such decisions highly political.

Regulatory permitting regime for pipelines

In the 1970s, a number of spectacular industrial accidents in Europe, e.g. Flixborough (UK) 1974, Beek (NL) 1975, Seveso (IT) 1976 provided impetus for the first European Seveso directive in 1982 (EC, 1982). The directive introduced a requirement for certain industrial sites to identify hazards and assess risks in a systematic manner, i.e. the application of methods of process risk analysis, and submit a written report, or 'safety case', on the hazards and their controls to a regulatory authority. The directive excluded certain activities that were covered by other types of safety legislation, including the transport of dangerous substances.

Serious incidents involving the transport of dangerous substances in various parts of the world provided evidence however, that this sector also had the potential to create a major hazard to employees, to the public or to the environment. A 1970 rupture of a propane pipeline in Port Hudson, USA, led to one of largest known unconfined explosions although no one was killed. It was attributed to the detonation of propane in air with an energy equivalent of about 50 t of TNT (Burgess and Zabetakis, 1973). A 1978 rupture of a road tanker carrying LPG killed at least 215 persons at the Los Alfaques campsite in Spain. The road tanker was grossly overfilled and thermal expansion of the liquid overstressed the tank, which had no overpressure relief device (Anon., 1978; Mannan and Lees, 2005a). A 1979 explosion in Ireland while unloading crude oil from the tank ship Betelgeuse caused 50 fatalities (Mannan and Lees, 2005b). These and other events led to deliberations about the need for the major hazard aspects of the transport of dangerous goods to be subjected to additional regulatory oversight, see e.g. the recommendations of the third report of the UK Advisory Committee on Major Hazards (Harvey, 1984).

Specifically, there were debates about the need for a new European directive on pipeline safety, also requiring the safety level to be demonstrated in a safety case. In response, the first pipeline risk analysis studies began to appear in the early 1990s (Hill, 1993). In the UK, the HSE initially proposed to include gasoline among the list of substances which would be covered, but the Health and Safety Commission eventually decided to remove gasoline from the list (Little, 1999). The early European initiative eventually stalled. The issue resurfaced again in 2010 with the European Commission (DG-ENV) commissioning a study on pipeline safety with a view to possible legislative proposals (DG-ENV, 2010). Following the study, no further action was taken however. As per 2019, no EU regulations requiring systematic risk analysis of pipeline transport of dangerous substances exist. Pipelines are not covered by the EU Pressure Equipment Directive either.

Pipeline risk studies – earlier work

Puncture of a gasoline pipeline and rapid evaporation of large quantities of flammable vapours due to spray and fountain effects is a scenario currently given little or no consideration in pipeline hazard analysis studies (Hedlund et al., 2019).

A 1999 pipeline risk analysis approach (Mather and Lines, 1999) briefly mentioned spray formation but evaporation was not addressed. A risk analysis of a Polish gasoline cross country pipeline published in 2006 (Dziubinski et al., 2006) did not consider spray evaporation. More recent oil and gas pipeline risk studies (Bonvicini et al., 2015; da Cunha, 2016) do not address spray evaporation of liquids with volatile components either. The work of (Atkinson and Pursell, 2013) is an exception, as they briefly attempt to extend their models of evaporation resulting from tank overfill events to cover evaporation from spray releases also. The approach however, is approximate and preliminary only.

Pipeline punctures – early DNV study on contribution to offsite risk

Some countries base land-use planning guidance on results of estimation of risk rather than estimation of the distance to a defined level of harm for a chosen dimensioning scenario. Or, if using common risk terminology, on the results of quantified risk analysis (QRA) rather than hazard (or consequence) analysis (BMIIB, 2008b; Hu et al., 2018; Pasman and Reniers, 2014).

In 2008, the Buncefield Major Incident Investigation Board issued a report on land-use planning and the control of societal risk around major hazard sites (BMIIB, 2008b). Annex 10 of the report comprises a summary of a study by DNV (a consultancy) on the application of a risk-based land-use planning approach to a fuel depot. The DNV study did consider failure of feed pipelines and reported that this could lead to large vapour clouds, although modelling uncertainties were said to be significant.

The contribution to offsite risk was found to be immaterial however. The brief description available in the annex does not state if this result was due to estimated consequences of pipeline puncture events being less severe (vapour clouds being smaller and explosions less violent) than other loss of containment scenarios considered, or if it was due to the assumed frequency of punctures being very small.

Interestingly, the results of the study indicate that for post-Buncefield depots, tank overfill events now contribute *less* to overall risk than catastrophic tank failures, a very rare event which often is of little concern in risk analysis work.

