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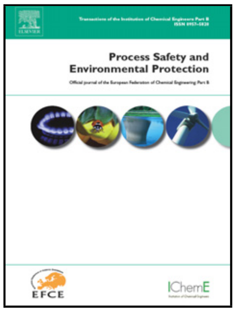

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Conditional probabilities of post-release events for hazardous materials pipelines

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Abstract

Pipelines are commonly considered a safe alternative for the transportation of hazardous materials. However, in case of failure, pipelines still pose major risks to the environment and to the population potentially exposed. The aim of the present work is to provide occurrence probabilities of the intermediate and final events following the accidental release of hazardous materials from pipelines. A collection of incidents and accidents occurred worldwide in connection with the use of onshore long-distance pipeline networks, has been gathered to make up a specific database for the analysis of incidents in pipelines. A qualitative and quantitative analysis of the data has allowed to develop detailed event trees for the different classes of hazardous materials, and to calculate the probability of occurrence of the final outcomes. The investigation has also aimed at identifying, for each type of release, the relationship between the final events and the causes of the pipeline failure. The results obtained represent a useful and needed starting point in Quantitative Risk Analysis of hazardous materials transportation via pipelines.

Keywords
Pipelines; Transportation; Accidental release; Event trees; Probabilities; Hazardous materials.

1. Introduction

Pipeline transportation is commonly regarded as a safer alternative compared to other transportation modes, such as road and rail, based on the low accident frequency and the generally limited number of fatalities historically registered (Papadakis, 1999). Nonetheless, due to the continually increasing extension of their network, pipelines often cross highly populated and industrialized areas, so that in case of a loss of containment involving a hazardous substance, significant damages can affect a large number of people. At the same time, given the close interaction between the pipeline and human activities, the frequency of occurrence of failures can become significant. When crossing rural areas, despite the low number of people possibly involved, environmental impact and pollution can result. As a matter of fact, a number of recent accidents, such as the one occurred in Ghislenghien, Belgium, on July 30, 2004, where the rupture of a high pressure natural gas pipeline and the subsequent large fire caused 23 casualties and around 150 hospitalized (ARIA, 2009), or the one occurred in Marshall, Michigan (NTSB, 2012), with an important pollution on a wetland and two rivers, confirm this concern.

Consequently, an increasing attention has been devoted in recent years to the quantification of the risk associated with this transportation mode based on the well-known techniques of Quantitative Risk Analysis (QRA) (Jo and Ahn, 2005; Dziubinski et al., 2006; Jo and Crowl, 2008; Casal, 2008; Han and Weng, 2010). This methodology consists in a stepwise procedure where the following main phases are carried out: identification of the accident scenarios, calculation of their consequences in terms of damaged areas and people involved, estimation of their frequency of occurrence and, finally, quantification of the overall risk (CCPS, 2000; CCPS, 2008). Each of these steps entails specific difficulties and uncertainties, but the step usually most affected by a higher level of uncertainty is the frequency estimation. The frequency of occurrence of the identified events can be estimated either by a statistical analysis of historical data, which, whenever applicable, is the most reliable methodology, or by means of some theoretical models, such as Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). Unfortunately, historical data are often lacking, and therefore the application of the latter techniques becomes necessary, which in turn require specialized and experienced personnel to be properly carried out. Even in this case, a rather high level of uncertainty remains when the system under investigation is not simple enough and clearly defined, and when not all the needed input data are known. This is the case of pipeline transportation, where a high variability of the characteristics of the territories crossed by the line and a wide range of unpredictable possible events is present (Dziubinski *et al.*, 2006).

Both approaches have been adopted in the literature, mainly devoted at identifying the frequency of occurrence of a release (Henselwood and Phillips, 2006; Han and Weng, 2010) rather than at calculating the probability of the different possible events following a release (Rew *et al.*, 2000; Moosemiller, 2011). Overall values of the accidents and release frequencies are also available in the generic literature (De Haag and Ale, 1999; Lees, 2005; EGIG, 2008; PHMSA, 2016).

Based on the above considerations, and with the aim of improving the knowledge of the data required to carry out a QRA, in this paper a statistical analysis of historical data on accidents involving pipelines occurred all over the world has been carried out. No consideration has been given here to the magnitude of the consequences of the releases. A preliminary analysis of data collected from sources of specialized information has already been presented (Ramírez-Camacho *et al.*, 2016), with particular emphasis on issues related to land-use planning. In the present paper the gathered historical data has been properly processed and a more detailed analysis of the historical data has been carried out to provide a useful basis for estimating the conditional probabilities of the different events that can occur following the accidental release of hazardous materials from pipelines. In fact, the release of a flammable and/or toxic material may evolve in different ways, depending on a number of factors, such as the physicochemical properties of the transported material, the type of release (puncture, leak, catastrophic) and its duration, the mass released, the outside environmental conditions, the time and circumstances of the ignition and many others. Consequently, dedicated event trees have been developed for the different substance categories identified, and the statistical analysis of the historical records has made it possible to estimate the conditional probabilities for each specific release sequence. These probabilities represent fundamental parameters to be used in QRA, when the risk generated by the presence of a pipeline transporting hazardous materials on the potentially exposed population has to be assessed.

2. Data gathering and filtering

An historical data collection has been carried out in order to gather as much information as possible about the events that take place after a loss of containment from onshore pipelines transporting hazardous materials. The survey has been performed by consulting accident databases and other open sources of information such as accident reports and technical reports covering pipeline incidents. The main consulted sources were:

- The Analysis, Research and Information on Accidents database (ARIA, 2014)
- The Federal Institute for Materials Research and Testing of Germany (BAM, 2009)
- The Major Hazard Incident Data Service database (MHIDAS, 2007)

- The Transportation Safety Board of Canada (TSB, 2014)
- The U.K. Health and Safety Executive (HSE, 2000, 2002)
- The U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration (DOT-PHMSA, 2014).
- The U.S. National Transportation Safety Board (NTSB, 2014).
- The Oil Companies European Organization for Environment, Health and Safety (CONCAWE, 2013).