Risk considerations for hypothetical fuel depot near a port

Release scenarios

For simplicity, we consider a hypothetical fuel depot that imports fuel from a tank ship at a nearby port. The ship's transfer pump provides the necessary power to overcome friction losses in the pipeline. We expect the pipeline to run above ground, some stretches along public roads and with some pipe bridges (road overpasses) at road crossings.

We examine two types of accidental release during import. 1) The receiving tank overflows in a worst-case Buncefield-type event leading to extensive evaporation. 2) The import pipeline is punctured resulting in a worst-case jet release with spray generation and fountain effects, leading to extensive evaporation. It is assumed that the time taken to detect the release and alert the tank ship's crew to stop pumping is the same for both release types.

Consequence estimation.

A paper (Hedlund et al., 2019) compared the evaporation of moderately volatile liquids for the tank overflow and pipeline puncture scenarios above. Estimation of the amount of vapour generated in the tank overflow scenario was based on large-scale experimental work reported by HSE/HSL and FABIG. The PHAST software suite (ver. 8.0) was used to estimate of the amount of vapour generated for the pipeline puncture scenario. The paper examined releases of moderately volatile hexane, low-volatility octane and winter gasoline. For all three substances, the spray release was found to evaporate significantly more fuel than the overfill event, in particular for gasoline. The paper also pointed to past incidents where spray releases of gasoline resulted in severe explosions.

For both types of accidental release during import to the hypothetical fuel depot, it is assumed that the vapour cloud will travel and disperse in the same manner, enter environs with the same obstacle density and encounter the same ignition source density. Because more fuel evaporates, the consequences of a flash fire or an OFCE are more severe for the pipeline puncture scenario than for the overflow scenario.

Several factors may influence these assumptions. It may be argued that a pipeline puncture may release vapours in environs where more ignition sources are present, in particular if the pipeline follows roads with traffic or other human activity. Early ignition will lead to smaller hazard distances as the cloud has had less time to build up. On the other hand, it may take more time for staff at the fuel depot to discover a pipeline release at some distance from the fuel depot and relay the alert to the ship to stop pumping. Overall, it would not seem unreasonable to assume that the pipeline puncture scenarios give rise to more severe consequences.

Frequency estimation

For a modernized post-Buncefield large tank we would expect an instrumented overfill protection system with a high-end SIL-1 reliability (probability of failure on demand of 1.7 $x10^{-2}$) comprising an independent level high switch, which closes a valve in the incoming pipeline that stops flow to the tank. We also expect the control room is manned during import and operators can close another valve and stop flow to the tank. For such a configuration, with about 10 filling operations per year , we crudely estimate a frequency of about 5.3 $x10^{-5}$ y^{-1} for an overfill event.

CONCAWE releases statistical overviews of reported spillages for European cross country buried oil pipelines. The spillage frequency time series, excluding theft, exhibits a distinctly downward trend but levels out and appears to stabilize at around 0.2 $x10^{-6}$ m^{-1} y^{-1} (Cech et al., 2018). Above-ground piping is more exposed to external impact and a frequency of 0.44 $x10^{-6}$ m^{-1} y^{-1} for the holes sized considered in (Hedlund et al., 2019) would not appear unreasonable. For a 1-2 km import pipe, the estimated puncture frequency would be around 6.7 x10^{-4} y^{-1}, about an order of magnitude larger than the overfilling frequency. This figure may not capture the full exposure to external impact to above-ground pipelines near roads, however.

Through the Danish equivalent of a freedom of information Act, we obtained a list of reported incidents involving vehicle collisions with pipe bridges. The data cover a tank farm that neighbours other industrial activities such as handling of scrap metal, recycling of construction waste materials etc. with which it shares some access roads. Pipe bridges have a typical clearance of 4.5 m. For the 10-year period 2009-2018, where reporting appears complete, there have been six reported collisions of which five resulted in significant material damage such as plastic deformation of piping, pipe supports etc. Two impacts led to breach of pipeline mechanical integrity, of which one took place during the transfer of a class II product (jet fuel), resulting in spillage of 30-40 m³ of product. The incidents with significant pipeline damage were exclusively caused by trucks with a raised crane. The limited and sporadic reporting for earlier years supports that about one in three impacts with a raised crane leads to breach of mechanical integrity, i.e. spillage, if a transfer is ongoing.

The authority issued an order in 2009 to erect dummy bridges at the exit gates of the neighbouring industries. There have been no collisions since 2014. A collision in 2012 was attributed to the fact that the dummy bridge was away for repairs, as it had been damaged in a collision three days earlier. The facility has since acquired a spare dummy bridge. While the hazard appears well-managed at this site, other facilities may be vulnerable, and the contribution to the overall pipeline puncture frequency may currently be unaccounted for. It has not been possible to find reliable data for dropped objects or for vehicle collisions with above-ground piping alongside roads.