The MHIDAS database (November 2007 version, containing 14,168 records), which has been used as the main source of information, is managed by the UK Health and Safety Executive; it includes incidents that have occurred during the transport, processing or storage of hazardous materials, which resulted in or had the potential to cause an off-site impact. This database stores each incident in individual fields (*i.e.*, date, location, incident type, origin, cause, abstract, deaths, injuries, among others); these same fields were used in this study. Moreover, for each incident more information was drawn up and placed in new additional fields: part of system involved, system type, pipeline diameter, operating pressure, environmental damages.

In order to identify the records of interest, a first filtering operation was conducted on the MHIDAS database, based on the fields "general origin" and "specific origin". Among the general origins, the transport activity was selected. Concerning “specific origin”, the incidents in onshore pipelines were filtered. Later on, the ‘‘Abstract” field of the incidents -one by one- was analysed in order to double-check that accidents were correctly selected. Accidents occurring in offshore pipelines, those caused by sabotage or from short-distance pipelines (i.e. transfer pipelines, gas service lines or LNG pipelines) were not considered in this study. A logical sequence of the steps adopted in the selection procedure is reported in Fig. 1.

After applying this extraction process, a collection of 639 accidents was considered. Subsequently, a parallel research by consulting freely accessible information on official sources was conducted. The goal was to complement the missing information in the selected records of MHIDAS. Simultaneously, the space-time search intervals up to 2014 were extended. As a result, a total of 542 additional accidents was included. Finally, a matching procedure between both sets of data was performed, with the aim of finding matching records. The ‘‘Date of incident” and ‘‘Location” fields were used as initial references for this purpose. Finally, after this procedure, a collection of 1063 accidents was obtained (for further details see Ramírez-Camacho *et al.*, 2016).

3. Information processing

The types of events occurring after the loss of containment of a hazardous material depend on a range of factors, either linked with the material itself (physical properties, hazardous properties, etc.) and/or with the internal and external pipeline conditions: physical state, pressure and temperature inside the pipeline, release rate and amount of material released, weather conditions (*e.g.*, wind velocity, atmospheric stability class), surrounding territory characteristics (flat/hilly, rural/urban), population distribution, etc. All these parameters can influence the evolution of the accident following the release, either by generating, promoting or hampering the occurrence of the possible intermediate and final events. Based on these considerations, the collected information has been analysed in order to estimate the probability of occurrence of each of the events identified.

3.1. Hazardous materials involved

The properties of the substances involved have a marked influence on the consequences of the release. If the released fluid is a gas and there is immediate ignition, a jet fire will occur; if there is no immediate ignition, a flash fire or a cloud explosion is still possible (delayed ignition), depending on the environmental conditions and if the explosive air/gas mixture is between its flammable limits. Conversely, a liquid spill will drop on the ground, forming a pool, which can be ignited, giving rise to a pool fire, or can evaporate generating a cloud subject to the same evolution as for a gaseous release. A pressure-liquefied gas can behave in either or both ways depending on its physical properties and transport conditions.

A number of different substances were identified; however, they were grouped into a few categories for estimating the corresponding probabilities.

Gases are usually transported at relatively high pressure and can represent a single class of substances. Concerning liquids, since in the vast majority of the cases the liquids involved were flammable, they have been grouped into two distinct classes, based on their flash point (T_f). Finally, pressure liquefied gases represent another specific group of materials, so that the following four groups of substances were finally identified:

- Compressed gases,
- Pressure liquefied gases,
- Volatile liquids (with $T_f \leq 21$ °C),
- Liquids with low volatility (with $T_f > 21$ °C).

According to the materials involved, and based on the above classification, the distribution of historical accidents reported in Table 1 was obtained. It is important to mention that 14 events involved more than one material, however, only the first material of the events has been considered here.

It can be seen that the following distribution among the defined classes is obtained: compressed gas 27.4% (291 entries); pressure-liquefied gases 4.7 % (50 entries), volatile liquids 57.2% (608 entries); low volatility liquids 10.73% (114 entries). More in details, most of the accidents included in the group of compressed gases involved natural gas (more than 99% of the entries), while LPG represented more than 68% of the cases with pressure-liquefied gases; in the case of volatile liquids, crude oil (47.2%), and gasoline (about 50%) were the main items, while jet fuel (42.1%), diesel (27.2%) and kerosene (12.3%), summed up to 80% of the low volatile liquid cases.

3.2. Types of release

The magnitude of the consequences of an accident also depends on the amount of material released, which in turn depends on the extension of the pipeline damage, the detection time, the time required to stop the flow through the pipe (via pumps and/or gate valves), etc. Similar to the procedure adopted for the type of material described above, three different release modalities were identified and defined as follows:

- Release from a hole: it refers to a hole of small size (a fraction of the pipe diameter), for which the detection time ranges between 20 s and 24 h (Dziubiński *et al.*, 2006). A long duration release from a hole is often referred also as a "leak"; a short duration release as a "spill".
- Full bore rupture: when the extension of the damaged area of the pipe is equal to, or larger than, its diameter.
- Catastrophic rupture: a sudden rupture that involves a significant section of the pipeline. When the substances involved are compressed gases or liquefied gases, this might generate a physical explosion.

3.3. Incident outcomes

Following an accidental loss of containment, a number of intermediate and final events, either alternative or coexisting, may happen, whose probability of occurrence depend on the combination of many factors, as explained before (materials properties, environmental conditions, etc.).

A general description will follow here, to qualitatively introduce and to account for the structure of the event trees set up for the different materials classes. The corresponding quantitative values obtained from the database analysis will be discussed in Section 4.

3.3.1. Fires

The ignition of a flammable substance can give rise to different types of fire, depending on the fuel properties and on the environmental conditions at the time of the ignition. A jet fire results from the immediate ignition of a turbulent jet of a flammable gas, vapour or liquid, which is usually associated with pressure releases. When the immediate ignition involves a large mass of flammable vapours (often derived from the catastrophic rupture of a large vessel or pipe), a fireball is generated; this is typical of releases involving directly a gas or a pressure liquefied gas with a large flash fraction. Alternatively, if a relatively large mass of flammable material first disperses and mixes with ambient air, and subsequently the generated fuel-air mixture is ignited, a very fast combustion of the cloud occurs (flash fire). This can be characteristic of many accidental scenarios such as a gas release, as well as after the evaporation (either immediate or continuous) of a liquid.