Contribution to risk

We have refrained from an estimation of risk as it involves many assumptions that are specific for the site, such as the number of tanks, the location of tanks and pipeline route relative to the general population at risk, pipeline usage, etc. which quickly make a direct comparison complicated. From a top-level perspective however, with consequences more severe and frequency of occurrence higher, it is a trivial finding that the contribution to overall risk from pipeline punctures is higher than that of tank overfill events.

Discussion

Limited recognition of risks from pipelines

Certain EU Member States have national legislation that covers pipelines and land-use planning, for example the PADHI methodology in the UK (HSE, 2011a). In response to the extreme explosion at that AZF fertilizer facility in Toulouse in 2001, France has implemented a land-use planning approach based on quantitative risk analysis that also covers pipelines (Descourriere and Chaumette, 2010).

The current EU Seveso III Directive (EU, 2012) covers so-called establishments; that is, a location under the control of an operator, where substances defined as dangerous are present in quantities exceeding certain threshold limits. Depending on the quantities present, establishments can be lower-tier or upper-tier. For upper-tier establishments, the Directive sets requirements for a so-called safety report (i.e. safety case in a specific format) covering risk analysis, land-use planning and information to the public, amongst others. For fuel depots that are upper-tier Seveso establishments (i.e. the inventory of petroleum products exceeds 25,000 t), Buncefield-type tank overfill scenarios and land-use planning considerations will most likely be addressed in a regulatory permitting procedure. The ownership structure can be important however. For a small tank farm with several different operators, each operator in control of relatively few tanks and hence a lower-tier establishment, few or no safety reports may be produced.

The Seveso III Directive covers connecting pipework and transfer pumps within an establishment but pipelines and other installations such as pumping stations outside the property line are not covered, nor is a tanker ship berthed at a port. Such pipelines are subject to general duties covering design, construction etc., but there are no requirements for risk analysis, an emergency plan, land-use planning or information to the public.

Release scenarios for high-capacity import pipelines connecting to a fuel depot are therefore unlikely to be examined systematically limiting the amount of information available for a regulatory permitting procedure. The omission is important if such scenarios are capable of generating very large vapour clouds that contribute significantly to overall risk in the vicinity of the depot.

Intensification may gradually increase the hazard potential

In the 1960s and 1970s there was a growing recognition that industrial activities involving dangerous substances required more regulatory attention. Intensification had increased. Driven by economies of scale, chemical plants rapidly grew in size, typically by a factor of 10 or more. Heat integration lead to more compact and complex designs and process operating conditions became more severe. By about 1970, the worldwide trend for accidental losses, began to rise more rapidly than the gross national product (Mannan, 2009). These developments eventually led to the first Seveso Directive (Simpson, 1976).

Intensification also played a role at Buncefield. The depot received fuel batches from distant refineries through three pipelines. The depot's throughput of product had quadrupled since it began operations in the late 1960s. Over time, staffing levels had been reduced. Two of the pipelines were controlled from elsewhere and import flow rates could change significantly without the operators' knowledge. A subcontractor was responsible for the safety critical overfill protection systems that failed (HSE, 2011b). The EEMUA guidance document (EEMUA, n.d.) on lessons learnt from Buncefield cites such contributing factors as the loss of corporate memory, loss of adequate technical competence and loss of 'intelligent customer' capability when work impacting on the control of major accident hazards is outsourced.

It would be unreasonable not to expect that comparable forces for higher efficiency and intensification are at work elsewhere in the fuel transportation network. Minimization of the time spent in port is important for the overall economic performance of an oil tanker. Import flow rates are large; 1,000 m^3/h, almost 200 kg/s, are not uncommon. While an examination of these matters is out scope this work, we consider it likely that automation has reduced manning levels, that critical tasks are subcontracted and language barriers can delay communications to the ship in an emergency.

Sudden tank rupture

Experience has shown with clarity, that in case of a catastrophic rupture of a bulk storage tank the bund will not retain all of the released material (Atherton et al., 2007). This so-called bund overtopping may lead to spread of the incident, fire escalation and environmental pollution. Authors have argued (Atherton, 2005), that while the event is rare, it has occurred too often to ignore, and there is a defined need to carry out assessments of the risks. An excellent overview of past tank failure incidents is provided in (Thyer et al., 2009).

An examination of the findings of the DNV study mentioned above, results reported in (BMIIB, 2008b), indicates that for a post-Buncefield depot, catastrophic tank failures contribute more to overall risk than tank overfill events. By implication, the application of rational decision making would recommend that regulatory attention and research efforts should be directed at catastrophic tank failures.