The ignition of the vapours generated by a liquid pool will cause a pool fire. However, different types of pool fires can follow a given initial release: the local (*i.e.,* close to the release site) ignition of the pool, either immediate or delayed, will generate a pool fire in the area of the spill; if the liquid moves away from the location of the release, and finally finds an ignition source, a pool fire away from the accident location will occur (this event will be hereafter addressed as a “fire on migrating liquid surface”). When the evaporation from the pool is capable of generating a flammable cloud “connected” with the pool itself, a delayed ignition of the cloud can also trigger the fire on the pool, so that more than one single dangerous event is produced. Pool fires are typical both of high and low volatility liquids, as well as of pressure liquefied gases; however, sometimes the delayed ignition is not considered for liquids with low volatility because it is believed that vapour clouds at concentrations within the flammability limits are not generated (Ronza *et al.,* 2007).

In addition to that, in the case of a turbulent jet release, a delayed ignition can give rise to multiple outcomes: a local ignition will directly and simultaneously generate the combustion of the cloud (flash fire or vapour cloud explosion, depending on the environmental conditions) and the jet fire, while a remote ignition will first start the cloud combustion and subsequently cause the jet fire.

3.3.2. Explosions

The failure of a high-pressure pipeline, such as those containing high-pressure gases or pressure-liquefied gases, can theoretically give rise to a blast wave, as in the case of storage/process vessels. Nonetheless, as can be seen in the next section, no specific reference was found in the accident reports used in the present investigation. It can be a matter of discussion whether this is because of a lack of information or because they actually never happened; however, based on this experimental evidence, the physical explosion has not been considered here in setting up the event trees.

Alternatively, when a large mass of flammable material is released and dispersed in the environment, in case of delayed ignition, besides a flash fire, a vapour cloud explosion (VCE) can occur. This occurs when the combustion rate markedly increases and the flame front is strongly accelerated, which usually happens in the presence of turbulence, and some level of confinement.

3.3.3. Vapour clouds and/or liquids dispersion

Besides the above considerations connected with the flammability characteristics of the released substance, other possible dangerous events have to be taken into account, depending on the substance properties. Following the loss of containment, a vapour cloud and/or a liquid pool will disperse into the environment. If the vapour is toxic, a very dangerous toxic cloud can affect the population in the surroundings of the accident site, and this often represents a serious possible consequence of a hazardous substance loss of containment; furthermore, even if the material is not toxic, the risk of asphyxiation at high concentrations is present, especially in partially confined or even enclosed areas (Bubbico *et al.*, 2014). Similar considerations apply to a liquid pollutant, which can disperse generating severe consequences to the environment and/or the population.

Since flammable materials have been involved in all the cases considered in the present analysis, and no, or very little, information was provided about the other possible effects, the above damaging events have not been included in the devised event trees. As a result, in the absence of combustion, the terms “no consequences” and “no fire/explosion”, adopted in the following event trees, have here the same meaning. Nonetheless, it must be observed that in the case of toxic or polluting substances, these final outcomes should be properly considered, otherwise severe consequences might be neglected and the overall risk would be finally underestimated.

3.4. Generic and specific failure causes

The causes originating the analysed accidents were assigned to a limited number of generic classes, and for each of them additional subclasses, corresponding to the specific cause of failure, were identified (see Table 2). This classification has already been discussed with reference to land-use planning (Ramírez-Camacho *et al.,* 2016).

Third party activity represents any external mechanical interference caused by third party operators unaware of the presence of the pipeline. In the particular case of buried pipelines, specific causes are related to excavators, construction companies or other equipment used in excavation activities or farmlands, etc. Pipelines crossing other utility service lines (*e.g.*, water/gas mains, phone lines, etc.) have an increased potential for third party incidents. Generally, mechanical interference leads to a puncture, a crack or to a gouge that reduces the wall thickness of the pipe; depending on these factors, the pipe failure can be immediate or may occur sometime later by fatigue or corrosion. On the contrary, when the pipeline company causes the damage to the pipe during operations of maintenance, repair/replace, start-up, etc., the failure origin is classified as operational/human errors.

It is important to stress that only the initial cause of the pipe failure has been kept here into account.

4. Results and discussion

An accurate analysis of the accident reports was carried out, and dedicated event trees were developed for each category of substances identified in Table 1. These instruments of quantitative analysis, reported in Figs. 2-5, allowed obtaining frequencies of occurrence of the different types of final events, following the initial release (“loss of containment”), either for each class of substances and for each type of release.

In the event trees of Figs. 2-5, along with the conditional probabilities, the absolute number of the accidents corresponding to each branch has also been included. This has been done to provide thorough information and to highlight the statistical significance of the calculations. As a final remark it must be stressed that all the following probability values might be somewhat overestimated, since it is expected that an unknown number of accidental releases from pipelines characterized by minor or no damages have not been officially reported.

4.1. Compressed gases

As already mentioned, among the 291 scenarios including compressed gases, 2 cases involved hydrogen and 289 cases (*i.e.*, almost the totality of accidents) natural gas (see Table 1), so that we could actually say that the considerations below essentially apply to natural gas.

From the event tree set up for this class of accidents (Fig. 2), it can be seen that the most frequent types of release are the "full bore rupture" and the “release from hole”, with 40.5% and 36.4% probability (118 and 106 entries), respectively. The "catastrophic rupture" (49 cases), corresponds to 16.8%, while only for 18 accidents (6.2%) it was not possible to specify the type of release. The immediate ignition is not very likely for the two most common release types, showing a probability of 0.24 for the full bore rupture and only 0.06 for the release from a hole. Moosemiller (2011) provides an average value of 0.15 for the immediate ignition probability, independent of the type of flammable released and the magnitude and duration of the release (however, the study does not cite the origin of this value). The averaged value of the immediate ignition probability obtained from the present data, with the weights being the fraction of cases of small and full bore ruptures releases, is found to be 0.157, thus perfectly matching the value found in the literature.

For releases from holes, when the cloud dispersion is almost certain (92 cases out of 98 characterized by the “no immediate ignition” option), a higher delayed ignition probability is observed with respect to the full bore rupture (60.9% and 46.4%, respectively); furthermore, the probability of flame front acceleration is higher for a release from a hole rather than from a full bore rupture, with 89.3% and 64.1%, respectively. It is apparent that, conversely to the case of the immediate ignition probability, the obtained probabilities for delayed ignition and explosion found based on the reported data are much higher (more than double) than those cited by Moosemiller (2011), *i.e.*, 0.3 and 0.2, respectively.

Table 3 reports the probabilities of occurrence of the possible final events occurring after the release of a compressed gas (VCE, flash fire, etc.): in the first four columns the probabilities associated with each type of release are reported (release from hole, full bore rupture, etc.), while in the last column the overall probabilities, for all compressed gas releases independently of the type, are shown. It must be observed that since some of the final accidents can happen simultaneously, the probabilities of each column can amount to more than 1.

The combination of all conditional probabilities reported above provides a final probability of a vapour cloud explosion (with or without a simultaneous jet fire) of 0.51 in the case of release from a hole, and 0.225 for a full bore rupture (see Table 3). Given the larger size of the release section for a full bore rupture with respect to smaller holes, this result looks rather strange and in contrast with the suggestion by Cox et al. (1990), who state that the ignition probability increases with the release flow rate. A possible explanation of the present result might be the longer detection times, usually required in case of smaller releases, compared with more serious accidents, which in turn can finally give rise to a larger amount of flammable gas in the dispersed cloud. Since the amount of flammable material in the cloud is recognized as one of the main conditions required for the occurrence of a cloud explosion, this can explain the results obtained. Differently, in the case of a catastrophic rupture, the immediate ignition, with subsequent fireball, is quite likely (0.61), while in the case of no immediate ignition a safe dispersion can be expected (0.39 probability).

If the overall probabilities are taken into considerations (fifth column in Table 3), some other interesting conclusions can be drawn. In more than one third of all the cases (specifically 38%) there were no dangerous consequences. This is a quite low value if compared to previous analyses (Wang and Duncan, 2014 and EGIG, 2015), where an overall ignition probability between 2% and 18% was obtained, depending on a number of factors like pipeline diameter, release magnitude, etc.

Among all the dangerous events, the jet fire is the most likely (41% of occurrence, compared to 31.4% occurrence of a VCE or a 7.4% occurrence of a flash fire), deriving either from an immediate ignition of the release, or generated by another preceding dangerous event like a cloud fire or a VCE. The relatively high probability of a VCE is in contrast with previous statements (Jo and Ahn, 2005), whereas similar considerations have been reported for jet fires.

If the catastrophic rupture of the pipeline is taken into consideration, which occurs in about 17% of the cases, another interesting result is found. While an immediate ignition with subsequent fireball and jet fire is the most likely evolution following the release, with more than 60% probability, in the remaining 19 cases, no delayed ignition has been observed, a safe dispersion of the cloud being registered in all cases. In other words, in case of a catastrophic rupture, if an immediate fireball is not generated, it seems that a safe dispersion of the released gas can unexpectedly be trusted. According to the above figures, a fireball is not very common (0.11 probability), being associated only with the immediate ignition of a catastrophic release.

Finally, it can be observed from Fig. 2 that the conditional probabilities of the events along the branches corresponding to the unknown release type, are very close to those characterizing the release from a hole; this consideration, along with the fact that the size of the release have not been explicitly mentioned in the accident reports, would suggest that these cases might be associated with the “release from a hole” class. Similarly to that class, even in these cases, the probability of VCE is very high (10 cases out of 13 for which the final consequences are known).

As far as the exclusive causes of the release are concerned, it can be seen from Table 4 that in more than one third of the examined cases, it was not possible to identify the immediate cause of the loss of containment, independently of its severity. In the case of release from full bore rupture and from a hole, nearly one third of the incidents had as a generic cause third party activity (30.5% and 32.1%, respectively), with excavation machinery covering the great majority of the cases (72.2% for full bore ruptures and 85.3% for releases from holes), thus representing in absolute the main cause of release (more than 0.22 and 0.27 absolute probability, respectively). This result is in line with previous literature reports (Hansler *et al.*, 2011; EGIG, 2015); mainly based on data from EGIG and BG Transco, Jo and Ahn (2005) claimed external interference as the main cause of release for more than 50% of the cases.

The remaining 1/3 of the accidents investigated here were originated by causes more or less equally distributed among the other generic classes, partly in contrast with Jo and Ahn where a larger influence of mechanical failures and corrosion was found. Similarly, Wang and Duncan (2014) identified construction and material defects as the main cause of failure for small releases (leakages); while external forces and construction/material defects have almost the same probability for all other failure types. Even though no specific distinction has been made in the latter work among the outside forces (*i.e.,* whether natural or anthropogenic) if the causes associated with human activity are taken preferentially into account, one of the possible reasons of the partial discrepancy between the present results and those reported by the previous authors may be found in the comment already highlighted by Wang and Duncan (2014), *i.e.,* “transmission pipelines in Europe transverse a much more urbanized and developed terrain than is found in the United States”; for the sake of truth this statement was originally referred to the difference in failures rates between Europe and US, but it is believed that it can be equally applied to the root causes of pipeline loss of containment.

A catastrophic rupture caused by third party activities (16.3%) is less common compared to corrosion (28.57%), particularly by external corrosion (57.14% of the whole corrosion types) and stress corrosion cracking (35.7%); mechanical failure also plays a significant role (14.29%) comparable to that of third party activities, and in most of the cases is associated with the generation of internal overpressure (57% of the mechanical failures).

Finally, it has to be highlighted that operational human errors, which are often and sometimes harshly accused of being responsible of the registered accidents, do not exceed 10% of the analysed records of small hole releases, with most of the accidents occurring during repair/replacement or maintenance operations. Conversely, a catastrophic rupture seems to be rarely caused by operational human errors (2 cases out of 49).

4.2. Pressure liquefied gases

According to Fig. 3, in almost 90% of the cases, the release of a pressure-liquefied gas (PLG) occurs from a hole or from a full bore rupture (53.1 and 34.7 %, respectively). A catastrophic rupture has been recorded only in two cases.