We argue however, that for existing fuel depots, attention to puncture of above-ground import pipelines near populated areas may be more productive and should take priority first. The consequences are severe (Hedlund et al., 2019) and the estimated frequency of occurrence is higher – we have estimated severe punctures at 6.7 $x10^{-4}$ y^{-1} and overfillings at 5.3 $x10^{-5}$ y^{-1}, whereas catastrophic tank failures generally are set at about 5 $x10^{-6}$ y^{-1} (Taveau, 2010). For new fuel depots with SIL-2 overfill protection availability, pipeline punctures become even more relevant.

Our rationale also hinges on more mundane and practical arguments. There are major uncertainties in the modelling of the consequences of a sudden tank rupture. Estimation of the size of a vapour cloud, for example, is sensitive to many assumptions, for example the behaviour of the liquid that overtops the bund wall and flows by gravity in a complex terrain with drainage systems of different capacity. Furthermore, the number of immediately available options for providing additional protection against sudden tank rupture for existing tank farms appear limited.

This is not meant to downplay the importance of the failure type. A catastrophic tank failure in Fredericia on Feb 3, 2016, released about 9,500 m^3 of UAN32 liquid fertilizer. The immediate cause was gross overfilling of an old tank designed for oil with a much denser liquid. Due to reaction forces, the tank shell moved and crushed a section of the concrete walls of the tank yard. An empty 7,000 m^3 tank in the common tank yard floated off its foundations and crushed another section of the tank yard walls. Several smaller tanks also floated away. For unexplained reasons, a nearby palm oil tank caught fire 35 minutes later, and a large blaze covering many tanks ensued. Other large tanks in Denmark holding heavy fuel oil and fish silage have failed catastrophically (Hedlund et al., 2016).

Risk mitigation options for pipeline puncture hazards

Effective risk mitigation measures are available to reduce both the frequency and consequence of pipeline puncture events and some are low cost. Examples are:

- Protection against pipeline impact damage. Dummy bridges are simple and effective means to protect pipe bridges. If the pipeline runs near roads, crash barriers or bollards can be erected along the pipeline route where necessary.
- Burial of pipelines at road crossings.
- Ensuring effective communication lines to the tank ship to stop pumping in case of leakage
- Installation of pipeline leak detection systems.
- Reduced import flow rate.

Conclusion

Several lines of reasoning support the view that leaks on pipelines to fuel depots may contribute more to offsite risk than other leak scenarios at the depot, particularly for above-ground import pipelines to depots near ports.

- The Buncefield incident triggered a general modernization of fuel depots. Much improved tank overfill protection systems have been installed to lower the probability, and hence the contribution to overall risk, of overfill events. For that reason alone, other scenarios may become dominant contributors to risk.
- Import pipelines often run above ground making them potentially vulnerable to external impact, e.g. vehicle impact or dropped objects.
- The transfer pump sits on the tank ship, perhaps a third-party vessel hired on a short-term contract. For this configuration, automated pipeline leak-detection and pump shutdown systems are rarely available. This is in

contrast to fuel depots that receive fuel from a distant terminal via a buried cross-country pipeline where such systems often are mandatory.

- Due to globalization and reorganization of industrial production, many ports in Europe are losing traditional industrial enterprises such as chemicals manufacturing or oil mills. Fuel depots stay however, in order to supply fuel to the urban centre. There is often a desire to develop and revitalize vacated lots at ports relatively close to expensive land near urban centres, for instance construction of upscale residential housing or office buildings. Such developments may increase the population at risk.

The current regulatory framework in the EU does not address pipeline risks. Pipelines are not covered by the Seveso III Directive. As such their contribution to risk in a land-use planning context may go unrecognized. This deficiency ought to be rectified.

The transport of gasoline in above-ground import pipelines is likely the dominant contributor to risk. The import of other moderately volatile speciality chemicals likely contributes less to risk as the receiving tanks are smaller and import rates are lower. Import of low-volatility hydrocarbons such as jet-fuel likely contributes little to risk. In case of puncture, very large vapour clouds cannot form and the scenario will then rarely be of interest in a land-use planning context.

Before Buncefield there was little recognition that overfilling of a gasoline tank had major accident potential. Had the precautionary principle been followed and warnings from past mishaps been heeded, the risk could have been recognized decades earlier. Many of the physical processes that lead to evaporation when liquid overflows from the roof of a storage tank and falls as a cascade also apply in a spray release if a pressurized pipeline is punctured. Indeed, past mishaps with spray releases leading to violent explosions have occurred. The work reported here suggests that the contribution to risk is significant. Application of the precautionary principle would call for directing attention to accidental spray releases.

We are conscious of the preliminary nature of our work and our conclusions. A measured response may be warranted. On the other hand, low cost options available to protect pipelines against impact damage could be introduced with little delay. Above all, there is a genuine need for further studies on the major hazard potential of pipelines transporting moderately volatile substance (gasoline, crude oil etc.) and the relevance of puncture scenarios to land-use planning.

Conflicts of interest

The authors declare that they have no conflicts of interests.

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