As for compressed gases, the immediate ignition of PLG continuous releases is not very likely, especially for releases from a hole, and the average value for hole releases and full bore ruptures (0.17) matches the literature average value (0.15) rather well. If the flammable cloud is dispersed, the probability of ignition is equal to or higher than that of no ignition, depending on the release size, and, once ignited, a vapour cloud explosion is always more likely than a simple flash fire: 0.6 *vs.* 0.4, and 0.78 *vs.* 0.22, for hole and full bore ruptures, respectively. For the sake of accuracy, it must be observed that the absolute number of events on which the final probability estimation is based is rather low, so that the conclusions should be taken with care. This is especially true for the catastrophic ruptures and for the remaining unknown release conditions, where only 4 reliable historical accident reports have been found. With these cautions in mind, as also found for compressed gases, much higher probabilities of delayed ignition and explosion were found here with respect to the literature (Moosemiller, 2011).

Table 5 shows the probabilities of the final accidental events. It can be seen that an average probability of 50% of a safe conclusion of the accidental loss of containment is calculated. However, it is worth pointing out that in this case “no ignition” does not necessarily mean “no consequences”, since some of the substances included in this class can have also toxic properties (*e.g.,* ammonia), and therefore in these cases “no ignition” stands for “toxic cloud dispersion”, which is usually characterized by even larger impact areas than fires and explosions. This was not the case with compressed gases, in which only natural gas and hydrogen were involved.

By considering all the possible accident evolutions among the dangerous final events, jet fire is by far the most probable for full bore ruptures (0.7), followed by VCE (around 0.4), while in the case of releases from holes, they are equally likely (0.27), but with a much lower probability with respect to larger leakages. As observed in the previous section, a more or less complete vaporization of the released liquid can occur for pressure liquefied gases; consequently, the local ignition of the release (either immediate or delayed) can give rise to both a jet fire and a pool fire, depending on the type of fluid and its transport conditions.

The number of historical cases for catastrophic and unknown releases is quite low to derive statistically meaningful conclusions, and therefore they will be ignored here.

Overall, it can be concluded that in the case of pressure liquefied gas releases, there is a 50% probability of concluding the accident without dangerous events (neglecting possible toxic dispersion, as already highlighted before) or with local damages (jet and pool fires); in addition, there is also a 30% probability of generating a higher impact VCE.

Even though based on a limited number of reported accidents, some general trend related to the exclusive causes of release, will be highlighted here (Table 6). With reference to the loss of containment from holes, it was found that the most common cause is associated with third party activity (approximately 23% of the total), particularly during excavation (2/3 of this generic cause), but a significant role is also played by mechanical failures and corrosion (around 15% each). As already found for compressed gases, the operational human error is responsible for a limited number of the recorded accidents. Excavation is again the most frequent cause of releases from full bore ruptures, being responsible of 6 out of 17 (35%) cases, with the remaining accidents more or less equally distributed among the other categories of causes: mechanical failures, natural hazards and operational human errors.

4.3. Volatile liquids

Volatile liquids represent the class of substances characterized by the largest number of reported accidents (608 cases) and the corresponding event tree is shown in Fig. 4. It can be seen that the branch relative to catastrophic release is not present. Also, given the very low number of records with uncertain information (only 7 out of 608), two release conditions practically cover the whole range of considered events: releases from a hole (with a probability higher than 0.75) and full bore ruptures (0.235). Similar to the previous classes of materials, the immediate ignition of the release is quite unlikely, with probabilities always well below 10%: namely, 0.4% for releases from holes, and 7.2% for full bore rupture. The average immediate ignition probability is now 0.02, much lower than for the previous classes and also with respect to the average value of 0.15 sometimes reported in the literature (Moosemiller, 2011). This suggests that this latter value should be better considered as referred to gases and flashing liquids rather than to liquid fuels. Alternatively, the value of 0.065 provided by the BEVI manual (RIVM, 2009), referred to Category 1 substances (*i.e.,* $T_f<21°$), is much closer to the probability derived here for full bore rupture (0.072).

A delayed ignition is also unlikely for both cases (hole and full bore rupture), with a “no fire/explosion” probability of around 0.9 for both rupture types. Overall, a “no outcome” conclusion of the accident was observed in 88% of all the cases analysed (see Table 7). Despite the low probability of occurrence, a delayed ignition can still give rise to serious accidents, and in 30 of 57 cases where ignition actually occurred a VCE was registered (Fig. 4), corresponding to an overall probability of 5%. As found with compressed gases, the probability of a VCE is higher for releases from holes (0.062) than for full bore rupture (0.014), and the same considerations about the detection time can be done here. As can be seen in Table 7, the overall probabilities of VCEs and “simple” flash fires are quite similar to each other (0.05 and 0.046, respectively); this can be explained by the lower amounts of vapours generated, compared with gases and pressure liquefied gases, which is one of the pre-requisites for the generation of a vapour cloud explosion.

Despite the high volatility of the substance, volatile liquid releases are always characterized by the presence of the pool and by much smaller amounts of vapours immediately generated. As a consequence, the frequent occurrence of liquid fires can be expected. Table 7 shows that the pool fire is the most common accidental event, following an ignition. Furthermore, as already highlighted in section 2, depending on the release conditions and the characteristics of the accident area, the liquid pool can move away from the release site before ignition and subsequently find a source of ignition giving rise to a fire on a migrating liquid pool; in particular, in Table 7 these two conditions have been detailed and it can be seen that the migrating liquid fire is the most common outcome (0.039 probability versus 0.019 for a local pool fire). It is also interesting to observe that a migrating liquid pool fire is always accompanied by another dangerous event (VCE or flash fire), confirming the generation by a delayed (or distant) source of ignition. If the two release conditions are compared, it can be seen that in the case of the full bore rupture, all the dangerous outcomes have a higher probability of occurrence, in accordance with the large amount of material released. Finally, due to the small amount of vapours immediately released, the jet fire is now overall the least frequent accident.

For this class of hazardous materials, different trends can be observed with regard to the exclusive causes of release, depending on its size (Table 8). Concerning releases from holes, third party activities are still the prevailing causation events, especially during excavation works, with slightly more than 30% of all cases. The second most frequent cause is corrosion (nearly 20%), mainly generated by external agents (more than 50% of the generic cause). Mechanical failures are most often associated with materials defects and/or weld failures (57% of the generic cause), while the remaining causes represent less than 10% each. Differently, in the case of the 143 full-bore ruptures analysed, a rather more uniform distribution of the causes was revealed. Neglecting about 1/3 of the cases where no information was available for the identification of the initiating event, the most common causes were mechanical failures (20.28%), and third party activities (16.08%), but also corrosion and natural hazards caused a significant number of accidents (12.6 and 10.5%, respectively). Again, operational human errors proved to be less frequent than might be expected, with less than 6% for both release modalities, and most often during repairs/maintenance operations.

4.4. Liquids with low volatility

Given the physical properties of the substances belonging to this class of materials, a significant amount of vapours capable of generating a dangerous event like a cloud fire or an explosion, following an ignition, is not expected even in connection with a long-lasting spill. As a matter of fact, no cases of vapour cloud explosion or flash fire are reported in the examined databases (Fig. 5). Conversely, a number of fires associated with the ignition of the pool generated by the release, either in the proximity of the leakage or in a different location due to migration of the liquid pool, are reported. Actually, disregarding the consequences, possibly associated with these fires in terms of people injured or structures damaged, their probability of occurrence is very low: on a total of 114 historical accidents investigated, the final event “no fire” was found to have an overall probability of nearly 0.94 (Table 9).

However, with reference to this latter scenario, it must be observed that, as already specified above, the term “no ignition” or “no fire” does not necessarily mean “no consequences”: they mean that no combustion of the flammable vapours was recorded, either because no ignition source was present during the accident, or because no vapour cloud was generated, or, finally, because the vapour cloud did not reach the flammable limit of the substance. Yet, depending on the properties of the particular chemical involved, other consequences are possible, like the dispersion of toxic vapours or some other kind of environmental pollution: in 84% of the analysed cases environmental pollution was actually reported, but these are outside the scope of the present paper and have not been further investigated here.

As with volatile liquids, no cases of catastrophic rupture have been reported for liquids with low volatility, and the release was found to occur from holes in the 86.8% of the cases (Fig. 5), and from full bore ruptures with a probability of only 0.132. The jet fire has a probability of occurrence of less than 1% overall (occurred in one out of 114 accidents), while that of a pool fire is higher than 5% (Table 9); compared to volatile liquids, a local pool fire is now more frequent than a migrating liquid, being associated mainly with the immediate ignition of the release (4 out of 6 pool fires registered). The immediate ignition probability of such substances (0.044) is lower than 0.15 (Moosemiller, 2011), but larger than reported in the BEVI manual (0.01 for Category 2 substances, see RIVM, 2009).

For this class of substances, similar results about the causes of release as those found for volatile liquids have been observed (Table 10). Since the total number of full bore rupture was quite low, only generic indications can be drawn: most of the releases were caused by mechanical failures, mainly associated with internal overpressure and weld or other construction defects. In the case of release from holes (99 cases), more meaningful figures can be derived; third party activity is the main group of generic causes (33%), with damages during excavation works representing the most frequent specific cause (88% of that class); mechanical failure is the second class in terms of frequency (more than 24% of the total accidents) with weld failures and materials defects being the most common specific contribution (42% and 29% respectively). Corrosion also plays a significant role, with 17% of the total release rupture causes, mainly due to external origin.

Conclusions

Even if no consideration has been given in the present paper to the magnitude of the possible consequences of the release of dangerous materials from pipelines, the results here presented are deemed of great interest for quantifying the risk associated with the use of such a transportation mode. In fact, one of the major uncertainties in Quantitative Risk Analysis is the estimation of the frequency of occurrence of the different outcomes following an initial dangerous event. In this paper, the conditional probabilities of the branches of the post-accident event trees associated with a range of hazardous substances have been calculated from historical records.

It has been quantitatively confirmed the intuitive hypothesis of the importance of the substance volatility: the overall probability of a safe conclusion of an accidental release, continuously and markedly increases with decreasing the substances volatility (namely 38, 49, 88, and 94%, for the four classes compressed gases, pressure-liquefied gases, volatile liquids and low volatility liquids, respectively). At the same time, a catastrophic rupture is only possible for high-pressure gases or pressure liquefied gases (17 and 4%, respectively), while it has been never registered for liquid fuels. Also, outcomes characterized by large impact areas, such as VCE and, to a lesser extent, flash fire, are likely for gases and PLG (between 7 and 30% probability), but very rare for liquids (5% only for high volatility liquids) except for the case of environmental impact. For liquids the most dangerous final event is represented by a pool fire, but with an occurrence probability hardly exceeding 5%.

Regarding causation events, third party activities were found to be the most common cause of damage to pipelines, independently of the release severity and for all substance categories, with the vast majority of damage caused during excavation activities. This should be properly taken into consideration since their occurrence might be significantly reduced by simple procedural improvements in work permits and information exchange among the companies involved. The second main causes of loss of containment are both mechanical failures and corrosion; in particular, corrosion was found to be the main cause of catastrophic rupture for high-pressure gas pipelines. Unexpectedly, operational human errors have shown a minor influence on the release frequency, ranging between 4 and 13% for the different classes of substances; this might be explained by the relatively limited involvement of the human factor on this kind of transportation, compared with other transportation modalities, such as road and rail.

It is believed that the quantitative results provided in the present paper can be of great help in the application of the QRA methodology to the transportation of hazardous materials via pipeline, both because of the significant amount of historical data analysed, and also because of their specific association with classes of substances instead of being referred to generic hazardous materials as a whole.

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Table 1 Summary of substances for each category identified.

Substance	Number of entries	% of category
Compressed gas		

Substance	Number of entries	% of category
▓Natural gas	289	99.3
▓Hydrogen	2	0.7
Pressurized liquefied gas		
▓LPG	34	68
▓Anhydrous ammonia	7	14
▓Ethane	3	6
▓Ethylene	2	4
▓Propylene	2	4
▓Butane	1	2
▓Carbon monoxide	1	2
Volatile liquids (with $T_f \leq 21$ ˚ C)		
▓Gasoline	303	49.8
▓Crude oil	287	47.2
▓Naphtha	7	1.2
▓Other organic products	11	1.8
Liquids with low volatility (with $T_f > 21$ ˚ C)		
▓Jet fuel	48	42.1
▓Diesel	31	27.2
▓Kerosene	14	12.3
▓Diesel fuel or heating oil	9	7.9
▓Fuel oil	9	7.9
▓Heating oil	2	1.8
▓Low-sulphur diesel	1	0.9

Table 2 Generic and specific causes of failure.

Generic cause	Specific cause
Third party activity	Vehicles/other equipment not related to excavation activity
	Excavation machinery
	Heavy loads
	High-voltage electrical
	Shipping traffic in river
	Pipe resting on rock
Corrosion	External corrosion
	Internal corrosion
	Stress corrosion cracking
Mechanical failure	Aging
	Construction defects
	Material defects
	Overpressure
	Supports failure
	Weld failure
Operational/human error	Decommission
	General operations
	Hot tapping

Generic cause	Specific cause
	Maintenance
	Pigging operations
	Pressure testing
	Repair/replacement
	Shutdown
	Start-up
	Valve operations
Natural hazard	Cold weather
	Erosion
	Floods
	Land slides
	Heavy rains
	Lightning
Equipment failure	Buckle in pipe
	Control system
	Flange
	Isolation valves
	Pumps/compressor
	Relief valves
	Rubber gasket
	Tap connection
	Thread
	Valves

Table 3 Total probabilities for each type of final event (compressed gases).

Final event	Type of release				Overall probability
	Hole (0.364)	Full bore rupture (0.405)	Catastrophic rupture (0.168)	Unknown type (0.062)	
Jet fire	0.357	0.360	0.612	0.462	0.410
Fireball	0	0	0.612	0	0.111
Cloud fire (flash fire)	0.061	0.126	0	0	0.074
Flame front acceleration (VCE)	0.510	0.225	0	0.769	0.314
No consequences	0.367	0.405	0.388	0.231	0.380

Table 4 Distribution of generic and specific causes of failure, according to the type of release of compressed gases.

specific cause	Type of release						
	Hole		Full bore rupture		Catastrophic rupture		Unknown typ
	No. of entries	% of release category	No. of entries	% of release category	No. of entries	% of release category	No. of entries
	3	*2.8*	*11*	*9.32*	*14*	*28.6*	*0*
rosion	1	33.3	5	45.5	8	57.1	-
osion	1	33.3	3	27.3	1	7.1	-
ion cracking	1	33.3	3	27.3	5	35.7	-

specific cause	Type of release						
	Hole		Full bore rupture		Catastrophic rupture		Unknown typ
	No. of entries	% of release category	No. of entries	% of release category	No. of entries	% of release category	No. of entries
ailure	*6*	*5.7*	*3*	*2.5*	*0*	*0*	*0*
	1	16.7	-	-	-	-	-
ves	-	-	1	33.3	-	-	-
ressor	1	16.7	-	-	-	-	-
on	-	-	1	33.3	-	-	-
	-	-	1	33.3	-	-	-
	4	66.7	-	-	-	-	-
failure	*5*	*4.7*	*11*	*9.3*	*7*	*14.3*	*0*
	1	20.0	1	9.1	1	14.3	-
defects	-	-	1	9.1	1	14.3	-
ects	-	-	-	-	1	14.3	-
e	-	-	4	36.4	4	57.1	-
	2	40.0	5	45.5	-	-	-
	2	40.0	-	-	-	-	-
rd	*8*	*7.6*	*7*	*5.9*	*1*	*2.0*	*0*
	-	-	2	28.6	-	-	-
	6	75.0	3	42.9	1	100.0	-
	1	12.5	1	14.3	-	-	-
	1	12.5	1	14.3	-	-	-
/human error	*11*	*10.4*	*9*	*7.6*	*2*	*4.1*	*0*
rations	1	9.1	-	-	-	-	-
	5	45.5	3	33.3	2	100.0	-
cement	3	27.3	4	44.4	-	-	-
	-	-	1	11.1	-	-	-
	-	-	1	11.1	-	-	-
ion	1	9.1	-	-	-	-	-
	1	9.1	-	-	-	-	-
ctivity	*34*	*32.1*	*36*	*30.5*	*8*	*16.3*	*1*
r equipment not related to ctivity	4	11.8	7	19.4	1	12.5	-
nachinery	29	85.3	26	72.2	7	87.5	-
	-	-	2	5.6	-	-	-
ffic in river	-	-	-	-	-	-	1
	1	2.9	1	2.8	-	-	-
use	*39*	*36.8*	*41*	*34.8*	*17*	*34.7*	*17*
Total	106	100.0	118	100.0	49	100.0	18

Table 5 Total probabilities for each type of final event (liquefied compressed gases).

Final event	Type of release				Overall probability
	Hole (0.531)	Full bore rupture (0.347)	Catastrophic rupture (0.041)	Unknown type (0.082)	

Jet fire+(Pool fire)	0.273	0.706	1	0	0.465
Fireball	0	0	1	0	0.047
Cloud fire	0.182	0.118	0	0	0.140
Flame front acceleration	0.273	0.412	0	0	0.302
No ignition	0.455	0.529	0	1	0.488

Table 6 Distribution of generic and specific causes of failure, according to the type of release of liquefied compressed gases.

Generic and specific cause	Type of release					
	Hole		Full bore rupture		Catastrophic rupture	
	No. of entries	% of release category	No. of entries	% of release category	No. of entries	% of release category
Corrosion	*4*	*15.4*	*0*	*0*	*0*	*0*
External corrosion	2	50.0	-	-	-	-
Internal corrosion	1	25.0	-	-	-	-
Stress corrosion cracking	1	25.0	-	-	-	-
Equipment failure	*2*	*7.7*	*1*	*5.9*	*0*	*0*
Valves	2	100.0	1	100.0	-	-
Mechanical failure	*4*	*15.4*	*3*	*17.7*	*1*	*50.0*
Construction defects	-	-	-	-	1	100.0
Construction defects and overpressure	1	25.0	-	-	-	-
Overpressure	-	-	1	33.3	-	-
Weld failure	2	50.0	2	66.7	-	-
Unknown	1	25.0	-	-	-	-
Natural hazard	*1*	*3.9*	*2*	*11.8*	*0*	*0*
Floods	1	100.0	-	-	-	-
Land slides	-	-	1	50.0	-	-
Lightning	-	-	1	50.0	-	-
Operational/human error	*1*	*3.9*	*2*	*11.8*	*0*	*0*
Maintenance	1	100.0	1	50.0	-	-
Repair/replacement	-	-	1	50.0	-	-
Third party activity	*6*	*23.1*	*6*	*35.3*	*0*	*0*
Vehicle/other equipment not related to excavation activity	1	16.7	-	-	-	-
Excavation machinery	4	66.7	6	100.0	-	-
Shipping traffic in river	1	16.7	-	-	-	-
Unknown cause	*8*	*30.8*	*3*	*17.7*	*1*	*50.0*
Total	26	100.0	17	100.0	2	100.0

Table 7 Total probabilities for each type of final event (volatile liquids).

Final event	Type of release			Overall probability
	Hole (0.753)	Full bore rupture (0.235)	Unknown type (0.012)	
Jet fire	0.011	0.065	0	0.024
Pool fire	0.051	0.072	0.200	0.057
▓Local pool fire	0.016	0.022	0.200	0.019
▓Fire on migrating liquid pool	0.036	0.051	0	0.039

Cloud fire	0.033	0.087	0	0.046
Flame front acceleration	0.062	0.014	0	0.051
No fire/explosion	0.900	0.826	0.800	0.882

Table 8 Distribution of generic and specific causes of failure, according to the type of release of volatile liquids.

cause	Type of release				
	Hole		Full bore rupture		Unknown
	No. of entries	% of release category	No. of entries	% of release category	No. of entries
	90	*19.7*	*18*	*12.6*	*0*
	47	52.2	6	33.3	-
	17	18.9	10	55.6	-
king	3	3.3	1	5.6	-
	23	25.6	1	5.6	-
	25	*5.5*	*4*	*2.8*	*2*
	1	4.0	-	-	-
	-	-	1	25.0	-
	10	40.0	1	25.0	-
	2	8.0	2	50.0	-
	1	4.0	-	-	-
	1	4.0	-	-	-
	1	4.0	-	-	-
	4	16.0	-	-	-
	5	20.0	-	-	2
	54	*11.8*	*29*	*20.3*	*1*
	5	9.3	2	6.9	-
	7	13.0	2	6.9	-
	11	20.4	4	13.8	1
weld failure	1	1.9	-	-	-
	-	-	4	13.8	-
ng	-	-	1	3.5	-
terial defects	-	-	1	3.5	-
	1	1.9	-	-	-
	18	33.3	5	17.2	-
g	1	1.9	-	-	-
rpressure	-	-	1	3.5	-
	10	18.5	9	31.0	-
	18	*3.9*	*15*	*10.5*	*0*
	1	5.6	-	-	-
	5	27.8	4	26.7	-
	1	5.6	-	-	-
	5	27.8	9	60.0	-
	-	-	1	6.7	-
	2	11.1	1	6.7	-
	2	11.1	-	-	-
	2	11.1	-	-	-

cause	Type of release				
	Hole		Full bore rupture		Unknown
	No. of entries	% of release category	No. of entries	% of release category	No. of entries
rror	*27*	*5.9*	*6*	*4.2*	*0*
	4	14.8	-	-	-
	1	3.7	1	16.7	-
	1	3.7	-	-	-
	5	18.5	3	50.0	-
	1	3.7	-	-	-
	11	40.7	1	16.7	-
	2	7.4	1	16.7	-
	1	3.7	-	-	-
	1	3.7	-	-	-
	139	*30.4*	*23*	*16.1*	*0*
ent not related to excavation activity	22	15.8	6	26.1	-
y	101	72.7	16	69.6	-
al	1	0.7	-	-	-
	1	0.7	-	-	-
ver	-	-	1	4.4	-
	14	10.1	-	-	-
	105	*22.9*	*48*	*33.6*	*4*
Total	458	100.0	143	100.0	7

Table 9 Total probabilities for each type of final event (liquids with low volatility).

Final event	Type of release		Overall probability
	Hole (0.868)	Full bore rupture (0.132)	
Jet fire	0.010	0	0.009
Pool fire	0.041	0.133	0.053
▓Local pool fire	0.031	0.133	0.044
▓Fire on migrating liquid surface	0.010	0	0.009
No fire	0.949	0.867	0.938

Table 10 Distribution of generic and specific causes, according to types of release (liquids with low volatility).

eneric and specific cause	Type of release			
	Hole		Full bore rupture	
	No. of entries	% of release category	No. of entries	% of release categor
orrosion	*17*	*17.2*	*2*	*13.3*
xternal corrosion	6	35.3	1	50.0
nternal corrosion	3	17.7	-	-
tress corrosion cracking	2	11.8	-	-
nknown	6	35.3	1	50.0
quipment failure	*8*	*8.1*	*1*	*6.7*
lange	5	62.5	1	100.0
umps/compressor	1	12.5	-	-

eneric and specific cause	Type of release			
	Hole		Full bore rupture	
	No. of entries	% of release category	No. of entries	% of release categor
alves	2	25.0	-	-
echanical failure	*24*	*24.2*	*5*	*33.3*
ging	2	8.3	-	-
onstruction defects	1	4.2	1	20.0
onstruction defects and weld failure	1	4.2	-	-
aterial defects	7	29.2	-	-
verpressure	1	4.2	3	60.0
eld failure	10	41.7	1	20.0
nknown	2	8.3	-	-
atural hazard	*0*	*0*	*1*	*6.7*
ow temperatures	-	-	1	100.0
perational/human error	*5*	*5.1*	*2*	*13.3*
eneral operations	1	20.0	-	-
aintenance	2	40.0	1	50.0
ressure testing	1	20.0	-	-
tart-up	1	20.0	-	-
alve operation	-	-	1	50.0
hird party activity	*33*	*33.3*	*0*	*0*
ehicle/other equipment not related to excavation activity	3	9.1	-	-
xcavation machinery	29	87.9	-	-
nknown	1	3.0	-	-
nknown cause	*12*	*12.1*	*4*	*26.7*
Total	99	100.0	15	100.0